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The concept of on-orbit-servicing for next generation space system development and its key technologies*

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Abstract. Over the last years many companies and national agencies in different countries have been involved in development of various technical aspects of on-orbit-servicing (OOS). US and Russian OOS experiences are described. The problem of OOS in general is considered as a bit wider. It is shown that OOS relates to development of the next-generation space infrastructure and the solution of the problem of OOS, to a great extent, predetermines the characteristics of the next-generation space systems. Two equally important directions are stressed for OOS activities: first, making satellites serviceable, and the second, creating directly servicing systems. Implementation of each direction includes a wide range of developments. In the first case, we have to consider a capability of docking with the serviced satellite, a guaranteed access to the satellite components, block-modular structure of the serviced satellite, standardization of hardware and connectors, etc. Implementation of the second direction varies from the development of servicing methods and servicing systems to satellite orbits and constellation optimization. The existing and perspective key technologies for serviceable and servicing satellite are presented. It is shown, that the economic benefit of OOS must be justified by more thoroughly from an end-to-end perspective taking into account the features of the future space infrastructure. Servicing allows extending operational lifetime of satellites and thus reducing lifecycle cost, or moreover enable for entirely new systems and mission. These effects could be achieved not only through refuelling or repairing of the satellites, but also through satellite orbit correction. OOS creates a prospect of establishing a commercial servicing and debris removal network lending form the same technology base, which constitutes, however, separate technological problems, which are closely connected with OOS.

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Концепция орбитального обслуживания для разработки космической системы следующего поколения и ее ключевые технологии*

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космические системы нового поколения, орбитальное обслуживание, ремонт, дозаправка, спутник на орбите, обслуживание спутников, блочно-модульные, стандарт, гибкость, экономическая выгода

Аннотация. За последние годы многие компании и национальные агентства в разных странах были вовлечены в разработку различных технических аспектов орбитального обслуживания. Описан опыт орбитального обслуживания в США и России. Рассматривается проблема орбитального обслуживания в целом. Показано, что орбитальное обслуживание относится к развитию космической инфраструктуры следующего поколения и решение проблемы орбитального обслуживания в значительной степени предопределяет характеристики космических систем следующего поколения. Для реализации орбитального обслуживания выделяются два одинаково важных направления: 1) обеспечение работоспособности спутников; 2) создание систем непосредственного обслуживания. Реализация каждого направления включает в себя широкий спектр разработок. В первом случае нужно учитывать возможность стыковки с обслуживаемым спутником, гарантированный доступ к компонентам спутника, блочно-модульную структуру обслуживаемого спутника, стандартизацию аппаратного обеспечения и разъемов и т. д. Реализация второго направления варьируется от разработки методов обслуживания и систем обслуживания до спутниковых орбит и оптимизации группировки. Представлены существующие и перспективные ключевые технологии для исправного обслуживающего спутника. Показано, что экономическая выгода орбитального обслуживания должна тщательно обосновываться с глобальной точки зрения с учетом особенностей будущей космической инфраструктуры. Обслуживание позволяет продлить срок службы спутников, снизив таким образом стоимость жизненного цикла, более того – создавать совершенно новые системы и миссии. Эти эффекты могут быть достигнуты не только посредством дозаправки или ремонта спутников, но и за счет коррекции их орбит. Предлагаемое орбитальное обслуживание создает перспективу создания коммерческой сети обслуживания и удаления мусора, сформированной на той же технологической базе, что, однако, представляет собой отдельные технологические проблемы, которые тесно связаны с орбитальным обслуживанием.

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Introduction

The general problem of the next-generation space system development based on the on-orbit-servicing (OOS) concept with a focus on its technological, theoretical, economic aspects is considered.

Over the last years many organizations in different countries have been involved in development of various technical aspects of on-orbit satellite servicing, which to a great extent predetermines the characteristics of next-generation space systems. Such efforts are now carried out in the USA (DARPA, Boeing Company, SSL, MDA), Russia (Roscosmos), Germany (German Aerospace Center DLR, Airbus Defence and Space ADS, OHB Group with formerly Kayser-Threde), Japan (JAXA, Tokyo Institute of Technology, Astrocale), Sweden (Swedish Space Corporation, Orbital Satellites Services AB), Spain (Sener), as well as in other countries.

Even though many companies and national agencies are currently conducting research in on-orbit servicing, there is an organizational challenge, as it is hard to tackle the big picture of the problem of OOS due to its scope. This complex problem demands a comprehensive top-down approach and can only be addressed properly by a coordinated group comprising specialists of different backgrounds beyond space and technology. It is also obvious that a successful study should incorporate ideas and experiences that come from different scientists and from different countries.

Moreover, we consider that the solution of the OOS problem to a great extent predetermines the characteristics of next-generation space systems. Whatever efforts have been made to this end are either incomplete or too specific. The solutions at hand deal with specific tasks and can only be regarded as a part of a bigger pattern that is yet to be described. The study has never been undertaken at such a scale, and it is a chance to generalize all the existing experience and take a step further, by improving particulars and integrating them into a complex infrastructure.

Servicing infrastructure can only be regarded within the context of advanced next-generation space systems the ones that are going to be economically feasible and effectively serviced. This means that anyone who commits to the study should possess knowledge not only of the basic on-orbit servicing concepts, but also of the future space systems themselves.

Researching a particular way of servicing could be pointless, if this study doesn't fit with the way the future space systems are going to operate. At the same time, a process of mutual adjustment and dialogue between the two parties – those who develop special-purpose space systems to be serviced, and those design servicing infrastructure – should be initiated as soon as possible in the design process to find an optimal solution that would make space systems serviceable and at the same time allow them to perform their main missions without loss in functionality.

The problem is still far from being solved – only separate specific solutions exist [2]. Therefore, a new comprehensive study must be initiated. Its distinctive features from other research in the same field are the following:

1) the generic challenges and opportunities of a next generation space on-orbit servicing infrastructure are investigated;

2) both study specific solutions for creation of space on-orbit servicing system, and different aspects of servicing infrastructure are investigated;

3) by uniting different fields of research, the attention is paid to details, as well as a guided, coordinated effort is presented to achieve a common goal.

This creates balance between diversity and purposefulness, leading to an all-encompassing and non-redundant study.

The study is aimed at following purposes:

1) to evaluate experience and detect trends and problems that matter today;

2) to set primary definitions and define the concept of OOS, to single out components of servicing and serviced systems, and to point out the stages of a servicing operation;

3) to identify the main technologies that must be enhanced with respect to servicing and serviced systems, and to propose solutions for optimizing and adjusting orbital formations of serviced and servicing satellites;

4) to evaluate the problem within the context of next-generation space systems by envisioning an outline of advanced servicing networks for the predicted space population;

5) to estimate economic and jurisdictional aspects of OOS, considering the possibility of complete interface standardization, calculating benefit, and researching international space law;

6) to outline roadmaps and to research options of international cooperation.

Thus, the study encompasses all sides of the problem – purely technological and engineering, mathematical and methodological, as well as economic, organizational, and legal.

1. Lessons learned

To plan, we need to know how the problem originated, how it has been dealt with before and what trends revelled themselves earlier that now still have some impact. Lessons learned in the past at the stage of creating the modern servicing space infrastructure should be studied closely and open-mindedly.

The problem of OOS emerged together with the problem of space exploration – as it happens, even the most reliable technologies tend to malfunction and even in the most successful missions there are cases of minor emergencies.

1.1. US

Some of the most prominent pages of the American space servicing chronicles relate to servicing the first US orbital station, Skylab. In 1973, the onset of its mission was accompanied by some major difficulties. Because of the damage that occurred during its launch, solar arrays of Skylab were not deployed properly; micrometeoroid shields, which also served as thermal managing device, failed, and the station could not be made sufficiently habitable. However, a crew of astronauts arrived at Skylab and saved the station, replacing thermal shields and deploying the solar panels, thus performing the first major on-orbit repair operation.

After the incident, many lessons were derived from the experience. One of the major ones concerned the approach to space systems development and is still relevant today.

Designing and operating a space vehicle is an interdisciplinary problem that requires good coordination at all stages. Excessive paperwork should be avoided when possible! Every stage of spaceflight relates to another and yet must be treated by a team of qualified specialists who know their trade. Moreover, as during many other events of manned space exploration era, OOS proved to be a dangerous and demanding enterprise – a field of many outstanding deeds but also a field to be made safer.

Another important year is 1984. It was marked by two landmark events, and the successful completion of the first one in a way inspired the courage with which the other one was undertaken.

After the failure of attitude control system, the Solar Maximum Mission (SMM) satellite had been out-of-order for quite some time. However, in 1984, a team of astronauts was sent to repair the malfunctioning vehicle.

After successful rendezvous and capture manoeuvres, the Challenger crew replaced the failed parts by taking advantage of the satellite's modular structure.

Moreover, this repair mission was the first-time that robotic tools were combined with human outer space operations, setting one of the most important ongoing trends.

Later in the year, Discovery's mission substituted two new telecommunication satellites for two damaged ones, returning the replaced spacecraft to Earth for refurbishment after complex manned on-orbit operations, thus saving great sums of money. Both satellites were later resold and re-launched into space.

The lessons learned from these operations could be stated as follows: Design of serviced spacecraft might tremendously facilitate servicing operations; however, one should be ready to service "unserviceable" satellite (like the Hubble space telescope which has been successfully repaired on several occasions). Moreover, on-orbit servicing could lead to direct commercial benefit, for millions of dollars spent could be salvaged in one operation.

1.2. Russia

Looking at the Russian OOS experience it is worthwhile mentioning a few selected seminal achievements.

In 1985 Russia restored Salut-7. After failure in main command link equipment, the station entered a stage of fully uncontrolled flight. Souyz-T13 crew (with astronauts Janibekov and Savinykh) performed an almost impossible operation and restored the station after completing the exhausting manual docking.

After that, humanity learned that almost any space object may be captured and restored with due efforts from ground systems and manned spacecraft.

However, we also understood that the less frequent such situations occur, the better.

In 1986–1996 Russia broadened its experience of operating Salut stations by managing the Mir Space Station. Countless docking and repairing operations of all kinds were performed during this period. Aside from purely technological and scientific advances, humanity learned that every servicing technology should be tested under operational conditions. Only tested and space-qualified technologies represent a real proof of concept.

1.3. Russia and US

Numerous expeditions to the Mir Space Station and later to the International Space Station have demonstrated that the efficiency of on-orbit servicing is dramatically enhanced by international cooperation – each nation should concentrate on what it does best.

Figure 1. “Soyuz TMA-10M” manned spacecraft (Russia)
(photo by S.P. Korolev Rocket and Space Corporation Energia)

Figure 2. “Progress M-M” cargo spacecraft (Russia)
(photo by S.P. Korolev Rocket and Space Corporation Energia)

Figure 3. “SpaceX Dragon” unmanned spacecraft (US)
(photo by Space Exploration Technologies Corporation)

Figure 4. “Orbital ATK Cygnus” automated cargo spacecraft (US)
(photo by Orbital ATK Inc.)

During the Mir Station operation, the Russian orbital facility received US Space Shuttles that docked to the station using ports initially intended for Russian Buran spacecraft. This signified how important unified and standard interface could be for successful international programs and acted as a precursor of ISS. The mode of current ISS servicing largely relies on Russian Soyuz (Figure 1) and Progress vehicles (Figure 2), that deliver astronaut crews and additional equipment to the station as well as US vehicles SpaceX Dragon (Figure 3) and Orbital ATK Cygnus (Figure 4) that carry out resupplies and logistics missions for ISS. Aside from the resupplying function, Progress spacecraft are used to assist in orbit correction of ISS, which is another promising direction of on-orbit servicing in general.

There is a significant backlog in the development of methods for calculating the parameters of optimal rendezvous maneuvers [3–5] performed by high or low thrust engines.

The rendezvous problem is solved, among other things, when the orbits of the active spacecraft and the target spacecraft have a significant difference in the longitude of the ascending node [3].

1.4. Germany

Globally, OOS has been initially promoted by the roboticists. Space automation and robotics have a long history in Germany. Among many world-recognized scientists, technologies, and projects (i.e., ROTEX and German Japanese ETS-VII in the 1990ies or later ROKVISS aboard ISS, and more, also related design and simulation tools), DLR and industry initiated a focus on OOS from around 2000, and, together with CSA and JAXA gave the topic OOS a boost last decade.

Since 2010, the German space program addresses two programmatic lines in the context of OOS. Taking into consideration that - besides i.e., life extension, re-orbiting or refuelling – any future OOS will require cooperative targets, hence space infrastructure elements designed to be serviced, DLR nowadays distinguishes between “active” and “passive” OOS. Active OOS comprises robotic technologies and capabilities to conduct any of the various “services” discussed, investigated and promoted by the global space community. Whereas passive OOS is geared around the necessary components enabling OOS. In other words, the latter means standardized functional building blocks and interfaces as pre-requisite for OOS. A Prominent activity is iBOSS – intelligent building blocks for on-orbit satellite servicing and assembly – described in brief further below (under 4.4). iBOSS is a collaborative research program funded by DLR Space Administration. The project is Being conducted by the iBOSS consortium comprising the renown German institutions TU Berlin (system lead), MMi and SLA of RWTH Aachen University, FZi, RIF and JKIC.

1.5. Other actors and summary of lessons learned

There are also further activities and experiences made in Europe, Japan, China, India, and others, which cannot be covered in detail here.

Key take:

– principally every space object may be captured and restored with due efforts from ground systems and manned or un-manned spacecraft;

– OOS technologies need to be tested under operational condition (mandatory) parallel to system studies;

– no routine OOS has been established due to missing proof of concept both technically and commercially.

2. Definitions and concepts

All the examples that we have considered so far demonstrate considerable progress and outstanding outlook. And yet they were all aimed at the solution of specific tasks, most of which had to be dealt with in the state of emergency. The problem in general is a bit wider, and in this effort, we shall attempt to cover it in its fullness and complexity.

Let us look at main definitions and concepts to make sure that we operate within the same notional reference system.

Satellite OOS relates to solutions for creating next-generation space infrastructure that will allow saving funds that are currently spent on replenishing expensive orbital systems, which has to be done for the lack of full-scale satellite on-orbit servicing. It would imply the capability to correct orbits and to visually examine, recover, repair and refuelling satellites. This property of the next-generation space infrastructure will revolutionize space industries worldwide.

OOS includes, but is not limited to:

– orbital corrections and modifications to failed and out of control satellites;

– detailed visual inspection of satellite assets;

– spacecraft salvage options and debris clean up;

– rescuing mis-launched, stranded satellites and delivering them to their intended orbits;

– on-orbit mobility to meet international and national mission needs;

– refuelling spent satellites in orbit to extend life;

– repairing and correcting malfunctioning satellite in orbits;

– transportation and support for lunar and planetary missions.

The servicing satellite is to provide the following three typical operations:

– observation of the satellites with the purpose of determination the nature of the issue;

– technical assistance – repairing, refuelling, etc.;

– graveyarding of the satellites (moving the satellites to graveyard orbits) is implemented in case if the satellite damage is irreparable.

Two equally important directions (Figure 5) could be revealed in the development of the next-generation space systems based on the on-orbit satellite servicing:

1) making satellites and satellite constellations serviceable;

2) creating servicing satellites and designing their constellations for the performance of the satellite on-orbit servicing operations.

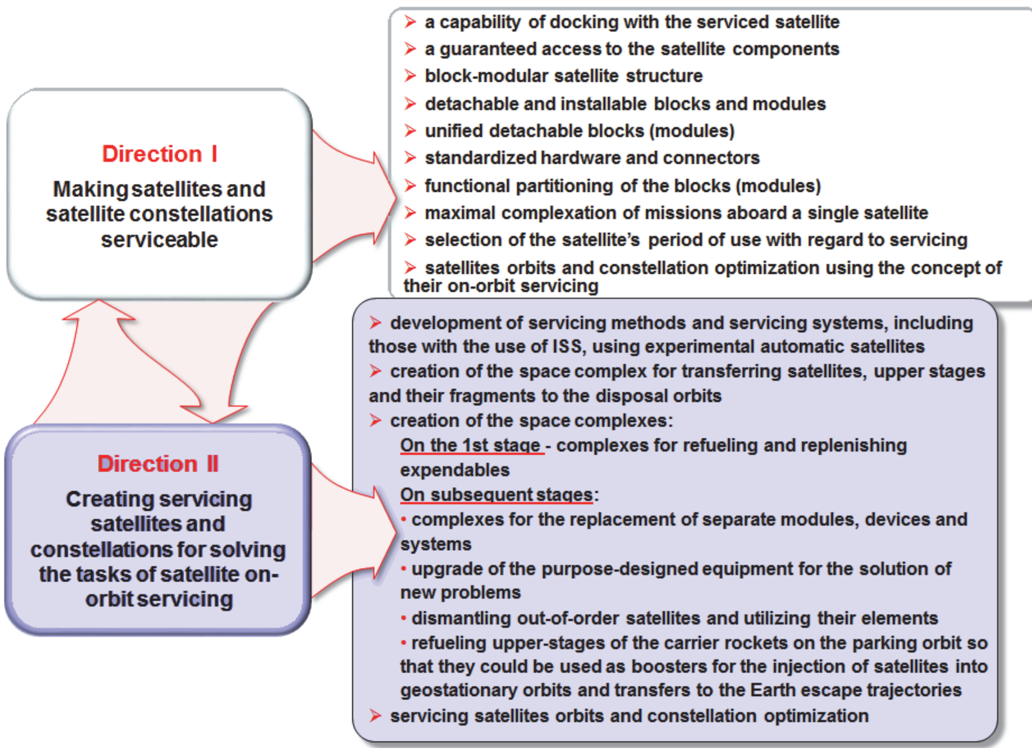

Figure 5. Directions for the development of satellite on-orbit servicing

Implementation of the first direction includes a wide range of developments, from providing the docking with the serviced satellite, even a non-cooperative one, to the serviced satellites orbits and constellation optimization which allows fully taking advantage of the benefits of OOS. The list of such developments includes (but is not limited to): a capability of docking with the serviced satellite, a guaranteed access to the satellite components, block-modular satellite structure, detachable and installable modules, unified detachable modules, standardized hardware and connectors, functional partitioning of the modules, maximal complexation of missions onboard a single satellite, selection of the satellite's period of use with regard to servicing, satellites orbits and constellation optimization using the concept of their OOS.

Implementation of the second direction includes:

– development of servicing methods and servicing systems, including those with the use of ISS, using experimental automatic satellites;

– creation of the space complex for transferring satellites, upper stages, and their fragments to the disposal orbits;

– optimization of satellite constellation on-orbit infrastructure;

– creation of the on-orbit-servicing space complexes in two sequential stages mentioned below.

The complexes for refuelling and replenishing expendables are created on the 1st stage, as well as on the subsequent stages : complexes for the replacement of separate modules, devices, and systems; upgrade of the purpose-designed equipment for the solution of new problems; dismantling out-of-order satellites and utilizing their elements; refuelling upper stages of the carrier rockets on the parking orbit so that they could be used as boosters for the injection of satellites into geostationary orbits and transfers to the Earth escape trajectories.

All the problems mentioned above for the development of the next-generation space systems require an extensive study.

3. Key technologies

This section focuses on some of the key technologies that could render satellites more serviceable. These technologies will be reviewed in the corresponding sections of this paper.

3.1. Key technologies enabling easier service (required functions for serviceable satellite)

Let us consider how to aid rendezvous and docking operations. Successful rendezvous is a problem of accurate and optimal manoeuvring that transfers a servicing satellite into the vicinity of a serviced spacecraft. Some reciprocation on the part of the serviced spacecraft should not be ruled out and could be implemented according to the task. For example, ISS sometimes implements short manoeuvres to facilitate its rendezvous with other vehicles.

Docking and capturing implies a different procedure. It concerns operation in the direct proximity of the serviced satellite. We could make the serviced satellites more noticeable both by mechanical and radio means, through equipping it with radiofrequency transponders for information exchange, as well as optical devices and surface features. Docking aides could be installed and when possible, standardized interface could be used; attitude control system could be enhanced to provide a desired relative position for servicing.

Some spacecraft are meant to be serviced by robotic means only, others are man-oriented. Depending on this the interfaces may also be adapted to the provisioned servicing agent. Those nodes that need to be serviced must be visible and accessible without breaching security and protection rules, which is a very complex engineering task.

Block-Modular Structure allows speeding up servicing operation by substitution of malfunctioning modules and easier detection of failures. However, it is a complex technological task because some systems are simply not meant to be modular and because we must provide a certain degree of redundancy that allows not affecting main operations while repairing of a certain sector is underway. The function of each module should be clear and understandable.

Common international interfaces or compromise solutions could make spacecraft more accessible. This concerns not only docking operations, but also all other kinds of electrical and data interfaces.

3.2. Key technologies for servicing systems (performing service menus with a focus on the robotic approach and a brief mention of the human approach)

Servicing systems themselves should also be upgraded and in some cases, developed with a clean sheet.

This problem should, on all levels, be solved in conjunction with the previous one of making the satellites more serviceable. The technological and data interface should be correlated, but also orbital formations and constellations should be selected in such a way as to make the servicing process optimal and less costly.

We should mention that the importance of robotic and automated operations will increase. Technologies of autonomous operations are currently the least developed among servicing technologies and are one of the most obvious candidates for extensive research. Some amazing specimens of the coming age, like the Canadian Special Purpose Dexterous Manipulator (SPDM, Dextre) that operates on ISS, are already functioning (Figure 6). However, there is still a long way to go to adapt robotic technologies to an even less friendly environment and increase its role in some daily operations.

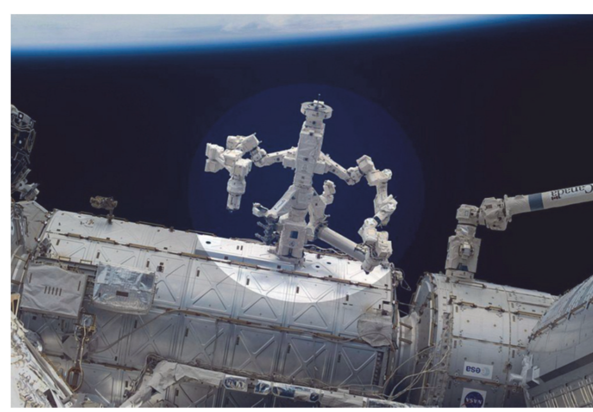

Figure 6. Canadian special purpose dexterous manipulator (SPDM) – robotic device for ISS repairs otherwise requiring spacewalks (photo by MDA Space Missions, MDA Ltd.)

This paper will expound on specific servicing systems that will have to be developed in the following categories:

– systems for satellite/debris transfer;

– systems for refuelling/replenishing expendables;

– systems for replacement of modules/devices;

– systems for dismantling old satellite and utilizing their elements;

– systems to refuel carrier rockets for higher energy orbit injection.

These are the concrete target-dependent technologies for capture/docking and carrying-out servicing operations that will engage whole teams of researchers from technological and theoretical domains.

On-orbit verification/demonstration/experiment is another important aspect that is currently researched by our study group. As was mentioned earlier, no technology can be considered as ready-to-use unless it has been successfully tested in its future environment.

3.3. Key technologies for orbit and constellation design for next-generation space infrastructure

Astrodynamics is as important a field as technological solutions. Without an expedient orbital structure and optimal manoeuvring, it is pointless to count on material profits. Multiple papers were devoted to the astrodynamical problems of on-orbit-servicing[1] [6; 7].

There are two approaches to Orbital Design of Next-Generation Space Infrastructures. The first one considers placing serviced and servicing satellites into the same or near-by orbits, which allows making the servicing manoeuvres less costly by means of avoiding expensive orbital plane change manoeuvres. Such groups of active and passive satellites are called clusters, and the method itself is referred to as *clustering*. However only historically established clusters are feasible – those at geostationary and GLONASS/GPS medium Earth circular orbits (MEO).

Creating low Earth orbits (LEO) clusters would imply sacrificing mission goals in favour of more convenient servicing or otherwise making an unreasonably extended servicing infrastructure. That is why we introduce a second approach for the most densely populated LEO orbits. We state that we shall have to design a general constellation of space stations to service satellites within their corresponding responsibility zones by optimal flybys.

Designing orbital formations of space stations with detachable modules that perform optimal flybys of designated satellites in a series of rational rendezvous manoeuvres is a complex problem. The problem includes optimization of orbits and orbital formations of the space stations. Moreover, the research reveals that constellations of serviced and servicing satellites should be considered as one complex dynamic system.

A modern satellite formation structure is marked by the presence of completed satellite clusters in the regions of geostationary orbits (telecommunication satellites) and medium circular orbits with altitudes about 20 000 km (navigation satellites). To some extent it can be stated that elliptic orbits of Molniya-type telecommunication satellites also form a cluster, but on-orbit servicing of these satellites is not considered now. Performing servicing of the satellites of these clusters could provide a high economic efficiency of on-orbit servicing. At the same time, a modern structure of operating constellations is also defined by a total absence of any order in the region of low-Earth orbits (in particular, important sun-synchronous orbits) and in the regions of Earth escape orbits or the orbits, providing transfers to the geostationary orbits. The absence of any order or, let's say, "clustering" in selection of these orbits is since the parameters of such orbits and constellations are selected only upon satisfying the mission objectives in a maximally efficient way.

Classification and feasibility estimation of the service schemes in the region of LEO yield results given in the Table. Here the classification of possible service plans is offered by the servicing facilities location (on-orbit/on an orbital station/ on Earth), by their re-use ratio (single-use/reusable), by the supply scheme of servicing facilities (from the Earth/from orbital station/no supply), by presence of crew on-board (manned/automatic), by the amount of satellites serviced per one voyage (one satellite/several satellites), as well as by the type of servicing operations performed (refuelling and/or maintenance). For each obtained servicing variant, an approximate estimation of required specific impulse of a servicing satellite's engine is given (in assumption that a mean angle of an orbital plane change required for a transfer to the serviced satellite is equal to 90°). Besides, duration (in years) of an actual implementation of such engine can also be found in Table.

The schemes marked in the table with a darker shade are realizable now (in 2018). The analysis of the results allows coming to a conclusion that in the short term it is possible to implement a ser-

[1] Razoumny YuN, Baranov AA, Kozlov PG, Malyshev VV, Makarov YuN, Moshnin AA, Razoumny VYu. *Space servicing system and method of its construction.* RF Patent for Invention No. 2535760. C1. Application 2013146588/11, 18.10.2013. Date of publication 20.12.2014 (bulletin No. 35). Int. Cl. B64G 1/10, G05D 1/00. (In Russ.)

vicing system for LEO satellites only by the means of servicing satellites located on the Earth. Moreover, it is only possible to provide servicing for one satellite per voyage. From the economic efficiency point of view such satellite should indeed be unique.

Classification and feasibility estimation of the service schemes in the region of LEO

<table>
<tr><th>Servicing facilities location</th><th>Reuse ratio</th><th>Supply scheme</th><th>Presence of crew on-board</th><th>Number of satellites serviced per one voyage</th><th>Type of servicing operations performed</th><th>Engine’s specific impulse, s</th><th>Years of possible implementtation</th></tr>
<tr><td rowspan="4">On-orbit</td><td rowspan="4">Reusable</td><td>From the Earth</td><td>Automatic</td><td>Several</td><td>Refuelling + maintenance</td><td>2500*</td><td>2040–2050</td></tr>
<tr><td>From orbital station</td><td>Automatic</td><td>Several</td><td>Refuelling + maintenance</td><td>2500*</td><td>2040–2050</td></tr>
<tr><td rowspan="2">No supply</td><td rowspan="2">Automatic</td><td>One</td><td>Refuelling + maintenance</td><td>1000*</td><td>2035–2040</td></tr>
<tr><td>Several</td><td>Refuelling + maintenance</td><td>2500*</td><td>2040–2050</td></tr>
<tr><td rowspan="4">On an orbital station</td><td rowspan="2">Single use</td><td rowspan="2">No supply</td><td rowspan="2">Automatic</td><td>One</td><td>Refuelling + maintenance</td><td>700*</td><td>2035–2040</td></tr>
<tr><td>Several</td><td>Refuelling + maintenance</td><td>2500*</td><td>2040–2050</td></tr>
<tr><td rowspan="2">Reusable</td><td rowspan="2">From orbital station</td><td>Manned</td><td>Several</td><td>Maintenance</td><td>10000*</td><td>After 2050</td></tr>
<tr><td>Automatic</td><td>Several</td><td>Refuelling + maintenance</td><td>2500*</td><td>2040–2050</td></tr>
<tr><td rowspan="8">On Earth</td><td rowspan="2">Single-use</td><td rowspan="2">No supply</td><td rowspan="2">Automatic</td><td>One</td><td>Refuelling + maintenance</td><td>310</td><td>Since 2018</td></tr>
<tr><td>Several</td><td>Refuelling + maintenance</td><td>2500</td><td>2040–2050</td></tr>
<tr><td rowspan="6">Reusable</td><td rowspan="4">No supply</td><td rowspan="2">Automatic</td><td>One</td><td>Refuelling + maintenance</td><td>310</td><td>Since 2018</td></tr>
<tr><td>Several</td><td>Refuelling + maintenance</td><td>1000</td><td>2035–2040</td></tr>
<tr><td rowspan="2">Manned</td><td>One</td><td>Maintenance</td><td>310</td><td>Since 2018</td></tr>
<tr><td>Several</td><td>Maintenance</td><td>10000</td><td>After 2050</td></tr>
<tr><td rowspan="2">From the Earth</td><td>Automatic</td><td>Several</td><td>Refuelling + maintenance</td><td>1000</td><td>2035–2040</td></tr>
<tr><td>Manned</td><td>Several</td><td>Maintenance</td><td>1000</td><td>2040–2050</td></tr>
</table>

Notes: * mean angle of an orbital plane change required for a transfer to the serviced satellite is assumed equal to 90°;
– schemes, implementable in the short term.

We have reviewed above the first of the two possible approaches to the selection of orbits and formations of serviced and servicing satellites based on “rigid clustering” of the serviced satellites. Even though such way may lead to a considerable increase in the efficiency of the usage of space systems, as it was shown before, still, this approach is characterized by several disadvantages.

First, the greatest economic effect is attained in case of servicing on the orbits of naturally (historically) formed clusters (like geostationary orbits). Another negative circumstance underlying “rigid clustering” is that servicing of the existing formation of LEO surveillance satellites is expedient only for the unique spacecraft, while clustering LEO formations leads to some loss in observation performance, and especially so in the cases of multi-satellite operation missions.

Let us review the subject-matter of a new technical solution for the optimal selection of satellite orbits and constellations, which are to provide the servicing of "non-clustered" satellite groups. It should be mentioned that the catalogue of serviced satellites, contained in such non-clustered structures, is always altering with time due to various reasons – because of the end of the satellite lifetime and injection of the new satellites, because of the fact that the orbits of serviced satellites constantly alter as being affected by various perturbations, and because of the regression of the servicing satellites' basing orbits relative to the orbits of the serviced ones under the influence of the same perturbing factors.

The orbital plane change cost amounts to the greater part of the total servicing manoeuvre cost. Therefore, to minimize this cost according to the technical solution offered here, the servicing facilities are distributed on basing orbits, with each orbit assigned to its own servicing region. The nodal regression rate is equal for all the basing orbits. In general, these basing orbits are elliptical (being circular case), with different values of semi-major axis, eccentricity, and inclination (all three of these parameters, or any pairwise combinations of them). The planes of the basing orbits are distributed in space by ascending node longitudes in accordance with their servicing regions. The servicing satellites can be of single use, as well as returnable to the orbital station for the repeated use.

The cost of changing the orbital plane accounts for the majority of the total cost of a maintenance maneuver. For low orbits, changing the inclination of the orbit by one degree requires about 130 m/s. Thus, the serviced object must be in an orbit which inclination differs by no more than a few degrees. On the other hand, the longitude of the ascending node of the target's orbit can differ by tens of degrees [3]. To minimize the cost of changing the orbit, according to the technical solution proposed here, the facilities are distributed over the base orbits, with each orbit assigned to its own service area.

The fact, that all the basing orbits have equal nodal regression rate, allows minimizing one-time delta-V (fuel) cost of servicing satellites on arbitrary "non-clustered" orbits by limiting required angle of the servicing satellite's orbital plane change (at most half an angle between the neighbouring orbital planes).

It should be mentioned that implementation of this method for the formation of servicing facilities constellation is not multi-purpose. It could be expediently used in cases when artificial "clustering" of the satellite formation leads to the performance losses in fulfilling the mission objectives of the satellites. Although in cases when we deal with the satellite servicing within historically developed orbital clusters, it is reasonable to distribute the servicing facilities upon the orbits which would be close to the ones of the serviced satellites, as it was described above. This would minimize the cost required for the change of the orbital plane.

3.4. Standards, interfaces and building blocks

Modular approaches are most likely the holy grail when talking "enabling" OOS[2] [8; 9]. Servicing and serviceable space infrastructure all the way to mega constellations would benefit from standards. Manifold efforts have been undertaken over several decades aiming at introducing modular spacecraft, standard interfaces, building blocks or other plug and play elements. However, there are still no such standards. This is for many reasons, but in recent years some more generic propositions have been made and investigated.

The above-mentioned iBOSS concept (Figure 7) is worthwhile mentioning as it represents a novel approach towards passive OOS and universal applicability (there are numerous papers other information available).

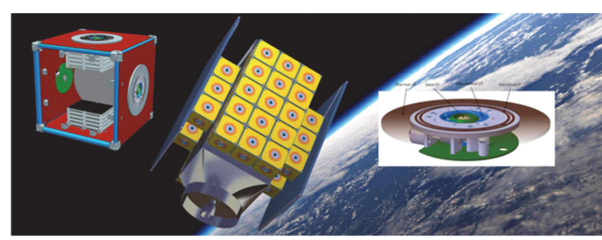

Figure 7. iBOSS Concept

In brief: iBOSS foresees a catalogue of standard functional building blocks (iBLOKCs, Figure 8) which are connected via an intelligent space system interface iSSI (4-in-1 interface: mechanical, power, data, thermal, Figure 9) and can be used in different ways, as standalone, e.g. hosted payload, experiment box or can be combined to an entire satellite (iSAT, Figure 10).

iBOSS also involves end-to-end software tools for fast-track design (iCASD – intelligent computer aided satellite design) and a full simulation environment (VTi – virtual testbed iBOSS).

[2] iBOSS – On Orbit Servicing Concept Video. Available from: https://www.youtube.com/watch?v=uvEoC0ifz7Y (accessed: 12.12.2022).

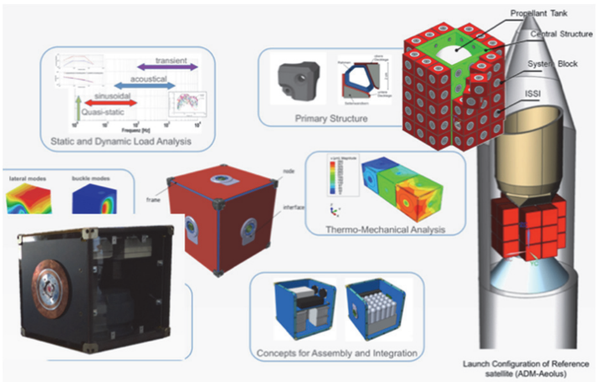

Figure 8. iBLOCK

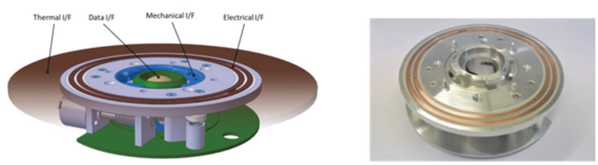

Figure 9. iSSI

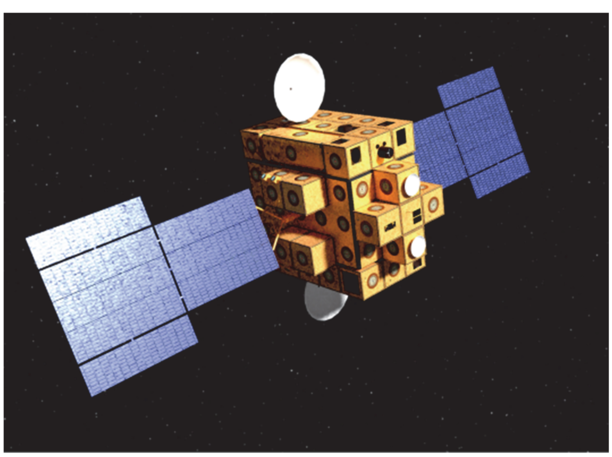

Figure 10. iSAT

Hence, iBOSS is a good example of a technology and plug and play approach supporting OOS across the board once established and introduced.

There are also other projects addressing similar features as i.e. Satlets and PACs (ref. Arkysis, Novawurks, DARPA).

4. Economic and jurisdictional aspects

The economic benefit is obvious. Servicing allows extending operational lifetime of satellites and thus gaining more time for revenue generation and reducing lifecycle cost. Salvaging systems that can still be repaired, up to their return to Earth, could be another such benefit. These effects could be achieved not only through refuelling and repairing but also through orbit modification assistance.

Clearing operational space by removing out-of-service satellites from highly populated areas (for example in GEO) opens new opportunities for satellite injection. Promoting space safety may one day lead to the outburst of space tourism.

On orbit servicing creates a prospect of establishing a commercial servicing and debris-removing network.

On the other hand, international space law needs to be revised to allow all these promising opportunities. Current international space law is not exactly favourable for some aspects of on-orbit servicing and space debris removal. For example, owners of a satellite must authorize removal of all debris resulting from the launch thereof. Other complications that concern insurance policy and other aspects of law hinder otherwise desirable operations making them almost impossible even with all the required technology developed and approved.

Standardization could also meet with some obvious difficulties. It is obvious that unified interfaces are not the best option for some of the space market players.

5. International cooperation

After all those challenges have been stated and reviewed, it is the more obvious that only an international alliance could endeavour to solve all the problems that are sure to come our way.

International cooperation is necessary for creating a serviceable space infrastructure.

Cooperation is expected to happen on all the levels. They include the following:

1) technological – which means a combination of best technologies from countries that are the most experienced in their specific fields;

2) experimental – that implies providing a training ground to international partners. Conducting real space experiments within the framework of global projects;

3) scientific – that means bringing together international research teams;

4) operational – data exchange and cooperative measurements;

5) law-related activities – international community may have to unite in a joint effort to establish convenient laws and promote standardization.

Conclusion

Both sides of the servicing process must be modified: both satellites must be made more serviceable, and the servicing spacecraft must be upgraded.

Servicing formation for optimal rendezvous flyby is one of the key elements of the future space systems and must be implemented regarding the serviced constellations.

The most underdeveloped technologies required for efficient on-orbit servicing are those connected with automated robotic operations. However, their role is ever increasing.

At this stage, international space laws do not fully facilitate cooperation and standardization.

International cooperation is an indispensable element of future and present space exploration.

On-orbit servicing leads to considerable economic benefits. Additional benefits of on-orbit-servicing are:

– the creation of a new high-tech industrial and manufacturing base with benefits today and far into future;

– opportunities of training and advanced education to the existing labour force and many new permanent employment positions.

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