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LETECKÝ ÚSTAV

SATELLITE REFUELING MISSION PROPOSAL

NÁVRH MISE PRO DOPLNĚNÍ PALIVA DRUŽICE

MASTER'S THESIS
DIPLOMOVÁ PRÁCE

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Assignment Master's Thesis

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As provided for by the Act No. 111/98 Coll. on higher education institutions and the BUT Study and Examination Regulations, the director of the Institute hereby assigns the following topic of Master's Thesis:

Satellite refuelling mission proposal

Brief Description:

Every year satellites providing weather data, communications, navigation, or Earth observation are retired. The reason is often satellite´s inability to maintain orbit position because they run out of the fuel. Process of replacing retired satellite is for the operators and customers expensive and time consuming. Alternatively to the complete satellite´s replacement are the existing concepts of the on orbit refueling missions. These concepts promise increasement of satellite´s life span, cost reduction and prevention from further space debris creation.

Master's Thesis goals:

– Description of satellite refueling process, benefits and challenges.
– Mission analysis of existing solution variants and projects.
– Identification of mission needs, requirements and constrains.
– Satellite refuelling mission proposal.

Recommended bibliography:

WERTZ, J. R., LARSON, W. ed. Space Mission Analysis and Design. 3rd ed. Torrance (California): Microcosm, 1999. ISBN 1-881883-10-8.

LEY, W., WITTMANN, K., HALLMANN, W. ed. Handbook of Space Technology. Chichester: John Wiley, 2009. ISBN 978-0-470-69739-9.

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Abstract

This diploma thesis deals with the topic of on-orbit satellite refueling. The thesis describes the concept of refueling on-orbit and provides the overview of the passed and planned missions and technology focused on the refueling and life-extension. The specifics of the refueling mission are identified as well as applicable constraints and needs resulting in the overall mission statement. A proposal for refueling mission is drafted further elaborating mission requirements and concept of operations. Payload critical to the mission is proposed. This work brings the description of on-orbit refueling process and provides a proposal of the mission to realize the task. Based on this work a spacecraft can be designed to provide satellites with fuel.

Abstrakt

Tato diplomová práce se zabývá problematikou doplňování paliva družicím na orbitě. V práci je popsán koncept doplňování paliva na orbitě společně s přehledem misí a technologií zabývajících se doplňováním paliva a prodloužením životnosti. Jsou uvedena specifika mise pro doplnění paliva, potřeby a omezení platné pro danou misi na základě kterých je formulováno programové prohlášení. Je představen návrh mise na doplnění paliva dále rozpracovávající požadavky mise a koncepci operací. Návrh zarhnuje možné klíčové vybavení pro misi. Tato práce přináší popis doplňování paliva družic na orbitě a představuje návrh mise určené k výkonu tohoto úkolu. Na základě této práce je možné navrhnout kosmickou družici určenou k zásobování jiných družic palivem.

Keywords

refueling, life-extension, satellite, servicer spacecraft, space mission, on-orbit, geostationary earth orbit, propellant transfer, mission objective, requirements

Klíčová slova

doplnění paliva, prodloužení životnosti, družice, servisní kosmická družice, vesmírná mise, orbitální, geostacionární oběžná dráha, transfer pohonných hmot, cíl mise, požadavky

Reference

ČUDA, Adam. *Satellite refueling mission proposal.* Brno, 2022. Master's thesis. Brno University of Technology, Faculty of Mechanical Engineering. Supervisor Ing. Ondřej Krepl, Ph.D.

Rozšířený abstrakt

Tato diplomová práce se zaměřuje na inovativní koncept doplňování paliva družicím přímo na orbitě v průběhu jejich provozu. Současný přístup k návrhu kosmických družic je poskytnout předdefinované množství paliva, které postačí po stanovenou dobu funkčnosti družice. U velkých družic s dlouhou dobou plánované životnosti (10 – 15 let) tvoří hmotnost paliva až 60 % hmotnosti družice. Pro podstatnou část družic operujících na různých orbitách kolem Země je množství paliva, kterým jsou vybavené limitujícím faktorem, protože při jeho vyčerpání není družice dále schopna udržovat svou pozici na orbitě. Přestože ostatní přístrojové vybavení zůstává v mnoha případech nadále plně funkční je provozovatel nucen nadále nefunkční družici nahradit, případně odstranit tu vysloužilou.

Alternativu ke kompletní výměně družice za novou nabízí koncept doplňování paliva na orbitě nabízející možné snížení nákladů na provoz kosmického systému a potenciální předejití tvorbě nového kosmického smetí v podobě odstavených nefunkčních družic. Koncepční řešení problematiky doplňování paliva na orbitě spočívá ve vypuštění servisní družice s robotickým vybavením schopné autonomního výkonu daných funkcí. Servisní kosmická družice je navedena na setkání s funkční družicí, které dochází palivo a blíží se tedy ke konci svojí životnosti. Obě kosmická tělesa se bezpečně spojí s pomocí robotického systému a servisní družice následně přečerpá danou část paliva do družice klienta, tímto způsobem je efektivně možné prodloužit životnost o jednotky let (další prodloužení životnosti není zpravidla vyžadováno z důvodu dalších selhání a zastarávání zbylého vybavení družic).

Cílem této diplomové práce je analyzovat problematiku doplňování paliva. Určit hlavní přínosy a motivaci k uskutečnění mise na doplnění paliva ve vesmíru a zároveň identifikovat úskalí a omezení spojená s danou misí. Dalším cílem je zpracování přehledu projektů a misí uskutečněných v minulosti a také misí, které jsou teprve ve fázi přípravy a realizace. Hlavním cílem práce je poté sestavit set klíčových požadavků, základních potřeb a limitujících faktorů, které mohou být na misi doplnění paliva aplikovány. Záměrem této analýzy je formulace návrhu vesmírné mise umožňující doplnění paliva na orbitě.

První kapitola diplomové práce se zabývá popisem problematiky doplňování paliva a představením obecného konceptu, který zasazuje do širšího kontextu tzv. servisních služeb na orbitě. Obsahem kapitol se sestavení přehledu hlavních benefitů, které doplnění paliva ve vesmíru může přinášet. Mezi hlavní identifikované přínosy patří prodloužení životnosti stárnoucích družic, které už se nacházejí na orbitě, což přináší další možný zisk pramenící z přidané operační doby. Dalším využitím pro doplnění paliva se může stát tzv. suchý start. Jedná se o přístup, kdy je nová družice vypuštěna pouze s minimálním množstvím paliva na palubě a počítá se s bezprostředním dotankováním nádrží až na orbitě. Tento přístup vede k výrazné úspoře celkové hmotnosti což se projeví snížením ceny za vypuštění družice, případně může být hmotnost uvolněná chybějícím palivem nahrazena přidaným přístrojovým vybavením, které zlepší přínos družice. Dalšími identifikovanými výhodami je přispění k udržitelnosti vesmírného prostoru a snížení tvorby kosmického smetí, které pramení z odstavených nefunkčních a neovladatelných satelitů a dále vytvoření prostoru pro vznik nového ekonomického prostoru těžištěm spočívajícím v službách na orbitě jako jsou opravy, konstrukce rozsáhlých kosmických těles a významné usnadnění výzkumných misí do hlubokého vesmíru.

Druhá kapitola přináší přehled misí zaměřených na prodloužení životnosti současných družic. Rozsah misí pokrývá mise plánované a realizované národními a nadnárodními agenturami ale také soukromým sektorem. Jsou zastoupeny mise sloužící jako demonstrátory technologie, ať už se jedná a autonomní operace v blízkosti kosmických těles, robotické systémy instalované na palubě družic nebo systémy pro bezpečné přečerpání a kontrolu skladovaní běžně používaných pohonných hmot družic. Objevují se ale také mise čistě komerční, navržené soukromými společnostmi pro provozovatele satelitů těžících z prodloužení životnosti. Společně s přehledem celých misí je uveden i doplňující přehled dalších jednotlivých technologií a vývojových projektů zaměřených na kosmický hardware určený k realizování doplňování paliva.

Další kapitola analyzuje získané poznatky a shromažďuje další potřebné údaje nutné k identifikaci potřeb a předpokladů mise zaměřené na doplňování paliva ve vesmíru. V kapitole jsou identifikováni potenciální zákazníci, kteří mohou významně benefitovat ze služeb prodloužení života, těmi jsou zejména provozovatelé komunikačních satelitů umístěných na geostacionární oběžné dráze. Je sestaven přehled klíčových technologických součástí nezbytných pro úspěšnou realizaci mise identifikující senzorické vybavení servisní družice, robotický systém, systém pro přečerpání paliva a nezbytný kontrolní a řídící software. Závěrem kapitoly je uveden standardně používaný přístup a hlavní kroky v řešení a navrhování vesmírným misí, kterými se řídí i tato práce.

Závěrečná kapitola obsahuje samotný návrh mise určené k doplnění paliva. Na základě formulovaného programového prohlášení mise jsou identifikovány hlavní a vedlejší cíle mise. Dále jsou vyvozeny hlavní technické požadavky související s problematikou doplňování paliva. Požadavky první úrovně jsou zaměřeny především na misi jako celek a také na hardwarové a softwarové vybavení družice zajišťující dotankování paliva pro družici zákazníka. Je proveden funkční a systémový rozbor dané mise a detailně rozpracovaný koncept operací popisující v krocích celý proces doplnění paliva. Pozornost je dále věnována předběžnému návrhu řešení splňujících definované požadavky formulované na počátku návrhu. Blíže je definována orbita a přístrojové vybavení. Závěrem je provedena základní analýza proveditelnosti.

Výsledkem a přínosem této diplomové práce je představení a analýza problematiky doplňování paliva na orbitě. Rozbor klíčových požadavků a specifik dané mise na základě kterých je představen návrh na realizaci takovéto mise. Tato práce může posloužit jako základ projektu zaměřeného na design a realizaci mise s cílem doplnit palivo družici a tím prodloužit její životnost.

Satellite refueling mission proposal

Declaration

I hereby declare that I am the sole author of this master's thesis which I elaborated under the supervision of Ing. Ondřej Krepl Ph.D. I have listed all the literary sources, publications and other sources, which were used during the preparation of this thesis.

. . . .
Adam Čuda
May 20, 2022

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I would like to express special thanks to my supervisor Ing. Ondřej Krepl Ph.D. from OHB Czechspace for his valuable insight and enthusiasm, you inspire me to think big and go beyond. My gratitude belong also to Ing. Václav Lazar for his advice and pragmatic comments. Lastly I would like to thank my girlfriend and parents who supported me in my studies.

Contents

Chapter 1

Introduction

Many technologies that are essential for daily life such as communication services, global and local navigation data for transportation, weather forecasting or Earth observation rely on hundreds of satellites that are orbiting Earth in various altitudes. Due to humanity's insatiable need for information and communication, up to 50 000 new satellites will be deployed in space in the next decade [21]. While many will be small, disposable micro-satellites, the need for larger high-powered systems will also increase [29]. These remarkable pieces of technology carrying high-tech equipment and instruments tend to be very costly in terms of development, manufacturing, assembly, launch and operation [2]. Until now, these have been designed to run on only the fuel they carried when launched and there was no way of getting in contact with stranded vehicle orbiting thousands of kilometers above the surface of Earth reaching speeds of several kilometers per second. The spacecraft had to stay in the position where they were initially deployed (or where they got by its own propulsion at a significant fuel consumption), and when out of propellant, or if struck by a malfunction, had to be abandoned.

A new service and supply industry is being born to provide propellant, parts, and repairs, as well as the ability to move satellites into different orbits. Tow trucks, gas stations, and robotic space mechanics will not only extended the life of space assets, they will also be the basis for an entirely new space economy built on the core frontier tenets of re-use, recycling, re-supply and re-purposing [29]. On-orbit servicing (OOS), the provision of services in space, is a key element in the continued exploitation of the space and in establishing and maintaining the required space infrastructure. It can considerably reduce the operating costs for contemporary unmanned space assets such as navigation satellites and geostationary communications satellites. For unmanned space activities it means the use of robots with a high degree of autonomy. This aspect of unmanned space flight is becoming increasingly important and necessary [6] and technology companies around the world are starting to work on a solutions.

This work focuses on the orbital refueling activities as one of the lucrative services in a broader category of in-orbit service operations describing the process of on-orbit refueling along with its merits and drawbacks. Thorough overview of the contemporary missions and technology developed to enable refueling of the satellites directly in-orbit is provided

The practical part of the thesis revolves around the proposal for the satellite refueling mission. Firstly, key mission needs and constraints are identified resulting in the formulation of particular mission statement. Secondly a proposal is elaborated into mission objectives, top level key technical requirements and concept of operations. Furthermore a technical solutions to the given needs are proposed. The proposal part is closed with discussion upon alternative technical solutions to the problematic and identification of the main risks and trade-offs.

Chapter 2

Satellite refueling process

The task of refueling may be encompassed into a broader category of satellite servicing activities which include additional tasks such as satellite inspection, operations to adjust orbit or different variants of repairs and augmentations to a satellite. These different in-orbit operations to a certain level all include Rendezvous, Proximity Operations and Docking (RPOD) a thus it might make sense from an economic and technological point of view to associate these capabilities under one mission and enable the servicing spacecraft to carry out a range of in-orbit tasks (examples given in Chapter 3).

A typical servicing tasks as grouped in Handbook of Space Technology are listed bellow [6]:

1. **Inspection:** Recording and collecting data from the target satellite. This task requires merely the capability to fly around the satellite plus the corresponding visual sensor technology:
    (a) **Remote Inspection:** Failure diagnosis by remote sensing of target.
    (b) **Close-up Inspection:** Scanning the target satellite using various kinds of sensor technology.
2. **Motion:** Translation services to the target satellite, which requires docking capability. These tasks relate to the assumption of orbit and attitude control, or orbit and station change. The service satellite must accordingly have an appropriate propulsion and attitude regulating capability:
    (a) **Reorbit:** This task includes the transfer of a stranded target satellite to its originally planned operational orbit, or a later change of operational orbit in case the former position is to be occupied by a new or superior satellite.
    (b) **Deorbit:** This task includes the transfer of the target satellite into a so-called graveyard orbit, or into a reentry orbit for its deliberate destruction and thus disposal in the atmosphere.
    (c) **Salvage:** This task involves either the transfer of the target satellite to another space vehicle, or its nondestructive reentry.

3. **Manipulation:** This involves dedicated control of subsystems or some type of intervention, which requires additional interfaces between the target and service satellites:
    (a) **Maintenance and Checkout:** Supplying the target satellite with consumables (liquids, fuel) as well as cleaning, resurfacing and decontamination tasks.
    (b) **Repair:** Diagnosis and correction of module failure in the solar generators, gyroscopes, antennas, etc.
    (c) **Retrofit:** Upgrading by replacement with more efficient modules.
    (d) **Docked Inspection:** Failure diagnosis by physical interrogation of the target satellite via connectors.

There is a natural hierarchy of tasks which can be carried out by on-orbit servicers in order of increasing complexity. Inspection involves investigating space assets for damage assessment and failure reporting of the externally visible state of the target. This requires the technology of highly precise maneuvering. For greater distances in the kilometer range, absolute navigation may be necessary, but in all other cases the preference, for safety reasons, is precise maneuvering with relative navigation to the target, whereby the attitude and orientation of the service satellite have to be determined with appropriate sensory instruments.

In order to carry out the next phases in on-orbit servicing, a rendezvous and docking maneuvers are necessary. In addition to the previously mentioned navigation capability required for remote inspection, a very precise resolution in determining the relative position of the two vehicles is particularly essential for docking maneuvers. This can be accomplished with exact distance measurements, but, ideally, with the aid of optical cameras and appropriate image processing. Whether a docking procedure is handled automatically or controlled from Earth mainly depends on the communication links from and to the service satellite, which are determined by the orbit.

Target satellites can be of constant attitude and status if their attitude control system is functional. This significantly reduces the effort involved in tracking the target and especially in docking maneuvers. A deactivated satellite may have an axial rotation around its longitudinal axis (a typical state after the so-called passivation) or may be tumbling randomly. In either case high demands are made on the maneuvering, navigation and docking capabilities of the service satellite. As a rule, such objects are approached only in emergency situations, in order to retrieve them or to initiate controlled atmospheric reentry.

The most profitable application for the already mentioned and yet to be mentioned types of on-orbit servicing might be docking with telecommunications satellites at End of Life (EOL) and taking over their attitude and orbit control for a number of years in order to maintain profitable telecommunication services. Such a rescue maneuver only makes sense if these usually expensive satellites are put into their target orbit at a cost that is considerably lower than the cost of new replacement satellite (or in case of failure the expected insurance sum).

Whereas technical solutions for the systems named so far (also for overall systems) have already been devised, some of which have even been demonstrated, the following on-orbit services are yet to be realized since they require appropriate active interfaces. As mentioned, only the next generation of satellites is apt to have such interfaces. In particular, refueling of orbiting spacecraft is probably the most lucrative aspect of the named scenario because it fully restores the target satellite function and, after the refueling procedure, the service satellite is free to attend to other tasks at other targets. The capabilities of robots on the ground are well known and have been demonstrated. But to carry out these kinds of tasks in orbit, the technologies have to be adapted to different marginal and environmental conditions. Reliability must also be extremely high since the service satellite should not itself become a repair case.

The first consideration when designing service satellites is to decide between single service and multiple service capability. The constructions differ in architecture, logistic support and financing models. There is little doubt that multi-mission service satellites are more useful for emergency operations. Many configurations include in-orbit depots for consumables or supplies [6].

In this chapter refueling process is introduced. General approach to refueling in orbit is given alongside the general process of refueling given in Section 5.4 and critical technology, further discussed in Section 4.3, for a refueling vehicle to have to be able to carry out given mission. Main benefits of the refueling are summed up and constraints and obstacles are presented.

2.1 Refueling satellites

Satellite refueling and in a broader sense satellite servicing is a technological enabler for a innovative new space approach with a potential to disrupt present space industry paradigm. Capability to refuel spacecrafts directly in orbit rather than rely on fuel provided before launch for full spacecraft operational life on ground unlocks previously unthinkable opportunities.

If refueling is realised, satellites and spacecrafts in general could be no longer limited by their fuel supply and thus able to freely maneuver and change orbits if needed, a option rather avoided by satellites operator because of the direct impact on satellite life time. The deep space missions, missions to the Moon and Mars might be solved with a refueling stop e.g. on Low Earth Orbit where the tanks are refilled for longer range or faster travel speeds. The heavy lift launch vehicles needed for reaching Geostationary Earth Orbit or cis-lunar space and deep space might be switched for less capable but cheaper alternatives taking advantage in the refueling on orbit. Satellites mass budget may be shifted in favor of useful payload equipment at the expense of fuel launched on-board the satellite (dry launch) maximizing the impact of the spacecraft with fueling only after reaching desired orbit. Refueling capability and fuel depots deployed in various orbits allow for a completely new concept of in space economy encompassing in-orbit assembly, repair, refurbishment or debris removal, fuel demanding activities for a higher degree maneuverability and flexibility in these systems.

The motivation to actually establish and perform refueling in space in a form of benefits is introduced hereafter. On the other side technological and programmatic constraints exist and are identified as a challenges to overcome in the space refueling venture.

2.2 Benefits

2.2.1 Life extension for existing satellites

Geostationary Earth Orbit (GEO) is a great position for a satellite to operate as it offers the unique option to secure the Spacecraft (S/C) in a fixed position relative to Earths surface. This advantage is mostly exploited by commercial communication satellites. Unfortunately GEO is a very limited asset for placing satellites, with specific altitude and spacing of the slots at around 2°[8] to avoid physical and signal interference, satellites need to be placed precisely and maintain the given position. Every year around 20 GEO satellites are spent [8] due to propellant exhaustion while the rest of the subsystems are fully operational. In this case the satellite needs to be moved to safe graveyard orbit because it is no longer controllable and might interfere with other satellites positions. Refueling these S/C is a natural way to extract more economic value from the asset and the life extension of a functional satellite is probably most obvious motivation to establish refueling capability on orbit.

2.2.2 Dry launch

With functional refueling services the current launching paradigm might change. So far every satellite was launched equipped with all the expendables - predominantly fuel - for its entire operational life. The result of this approach are fuel tanks of considerable size for satellites designed to operate for long time spans. The expendables in case of GEO telecommunication satellites typically account for 40 - 60 % of launch mass (see also Figure 4.3b) The on board fuel obviously reduces space for payload equipment which is of interest and makes the whole S/C heavier and thus more expensive to launch.

In-orbit refueling might enable launching satellites with much smaller tanks designed to be refueled during service to meet the operational life time. Furthermore the S/C might be launched with only minimal fuel on board, reducing the launch weight (and directly the launch cost). This approach is known as a dry launch and the S/C is fully fueled only after it reaches temporary or final orbit.

2.2.3 Sustainability

Refueling might also play substantial role in more sustainable usage of space. As launched costs have dropped significantly space became more accessible to all. Yet the earth orbits of interest are limited asset and humanity needs to control this precious domain. Another issue with sustainable orbit management is the rising thread of space debris and so called Kessler effect.

Refueling capability may shift the approach of replacing aging satellites with new ones to more sustainable model of keeping the satellites operational as long as possible thus potentially reducing the total amount of launched satellites to orbit. Another contribution to the space sustainability might become refueling space tugs which will actively remove space debris and defunct satellites from active orbit (both for graveyard orbit and down to atmospheric reentry). These tugs will need to execute rather complicated maneuvering sequences to capture non-cooperational items and consequently transport those to a safe location. Both these parts require substantial ammount of ΔV resulting in considerable fuel consumption. It would considerably improve overall efficiency of these Active Debris Removal space tugs if they could be refueled during service and execute multiple removal missions.

2.2.4 Refueling as a technological enabler

Refueling and other emerging technologies such as on-orbit repair or assembly have the potential to disrupt present space industry concept. Refueling allows for higher payload to launcher mass ratio, maximizing the potential payoff, supports transport and relocation of assets between different orbits a fuel-demanding process generally avoided by satellite operators or makes deep space ventures less demanding in terms of total launcher (propellant) needed. The scientific experts and industry [8] [7] [13] agree on the importance of the refueling as a steppingstone to bustling in-space economy and technological enabler to future space exploration and commercial ventures.

2.2.5 High technology maturity

In the range of task expected from a refueling spacecraft, the technology does not appear to be a limiting factor, as a study conducted at NASA in 2010 claims [8]. Complex servicing tasks have already been demonstrated with human astronauts involved to which an International Space Station served as a great platform. Advanced robotic analogues have also been demonstrated on ground with overall success. Since 2010 many demonstrator mission has been launched and the shift to robot only servicing has seen significant improvement (examples are given in Chapter 3).

The maturity of the technology is typically classified in Technology Readiness Levels (TRL). These are management metrics to determine the overall maturity of given technology - either hardware, software or a process. Overview of the TRL is given in Figure 2.1 where basic description to each level is given. TRL 1 is the lowest, least developed state while TRL 9 is the most developed stage. Majority of the critical technology for refueling mission has been demonstrated and flight proven, therefore have reached TRL 9.

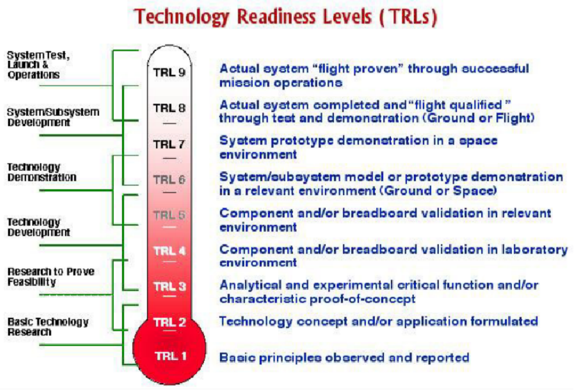


Figure 2.1: Technology readiness levels [4]

2.2.6 Satellites designed to be serviced

So far no satellites have been designed and launched with a future servicing in mind, yet rendezvous and contact with such S/C has been successfully demonstrated. The unaided proximity operations certainly impose higher risk and task complexity for a servicer S/C to undergo. With satellites designed to be refueled and already prepared to be serviced this task is still of high risk and complexity, but significantly aided by active involvement on the side of the client (serviced) S/C. This can mean active and passive relative navigation aid, cooperative attitude control or grappling surfaces and interfaces.

2.3 Challenges and constraints

2.3.1 Standardisation needs

A major challenge to having a more efficient practise in space industry is the lack of widely agreed-upon standards for spacecraft design that would permit more straightforward on-orbit upgrade, refueling, and recovery. A set of basic design standards for S/C subsystems that would be serviceable, such as fueling ports, connectors, power systems (batteries, solar arrays), antennas, and instruments whose components are likely to take advantage of technological improvements. If such voluntary design standards were adopted industry-wide the on-orbit serviceability of new spacecraft would improve and could potentially improve ground processing efficiency as a side benefit [8].

2.3.2 Cost of servicing

A cost effectiveness analysis [1] looked at the possibility of extending a satellite's life through the use of on-orbit servicing and found that fuel depletion has a significant impact on satellite operations in geostationary orbit. By using a cost-per-year approach and comparing the replacement cost of a satellite and its design life to the cost of a servicer and its refueling capacity, analysis showed that the servicer must refuel three to five customer satellites to be cost-effective.

These simplified analyses do not take into account the intrinsic value of servicing, such as providing options that allow the mission to adapt to changing requirements. They also overlook the effect that a servicing paradigm would have on driving down costs by encouraging satellites with shorter lifetimes and reduced redundancy, effectively being a risk mitigation tool and potentially making satellites cheaper to build.

2.3.3 Client spacecraft readiness

Although possibility to refuel even spacecraft not originally designed to be serviced as demonstrated in various missions mentioned in Chapter 3 a servicing-ready customer satellite is a significant enabler to the whole process. In order to ease in-orbit refueling (and in general servicing) the S/C may feature some of the following: optical retro-reflective surfaces or other visible surface features, transponders for telemetry and ranging exchange with servicer, suitable grapple fixtures and/or proper attitude control system modes suitable for RPOD [8].

Notice that the implementation difficulty impact of such features on the S/C is relatively little in comparison with the benefits that refueling introduces. Apart from the added telemetry communications these features do not require power. Optical surface features impose little to no change for a spacecraft design and mass. The radio frequency transponders certainly take up some volume and mass form a S/C budget and the use of such is for consideration, however in comparison with other S/C communication and data flows, telemetry is modest in volume [8]. A grapple fixture designated for servicing activities allows for safe a robust means for berthing and docking compared with e.g. berthing to Launch Vehicle Adapter. Use of the grapple fixture introduces added mass to the S/C and a mass trade-off is likely. Logical step to do is to reduce the amount of on-board fuel which can be later refilled. Additional operations mode for RPOD is of similar complexity with other standard modes and should be possible to incorporate to existing control software of the S/C ensuring cooperative attitude control and safer proximity operations for both servicer and client S/C.

2.3.4 Refueling demonstration

Even though individual refueling mission elements have been demonstrated during various missions (examples given in Section 3) the concept of refueling is still perceived as new and risky among potential customers. Being and emerging concept as on-orbit refueling missions still are, they have to earn trust throughout the market. Currently its hard to sell a refueling mission to the customer as they have never encountered it and do not have a reference in most cases.

Once the satellite on-orbit refueling will reach maturity and become a standard procedure satellite manufacturers and operators themselves might require a refueling capability and refueling ready spacecraft. Currently there are promising ventures preparing to deploy a fully capable autonomous refueling spacecraft sometime in second half of the decade, but such capability is still yet to come and prove itself to the potential customer. With each demonstration however the development leads into full missions, each additional mission adds maturity and confidence in the concept and trust and willingness of the satellite operators to prepare their assets for refueling [8]. P

Chapter 3

State of the art refueling projects

In this chapter an overview of the past and planned missions and projects regarding satellite refueling is given. Missions with the direct objective to refuel a spacecraft are listed in the first place, afterwards other related projects and technologies are presented.

3.1 Northrop Grumman missions

Northrop Grumman - one of the leading space players is developing satellite servicing technologies for commercial market including satellite refueling. Through its subsidiary Space Logistics Northrop already demonstrated its capability to rendezvous and dock with a satellite nearing its EOL. Space Logistics is the first and only company performing on-orbit servicing for commercial GEO satellites so far. Company's planned series of vehicles will extend service life, provide enhanced capabilities and enable future missions for a variety of customers [30].

The approach of the Northrop Grumman missions favours attaching a special developed self sustaining equipment to the client satellite rather than directly transferring fuel to the build-in tanks of the satellite. Using this approach the need of refueling interface is avoided and thus it is suitable for satellites not originally designed to be refueled. In company vision Northrop Grumman states the establishment of a fleet of commercial servicing vehicles in GEO that can address most servicing needs. Northrop Grumman continues to make deep investments in in-orbit servicing and is working closely with U.S. Government agencies to develop the next generation space logistics technologies. These technologies include robotics and high-power solar electric propulsion to enable future services [20].

3.1.1 MEV - Mission Extension Vehicle

The SpaceLogistics MEV delivers life-extension services using a suite of integrated proximity sensors and a simple mechanical docking system to rendezvous and dock with a client satellite running low on fuel, taking over its attitude and orbit maintenance.

With two ongoing commercial missions (MEV-1 in 2020 and MEV-2 in 2021), SpaceLogistics is the first and only company to successfully perform on-orbit satellite servicing of commercial geostationary orbit (GEO) satellites. MEV-1 successfully docked - see Figure 3.1 - with the customer Intelsat IS-901 on February 2020 and took over the attitude and orbit maintenance of the combined vehicle stack to meet the pointing and station keeping

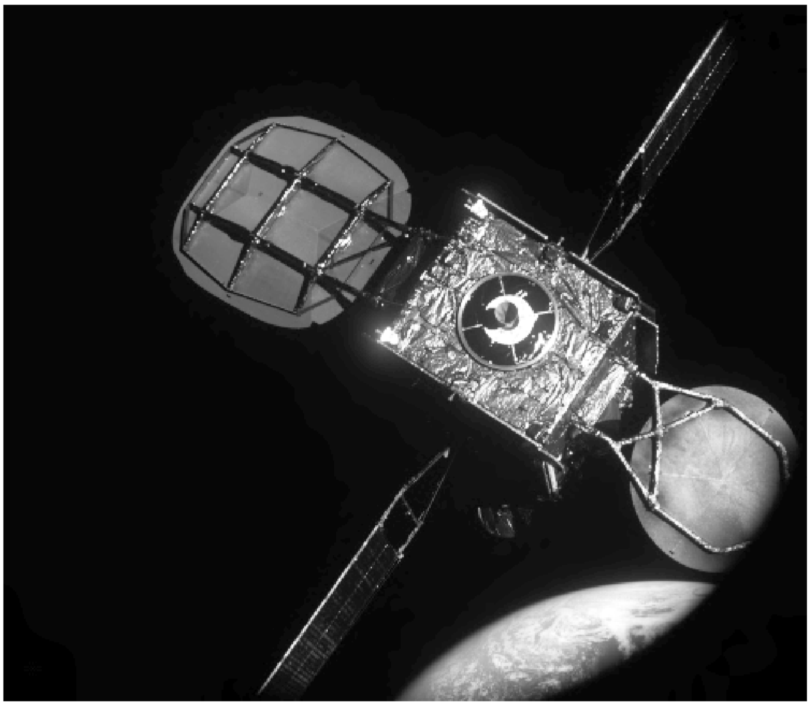


Figure 3.1: View of IS-901 satellite from MEV-1 „near hold“ position during approach (figure courtesy [20])

requirements of the customer. MEV-1 will provide five years of life extension services to the Intelsat satellite before returning the spacecraft to a final decommissioning orbit [20]. Similarly the second mission MEV-2 docked with the Intelsat IS-1002 satellite on April 2021.

Designed to service multiple client satellites and carrying fuel for a planned 15+ year service life, when a customer no longer requires life-extension service the MEV is able to undock and proceed to its next client. The MEV is specifically designed to fit commercial operators' business models and technical requirements with a docking system compatible with nearly 80 % of all GEO satellites on orbit today [30].

3.1.2 MRV - Mission Robotic Vehicle

The MRV in Figure 3.2 is SpaceLogistics' 3 000 kg next-generation on-orbit servicing vehicle. The MRV leverages the heritage Rendezvous Proximity Operations and Docking system of its highly-acclaimed predecessor, the MEV, but incorporates a robotic module in place of the MEV's docking system [30].

While the MRV's primary function will be the installation of Mission Extension Pods (MEPs) or other augmentation payloads on current operational satellites, its robotics capabilities enable MRV to conduct detailed inspection of customer satellites, augmentation, orbit relocation, refueling, repairs or even active debris removal. The versatility as achieved with the help of exchangeable tools for the robotic arm.

The MRV spacecraft features electric propulsion for orbital maneuvers and refuelable chemical propulsion system for Rendezvous Proximity Operations and Docking System. The

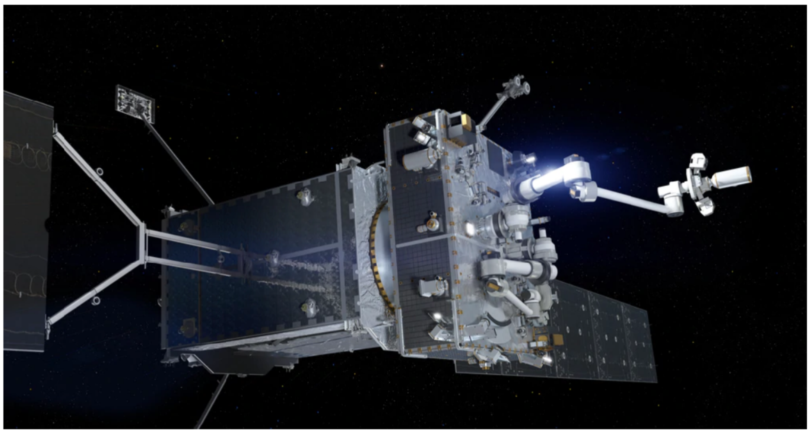


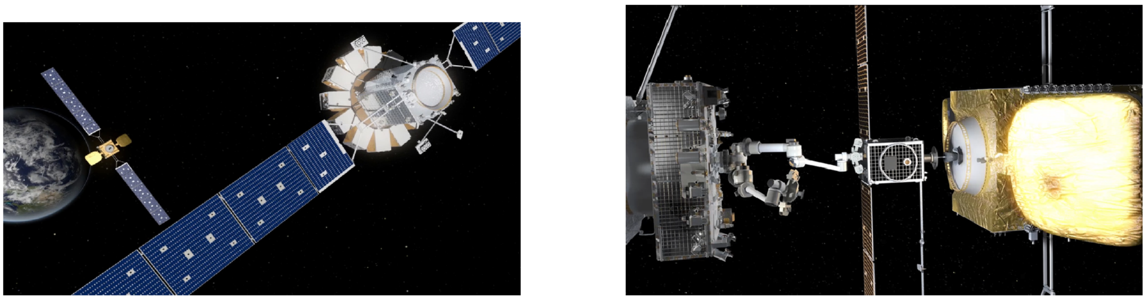
Figure 3.2: Artists Impression of Northrop Grumman MRV (figure courtesy [30])

proximity operations are enabled through the use of robotic arm capabilities and two visible light sensors, two IR cameras and two light detection and ranging (LIDAR) sensors [30]. The MRV is scheduled to launch 2024 on top of SpaceX Falcon 9 rocket [28] and is designated to operate for approximate time of 10 years.

3.1.3 MEP - Mission Extension Pod

Sold as a product, the MEP is approximately a 400 kg, customer-owned, customer-controlled propulsion augmentation device that is installed by the SpaceLogistics MRV on a client satellite already on-orbit and running low on fuel. Once installed, the MEP uses xenon propulsion module to provide orbit control and momentum unloading for a client satellite.

MEPs are designed to launch separately (due to their rather small dimensions presumably in a rideshare mode) and reach desired destination on orbit independently. Once in proximity of the target the MRV will first capture and then install - see Figure 3.3 - MEP to a client satellite [28].



(a) MRV with MEPs approaching client satellite

(b) MEP being instaled by MRV to a client satellite

Figure 3.3: MEP mission renderings (figure courtesy [28])

The MEP is controlled by the customer via a self-contained C- or Ku-band telemetry and command system, and capable of providing six years of life extension for a typical 2,000 kg satellite in GEO. The MEP provides a solution that does not involve high-risk fuel transfer or robotic operations on satellites not prepared for refueling [30].

The first MEP was sold recently to a satellite operator and should come in service as soon as 2025 [28].

3.2 ESA e.Deorbit mission

Mission e.Deorbit was originally designed by ESA to deorbit defunct Envisat spacecraft from LEO but was later redirected to a more general goal of servicing satellites as the capabilities of both servicing and debris removing spacecrafts feature autonomous guidance, navigation, control and capture capabilities. These synergies between e.Deorbit and a broader mission concept, referred to as 'in-orbit servicing' involve the development of spacecraft and technologies that could refurbish, refuel or re-boost satellites already in orbit [12].

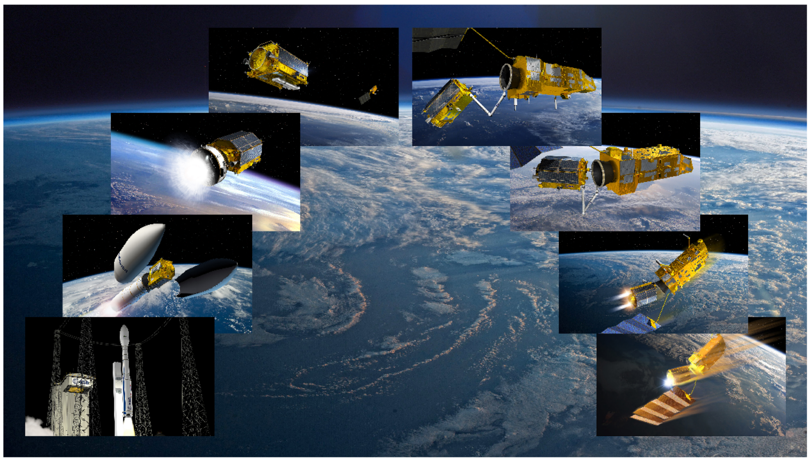


Figure 3.4: e.Deorbit mission lifecycle (figure courtesy [12])

In Figure 3.4 an illustrative mission life cycle of e.Deorbit is presented. Note the similarity between intended debris removal mission and satellite servicing mission - approach, motion synchronisation, capture and task execution. Based on development and knowledge acquired during e.Deorbit mission, ESA encourages industrial sector to make proposals to remove a defunct ESA satellite while demonstrating in-orbit servicing.

In support of European industry, ESA is continuing development of a robotic arm, not only for active debris removal but also to perform multiple satellite servicing activities such as refuelling or tugging. The sheer versatility of the robotic arm makes it an attractive prospect [12].

3.3 Thales Alenia Space

3.3.1 EROSS+ - European Robotic Orbital Support Services

European servicing efforts are led by Thales Alenia Space and the aim is to demonstrate capabilities by year 2026. The project is financed from the Horizon 2020 frame by the EU. The current phase of the project which is headed for ground demonstrators was preceded with the key technologies research and development throughout the European institutions focused on sensors, robotics and orbit operations the projects.

The space vehicles will be able to carry out a wide range of operations in orbit, including controlled re-entry of space debris, robotic manipulation, the extension of a satellite's operational life, in-orbit re-fuelling, inspection, and many more [23]. The spacecraft is designed to be as versatile and adaptable as possible to enable such a wide range of missions. Secondly, a client satellite is considered ready for collaborative and prepared rendezvous with specific features to ease its capture and manipulation, for instance, being attitude-friendly during rendezvous [33]. An artists impression of the EROSS+ spacecraft is in Figure 3.5.

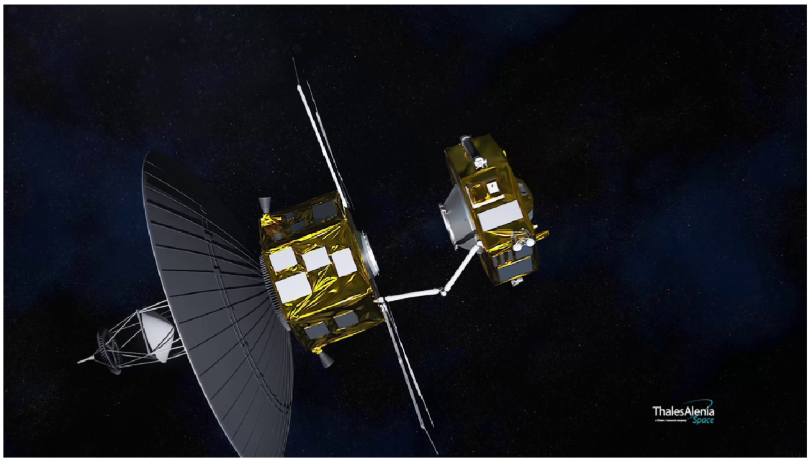


Figure 3.5: EROSS+ spacecraft docking to a client satellite (figure courtesy [23])

3.4 NASA missions

3.4.1 RRM - Robotic Refueling Mission

NASA Robotic Refueling Mission was a technology demonstration mission conducted onboard International Space Station (ISS) using ISS robotic arm and a dedicated RRM Module containing tools and satellite interfaces mock-ups. The module incorporates various valves, caps, protective thermal blankets or simulated fuel to demonstrate refueling capabilities on spacecraft not originally designated to be refueled or serviced [40]. The RRM launched with the last Space Shuttle mission in 2011 and is fully operated by flight controlers at NASA.

The mission steps involve cutting through thermal protection blankets in order to get to sealed fueling valve, cutting a lock wire on a tertiary cap, removing caps from the fuel valve, attaching nozzle, fluid transfer, detachment of the nozzle and finally the valve is left with a special adapter attached to ease possible future refueling [40].

The RRM continued in 2015 with second phase demonstrating a coolant transfer, inspection tool or replacement of satellite parts as a part of the satellite servicing capabilities. During the phase 3 of the RRM a cryocooler failure occurred leading to wenting of the cryocoolant but the remaining test were still executed [39].

3.4.2 OSAM-1 - On-orbit Servicing, Assembly and Manufacturing

Previously known as a RESTORE-L mission with a target of defunct Landsat 7, the On-orbit Servicing, Assembly and Manufacturing 1 (OSAM-1) is another NASA led effort to demonstrate servicing capabilities in orbit in collaboration with Maxar Technologies. The spacecraft is equipped with 2 robotic arms enabling life extension even for satellites not designed to be serviced. During the mission OSAM-1 shall rendezvous, grasp, refuel and relocate a satellite to extend its life. The target destination of the OSAM-1 is a polar LEO orbit where the U.S. Government customer satellite is located.

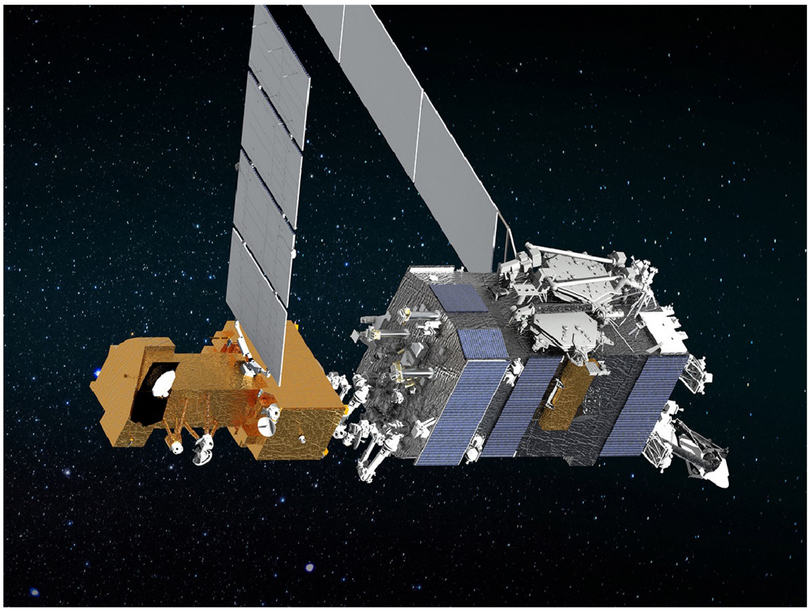


Figure 3.6: Artists vision of OSAM-1 (figure courtesy [38])

Apart from refueling itself, the OSAM-1 mission incorporates Space Infrastructure Dexterous Robot (SPIDER) payload designed to assemble a seven element communication antenna using dedicated robotic arm and manufacture a 10 meter long lightweight composite beam using pultrusion. Together these task are meant to verify the capability to construct large structures directly in orbit [38].

The OSAM-1 mission passed a CDR in February 2022 marking the readiness for manufacturing, assembly and integration of the spacecraft. Launch is not expected sooner than 2025 [27]. Artists vision of OSAM-1 is in Figure 3.6.

3.5 Astroscale

Astroscale provides satellite life-extension and other on-orbit services. The company signed a contract with Orbit Fab regarding the use of Orbit Fab's Tanker-001 service for its servicing vehicle [42].

3.5.1 LEXI - Life Extension In-orbit

The Life Extension In-orbit (LEXI) spacecraft by Astroscale displayed in Figure 3.7 is a life extension vehicle designed to dock with a client satellite and overtake station keeping and attitude control of the new stack.

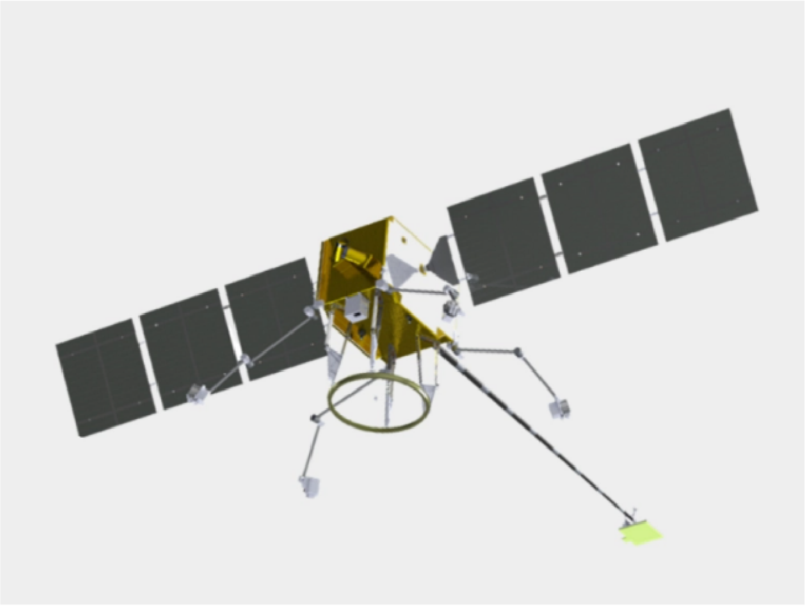


Figure 3.7: LEXI spacecraft (figure courtesy [25])

The spacecraft main propulsion system consists of four electric powered xenon thrusters placed on four independent robotic arms for precise maneuvering. Docking is realised via four robotic grappling arms which capture the clients launch vehicle adapter ring.

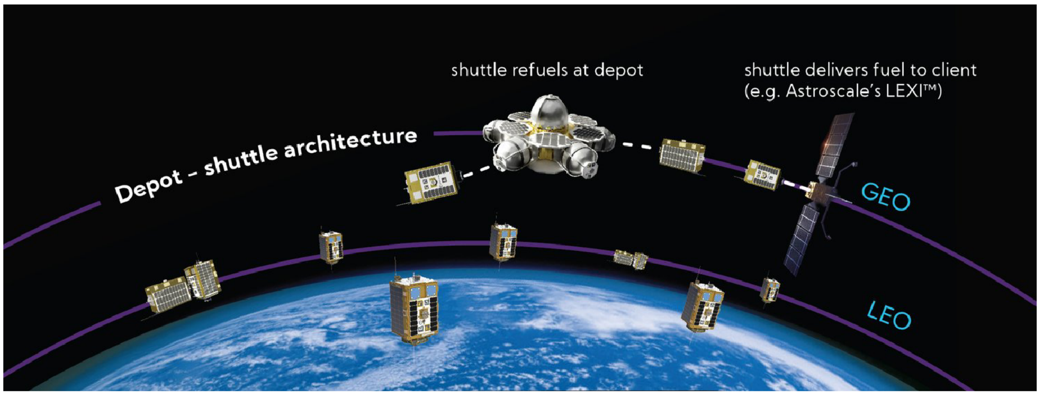
The LEXI spacecraft is also capable of relocation of the client satellite to different orbit or new GEO Location as well as delivering satellites close to their EOL to graveyard orbit. After completion of the mission LEXI spacecraft is able to undock and relocate itself to a new customer.

3.6 Orbit Fab

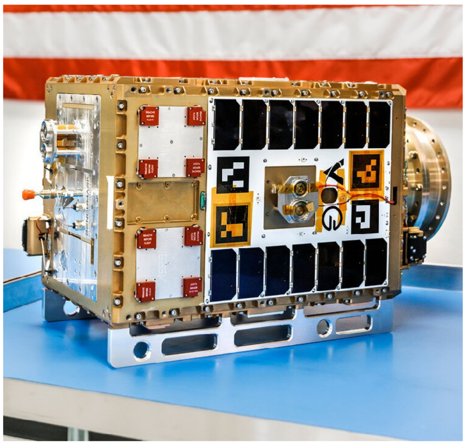
3.6.1 Tanker-001 TENZING

Orbit Fab's Tanker-001 (displayed in Figure 3.8b) technology demonstration mission is a first operational fuel depot on orbit storing the High-Test Peroxide propellant [36]. The spacecraft launched in June 2021 and orbits in sun-synchronous orbit in an altitude of approximately 525 km above the Earth surface.

The Orbit Fab refueling concept is visualized in Figure 3.8a. The architecture is based on a depots placed in various orbits and shuttles such as Tanker-001 delivering fuel to customers on demand given that the customer spacecraft is equipped with Orbit Fab's refueling interface (read bellow) [36][37].



(a) Orbit Fab refueling service architecture



(b) TENZING-001 spacecraft

Figure 3.8: Orbit Fabs' TENZING system (figure courtesy [36])

3.7 Starfish Space

Another venture aiming at satellite refueling, servicing and active debris removal is Starfish Space. The company is developing autonomous robotic systems capable of execution of satellite Rendezvous, Proximity Operations and Docking (RPOD) missions [34]. Starfish

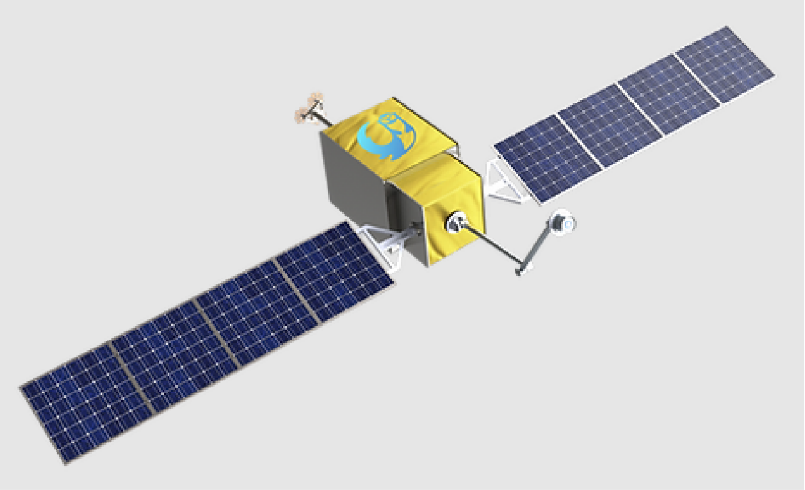


Figure 3.9: Artist impression of the Otter spacecraft (figure courtesy [34])

Space partnered with Orbit Fab on Tanker-001 mission providing it's Cephalopod software.

Otter spacecraft
An Otter spacecraft (in Figure 3.9) is a small satellite servicing vehicle capable of versatile tasks in highly autonomous regime [34].

Cephalopod software
Cephalopod is an autonomous RPOD software that can use electric propulsion, enabling small RPOD spacecraft. This on-board guidance, navigation, and control capability can give small servicing vehicles 8x more maneuvering capability [34].

Nautilus capture mechanism
The Nautilus capture mechanism attaches to satellites for docking and manipulation. The versatile mechanism works on surfaces that were not designed for docking. The system features dynamic damping of docked bodies, multi-year operational life and reuse capability [34].

3.8 China's refueling vehicle

China as a space faring nation also developed it's own refueling spacecraft which was developed by the Shanghai Academy of Spaceflight Technology under the China Aerospace Science and Technology Corporation [26].

According to the designers of the spacecraft the functions of the refueling vehicle have been simplified in the design stage in order to load as much fuel as possible. In result the spacecraft can carry up to 1.3 tonnes of fuel, more than half of its own weight, while the designers claim that 50 kilograms of fuel could help extend the life of a satellite by one year, reducing the costs by 35 percent compared with re-launching a geostationary orbit satellite.

The spacecraft is equipped with a navigation system composed of radars and cameras, enabling the vehicle to track and approach the satellite low on propellant under the guidance

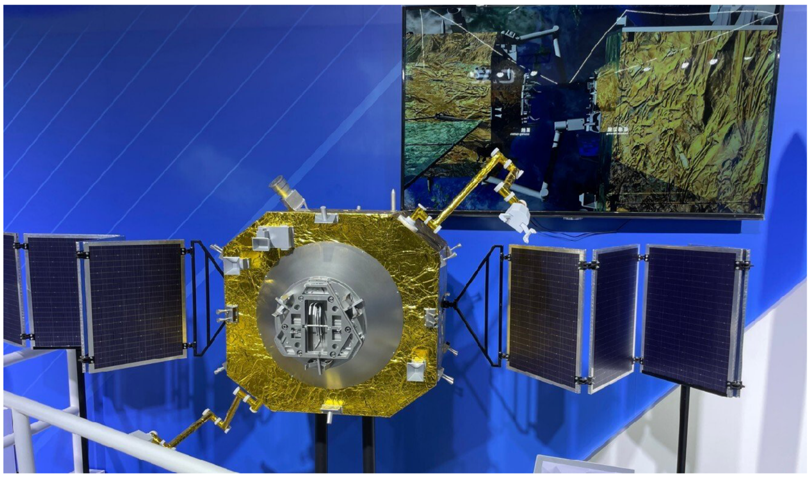


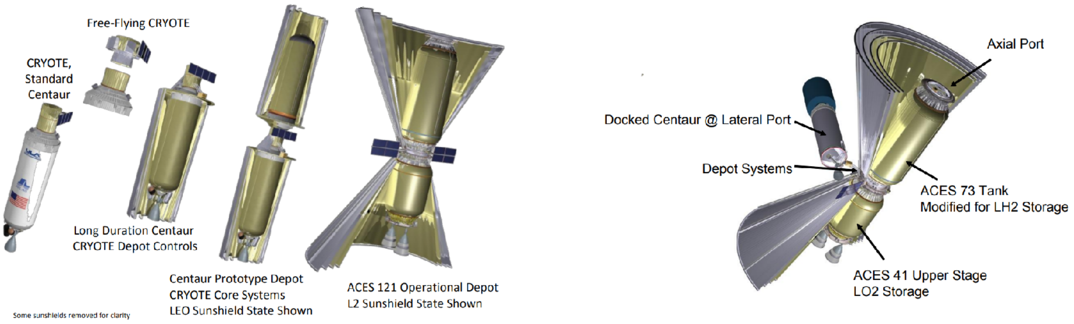
Figure 3.10: Chinese refueling spacecraft (figure courtesy [26])

of the ground control system. When reaching approximately two meters from the satellite, it can dock with the satellite's refueling port with the help of the mechanical arm and complete the fuel transfer [22]. Satellite was first introduced at the south China Airshow in 2021 - Figure 3.10.

3.9 On-orbit refueling related technologies

3.9.1 United Launch Aliance

The article by United Launch Aliance (ULA) [7] discussed possible approach to building fuel depots in LEO or Earth-Moon Lagrange points designed to serve either satellites orbiting Earth or deep space exploration missions and Mars missions. The philosophy presented suggests that refuelling on orbit might allow greater payloads to be carried or life extension of orbiting satellites compared to current approach which provides satellites all the propellant needed for a whole mission life time. The result of this approach according to the authors is that about 70 % of all the mass launched into LEO is simple propellant.



(a) Orbital depot evolution

(b) The ULA depot main parts

Figure 3.11: ULA depot sysytem
(figure courtesy [7])

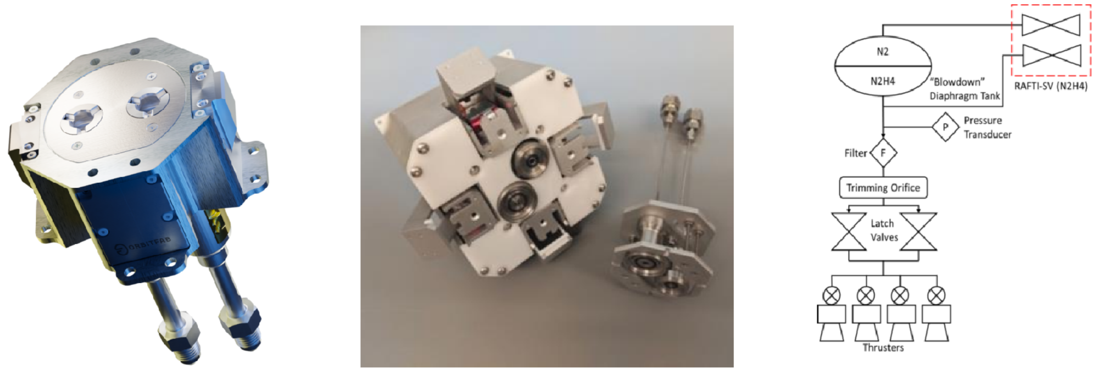
An issue with long term storage of the propellant and oxidizer (LH2 and LOX in this case) is that the cryogenic fluids tend to boil off as they are subjected to radiant heating of the Sun and the Earth. In the presented concept this obstacle is overcome by higher rates of flow of the propellant. Rather than having large tanks and cooling systems to achieve close-to-zero boil off, smaller system with mediocre boil off rates which is regularly emptied and re-filled can combat the losses simply by bringing those to acceptable portion of the overall fuel flow. Furthermore the waste hydrogen that has boiled of can be used for depot station keeping and RPOD maneuvers.

The depot architecture as seen in Figure 3.11b is based on ULA Advanced Common Evolved Stage (ACES) for Centaur and Delta launchers.
The depot is designed to be multi-launch assembly as seen in Figure 3.11a the propellant tanks are connected to the middle module housing necessary valves, piping, cooling systems and featuring Integrated Vehicle Fluid system which consumes the waste hydrogen and oxygen for power generation and maneuvering replacing majority of batteries, hydrazine and helium. Sunshield is deployed around the cryofluid tanks to combat excessive heating [7].

The ULA is working on necessary technologies such as Integrated Vehicle Fluids system, cryogenic storage ad transfer research long term and is promoting this innovative approach to getting payloads to space more efficiently.

3.9.2 RAFTI - Rapidly Attachable Fluid Transfer Interface

The Rapidly Attachable Fluid Transfer Interface (RAFTI) - Figure 3.12 - developed by Orbit Fab is a system designed to support spacecraft refueling by providing interface designated for refueling. RAFTI consists of the service valve itself and also at least three alignment markers (see in Figure 3.8b) placed on the surface of the client spacecraft to enable cooperative docking in both light and dark visibility conditions [36].



(a) RAFTI service valve (b) RAFTI coupler part (c) RAFTI functional scheme

Figure 3.12: Orbit Fabs' RAFTI system (figure courtesy [36] [13])

The RAFTI service valve comprises of octagonal grapple fixture and two valve cores allowing for two separate fluids transfers e.g. propellant and pressurant - Figure 3.12c. RAFTI allows the spacecraft to take advantage of refueling and also doubles as an effective fill/drain valve during ground operations [36]. Selected parameters of the RAFTI system are presented in Table 3.1.

Table 3.1: Selected RAFTI parameters (courtesy [36] [13])

RAFTI PARAMETERS		
Parameter	Low Pressure	High Pressure
Mass (service valve)	500 g	
Mass (coupling half)	2 000 g	3 000 g
Max Operating Pressure	500 psig	3 000 psig
Flow Rate	4 l/min @20 psi ΔP	0.5 l/min @20 psi ΔP
Compatible Media	High-Test Peroxide, Hydrazine, Kerosene	Nitrogen, Helium, Xenon, Krypton, N_2O
Operational Life	15 + years LEO & GEO	
Cycle Life	200 cycles	
Operational Temperature	-40 to 60 °C	
Max Docking Misalignment	+- 10 mm (X,Y) +- 10 degrees (X,Y,Z)	

3.9.3 ASSIST docking technology

The ESA led effort to develop a new refueling mechanism, called ASSIST, depicted in Figure 3.13, will allow satellites to be refueled and serviced while in orbit, extending their life in the future. The goal of ESA and it's industrial and academia partners in ASSIST project is also to develop a standard across the space industry for satellite refueling – allowing future built satellites to be equipped with basic passive interfaces that can be used to capture and refuel them.

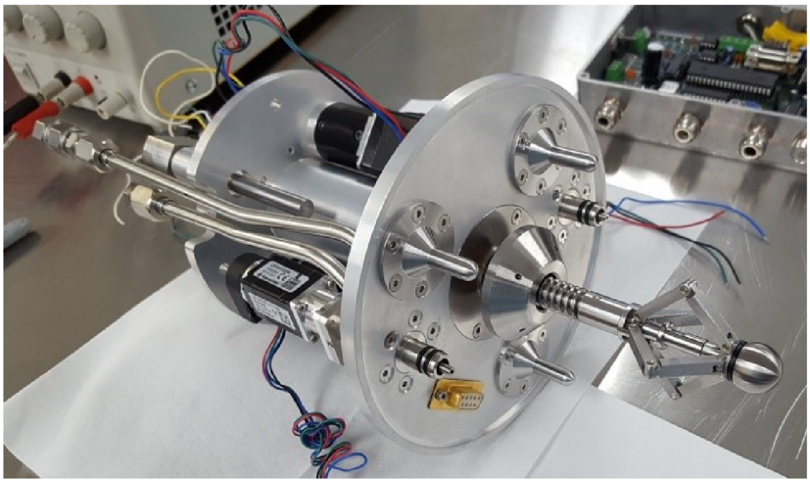


Figure 3.13: The ASSIST docking mechanism (figure courtesy [14])

A servicing/refueling system for GEO satellites, which has a minimum impact on internal structures of GEO telecom satellites and minimum impact for the servicing satellite on the flexibility and configurability of the berthing fixtures was developed as a result and was environmental and dynamic tested in 2D space simulator [14].

3.9.4 NASA CSV - Cooperative Service Valve

NASA Goddard Space Flight Center has developed the Cooperative Service Valve (CSV) depicted in Figure 3.14 to facilitate the resupply of media, such as propellants and pressurants, to satellites. The CSV replaces a standard spacecraft fill and drain valve to be used both during ground operations and in orbit. The tools used to interface with the CSV, were also designed and tested by NASA. The CSV architecture and approach is extensible to all space assets that could potentially be fueled/re-fueled on and off the ground, including manned crew vehicles, planetary rovers, and space habitats [11].

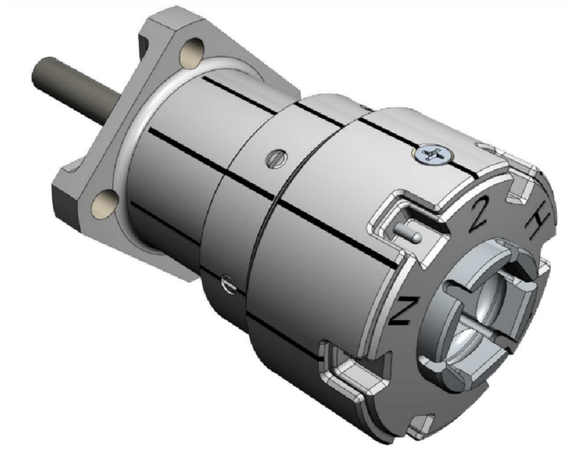


Figure 3.14: NASA Cooperative Service Valve render (figure courtesy [11])

The CSV offers various advantages over standard service valves: a robotic interface, three individually actuated seals, a self-contained anti-back drive system, and built-in thermal isolation. When mounted to a spacecraft as designed, the CSV transfers all operational and induced robotic loads to the mounting structure. An anti-back drive mechanism prevents the CSV seal mechanism from inadvertent actuation. Alignment marks, thermal isolation, and a mechanical coupling capable of reacting operational and robotic loads optimize the CSV for tele-robotic operations. The CSV has four configurations for different working fluids (see Table 3.2), all with essentially unchanged geometry and mechanics [11].

Table 3.2: Selected CSV parameters (courtesy [11])

CSV PARAMETERS				
Configuration	-301	-303	-305	-307
Working Fluid	Pressurant (He, Xe, other)	Hydrazine N2H4	MMH	NTO
Operating Pressure	3 000 psig	650 psig		
Min Flow Rate	9.62 SFCM GHe	10 lbm/min H_2O		
Mass	0.27 kg			
Leakage rate	$< 1X10^{-5}$ sscs GHe			

Chapter 4

Mission identification

The process of orbital refueling with its merits and constraints has been described in detail in Chapter 2. In Chapter 3 state of the art project and technology has been presented. Based on the number of projects and investments into refueling technology the idea appears to be appealing not only to the national and multinational agencies investing into development but also to the private companies exploring new market areas and seeking profit. The last party interested into on-orbit refueling are the satellite operators themselves who will in the end benefit from the service.

In this chapter the current status of the refueling market is summed up based on the Chapter 3, rationale of the mission is presented along with foreseen mission needs and constraints.

4.1 Initial situation

Table 4.1 provides comparison of the selected life-extension missions from Chapter 3. Please note that both the mission list and the selected parameters are not exhaustive.

Table 4.1: Selected life-extension missions comparison)

SELECTED MISSIONS PARAMETERS							
Mission	Mission Type	Task	Orbit	S/C Mass**	Transfered fluid	Robotic arm	Launch date
MEV	Comm	Life-ex	GEO	2 500 kg	N/A	-	2020
MRV + MEP	Comm	Multi	GEO	3 000 kg	N/A	Yes	2024*
e.Deorbit	Demo	Multi	LEO	1 600 kg	-	Yes	2025*
EROSS+	Demo	Multi	-	-	-	Yes	2026*
RRM	Demo	Multi	LEO	N/A	various	Yes	2015
OSAM-1	Demo	Multi	LEO	-	N_2H_2	Yes	2025+*
LEXI	Demo	Life-ex	-	-	N/A	Yes	2026*
TENZING	Demo	depot	LEO	35 kg	HTP	No	2021
China	Demo	Life-ex	-	2 600 kg	-	Yes	-

Comm = Commercial, Demo = Demonstration, Life-ex = Life extension
* declared/estimated date
** approximate

As seen in the Table 4.1 above there is a number of refueling and life extension missions already of which the majority are technology demonstration missions. These are predominantly governmental sponsored ventures focused on target already inactive targets in LEO (e.g. e.Deorbit, OSAM-1). This is for the obvious reasons as LEO is much easier to access compared to GEO and if anything should go wrong, the harm to the target is not a factor. Other demonstration missions are mainly allocated to LEO as well, as it makes little sense to demonstrate capabilities on GEO due to higher launch costs.

Apart from the rescue missions to specific asset the commercial missions are targeted to GEO. This is the area where the customers are and they are willing to pay substantial sums to keep their S/C operational for extended time period. The reason and detailed analysis is presented later in section 4.2.

Fluid transfer is the area that has been demonstrated quite well in the past but yet not introduced to the commercial market where the selected solution remained in docking with the target and staying attached, overtaking the station keeping and attitude control functions (e.g. MEV, MEP, LEXI). IF the propellant transfer was introduced to the customer its obvious that the fluid (or gas) has to be the same which the customer used, as the spacecraft is accustomed for the given propellant and a contamination would not be acceptable.

The common nominator across all the missions is the presence of the robotic manipulator arm. The robotic capability presents a clear enabler in the docking process, saving precious fuel for maneuvering and introduces the opportunity to expand the servicer capability not only to refueling but with the right set of exchangeable tools also simple augmentation and repair task can be executed such as failed solar array deployment.

The last aspect of the missions is programmatic. The launch date of most of the missions is declared in the second half of the decade illustrating the novelty of the whole concept of on-orbit refueling. Furthermore as it is usual in space missions a delay in the schedule would not be surprising especially among challenging missions such as refueling mission are.

4.2 Customer identification

Servicing satellites in near-Earth environments can be accomplished in two modes: prepositioned and as-needed. The nature of orbital dynamics is such that it is expensive (from a propellant and time point of view) to change inclinations. Therefore, pre-positioned servicing assets should be placed in the most-used orbits. These include the Geostationary Earth Orbit (GEO) belt that surrounds the Earth at high altitude and low inclination (generally over the equator) and the Low Earth Orbit (LEO, 200-1,000 km altitude) near-polar inclinations. Pre-positioned servicers would move in these two orbital regimes to satisfy the requirements of many customers. These multi-mission, multi-customer servicing vehicles must have sufficient propulsion to move amongst nearby orbits and would be serviceable and refuelable themselves to maintain the most utility [8].

Other high-value servicing missions could also be conducted in other orbits, but likely on an as-needed basis. Satellites requiring long "hang-time" over northern latitudes use highly elliptical orbits. Large, expensive, astronomical observatories work best in the cold environments of deep space, such as at the second Sun-Earth Lagrange point (SEL2). Critical

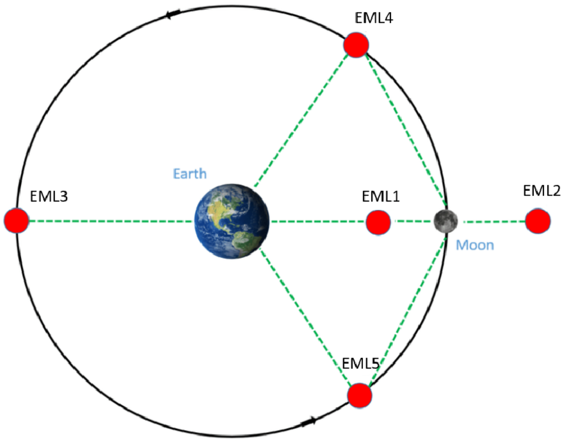


Figure 4.1: Earth-Moon Lagrange point (figure edited from [15])

space weather missions stand watch between the Sun and the Earth at the first Lagrange point (SEL1). Staging depots for trips to and from the Moon, lunar orbit, and deeper space destinations are attractive at the semi-stable locations in the Earth-Moon system (see in Figure 4.1), namely Earth-Moon L1 (EML1). All of these orbits interact with the Earth's gravity and are considered near-Earth. The Earth-Moon locations, a few days' travel from Earth, would be relatively easily reached with a small, crewed spacecraft as well as robotic servicers. A customer spacecraft could also travel from an operational SEL2 location to EML1 for a servicing episode closer to Earth and then return to the operational location. Only a small amount of propellant is required to transfer between any two Lagrange points, though the flight times can be long [8].

Refueling a satellite is a costly venture even if the customer spacecraft is adapted for proximity operations and refueling and those pose a potential thread to the both servicer and a customer if failure should occur.

Essentially there are three types of the satellites in terms of cost of the S/C. Cheap and rather small satellites operating typically LEO orbits often as a part of the constellation such as Starlink or OneWeb. These satellites could benefit from refueling but the design and philosophy of these are to be easily replaceable. The cost of refueling might be even greater than launch of replacement satellite.

Than there are unique spacecrafts build built for special purposes such as scientific space telescopes (e.g. Hubble Space Telescope, James Webb Space Telescope) often located at exotic locations such as Lagrange points discussed above. These S/C are often extremely valuable not only for the scientific community which processes the observation data but also in a literal sense - in terms of cost (James Webb Space Telescope cost approaches the $10 billion threshold [24]). These S/C would benefit from refueling or even servicing missions as they are almost irreplaceable pieces of technology, even dedicated mission to one specific S/C might prove feasible but the design of such servicer would require high degree of specialization.

The third and last category of S/C are large and long-life satellites operating in Geosynchronous orbits. These are dominantly telecommunication satellites, valuable and costly enough to benefit from refueling in-orbit and posing considerably large commercial market to focus on.

4.2.1 GEO Satellite Market

The data on operating satellites [31] has been analysed, focusing on the Geosynchronous Earth Orbit the information on number, mass, expendables share in the mass (these could be also coolants or separable mechanical parts, but in case of communication satellites propellant is the major expendable mass) and predicted EOL has been derived.

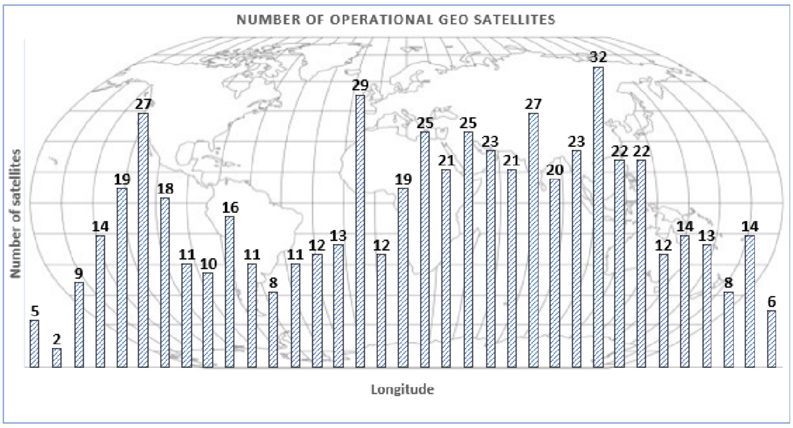
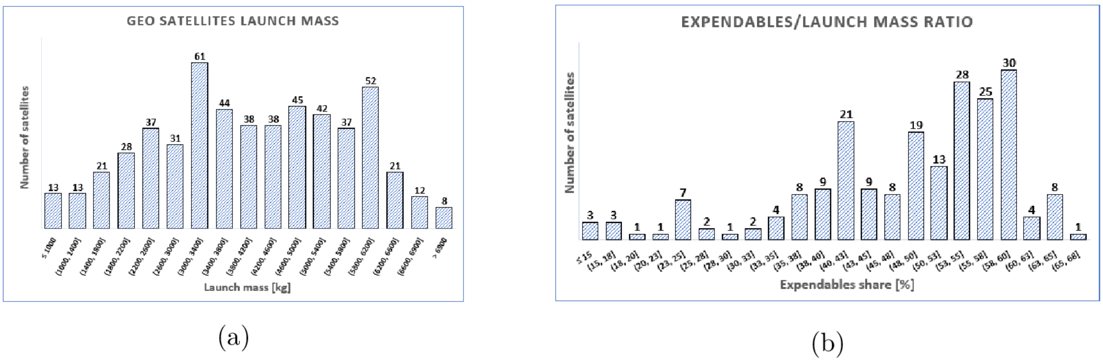


Figure 4.2: Number of operational GEO satellites according to longitudinal position (data source [31])

There are 574 operational satellites located at GEO as of January 2022 of which about 82 % are communication satellites [31]. The distribution on the orbit is not even as shows Figure 4.2 and clear peaks can be seen above North America (USA), Europe and China where the demand for telecommunication service is high. In contrast the Pacific Ocean area is nearly clear of satellites.

Figure 4.3a shows the launch mass of GEO satellites. In terms of satellite masses these are rather large S/C, 73 % heavier than 3 tons and about 2/3 ranging between 3 to 6 tons. Figure 4.3b shows the weight share of expendables on the total launch mass of the satellite. In case of GEO satellites expendables (propellants) account for as much as 40 % to 60 % of total mass in case of 74 % of satellites [31].

The propulsion of choice for the GEO communication satellites has become the biopropellant solution. A mixture of Monomethylhydrazine (MMH) as a fuel and N_2H_2 as oxidizer, to avoid stress corrosion a portion of nitrogen oxide (NO) is added to the oxidizer. The resulting mixture is referred to as Mixed Oxides of Nitrogen (MON). The whole propulsion system is than usually referred to as MON/MMH propulsion. Whole propulsion system than comprises of at least two tanks (one for fuel and one for oxidizer) and at least one high pressure tank with a pressure regulation gas (typically He) [6].



(a) (b)

Figure 4.3: GEO satellites (a) launch mass , (b) mass ratio of the expendables onboard (data source [31])

The next graphic in Figure 4.4 shows the number of currently operational GEO satellites to reach EOL each year. There are around 26 satellites on average to reach EOL every year [31] and to be decommissioned and replaced. The notable degressive trend appearing from the year 2031 means there is fewer and fewer satellites today to last that long. These are continuously replaced and the average of replacement satellites will remain roughly the same with the current development.

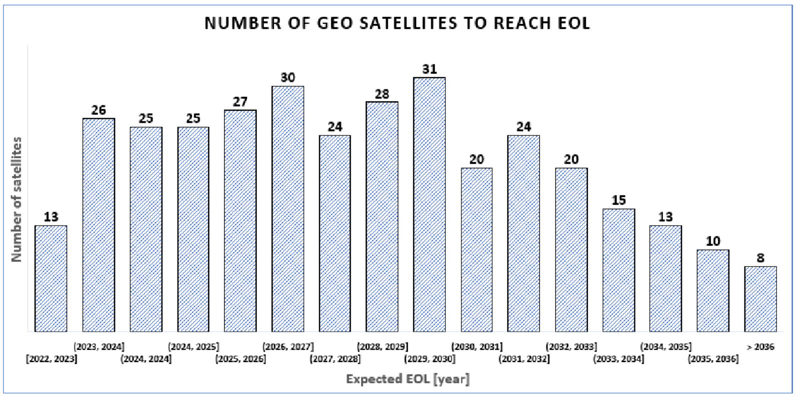


Figure 4.4: Expected number of GEO satellites to reach EOL (data source [31])

From the gathered data [31] a typical representative of GEO satellite class has been established with the characteristics summarised in the Table 4.2 below. Such a satellite is considered to be a target for refueling mission described in this thesis.

The GEO satellite market is foreseen as a attractive area for refueling service. The spacecrafts allocated all around Earth are suitable target for refueling for several reasons. First they would benefit the most from the life extension refueling offers as extended operational time on orbit directly results in operators profits. Secondly the design of the satellites although by different manufactures is of common features. Satellite dimensions and weight, spacecraft bus design, utilized propellant etc. This fact enables missions with multi customer profile as the servicing S/C can be tailored to dock to slightly different satellites using the same general approach and steps.

Table 4.2: Typical GEO satellite parameters (data source [31])

TYPICAL GEO SATELLITE	
Cost	$>\$250$ million*
Life expectancy	15 years
Launch mass	$3\,000 \sim 6\,000\ kg$
Expendables mass	$\sim 2\,000\ kg$
Propellant	MON/MMH
Inclination	$< 1^{\circ}$

* estimation

4.2.2 Future outlook

As discussed in preceding sections refueling is a service suitable for rather large, expensive S/C. These involve large scientific telescopes and observatories, a portion of earth observation satellites and majority of satellites which operate the GEO. Currently private communication satellites represent majority of S/C operated at GEO and according to Euroconsult report [21] this market will remain relatively stable throughout of this decade. Also some estimates show that more than 50 percent of GEO satellites will experience operational impacts due to fuel depletion [1] while their remaining hardware and payload might remain operational for total of 20-30 years despite the designed life of 10-15 years [9]

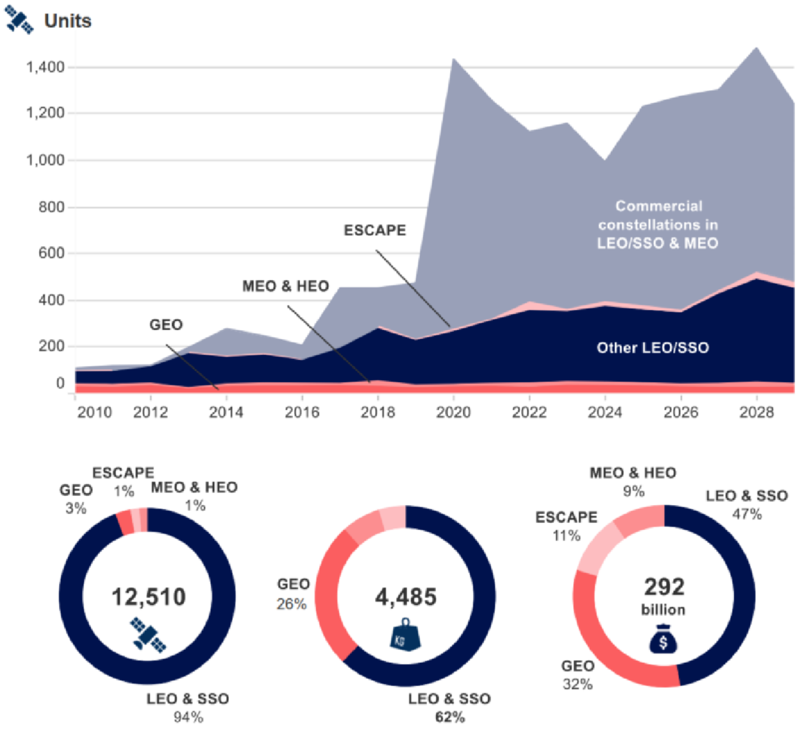


Figure 4.5: Satellite market forecast per orbit (data source [21])

The report presents an outlook up to 2029, analyses current trends and predicts satellite market development in upcoming years. GEO communication satellites market will probably experience slight decline in the number of new satellites launched. This is partly because of the fact that on-orbit servicing is already accounted for and thus fewer launches of new satellites will be actually required. The other cause of the decline is current trend in launching quantities of small, inexpensive and easily replaceable satellites into LEO to form a constellation (e.g. Starlink, Kuiper, OneWeb) which can somewhat dampen the on-orbit servicing demand, there will still be a market for refueling in GEO as operators are finding an increasing need to extend satellites lifetimes [16].

As presented in the info-graphic in Figure 4.5 the GEO satellite market was dwarfed by the number of S/C of mega constellations at LEO, but at the same time the GEO market remains stable as there is uninterrupted demand for the services. The fact that an average GEO satellite is a valuable asset is stressed out as well as 3 % of the satellites present 32 % of the whole market value.

The interest into satellite refueling technologies is declared by commercial ventures and industry (demonstrated in Chapter 3) as well as by science community and national space agencies [19] [17]. On-orbit servicing presents a robust and compelling set of value propositions to GEO satellite operators, with independent valuations estimates that life extension and other on-orbit satellite services will generate more than $4 billion in revenues by 2028 [25].

4.3 Critical technology for refueling

4.3.1 Spacecraft bus

The servicer element imposes requirements on spacecraft subsystems such as attitude control, electrical power, command and control, data handling, communications, propulsion, thermal control, and structures and mechanisms. Regarding the requirements the subsystems are fully mature and well within the current state of the art. Advances in lighter-weight or more power-efficient components and subsystems would, of course, improve capability in a given mission class, but in general no new technologies are required for the spacecraft bus [8].

There are high requirements placed on the ΔV budget, which directly determines the lifetime and efficiency of the service satellite. The platform also requires an extremely precise and adjustable propulsion system when near the target and for the docking maneuver. In addition, all the classic elements have to be on hand to control the service satellite and maintain communication with the ground station. If video data is used, an appropriately powerful ground link has to be available.

4.3.2 Sensor Technology

In order to carry out in space the operations described above, corresponding sensor equipment has to be on-board. It serves on the one hand to grasp the target satellite in the rendezvous phase and on the other hand to determine as precisely as possible after approach the attitudes and relative positions of both the service and target. satellites during docking or close-up inspection. It is therefore desirable to work with optical cameras which can be used for object recognition as well as inspection tasks.

Correct function of the servicer sensory system can be significantly aided by the adoption of visual markers and reflective surfaces installed on the client S/C in defined position. These features aid the robotic system with correct recognition of the target and its attitude and motion.

4.3.3 Robotic arm end-effector

The robotic elements required for each particular mission scenario must satisfy high demands as to precision and reliability. Such systems have long been available in the laboratory. The challenge is to make the complex robotic system suitable for the space environment. In most cases there is no redundancy for primary elements like the docking mechanism and manipulator arm. In order to increase reliability, elaborate ground testing under the most realistic conditions possible as well as the use of robust components are therefore necessary. The specialized fields to be addressed are electronics, mechanics and mechatronics.

4.3.4 Propellant transfer system

Propellant transfer system is the core to the refueling technology as it carries out the actual supply of the fluid from the servicer tank(s) to the customer S/C. The transfer shall ensure that the supply of the fluid is continuous, free of impurities and bubbles. Precise flow rate or transferred amount of the fluid needs to be measured to prevent excessive depletion or insufficient supply to the customer. The pressure and the temperature level is required to be measured during the whole transfer process for safety reasons and to ensure smooth course of the action.

4.3.5 Software and Operational modes

High demands are placed on the software algorithms which must be able to close the control circuit between the sensor and actuator technology (attitude regulation, mechanisms), for some operations, fully autonomously and in real time. Rapid processing of sensor data and comparison with available models are key elements in autonomous robotic activities in space.

Anything which the service satellite cannot carry out fully autonomously must be controlled by appropriate operation commands from the ground. This includes primarily the complete approach and rendezvous phase as well as the first part of the docking phase. Since there is always a high risk of collision, the design and verification of these operations must be carried out with extraordinary care.

The main operational modes for both client and servicer S/C connected to refueling were identified. The scheme of the modes is presented in Figure 4.6. The refueling operations require adaptation of both S/C involved, for the servicer spacecraft following modes shall be introduced:

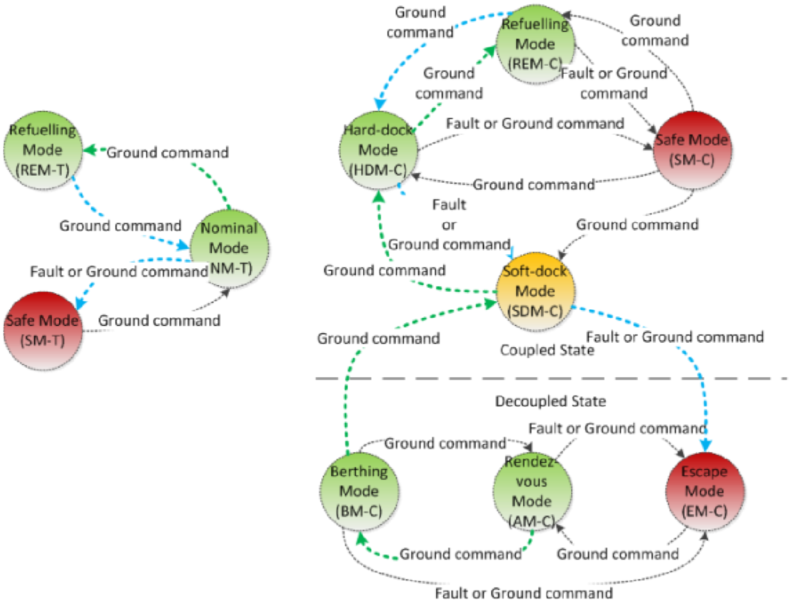


Figure 4.6: Spacecraft refueling modes - client (left), servicer (right) (figure courtesy [10])

Rendezvous mode

Rendezvous mode represents the approach of the servicer to the client S/C enabled through the use of set of sensors and actuators. When the sufficient proximity is achieved and relative position of the two S/C is is stable the mode is switched to docking mode. Escape mode is activated in the event of any failure or when initiated by ground control.

Docking mode

Docking mode lasts from the end of rendezvous to the beginning of the soft-dock phase. During this mode, precise attitude shall be maintained. The contact is achieved by means of the servicer robotic arm. In case of any unexpected event or failure escape mode is activated.

Escape mode

Escape mode enables the servicer S/C to recede from the client S/C until safe distance is reached between the two S/C. This mode is activated automatically whenever any unexpected event arises or when initiated by the ground control.

Soft-dock mode

Soft-dock mode is activated to establish loose connection between both S/C to ensure that they do not drift away. Alignment of the contact interface is carried out by the robotic arm. Soft-dock mode might not be applicable for all end-effectors.

Hard-dock mode

Hard-dock mode goal is to establish firm connection between both S/C and mate the refueling and support interfaces.

Refueling mode

Refueling mode introduces the fluid transfer from the servicer S/C to the client S/C. Attitude control is taken over by the servicer.

Safe mode

Safe mode is introduced in case of major issues occurrence during the coupled phase. Controlled disconnection through hard-dock mode, soft-dock mode and escape mode is preferred when possible. Safe mode should bring the servicer S/C to safe configuration.

For the client spacecraft following modes are considered:

Nominal mode

Nominal mode is a standard mode in which every spacecraft operates during its mission lifetime. All the subsystems are fully operational.

Refueling mode

Refueling mode shall be introduced to enable refueling. During this mode client S/C thrusters shall be disabled and attitude control system shall run on constant speed to avoid rude maneuvers. This mode shall be enabled during the whole servicing process until spacecraft separation. Switching to safe mode shall be prohibited to avoid commands conflict with the servicer S/C.

Safe mode

Safe mode is dedicated to provide optimal Sun orientation to provide enough power to the satellite systems in case of failure or unexpected event. Approach and docking of the servicer S/C to a client S/C in safe mode shall be not permitted.

4.3.6 Autonomous operation

Autonomous operation and on-board data handling is required for multiple reasons. Firstly autonomy brings improved efficiency of the system. The spacecraft is no longer required to hold operation and wait for command/approval from ground control centre and is able to carry out the whole operation. Ground control of course still has the ability to monitor the whole process and intervene when necessary. This aspect becomes more important when communication periods are limited or when the communication latency is high. The communication latency might even become a single reason to implement complete operation autonomy in the process of the docking where quick actions might be required and the wait time in ground communication becomes crucial obstacle. Secondly robustness of the system is improved if the on-board computer is able to continuously process sensor data in real time and tailor the actions accordingly [8].

4.4 Proposal approach

The space projects typically subject to standardized project planning according to the ECSS standardisation [5] applicable within ESA projects as well as other applicable standardisation issued for the purpose of coordination of space projects across the ESA. Even project outside of ESA might benefit from incorporation of applicable standards as a means of quality insurance and product assurance.

This proposal is drafted based on the applicable ECSS standardisation, predominantly Project management and system engineering are the key areas of interest to this work. The work applies the requirements originating from the standardisation and follows the standard procedures and steps taken during the project initiation. Substantial part of the approach is also driven by the legacy projects and good practice employed in the commercial sector. The detailed step decisions and solutions are in line with standard approach to space projects as described in [2] [6] [3].

4.4.1 Project course

A complete space project typically comprises a space segment and a ground segment which are implemented in parallel. They rely on, and have interfaces with the launch service segment. These three segments comprise a space system. However in this thesis a focus is with the space segment primarily and more specifically on the payload subsystem being the critical subsystem of the whole mission. The launcher segment (Section 5.8) is added for completeness but not detailed and the ground segment is omitted.

European standardisation divides a project typically into 7 phases (project division according to ECSS in Figure 4.7) of which this proposal covers first two - as highlighted in the Figure 4.7 - with an outlook into the third phase. At the closure of major activities there is a review held between supplier and customer, which is not subject to this thesis. Level of detail is tailored to the needs of this work.

Phase 0 - Mission analysis/needs identification

Activities in phase 0 are typically carried out by the initiator of the project who might be the top level customer at the same time. The tasks of this phase are:

- to elaborate the mission statement in terms of identification and characterization of the mission needs
- to elaborate expected performance and mission operating constraints with respect to the physical and operational environment

- develop the preliminary technical requirements specification
- identify possible mission concepts
- perform preliminary risk assessment

Outcome of the phase at mission definition review is typically mission statement, preliminary technical requirements assessment and programmatic aspects [5].

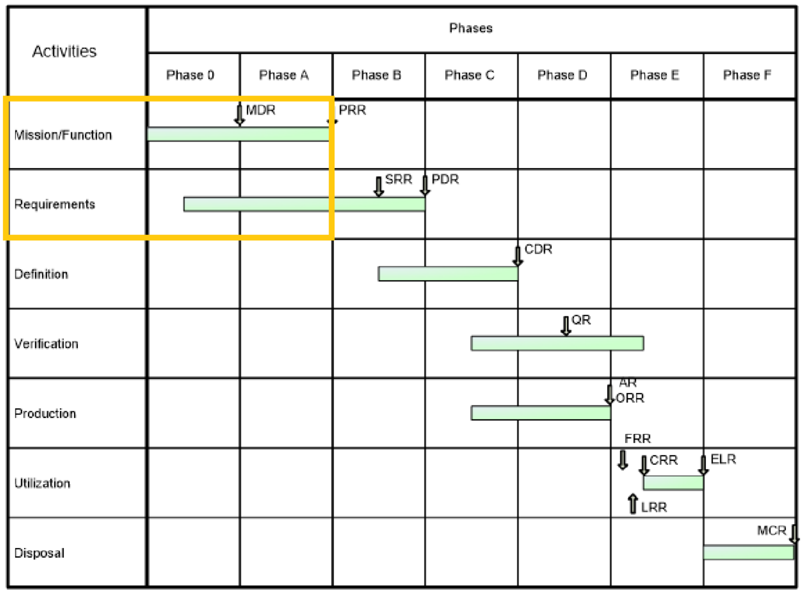


Figure 4.7: Typical project life cycle (figure courtesy [5])

Phase A - Feasibility

Feasibility study is mainly done also by the top level customer and first level supplier or prime contractor. Major task associated with the phase A are:

- establish the preliminary management plan, system engineering plan and product assurance plan for the project
- elaborate possible system and operations concepts and system architectures and compare these against the identified needs
- establish the function tree
- assess the technical and programmatic feasibility of the possible concepts by identifying constraints relating to implementation, costs, schedules, organization or operations
- identify critical technologies and propose pre-development activities
- quantify and characterize critical elements for technical and economic feasibility
- propose the system and operations concept(s) and technical solutions
- elaborate risk assessment

The phase A is concluded in the preliminary requirements review. The main objective of the phase is to release technical requirements specification, confirmation of technical and programmatic feasibility and selection of system, concept of operations and technical solutions.

4.4.2 Assumptions

The following proposal part of this thesis is tailored to assumptions presented in the Table 4.3 below:

Table 4.3: Refueling mission assumptions

Assumption	Justicifation
Cooperative customer	Customer spacecraft is assumed to be cooperative or at least partially cooperative. The minimal requirements for the customer to be serviced are: operational attitude control system, refueling and docking interface available. Optional requirements include but are not limited to: visual reflective marks to aid docking procedure, possibility to establish communication link between servicer and customer.
Typical GEO satellite	The customer S/C is assumed to be genrrally typical GEO telecommunication satellite as specified with the set of parameters in the Table 4.2 above

4.4.3 Mission statement

Mission statement for satellite on-orbit refueling mission based on the assessed data from the chapter 3 and this chapter concerning is formulated as follows:

MISSION STATEMENT
Current satellite design approach is to supply the satellite with enough propellant for the entire design life, adding considerable amount of mass to the system and sending a satellite to space never to be touched again. For many satellites a fuel supply is the limiting factor and even as the rest of the hardware is healthy, they are no longer able to keep position and are forced to retire. A dedicated satellite servicer spacecraft utilizing high level autonomy and robotic systems can supply additional propellant to the geostationary communication satellites effectively providing a life extension. The impacts of such service are lessened need for new satellite launches, reduction of operating cost for the satellite operator and contribution to space sustainability.

Chapter 5

Mission proposal

The proposal part of this thesis states the main objectives of the refueling mission based on the stated mission statement 4.4.3. The mission needs and constraints are elaborated in the form of key technical requirements. Mission breakdown structure is provided describing main mission functions in relations as well as individual mission elements. Proposed concept of operations is introduced in detail. Afterwards orbit segment, payload segment, platform segment and launcher segment are described. Finally possible trade-offs are outlined along with main risks.

5.1 Mission objectives definition

The primary objectives of the satellite refueling mission are defined as follows:

- To autonomously rendezvous and dock to a customer satellite.
- To transfer propellant to operational customer satellite on-orbit resulting in life-extension of the customer satellite.
- To allow for re-usability of the servicer (ability to mate with multiple satellites over its lifetime and to be refueled itself).

The secondary objectives of the satellite refueling mission are defined as follows:

- To demonstrate the feasibility of the on-orbit satellite refueling
- To establish a basis for on-orbit servicing operations including on-orbit repair and augmentation.

5.2 Requirement definition

This section identifies key technical requirements of the satellite refueling mission. The requirements comprise of general mission requirements (Table 5.1), orbit requirements (Table 5.2), mission payload requirements (Table 5.3) and platform requirements (Table 5.4).

Table 5.1: Mission requirements

Requirement	Title	Requirement	Justification
MR-01	Customer	The servicer S/C shall be able to supply propellant to all potential customer S/C featuring compatible docking I/F.	Extended market reach and multi customer service is desirable. Driven by the business case.
MR-02	Propellant	The propellant of the servicer S/C shall be identical as a propellant provided to the customer S/C.	Unified propulsion system.
MR-03	Propellant consumption	The servicer S/C shall consume no more than 80 % of propellant for orbital maneuvering.	Efficiency requirement. TBC
MR-04	Propellant mass	The total fuel and oxidizer mass shall be minimum 2 500 kg.	Total propellant mass is driven by business case and servicer internal consumption.
MR-05	Orbit	The servicer S/C shall be able to reach and match customer orbit by its own means after GTO insertion.	Servicer will have the ability to change and adapt its orbit also throughout the mission life cycle.
MR-06	Autonomy	The servicer S/C shall be able to operate autonomously upon ground instructions.	Autonomous operation is needed to perform RPOD on GEO where significant communication lag occurs.
MR-07	Switching modes	The servicer S/C shall allow for ground override of autonomous operation upon ground command.	Autonomous operation might need to be discontinued due to unexpected events.
MR-08	Power	The servicer S/C shall maintain power positive mode.	Power supply and communication of both S/C must be maintained. Included - customer S/C attitude, servicer shadowing, optimal power configuration.
MR-09	Customer Operation	The servicer S/C operations shall respect customer S/C keep out zones and envelopes.	Disturbance to customer operation caused by the servicer shall be minimized.
MR-10	Customer safety	The servicer operation shall not cause any degradation to both servicer and customer S/C.	Hardware damage to solar arrays, radiators, antennas etc.

Table 5.1: Mission requirements

Requirement	Title	Requirement	Justification
MR-11	Plume	The servicer spacecraft shall not plume customer vehicle such that its solar cells/power system are degraded.	Customer S/C must not be degraded due to refueling.
MR-12	EOL	The servicer S/C shall perform EOL maneuver and safely dispose itself.	Space sustainability and safety.

Key technical requirements related to loitering orbit of the servicer S/C are listed in the Table 5.2 below:

Table 5.2: Orbit requirements

Requirement	Title	Requirement	Justification
OR-01	Eccentricity	Orbit eccentricity shall be no greater than 0.002	Circular orbit concentric to GEO.
OR-02	Semi-major axis	Orbit semi-major axis shall be $42\,664 \pm 100\,km$	500 km above GEO. Orbit close but not interfering with GEO of potential clients.
OR-03	Inclination	Orbit inclination shall be $0 \pm 0.01°$	Matching inclination to potential customer satellite.

Key technical requirements related to space segment payload are presented in the Table 5.3 below. In the sence of on-orbit refueling mission, payload is considered to be the hardware and software directly engaged in the refueling task.

Table 5.3: Payload requirements

Requirement	Title	Requirement	Justification
PR-01	On-board computer	The OBC shall be fully capable of controlling autonomous operation as per predefined task lists.	Autonomous operation is required due to communications lag.
PR-02	On-board computer	The OBC shall have integrated error detection and correction system.	Standard practice. Safety ensurance and error prevention.
PR-03	Long range detection	The servicer spacecraft shall identify customer relative position and distance from 300 km with the accuracy of $\pm 50\ m$.	Long range detection with sufficient precision is required for rendezvous and approach phase.

Table 5.3: Payload requirements

Requirement	Title	Requirement	Justification
PR-04	Close range detection	The servicer spacecraft shall identify customer relative position, distance attitude and movements from 500 m with the accuracy of $\pm 25\,cm$ ($\pm 0.5°/sec$)	Close range detection with sufficient precision is required for proximity operations. TBC.
PR-05	Very close range detection	The servicer spacecraft shall identify customer relative position, distance attitude and movements from 5 m with the accuracy of $\pm 5\,mm$ ($\pm 0.2°/sec$)	Very close range detection with high precision is required for proximity operations and docking.
PR-06	Sensor pointing	Pointing of the sensors shall be independent of that of a S/C in the range ±20° lateral and transversal.	Sensors are required to point on the customer spacecraft semi-independent of the S/C bus at all phases during the maneuvering.
PR-07	Visual camera 1	A visual camera shall be included in the S/C sensor set with minimal FHD resolution and 30 FPS framerate or higher.	Body mounted camera to aid RPOD, docking and visual marks recognition.
PR-08	Visual camera 2	A visual camera shall be mounted an the robotic arm end effector with minimal FHD resolution and 30 FPS framerate or higher.	Robotic arm mounted camera to aid RPOD, docking and visual marks recognition. Arm mounted camera utilized to provide appropriate field of view.
PR-09	Lighting	The servicer S/C shall feature a lighting source to provide illumination during RPOD.	A source of light is desirable in the event there is no natural lighting. The servicer is enabled to exploit visual footage during eclipse period.
PR-10	Robotic arm	The servicer S/C shall feature a robotic manipulator arm with 7 degree of freedom movement.	Robotic arm is utilized to enable docking and refueling and potential other operations.

Table 5.3: Payload requirements

Requirement	Title	Requirement	Justification
PR-11	Arm reach	The robotic arm shall have the operational reach 2 m minimum.	Longer reach of the arm presents increased safety of the proximity operations as the servicer is able to keep distance and escape if needed.
PR-12	Arm precision	The robotic arm shall be actuated such that the precision of the end effector is $\pm 5\,mm$ in each axis and $\pm 5\,^{\circ}$ or less.	A substantial precision must be achieved to safely execute the docking sequence.
PR-13	Docking	A status of the docking sequence shall be monitored as well as docking completion.	Information status of the docking operation is required during docking operation as well as confirmation of safe docking.
PR-14	Health monitoring	Performance and health of mission critical elements shall be monitored.	Failure or error must be detected prior to engaging given element. Critical elements include but are not limited to: relative navigation sensors, end-effector, battery depth of discharge, activation of safe and escape mode triggers
PR-15	Calibration	Payload calibration shall be verified to be within the acceptable limit prior to engaging.	Calibration applicability includes but is not limited to: relative navigation sensors, end-effector, robotic arm.

A set of platform key requirements related to the on-orbit refueling task is listed in the Table 5.4 below. Please note that the list is not extensive and platform requirements not related directly to the refueling task are excluded but still applicable. Those requirements might be applied as standard requirements applicable to any representative mission.

Table 5.4: Platform requirements

Requirement	Title	Requirement	Justification
PF-01	Attitude control	Attitude control system shall be capable of 3-axis orientation of the S/C.	Unconstrained pointing is desirable for RPOD.

Table 5.4: Platform requirements

Requirement	Title	Requirement	Justification
PF-02	Attitude control performance	Attitude control system shall be reach rates $> 1°/sec$ and a precision better than $\pm 0.5°$ in each axis.	High rates and precision is a key to achieve successful RPOD.
PF-03	Attitude control of the stack	Attitude control system shall be capable to temporarily overtaking the attitude control of both servicer and customer S/C when docked.	Attitude control of the docked stack will be ensured by the servicer, therefore the attitude control system needs a substantial margin of capability.
PF-04	Propulsion system	Propulsion system shall be capable of GEO insertion burn, orbit maintenance and attitude control functions.	Propulsion system needs to feature apogee engine capable of coarse burns for orbit transfers and adjustments as well as fine thrusters allocated such that 3-axis stabilisation and station keeping is enabled.
PF-05	On-board Data Handling	The on-board data handling system shall collect and store key operation data.	Key operation data include but are not limited to: absolute and relative position and rates to the customer S/C, time, autonomous commands, position and rates of the robotic arm, propellant temperature, pressure and amount.

5.3 Mission breakdown structure

A functional analysis was conducted for the refueling mission to determine the functional architecture of the mission, identify individual functions and provide hierarchical order of the functions of the system. To describe the hierarchical decomposition of the system a function tree in Figure 5.1 was assessed providing overview of the top level functions and sub-functions. Applicable instruments of the servicer S/C (in green) and the customer spacecraft (in yellow) for each function are incorporated into the function tree structure.

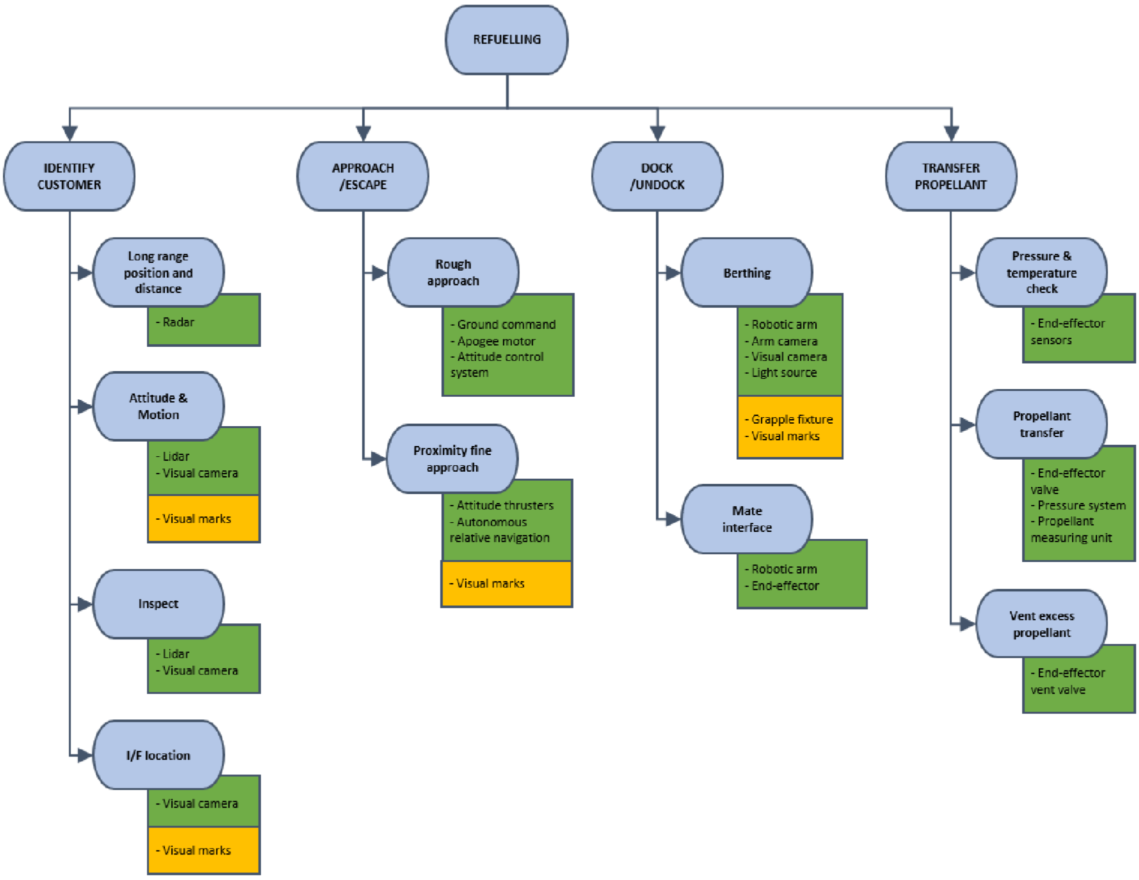


Figure 5.1: Function tree

Based on the function tree a Product tree was established in Figure 5.2. Product tree provides a breakdown structure of the project hardware and software into successive levels. Further details regarding the mission hardware are provided in the following Section 5.6 and Section 5.7.

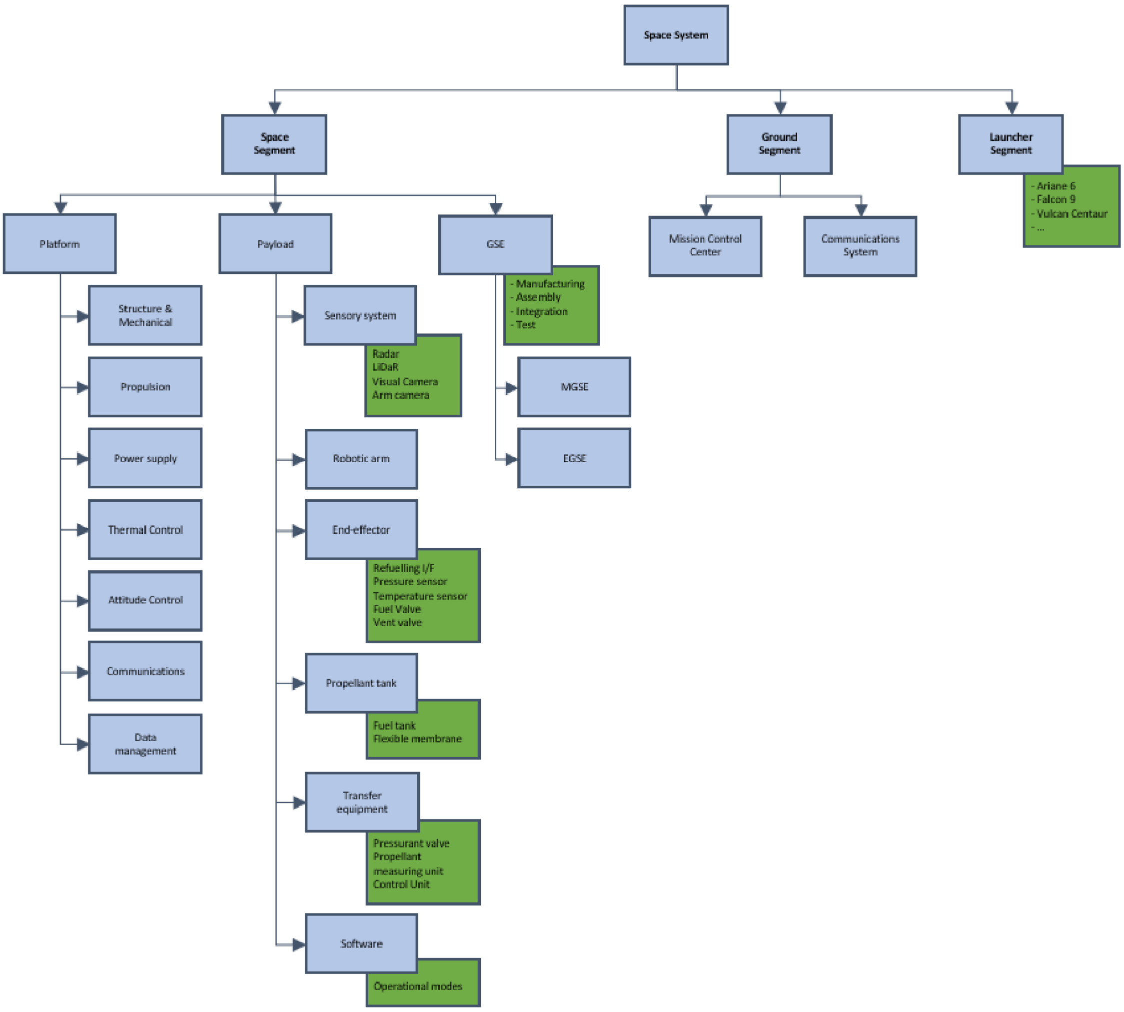


Figure 5.2: Product tree

5.4 Concept of operations

Concept of operations is divided into four main phases which describe in detail the task associated with refueling mission. Autonomous tasks can be accomplished by ground-provided task lists of appropriate commands to the current operating mode. Ground authority-to-proceed (ATP) commanding is built into these lists as checkpoints. Schematic graphic in Figure 5.4 shows the pre-mission activities associated with launch sequence. Immediate tasks after the vehicle separation are described below. The simplified logical flow of the operation tasks is presented in the Figure 5.3

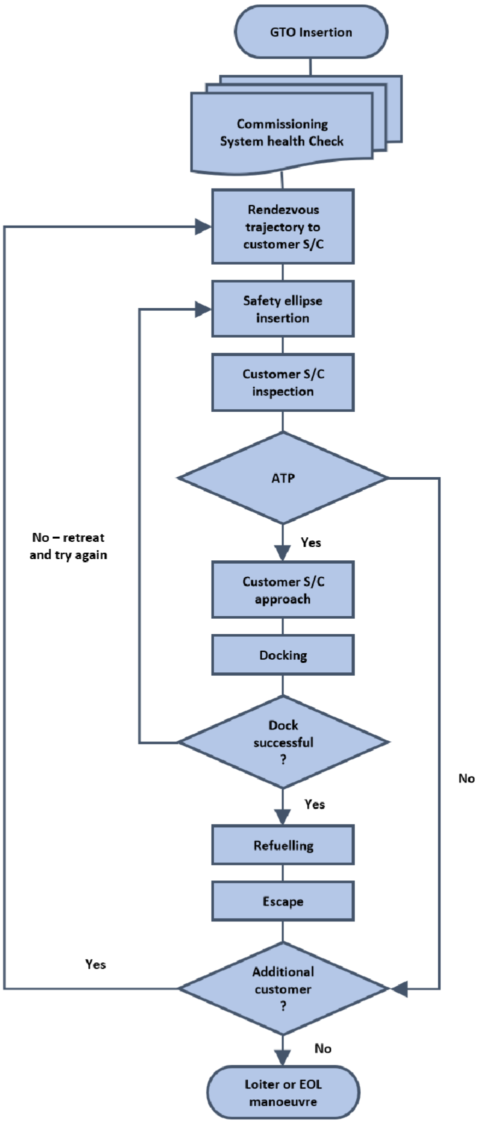


Figure 5.3: Operations flow logic - overview

5.4.1 Phase 0: Launch and commissioning

Individual operation of the servicer begins after the launch vehicle separation and deployment to the Geostationary Transfer Orbit (GTO). Among the first tasks is establishing sufficient power supply by deployment of the solar arrays and establishing communication link with ground control. During the transfer to designated operation orbit all the spacecraft subsystems shall be commissioned and fully operational. The commissioning includes also health check and calibration of the on-board sensors and exercise of the robotic arm actuators. It shall be confirmed that all the critical mission elements are operational within the acceptable margins.

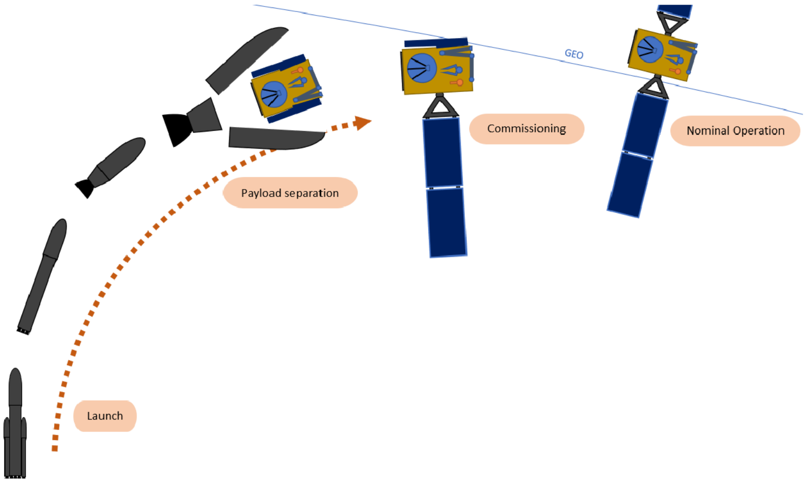


Figure 5.4: Launch and commissioning

5.4.2 Phase 1: Rendezvous

The distance range begins with the servicer several tens of kilometers above and several hundred kilometers in front of the customer spacecraft assuming concentric circular orbits. The servicer will naturally drift towards the customer spacecraft parallel to its orbit track, where the drift rate is proportional to the difference in altitude between the orbits.

The rendezvous operation mode is activated. Servicer will begin the rendezvous operations by pointing its sensors to the expected customer S/C position based on the data from the ground control of the servicer and customer S/C and the knowledge of the dynamics of both objects.

Once the customer position is acquired the servicer will periodically perform small maneuvers (e.g., Hohmann transfers) to gradually lower its orbital altitude as it approaches the customer (in theory these coarse maneuvers can still be based on absolute navigation without the relative position information. Once within several km of the customer, servicer S/C is able to detect the client S/C by its own sensing means in greater detail and determine the customer S/C velocities and rates. An autonomous proximity phase with relative navigation can be initiated. Servicer will subsequently execute a series of correction maneuvers based on the observation of the target and computational relative navigation software to match the required velocities and rates with the target and generally insert itself into a small safety ellipse, up to approximately 100 m in diameter, centered on the customer spacecraft. Contamination to the customer S/C due to thruster maneuvering should be minimized.

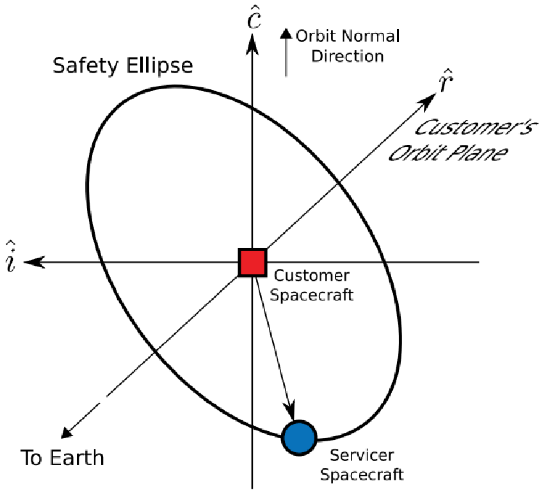


Figure 5.5: Safety ellipse (figure courtesy [8])

Safety ellipses (in Figure 5.5) are natural periodic relative motion trajectories in which the servicer spacecraft will fly around the customer spacecraft on an elliptical path centered on the customer. Safety ellipses are so named because they are tilted with respect to the plane of the customer's orbit such that the servicer never crosses the customer's velocity direction, making the relative motion passively safe. Thus safety ellipses provide an efficient configuration from which the servicer spacecraft can repeatedly fly around the customer to gather situational awareness data: collect range, bearing, and pose measurements, and allow the relative navigation filter sufficient time to converge [8].

Inspection of the customer S/C shall determine the readiness of the customer S/C to refueling and confirm that all parameters are nominal and inline with the expected. Once the inspection is finished and ground ATP is received servicer engages in further approach to the customer to close the distance to a point when the robotic arm can actually reach out and grapple the customer S/C.

In this phase, the robotic arm is not used and the approach is entirely done by the servicing spacecraft bus driven by the output of rendezvous sensor suite (supported by optical/radio markers on the serviced S/C). At the end of this phase the servicing S/C has adapted its movement performing a null relative movement with respect to the serviced S/C.

5.4.3 Phase 2: Docking

The docking phase is almost exclusively operated by the robotic arm whose objective is to mate the robotic arm end-effector part with the serviced S/C docking fixture counterpart. It is important that during the docking phase the actuators of the customer S/C are disabled to avoid unexpected relative movements bringing to collision with the servicing S/C. The servicing S/C will maintain stable position relative to the customer S/C. The docking mode is utilized in this phase along with soft-dock (if applicable - depending on the utilized end-effector) and hard-dock modes.

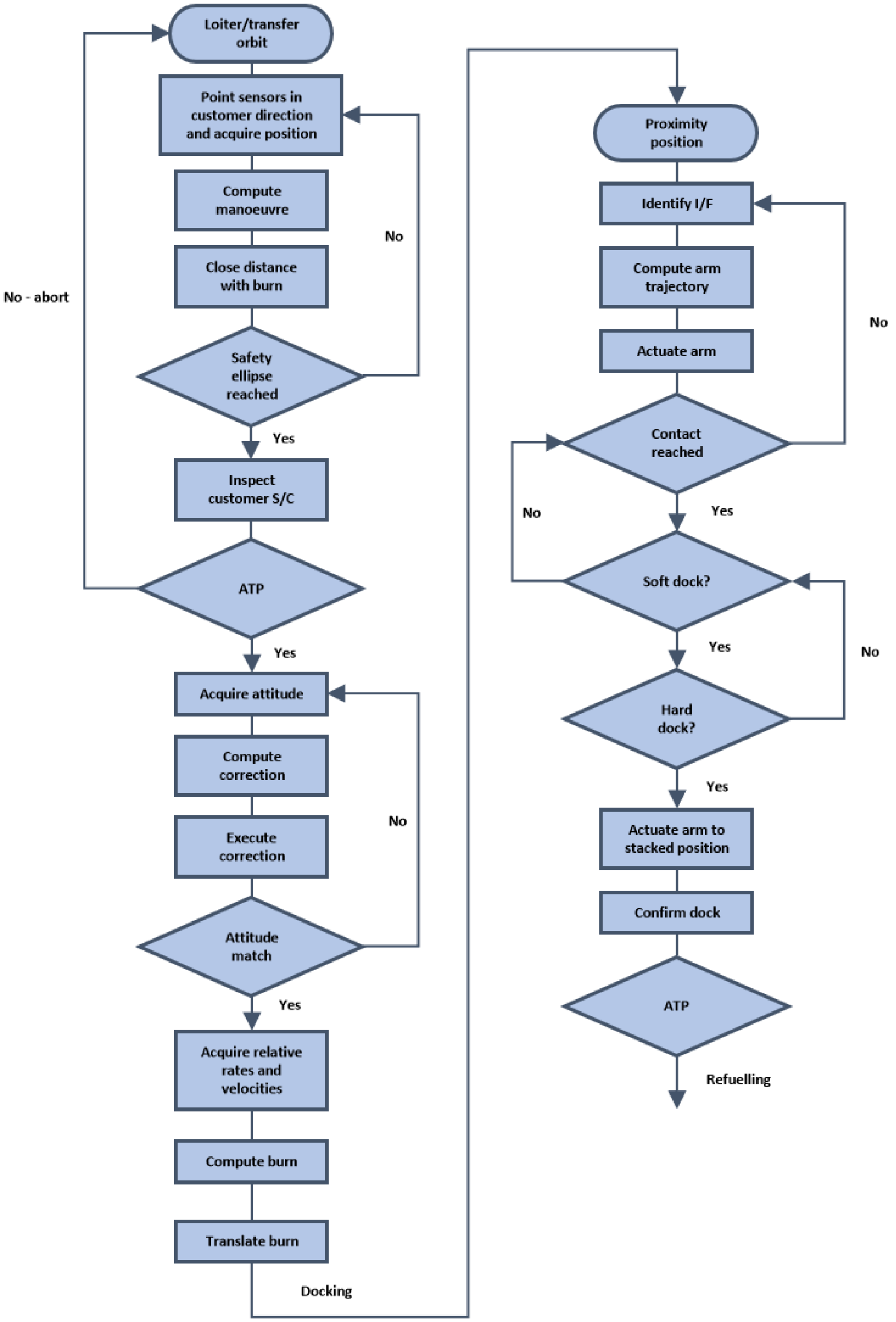


Figure 5.6: Operations flow logic - rendezvous (left) and docking phase (right)

Docking interface shall be identified by visual means (aided by the reflective visual markers mounted on the customer S/C). When the location of the docking/refueling I/F is confirmed autonomous on-board computer will compute the trajectory of the robotic arm and issue a command to the arm actuators.

After the end-effector captures the docking fixture a loose connection is established and the two S/C should not drift apart (Soft-dock Mode). Immediately after the connection should be rigidized. Mating interfaces are aligned in the defined geometry and fixed connection is established, effectively pairing the two vehicles (mechanically, electrically and thermally if applicable)

The final steps of the docking phase include the robotic arm moving to a „stacked“ position where it locks and remains still until undocking. Successful establishment of the connection is confirmed.

Flow logic of the combined rendezvous and docking phases steps is shown in Figure 5.6.

5.4.4 Phase 3: Refueling

After the firm connection is confirmed the two spacecraft remain locked thanks to servicer mechanisms and the ATP from ground command is issued to commence the actual refueling. The refuelling takes place during this phase and the refueling mode is applicable.

Initial measurement of the propellant management system are taken prior to engagement of the transfer. Predominantly the propellant pressure and temperature must be withing the acceptable range to commence the transfer. If otherwise a fault in the system might be present and the issue should be resolved by ground control.

The actual propellant transfer begins with the valve opening and the first component transfer (either fuel or oxidizer) might be initiated while monitoring the critical parameters during the whole process. In case of any unexpected development, or should the parameters exceed acceptable limits the transfer process should be safely interrupted based on autonomous command. The process is repeated with the other fluid.

When the total amount of the propellant is transferred, the propellant transfer valves are shut and the excess fluid is safely vented out-board. Status of the refueling is reported to the ground control and the servicer spacecraft awaits ATP for disengaging.

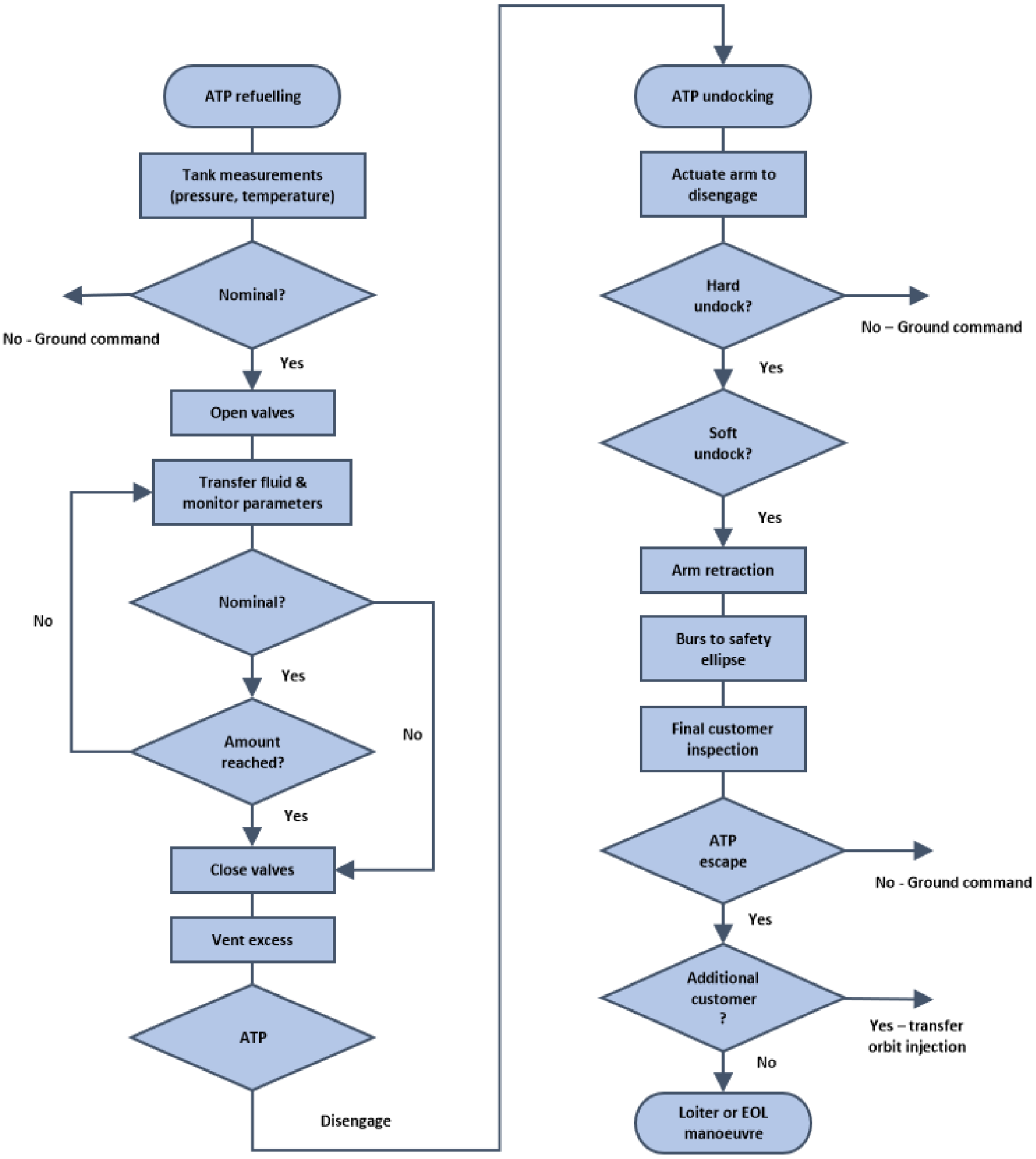


Figure 5.7: Operations flow logic - refueling (left) and detachment phase (right)

5.4.5 Phase 4: Detachment

The de-mating phase follows after the successful propellant transfer or also in case of some unexpected chain of events due to which the operation had to be interrupted for safety reasons (either customer S/C or servicer S/C). The whole process mirrors the docking phase employing the same operation modes in reverse order: hard-dock mode, soft-dock mode if applicable, docking mode. Following with escape mode.

The robotic arm is unlocked so it could move from the „stacked“ position. The end-effector is actuated to release the firm grip on the customer spacecraft. If disengagement of the connection is not possible the ground command shall take control as this might mean that the interface is jammed.

The connection between the two S/C is terminated and the robotic arm safely retracts to inert position respecting possible keep out zones of the customer S/C. The propulsion system is engaged and the servicer moves to safe distance onto the safety ellipse around the customer as during the docking sequence. From the elliptical trajectory the final inspection of the customer S/C is executed ensuring that the integrity of the vehicle was not breached and the S/C generally appears healthy.

Finally the servicer is free to move to the next customer and execute orbit adjustment burns to inject itself to transfer trajectory. If no immediate customer is ready. The servicer moves to the loitering orbit in order not to interfere in the GEO and drifts until a new customer is at hand.

Flow logic of the combined refueling and detachment phases steps is shown in Figure 5.7. The overall info-graphic mapping the main steps of refueling operations is shown in Figure 5.8.

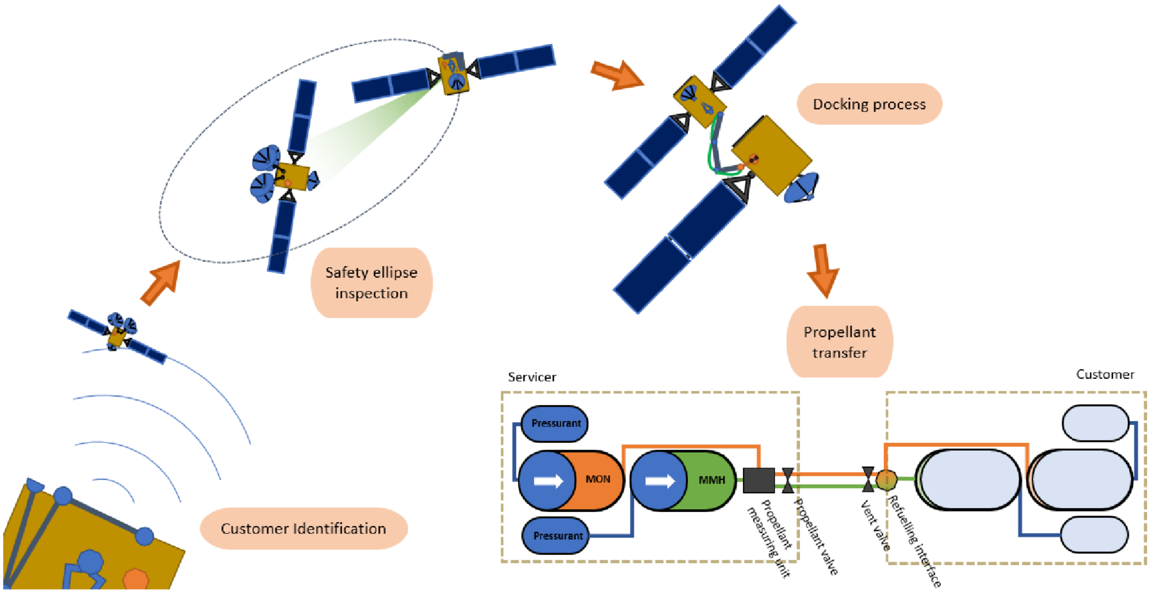


Figure 5.8: Concept of operations

5.5 Space segment orbit

The specific of the servicing missions in general is that there is no actual orbit of the servicer S/C. The servicer always matches its orbit with the orbit of the target. In exaggeration it can be stated that most of the time servicer spends on various transfer orbits between individual customers.

In spite of the fact that the servicer in ideal case transfers to the next customer effectively making profit from the refueling and life-extension service. There is a parking orbit defined for the service in the event that no immediate customer is available the servicer S/C is foreseen to clear out the GEO. To prevent possible interference of the communication this parking orbit is slightly above the GEO. General parameters of the parking orbit are in the Table 5.5.

Table 5.5: Servicer S/C parking orbit parameters

Servicer parking orbit		
Semi-major axis	a	42 664 km
Eccentricity	e	0
Inclination	i	0°
Ascending node	Ω	N/A
Argument of periapsis	ω	N/A

Associated parameters were calculated using basic formulas for overview.

Orbital period:

$$T = 2\pi \cdot \sqrt{\frac{a^3}{\mu}} = 1\,461.68\,min$$

where $\mu = 398\,600\,km^3 \cdot s^{-2}$

Orbital speed:

$$v = \frac{h}{p} = 3.0566 km \cdot s^{-1}$$

where $h = \sqrt{p \cdot \mu}$ and $p = a$

Compared to the velocity of the objects placed on the GEO the parking orbit speed is lower and in relative motion the GEO satellites will rather slowly pass below the servicer S/C. Effectively this means that just by station keeping maneuvers on the parking orbit the servicer will complete the full orbit relative to objects on GEO in nearly 2 months time.

Calculation - least common multiple:

$$T_{GEO} = 1\,436.06\,min$$
$$T_{park} = 1\,461.68\,min$$
$$LCM = 81\,927\,min \approx 57\,days$$

5.6 Space segment payload

Space segment payload in terms of satellite refueling mission comprises of three main groups of equipment directly and actively engaged in the process. Each group is described in brief in this section and instruments perceived as capable to fulfill the requirements are drafted. Please note that other alternatives are also possible and not necessarily less suitable.

5.6.1 Sensory equipment

The first groups of the payload instruments presents the sensory equipment with a crucial role predominantly in the RPOD as the servicer S/C fully relies on the relative navigation based on the data acquired from the sensors. Relative navigation sensors are percieved to be mounted on the semi-independent sensor platform with the pointing capability to allow for constant pointing in the direction of the customer S/C during the servicer maneuvering. Second group of sensors presents the internal sensory equipment designated for propellant and propellant transfer process monitoring. As a sensory equipment plays a critical role a degree of redundancy shall be considered and accounted for in the design process.

Radar

Long range radar sensor might serve as a means for long range detection of the customer S/C position. Radar detection is perceived to be utilized in the early phase of the rendezvous phase to acquire first estimation of the client position where the total relative position determination error is still allowed to be present.

LiDaR

Light Detection and Ranging sensor is a sensor of choice for proximity operations and precise determination of the customer S/C position as well as relative parameters of the both spacecrafts being relative velocities, attitude, tumble rates etc. LiDaR technology is sufficiently precise to fulfil the close range precision requirements and a level of redundancy is achieved as the system compliments the visual sensors.

Visible light sensors

Visible light sensors are utilized in the close proximity relative navigation and also applicable I/F recognition within the customer S/C. These sensors should achieve high performance in terms of image resolution and frame rate as these are key to smooth and precise navigation and docking. Visual cameras are foreseen to be mounted both on the S/C body and the robotic arm end-effector to provide complementing angle of view and a degree of redundancy.

Contact sensors

Contact sensors are build into the end-effector of the robotic arm and their main purpose is to confirm the first contact during the mating process as well as full docking sequence completion. Various working principles for the contact sensors are available (mechanical, resistance, magnetic etc.) and suitable technology with high reliability should be preferred (TBC).

Pressure and temperature sensors

Another groups of sensors shall be installed across the propellant management system to monitor key parameters (pressure and temperature predominantly). The sensors should be placed inside the propellant components tanks, the propellant transfer lines as well as in the end-effector and refueling interface to ensure thorough monitoring of the process progress.

5.6.2 Robotic equipment

The robotic equipment of the servicer S/C is the active element of the whole system. The critical task of docking and mating interfaces with the customer S/C is secured via the robotic means. As there is no redundancy in the system, the robotic shall be of high reliability. High precision of the actuation is needed in the whole range of operation.

Robotic arm

The robotic manipulator arm is the critical equipment of the system with strict requirements on the achievable precision and reach. The arm should be seven degree-of-freedom ensuring a level of redundancy and a means to avoid interference with customer S/C keep out zones. The operation of the robotic arm foreseen to be actuated electro-mechanically as it offers suitable range of control, precision, achievable forces, swiftness and speeds in actuation the arm movements. The robotic arm should be lightweight and rigid.

End-effector

The end-effector is in this particular case deemed to combine the functions of the structural mating I/F and also the fluid transfer I/F (e.g. ASSIST). The docking and fuel transfer are thus enabled via single end-effector. Otherwise a second robotic arm would be required to execute the docking sequence while the other arm would be free for subsequent operations. The end-effector is equipped with the sensory suite for relative navigation, contact confirmation and propellant transfer control.

5.6.3 Propellant management system

Propellant management system of the service S/C is closely linked (in case of some elements the function is matched) to the propulsion system of the S/C which falls under the space segment platform. In this case however, the function related to refueling is deemed superior and driver. For reduced complexity reasons the service S/C is foreseen to feature unified propulsion system ($\approx$ propellant management system) utilizing biopropellant. This kind of system is also the choice of many customer telecommunication satellites and the similarities of the two systems bring reduced risk during the transfer operations. The system comprises of two tanks for fuel and oxidizer (typically MON/MMH) and a pressurant tank/tanks. The propellant is then fed to all the spacecraft thrusters - apogee and fine attitude and correction thrusters located across the platform.

Propellant tanks

Two tanks should hold at least 2 500 kg of propellant (fuel + oxidizer) which will be fed to the servicer S/C thrusters to adapt and correct orbits and perform station keeping maneuvers. At the same time the very tanks are connected to the transfer line and serve as a storage volume for the actual propellant to be transferred to the customer S/C. Propellant tanks are typically designed to be titanium but composite solution promising weight saving are emerging. A flexible membrane is installed inside the tank separation the propellant component and the pressurizing gas allowing for positive expulsion and correct transfer rates.

Propellant transfer line

Function of the propellant transfer line is to connect the supply tank of the servicer with the receiver tank of the customer S/C. The supply line passes through series of valves, the propellant metering unit and the mating interface. Contamination and leakage of the propellant shall be minimized. The propellant transfer line along the robotic arm needs to be flexible to allow for free movement of the arm. As it passes outside the shielded S/C body the transfer line should be properly isolated from the outer environment to minimize the effects on propellant. Separate transfer lines are necessary for each component as contamination is not acceptable.

Mating interface

Mating interface is a standardized structure and function interface common to the servicer and customer S/C. In the absence of the connect I/F the servicer would be forced to access the original filling valves to actually supply propellant. This task significantly increases the complexity of the task and for the servicer featuring single manipulator arm not possible to execute. Mating interface should allow for a misalignment in the docking sequence, ensure tight coupling with minimal leak rate of the propellant.

Propellant, pressurant and vent valves

Valves included in the propellant transfer system shall be able to repeatedly open and close as the operation of the servicer requires both states, pyrotechnic technology is thus excluded. Similar to the transfer line valves should show minimal (close to zero) leak rates as they separate pressurized environment and vacuum of open space.

Propellant metering unit

Propellant metering unit ensures that the correct predefined amount of propellant is transferred to the customer S/C. A suitable and reliable method should be utilized without excessive moving parts which tend to lower the overall reliability of the system. Electromagnetic or ultrasound measurement methods are deemed suitable.

5.6.4 Control hardware and software

The on-board computer is a critical equipment as it controls complete operation of the servicer S/C and the refueling process. A level of redundancy, error detection and correction is needed for the on-board computer as is common practice in case of other satellites. Furthermore the capability of the refueling mission on-board computer is required to achieve high performances. The performance demanding tasks are predominantly real-time sensor data processing, robotic object recognition and interpretation of the input data in relations. Communication and downlink/uplink capability does not need to achieve excessive performance as real time ground controlled operation is not foreseen. The servicer will rather execute task autonomously or semi-autonomously based on the predefined ground control issued task lists and issued authority to proceed. Software involves incorporation of applicable operation modes as described in Section 4.6.

5.7 Space segment platform

The space segment platform task is to enable and support the tasks carried out by the S/C payload. In case of the refueling mission certain platform subsystems are considered as a part of the S/C payload, more precisely the function of the platform subsystem and a payload equipment is fused (e.g spacecraft propulsion system or partially attitude control subsystem). The mission objectives do not pose special requirements on certain subsystems, in that case a standard requirements and legacy solutions are applied and not subject to this thesis.

Structure and mechanical subsystem

Standard design approach is deemed suitable in case of structure subsystem featuring primary (central tube), secondary (sandwich panels) and tertiary (complementary) structures. The structure subsystem goal is to provide platform for all of the other system to fix on and transfer loads and stresses introduced to the spacecraft, these are first and foremost the loads imposed during the launch sequence. Other load after the separation of the spacecraft are negligible in comparison. The nature of the refueling mission poses a need to get in contact with other objects and certain mechanical loads and shocks might be introduced to the structure via the robotic arm, those are still very minor compared to harsh launch environment.

Spacecraft propulsion subsystem

See section 5.6.3.

Electrical power supply subsystem

A standard photovoltaic electrical power generation is deemed convenient as the spacecraft stays in the range of acceptable usability of the solar power generation. Detailed analysis on the total electrical power consumption and battery capacity is to be done.

Thermal control subsystem

A conventional thermal control system is foreseen to be utilized as the servicer S/C and the refueling mission do not require special care in terms of thermal control subsystem compared to other representative satellites. System will comprise of multi-layer insulation, heat radiators and internal heaters and complementary thermal control hardware.

Attitude control subsystem

Attitude control is a key subsystem in relation to the refueling mission. Attitude control system shall achieve considerably high level of accuracy in 3-axis stabilisation of the S/C and be robust enough to temporarily overtake the attitude control of the docked stack of servicer and customer S/C. In practise the mass to control might be more than doubled when docked.

The system typically comprises of the attitude sensors in case of the refueling mission these would be precise sun sensors and star sensors. The attitude control itself a system of choice would be zero momentum control momentum gyros. The system achieves high precision and high achievable roll rates needed for required maneuverability of the servicer S/C. The gyros spin at constant speed providing high torques when despinning/accelerating. The drawbacks are high overall cost and weight of the system and the need for periodical desaturation of the gyros performed by precise thruster burns.

Communication subsystem

A conventional solution for the communication subsystem will be employed. As autonomous operation does not require high volume data exchanges with ground control. The servicer S/C needs to receive relatively simple command list or updates on the upcoming mission and downlinks the operational data in predefined frequency. No large volume data exchange is foreseen.

Data management subsystem

On-board data management plays a significant role in the autonomous operation of the servicer S/C. The ability to promptly process rather large volumes of data from the on-board sensory system is a key capability ensuring correct function of the system. On-board mass storage capacity of large volume should be considered.

5.8 Launcher segment

Launcher segment is employed at the very beginning of each space mission as it deliver the payload in the form of spacecraft to the desired orbit. Launcher segment selection may have significant impact on the total mission cost as it presents substantial fraction of the total mission (see typical costs in Table 5.6).

Apart from the cost launcher imposes constraints in the maximum deliverable mass to the given orbit (launcher performance) and the total volume of the payload that is able to fit in the launcher fairing. The launcher segment also introduces very harsh quasi-static load, vibration load and shock loads to the spacecraft structure which needs to be designed to withstand these stresses.

For the satellite refueling mission to the GEO a suitable launchers are deemed to be currently available Falcon 9 launcher, Ariane 5 and in the near future also Ariane 6 and Vulcan Centaur.

5.9 Feasibility assessment

5.9.1 GEO satellite cost estimation

Although the detailed financial data are generally not publicly available a rough cost estimate regarding refueling is done below. To be economically viable refueling cost must underscore the cost of a new replacement satellite for the S/C approaching EOL. The cost estimation for a typical GEO communication satellite based on similarity and analysis is assessed in the Table 5.6 below. Major budget items are considered comprising cost of the S/C itself, cost of launch, cost of operations and insurance cost.

Table 5.6: Cost estimation for GEO satellite

Budget item	Cost $M	Source
Satellite		
GEO communication satellite	150 - 200	[2] [3] [41]
Launch		
Ariane 5	177	[35]
Ariane 6	77	[35]
Falcon 9	67	[43]
Falcon Heavy	97	[43]
Altas V	109	[32]
Vulcan Centaur	82	[32]
Launch insurance	20	[2] [42]
Operation		
15 years GEO	15	[2] [3]
Operation insurance		
15 years GEO	20	[2] [42]
TOTAL	**272 - 432**	

As seen in the Table 5.6 the cumulative cost of a single GEO satellite can be well over $250 million. Which is confirmed by other estimates [1] [41] [18] ranging from $150 to $300 million. In comparison Northrop Grumman mission MEV-1 3.1.1 purchased by the satellite operator Intelsat for their mission Intelsat-901 required estimated internal investment by Northrop of $100 - $200 million [33] and the cost of such service for Intelsat is estimated at $13 million per year. That is $65 million for the 5 year life-extension purchased by the Intelsat. This cost represents a substantial fraction of the new replacement satellite which can last up to 15 years

For a refueling service to be commercially competitive a price for life extension needs to underscore the price of a replacement satellite with a substantial margin. This can be achieved with different approach compared to MEV philosophy, that is servicer S/C able to refuel multiple clients during a period of time without the need to stay attached and overtake station keeping.

Dedicated feasibility study have been conducted in the past, focusing on on-orbit refueling [1]. As the study points out the refueling GEO satellites is cost effective compared to new satellite launch but the effectiveness is dependant on several factors. Refueling spacecraft mission should be designed such that the consumption of the fuel by the servicer itself is minimized while the number of clients refueled is maximized. First can be aided by careful trajectory planning and trading transfer speed (required total ΔV) for transfer time between individual clients. This results in longer relocation times of the servicer with the benefit of spared fuel. The ability to tend to higher number of customer would be significantly improved should the servicer itself have the capability to be refueled on-orbit. Fuel depot system is one of the solutions to this challenge. Nevertheless the study [1] proves the cost effectiveness of refueling under certain conditions even in the case of single use servicer.

5.9.2 Servicer spacecraft determination

For a business case the 5 year life extension to the customer spacecraft is considered. Five year span poses a reasonable life extension before the risk of failure of other spacecraft systems is too high. The case is applied to the standard GEO satellite as described in parameters in Table 4.2.

Satellite disposes on average with a 2 000 kg of propellant of which nearly 80 % is burned in the GEO insertion as the satellite usually propels itself from GTO [2]. That leaves the communication satellite with some 400 kg of propellant for entire life span of 15 years including the EOL burn. To provide the satellite with additional 5 years of lifetime requires transfer of $\approx$ 100 - 130 kg of additional fuel and oxidizer

At the same time a refueling service cost has to underscore the cost of equivalent prolonging of the service by replacement satellite to be economically viable. A cost of communication satellite might be spread across its entire life time. That results of sum of about $100 million for 5 year service of $300 million space system.

A projected price estimate of the servicing S/C is comparable but higher to a current GEO telecommunication satellite. Reaching to a threshold of about $400 million with development margins accounted for. The cost requirement implies the need to refuel at least 4 customers to bring the cost of refueling service for the customer at least to the threshold of the dedicated replacement satellite launch. To become financially viable the servicer would need to execute more than 4 refueling operations at GEO.

The need to execute more than 4 refuelings of approximately 100 - 130 kg of propellant drives the amount of propellant designated to transfer to reach at least 500 kg. Assuming the servicer S/C will burn comparable amount of propellant as the communication satellites during transition from GTO to GEO (80 %) results in the total propellant amount on board to be at least 2 500 kg (MR-04). Assuming also comparable ratio of expendables on board to total launch mass of the satellite results in total estimated mass of the servicer S/C to be at least 3 500 kg.

5.10 Technology Readiness Level

Assessment of TRL of mission elements is a key step to determine the readiness of the mission to be completed. If one or more elements of the mission are low TRL the cost and schedule impact on the mission should be accounted for. Technology Readiness Levels of selected key mission elements for satellite refueling are listed in the Table 5.7 bellow.

Table 5.7: TRL of selected mission elements

Mission Element	TRL	Justification
Robotic arm	9	Flight proven - RRM, Space Shuttle program, ISS Canadarm.
Exchangeable tools	9	Flight proven - RRM
Grapling device	9	Flight proven - RRM, MEV program.
Fluid transfer interface	9	Flight proven - RRM, RAFTI, Space Shuttle STS-53 and STS-57
Fluid measuring unit	9	Flight proven - RRM
End-effector	9	Flight proven - RRM, MEV program
LiDaR	9	Flight proven - MEV
Visual camera	9	Flight proven - MEV, RRM
On-board computer		
Platform	9	Flight proven - no special requirements imposed on the platform, commercially available options with flight heritage can be used.
Fuel tank	9	Flight proven - RRM, Progress refueling ISS
Software	9/6	Flight proven - Autonomous rendezvous and docking, Prototype - autonomous fuel transfer - Cephalopod SW
On-board control	9	Flight proven - MEV

In this particular case the TRL of individual elements has achieved high maturity through extensive development and testing activities and is already flight proven. This fact is beneficial as high level of TRL helps to bring the total risk associated to the mission down, because little development is needed and investments to verify the technology are low. The challenge in this case still remains in integrating these elements into one complex system capable of refueling in-orbit.

Chapter 6

Conclusion

This diploma thesis fulfilled the laid out goals to a sufficient extend by attending to each of the goals and exceeding them in few areas. The work brings thorough overview of the on-orbit satellite refueling problematic. The first chapter of the thesis identifies on-orbit refueling and analyses the foreseen benefit of such service. Key benefits and motivation to actually implement refueling into existing space systems are presented along with technological and programmatic constraints connected to high demands of the given mission.

Second part of the thesis maps the contemporary situation in the field of on-orbit refueling. Introduction to past and planned missions and projects aiming at establishment of refueling capacity is made, compiling private and government funded missions. Along with the stand alone mission a research of related technologies was made and the results are presented.

Afterwards based on the identified constraints, benefits and potential utilisation of the refueling service accompanied by the outcomes of the existing solutions from the previous part a set of mission needs was identified. Initial conditions and base assumptions were made. Potential customer was identified to be the GEO communication satellites operators who might directly benefit from the life extension of their assets. Mission statement for the on-orbit satellite refueling mission was formulated and the standard practise of execution and management of space projects utilized in this thesis was introduced.

The proposal part of this thesis being the center of the thesis formulated primary and secondary mission objectives. A set of applicable requirements with justification was made affecting the general mission requirements, space segment orbit requirements, space segment payload requirements and applicable platform requirements. The mission was then broken down to individual tasks to be executed during the course of refueling forming hierarchical structure of the function tree. Similarly a product tree was established providing overview of the spacecraft systems and subsystems. Detailed concept of operations was introduced breaking down the refueling process to individual tasks to be conducted either by the spacecraft platform or refueling payload. On top of the proposal a draft of technical solutions to each subsystem and mission element is included. Finally, simplified cost estimates and feasibility conditions are discussed.

Based on this work a detailed work on refueling mission concept might be started, drawing from the work solid base in the process understanding and identification of critical points. Preliminary assumptions and design solutions could be justified and detailed. The possible area to expand the work would be exploration of alternative or different concepts of the refueling service. That might include for example refueling Xenon propellant for electric hall thrusters instead of conventional MON/MMH mixture being used today. Interesting area of refueling is also cryofluids replenishment and storage on-orbit. Based on the spacecraft capable of autonomous refueling the option to tailor and expand the service also to other areas of on-orbit servicing might prove viable.

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Appendix A

List of Abbreviations

ATP	Authority to Proceed
CDR	Critical Design Review
CSV	Cooperative Service Valve
EOL	End Of Life
ECSS	European Cooperation for Space Standardization
ESA	European Space Agency
GEO	Geostationary Earth Orbit
GTO	Geostationary transfer orbit
GNC	Guidance, Navigation and Control
ISS	International Space Station
LEO	Low Earth Orbit
LH2	Liquid Hydrogen
LiDaR	Light Detection And Ranging
LOX	Liquid Oxygen
MEP	Mission Extension Pod
MEV	Mission Extension Vehicle
MON	Mixed Oxides of Nitrogen
MMH	Monomethylhydrazine
MRV	Mission Robotic Vehicle
NTO	Dinitrogen Tetroxide
N/A	Not Applicable
NASA	National Aeronautics and Space Administration
OOS	On-orbit servicing
RAFTI	Rapidly Attachable Fluid Transfer Interface
RRM	Robotic Refueling mission
RPOD	Rendezvous, Proximity Operations and Docking
S/C	Spacecraft
TBC	To Be Confirmed
TRL	Technology Readiness Level
ULA	United Launch Alliance