A MULTIPURPOSE GRIPPER CONCEPT AND PRELIMINARY ARCHITECTURE FOR ON-ORBIT SERVICING MISSIONS

Dymitr Osiński[(1)], Ignacy Kraciuk[(2)]

[(1)] PIAP Space Sp. z o.o., al. Jerozolimskie 202, 02-486 Warsaw, Poland, Email: dymitr.osinski@piap.space
[(2)] PIAP Space Sp. z o.o., al. Jerozolimskie 202, 02-486 Warsaw, Poland, Email: ignacy.kraciuk@piap.space

ABSTRACT

Robotic servicing of Earth orbiting satellites is a rapidly growing market that historically supplemented manned maintenance missions and is currently heading to surpass them. Polish aerospace company PIAP Space is designing a new solution that is intended to be used to conduct upkeeping operations on third-party satellites. In this article a conceptual architecture of multipurpose rotary gripper is described. The device is intended to be mounted as end effector on a robotic manipulator and provides main functions required for satellite repairs. The choice of basic operations conducted by the gripper and additional tools is discussed and evaluated basing on the operations performed during previous manned and unmanned servicing missions. Conclusion of this analysis serves as an indication of future work.

1. INTRODUCTION

PIAP Space is an aerospace company dedicated to space-related industry activities that has been ESA contractor since its conception. The company specialises in development of robotic solutions for space applications, especially on-orbit satellite servicing, active debris removal and human-robot interaction. Its products portfolio includes manipulators, end-effectors, vision systems and mechanical ground support equipment [1]. Among the systems being developed by PIAP Space in the scope of project "Development of the family of modular grippers for orbital and planetary applications – ORBITA" (POIR.01.01.01-00-0464/20-00) is a Multipurpose Servicer Gripper intended as a building block for future on-orbit servicing missions, especially those including previously unplanned inspections, repairs and maintenance. This system is intended to enable conducting complex servicing missions on Earth's orbit and supplement other modular devices the company is working on, mainly a robotic arm and a launch adapter ring (LAR) gripper meant for capturing satellites. The main task of Multipurpose Servicer Gripper is to perform generic on-orbit servicing functions on unmanned missions in order to extend the operational life of the systems. The target satellite should not require any special modifications before launch and all the tools necessary for the maintenance and repairs should be carried by the servicing satellite. There is also a possibility for complex and atypical repairs using tools tailored for the mission, but in such case the servicing satellite needs to be customised prior to the mission. As the number of commercial satellites rise, interest in the robotic satellite servicing market is growing [2, 3].

2. ON-ORBIT SERVICING – STATE OF THE ART

Nowadays the number of Earth's artificial satellites is highest in the history and is growing, especially due to large constellations such as Starlink and OneWeb being deployed. A significant number of the satellites, estimated to be nearly half of total number, are no longer operational [4]. A failure or anomaly of operation can shorten the mission or end it entirely, as providing repairs and maintenance for on-orbit satellites (OOS) is difficult and often prohibitively expensive. Nevertheless, such operations have been done – historically in manned missions, but new systems for repairs and refuelling of orbiting satellites are in development, with strong shift towards prospect of autonomous servicing. The main timeline is shown in Fig. 1.

In 1984 first orbital servicing mission was conducted. The Solar Maximum Satellite was brought for repairs into the payload bay of Space Shuttle orbiter with help of astronauts performing extravehicular activity and a robotic arm [5]. The Space Shuttle was also used in 5 servicing mission of the Hubble Space Telescope in years 1993-2009 [2]. Unmanned robotic activities were demonstrated by Japanese Engineering Test Satellite No. 7 after its launch in 1997. This first uncrewed orbiter with robotic arm used the manipulator to test autonomous docking capabilities with target satellite that was launched together with it [6]. NASA and DARPA performed Orbital Express Mission in 2007. The mission was part of research and development endeavour focused on developing capabilities of on-orbit servicing for satellites and successfully performed activities of battery module installation on target satellite and its refuelling [7]. A pair of Mission Extension Vehicles, MEV-1 and MEV-2, were launched in 2019 and 2020. The orbiters docked with client satellites on geostationary orbit and currently provide stationkeeping. The MEVs are able to undock from client satellites and support other satellites during the same mission [8]. NASA is developing two On-orbit Servicing, Assembly, and Manufacturing

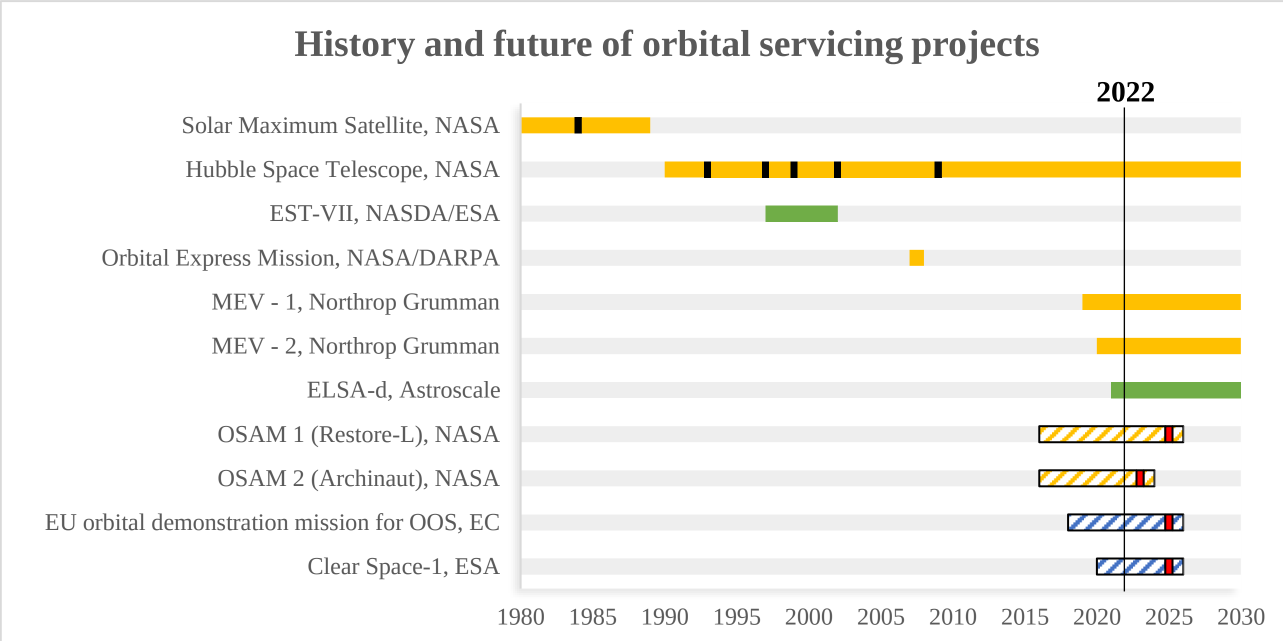

Figure 1. History and future of orbital servicing projects. Bars represent mission timespan. Black markers represent the on-orbit servicing operations while red markers signify planned demonstrations. Hatched pattern represents the project/development duration. Yellow color indicates NASA and private USA missions, green indicates Japanese missions and green indicates European missions.

missions that are planned to launch in years 2023 and 2025. The vehicles OSAM-1 and OSAM-2 are intended to demonstrate not only servicing capabilities that employ autonomously controlled robotic arm, but also provide relocation of target satellite, refuelling, additive manufacturing and assembly of produced parts [9]. ESA is preparing ClearSpace-1 mission that is scheduled for launch in 2025, during which a satellite with robotic manipulator is going to capture and deorbit a derelict rocket stage [10].

Innovations in the field of teleoperated and autonomous maintenance are of interest to operators of satellites, as they allow to reduce costs by expanding mission time and reducing risk of mission failure. Increasing number of commercial companies plan to provide such services in future [11]. Capabilities required for this kind of servicing activities can be considered as technologically demanding and require further development, especially with respect to the robotic manipulation, needed for grasping target satellite and performing servicing activities. Research and innovation as well as development projects are conducted to develop hardware and software solutions for upcoming servicing missions.

In Europe the PERASPERA consortium, a part of Strategic Research Cluster of the European Commission, is developing roadmap and activities for space robotics applications. This future space ecosystem includes systems for on-orbit servicing, assembly and manufacturing. Components of the systems are to be assembled from an assortment of building blocks, standardized modular parts that are compatible with each other. Main goals of the programme are to reduce costs of satellite missions by lowering the launch mass, extending operational life of satellites and promoting development of space infrastructure, leading to improved competitiveness of European space programme. Demonstrations of space robotic technology are planned for coming years [12]. One of the main fields related to the new paradigm is automation involving robotic solutions for on-orbit and planetary missions. The whole system that is intended to lead to more sustainable and adaptive space exploration is meant to resemble "app-store" with a variety of compatible tools that can be combined to produce solutions for different space missions. This approach can shorten time of development, qualification and testing owing to the use of standardised building blocks, resulting in cost savings. Moreover, modular satellites can be reconfigured while on-orbit or disassembled and recycled. Increasing operational life of satellites by providing refuelling and repairing failures requires sophisticated technology, especially related to robotic manipulation. The array of robotic tools can be used in a future servicing mission of on-orbit satellite that involves visual survey of the target, capture of its launch adapter ring and repairs that could be conducted with generic universal tools or tailored devices for specialized maintenance. These actions could extend operational life of client satellite or even prevent mission termination caused by anomalies. Such approach should not only save costs, but also reduce the number of non-functional satellites orbiting Earth, often referred to as space junk.

3. MULTIPURPOSE SERVICER GRIPPER

The Multipurpose Servicer Gripper design for an end effector of a robotic arm is intended to provide servicing of on-orbit satellites. End effectors of robotic arms that are used on satellites usually belong to one of two categories: launch adapter ring grippers and multipurpose servicers. The former devices are used to grab a launch adapter ring, part of satellite that is used to secure it to launch vehicle, during docking of the servicer satellite with the target satellite. The latter devices provide various functions related to repairs and refuelling of satellites. An example of first category is Launch Adapter Ring Capture Tool developed by MDA [13]. Robotic Tool Changer by DARPA is a design that belongs to the second category [14]. The developments of the Multipurpose Servicer Gripper started with review of previous manned and unmanned servicing missions in order to determine the most important functions and features of the upcoming robotic servicer. A basic survey of causes of on-orbit satellite failures and anomalies was also conducted. Among the causes of mission failures were loss of communication and antenna deployment failures, power unit anomalies, solar panel deployment anomalies and failures of modules such as gyroscopes and reaction wheels [15, 16, 17]. The significant costs of such failures justify development of new systems for autonomous or teleoperated on-orbit servicing missions.

3.1 Main Functions and Requirements

The results of surveys enabled the choice of requirements with respect to the main functions for a Multipurpose Servicer Gripper. The requirements are mainly derived from the survey of historical and planned servicing mission and the review of most frequent anomalies of on-orbit satellites, but not limited to them. A basic cost and frequency analyses were made in order to select most prominent failure modes and determine requirements concerning their mitigation. Those requirements were considered as baseline for the development of Multipurpose Servicer Gripper that could exhibit a large degree of universality and service wide variety of target satellites.

As the ORBITA project does not target a specific mission, but rather aims at providing key functionalities that are generic and applicable to different scenarios, the main functions for Multipurpose Servicer Gripper are intended to be common for wide variety of servicing missions. The main functions, that were chosen as they can be applicable to multiple missions, are:

- Visual inspection augmentation – an examination of the satellite performed from outside or inside, e.g. by opening access hatch;
- Support for antenna and solar panel deployment – an operation that can be conducted by applying point force or torque to a part of satellite or applying vibrations to whole structure;
- Insulation regeneration – including partial isolation removal by cutting and applying a patch of new material;
- Module replacement – conducted by gripping part of module, removing its fasteners, exchanging module and installing fasteners again. The operations differ depending on whether the module is equipped with a standard interface.

While refuelling is a trending topic in the field of on-orbit servicing, it was not considered as function in the first version of architecture, as this iteration is more focused on mechanical manipulation. Refuelling could be considered as an addition in upcoming versions of the system.

Main functions for the system were stated and divided into subsidiary functions. Each of the functions was evaluated in terms of marked demand, basing on review of literature and survey of potential clients interested in on-orbit servicing operations, from today up to 10 years in near future.

The main features of the servicing system thus are deemed as follows: a possibility of gripping part of serviced satellite as well as a number of various tools, rotation of gripper within 360° without limit of revolutions and possibility of mounting and dismounting the Multipurpose Servicer Gripper on the servicing satellite's Robotic Arm with typical interface such as HOTDOCK [18] or SIROM [19]. Additional requirements also indicate the upper limit of the system's mass, specify the grasping force, rotation torque and rotational velocity.

3.2 Concept of Architecture

With the main requirements outlined, a conceptual work on the architecture of the system could begin. Four main concepts of the architecture of Multipurpose Servicer Gripper were considered, differing mainly in how the kinematic chain of the device was designed. Solutions employing tools with their separate drives were evaluated in contrast to solutions employing single main drive compatible with all tools. A concept powered by rotation of last joint of satellite's robotic arm was also considered. After a trade-off analysis, architecture employing Rotary Gripper with interchangeable End Tools was chosen for further development, as it has best overall points score in categories considering functionality, mass, modularity, simplicity, use of know-how of the company, energy efficiency, use of market components and risk of failure.

The schematic of chosen concept is depicted in Fig. 2.

3.3 Preliminary Architecture

The Multipurpose Servicer Gripper is equipped with gripping claws and set of interchangeable end tools. The whole end effector is capable of unlimited number of rotations independently from the rotation of the last joint of the robotic arm. The purpose of this basic design is to allow performing an array of servicing operations for the most common failures and anomalies that affect on-orbit satellites. While repairing any possible malfunction is unlikely, a selection of basic tools can be used to perform maintenance operations and to overcome typical failure scenarios.

The main component of the system is the End Effector. It includes a Stationary Base with interface for connecting with Robotic Arm that houses the drives and a Rotating Gripper that can turn with respect to the Stationary Base. The rotating part contains a gripper that can grasp objects – other than launch adapter ring of the maintained satellite, as separate specialised gripper is intended for that task. The Stationary Base is equipped with two kinds of interfaces: a Standard Interface that allows for connection with Robotic Arm and Docking Interface for storage.

Rotary part is connected with Stationary Base via interface in order to allow for the transfer of electrical signals. The gripper can be used both for gripping parts of serviced satellite as well as securing End Tools, which means it is double purpose. Sensors of temperature, force, number of rotations and tool presence deliver status feedback from the mechanism.

The End Tools types that are currently being developed are:

- Bit/Socket Wrench – used for mounting and dismounting threaded fasteners;
- Space Crowbar – used for applying point loads;
- End Tool for Standard Interface – used for inserting and removing parts equipped with a Standard Interface, to be chosen at a design stage;
- Forceps for Connector – used for inserting and removing electrical harness with a connector and manipulating other small objects;
- Scissors – used for cutting sheets such as Multi-Layer Insulation.

Each End Tool type can be made in different versions, varying in size as in case of Bit/Socket Wrench or in shape as in End Tool for Standard Interface. This allows to broaden the spectrum of performed operations.

The choice of End Tools types allowed to define requirements for each tool necessary for fulfilling functions of the Multipurpose Servicer Gripper. If a need arises, additional End Tools may be developed – this enables performing highly specialized servicing missions for satellites that require customized solutions.

Additionally, the system has two Holsters located on non-movable parts of the servicing satellite. One is intended for storing unused End Tools and the other is

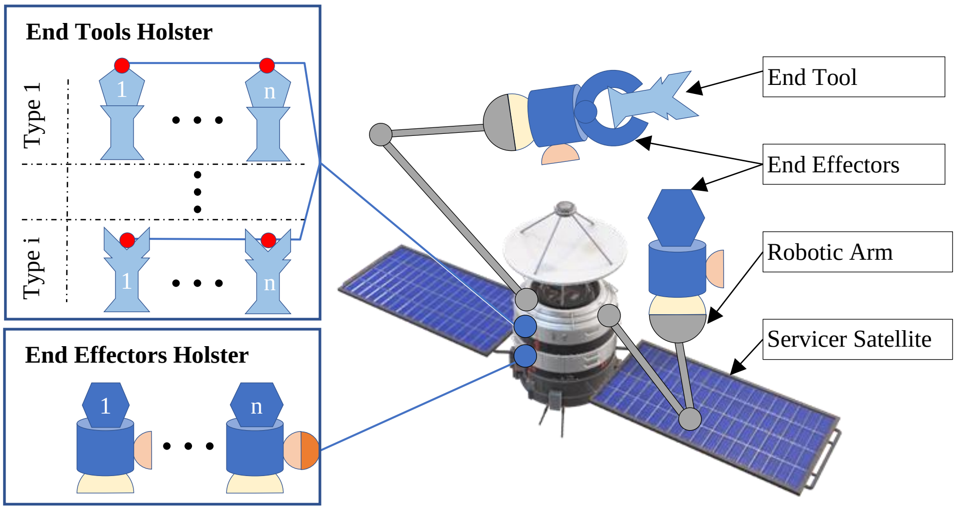

Figure 2. Schematic of the Multipurpose Servicer Gripper concept. Main spatial arrangement of Servicer Satellite with Robotic Arms equipped with End Effector using End Tools is shown. Holsters for both End Effectors and End Tools are expanded.

intended for storage of whole End Effector. End Tool Holster contains proprietary docking slots with locking mechanism and sensor of tool presence for each tool. The End Effector Holster allows for operation of satellite's robotic arm with End Effector other than the Multipurpose Servicer Gripper.

The Multipurpose Servicer Gripper can be equipped with Force and Torque Sensor, which is an optional module intended to be included in case the robotic arm lacks this component or does not have adequate capabilities in terms of force and torque measurement. The whole system is controlled by a single main computer located in the body of servicing satellite. The preliminary architecture is illustrated in Fig. 3.

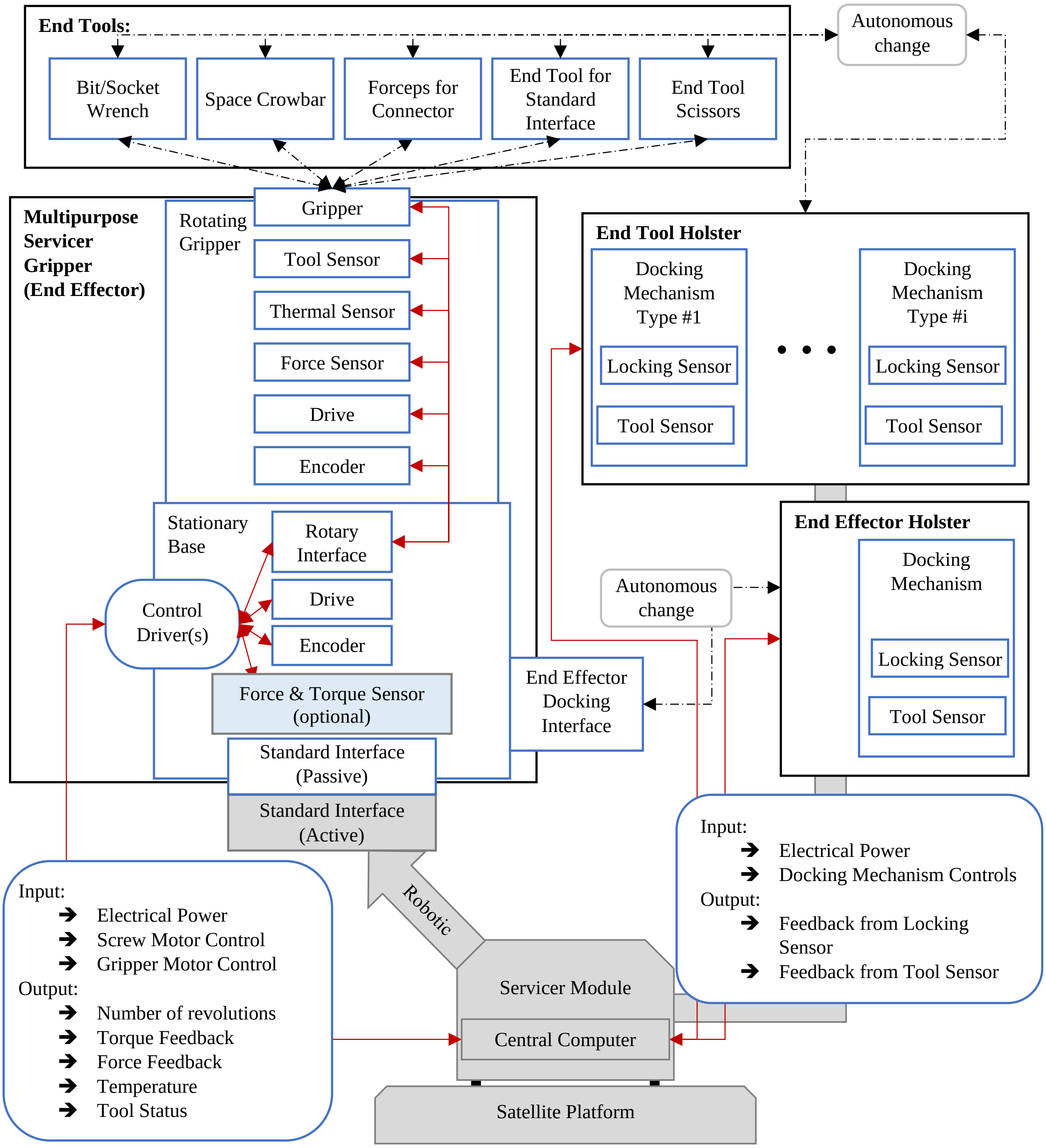

Figure 3. Preliminary architecture of Multipurpose Servicer Gripper. Black frames contain modules of the system and blue rectangles indicate submodules. Shapes filled with grey indicate the satellite body and robotic arm outside of scope of Multipurpose Servicer gripper. Solid red lines indicate information or energy transfer while dashed black lines indicate interchangeability.

4. DISCUSSION

The modular approach to the architecture of Multipurpose Servicer Gripper follows the paradigm of developing functional building blocks for future European space ecosystem. Using a single main drive for operation of any End Tool installed reduces risk of failure by decreasing the number of mission-critical devices. The technical parameters of the motor need to compromise between parameters required by various end tools, mainly the torque and angular velocity characteristics.

As the main end effector of Multipurpose Servicer Gripper is always equipped with grasping claws, regardless of whether an End Tool is installed or not, it is important that its design is compact and does not impede operations of any of the end tools. For proper operation the Rotating Gripper should be balanced, optimally both statically and dynamically when operating with any end tool and without end tool installed. Its mass moment of inertia, especially about the rotation axis, is an important parameter that, coupled with characteristics of the motor, will strongly affect performance of the device.

The Multipurpose Servicer Gripper is to be placed at the end of robotic arm. Due to that, its mass is crucial as it constitutes a dynamic load in microgravity and both static and dynamic loads during testing of the system on the ground. Optimization of that parameter is expected to be one of the design challenges. The forces and torques acting on the robotic arm are also going to by contributed by reactions caused by the operation of various end tools and the gripper. Even with relatively small force acting on end tool, the torque on the base of robotic arm may be large due a significant distance from the base of the manipulator. Analysis of approach vectors for various operations could help in reducing the reaction forces. The information about current forces and torques on the end effector is required for its proper operation and this is why it is intended to be equipped with six axis force and torque sensor.

The position of end effector and end tool holsters should be chosen for easy accessibility, especially when servicer satellite is in close proximity of target satellite.

The design of Multipurpose Servicer Gripper should allow for the future development of additional end tools that will expand the servicing possibilities. Development of both universal tools and devices tailored for specific client satellites is foreseen. The ability to detach both End Tools and End Effector and install other devices allows wide range of operations and facilitates compatibility with the European designs of universal building blocks for space systems.

5. CONCLUSION

Preliminary prototypes of the components belonging to Multipurpose Servicer Gripper are being developed at PIAP Space. The protypes are will be used for primary tests, including preliminary assessments and validation of viability of the concept. After the functional prototype is accepted, Engineering Model will be developed and tested. The design process is planned with iterative approach of all main components. Before a single iteration can be considered as complete, a verification of the model against the requirements will be conducted. After end of the iteration, works on another design may be started, or the design current at the time can be considered as finished development. The Engineering Model of Multipurpose Servicer Gripper with Technology Readiness Level 6 is foreseen to be completed in the turn of the year 2024/25.

6. ACKNOWLEDGMENTS

This publication is the result of the project “Development of the family of modular grippers for orbital and planetary applications – ORBITA”. The project is co-financed by the European Regional Development Fund under the Smart Growth Operational Programme contract number POIR.01.01.01-00-0464/20-00.

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