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Development and application of Interchangeable Tools for Modular In-Orbit Assembly Scenarios

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Abstract

As space ecosystems are expected to experience significant growth, leading to an expansion of the infrastructure, the demand for In-Space Servicing, Assembly, and Manufacturing (ISAM) to maintain and manage this infrastructure is steadily rising. The European Robotics for Space Ecosystem (EU-RISE) project aims to increase Europe's independence in participating in future space ecosystems and developing new space technologies by providing a modular approach for the autonomous assembly of a satellite with an antenna reflector as an assembly scenario.
As part of the project, the scenario will be demonstrated to illustrate the application of modularity and autonomy as a future solution for on-orbit assembly. By utilizing Multi-Purpose Tools (MPT) mounted on robotic arms, a range of assembly tasks can be executed with a single tool. This versatility is enabled by three different Tool Sockets that can be modularly attached to the MPT via the Standard Interface for Robotic Manipulation (SIROM) and interchanged according to the specific assembly task. With two gripper sockets and one wrench socket, different geometries can be autonomously gripped and assembled.
This paper describes the different components involved and presents the assembly demonstration scenario, detailing the roles of each component.
Keywords: orbital, robotics, interface, ISAM, tool, space mechanism

1. Introduction

Over the past decades, the reduced barrier to entry has led to a significant increase in the number of satellite launches and space missions, a trend that is expected to continue. This will eventually result in a significant growth of the space ecosystem, leading to expansion of the infrastructure. Meanwhile, missions are becoming more demanding, making it increasingly challenging to launch fully integrated systems in single launch vehicles [1]. Consequently, there is an ongoing need for In-Space Servicing, Assembly, and Manufacturing (ISAM) to manage and maintain this infrastructure and systems.

Robotic solutions offer a lower-risk alternative to assembly and maintenance by astronauts, making them a key technology for ISAM [2,3]. Developing robotic systems capable of performing these tasks within space ecosystems could vastly enhance the performance and lifetime of space systems, increasing the sustainability of space operations [1].

The European Robotics for Space Ecosystem (EU-RISE) project [4] aims to contribute to this solution by realising a modular approach for autonomous assembly tasks and by that helping increasing Europe's independence in participating in future space ecosystem and developing new space technologies. Although the assembly of large structures in space was already covered by previous EU projects such as PULSAR [5] and PERIOD [6], EU-Rise focuses on modularity and sustainability to contribute to a cleaner space environment.

To achieve this, a market analysis for ISAM was carried out within the project. This included a market assessment and the identification of needed capabilities, as well as the definition of a system concept where an end-to-end approach was adopted. Further details can be found in [4]. This approach is then implemented in a demonstration scenario with the help of robotic elements, which are being newly developed or improved in the course of the project.

One of these robotic elements is an assembly tool consisting of the Multi-Purpose Tool (MPT), the Standard Interface for Robotic Manipulation (SIROM) and three different Tool Sockets. This paper focuses on this tool, explaining the development of its components and its application within the demonstration scenario.

2. Multi-Purpose Tool (MPT)

The MPT (Fig. 1) is a key component of the robotic end effector and tooling system, designed as a modular and reconfigurable end-effector for ISAM. The MPT's design prioritizes reusability and efficiency by leveraging a common architecture for diverse on-orbit tasks. Additional details about the MPT can be found in [7].

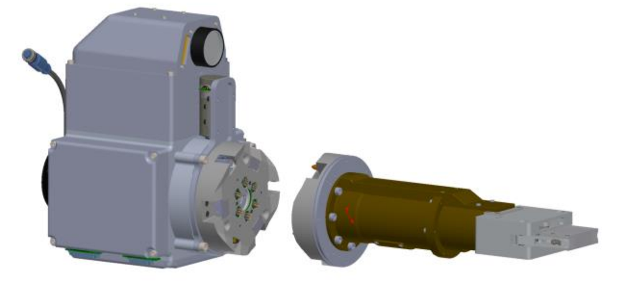

Fig. 1. MPT (left) with tool socket (right)

2.1 Design and Architecture

The MPT is built around three core subsystems: a high-torque actuator, a modular avionic stack, and a versatile socket interface. The system utilizes the same actuator as the Versatile In-Space and Planetary Arm (VISPA [8]), providing a rotational degree of freedom with a continuous torque of at least 15 Nm. This commonality streamlines verification efforts and reduces system-level complexity.

The avionic architecture is based on a modular, PC104-Plus compatible stack, integrating several custom-designed boards:

- Tool-Controller (TC): A central micro-controller unit (MicroChip) that manages all command and telemetry data via a CAN bus.
- Power Conditioning Unit (PCU): Converts the 48V primary power bus to the necessary secondary voltages (5V, 3.3V) and includes a Latching Current Limiter (LCL) for fault protection.
- Electro-Magnet Driver (EMD): Provides independent drivers for activating electromagnets, heaters, and motors within the tool sockets.

The MPT's modularity is enabled by its tool to socket interface. Therefore, as part of the EU-RISE project, an active SIROM interface was integrated into the MPT, enabling mechanical and electrical connection as well as data transfer. An integrated "eye-in-hand" camera, strategically positioned to view the Tool Sockets, supports visual servoing and remote operations.

2.2 Verification and Validation

Preliminary verification activities were conducted to validate the MPT's design. A Finite Element Analysis (FEA) confirmed the structural integrity under a nominal operational torque of 45 Nm, with modal analysis showing the lowest Eigen frequency to be well above the requirement. This confirms the structure's robustness for launch and operational loads.

Board-level tests successfully verified the functionality of the PCU and TC, including voltage regulation, current limiting, and communication protocols. Finally, a functional validation was performed on a ground-based Robotic In-Space Manufacturing & Assembly Testbed (RISMAT). While a full functional test awaits the EU-RISE V&V phase, these initial results affirm the feasibility of the MPT's modular and operational concept.

3. SIROM Interface

SIROM is a development by Sener started in 2016 as a mechanical, electrical, data and fluidic interface to aid in robotic operations and modular systems [9]. The key characteristics of the SIROM interface are:

- Capture before contact, using three latches positioned at 120º symmetry.
- Form-fit shape integrated in the housing for self-alignment, providing tolerance to the mechanical connection.
- Two versions, one active with the actuation system and one passive for volume and cost saving needs.
- Electrical and data connection, allowing high-power transfer, CAN bus and high-speed data transfer.
- Optional fluidic connector for refuelling applications and life extension missions.

During EU-RISE, the possibility arose to make SIROM compatible with the MPT and Tool Sockets design, producing the so-called SIROM Tool Exchange, or SIROM TE (Fig. 2 and Fig. 3). This SIROM serves as the interface between MPT and the different tools, providing a central socket for the driving shaft and alignment pins as the two main upgrades with respect to previous versions. The rest of the capabilities are maintained, including electrical and mechanical performances.

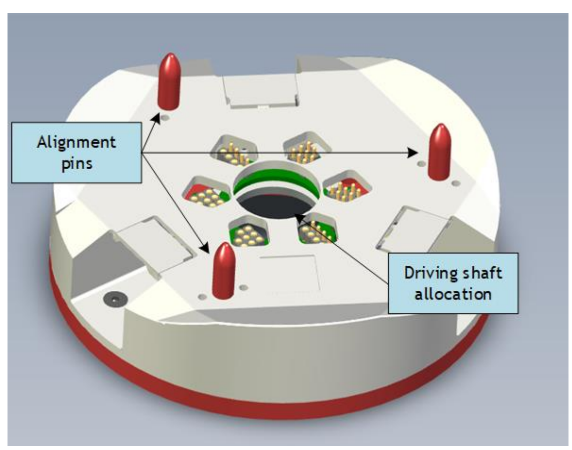

Fig. 2. SIROM TE Passive features

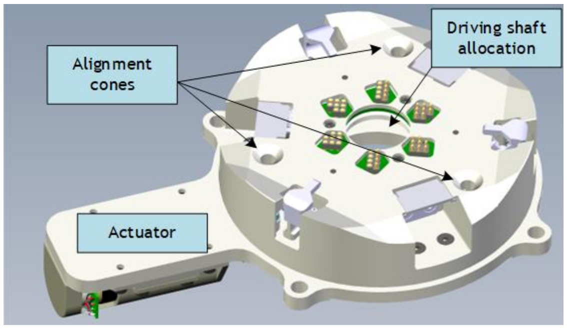

Fig. 3. SIROM TE Active features

The specific requirements that need adaptations for the MPT interface, summarized and simplified for the purpose of this paper, are the following:

1. The MPT interface shall include a central socket to accommodate the driving shaft of the tools.
2. The volume of the MPT interface shall be minimized to allow integration on the existing design.
3. The MPT interface shall have alignment pins/cones to allow pre-alignment of the driving shaft and the socket.
4. The MPT interface shall provide electrical connection to supply power and read the status of the sensors placed on the passive Tool Sockets.

The rest of the design was driven by the intention of maintaining the MPT, SIROM and Tool Sockets design from previous projects. The SIROM TE design was derived from the latest SIROM E family, with simplifications to make integration easier.

4. Tool Sockets

As modular interchangeable end effectors for the MPT three different Tool Sockets were developed by the German Research Center for Artificial Intelligence (DFKI). The Frame Gripper and Cleat Gripper are developments from an earlier project (STARLIT [1]) and were adjusted as part of EU-Rise, while the Wrench Socket is a completely new development.

4.1 Updated Tools

Since the Frame and Cleat Gripper had already been extensively tested and their designs were described in detail in [10], this paper only provides a brief overview of their designs and functions, as well as the adjustments made as part of EU-Rise.

In general, these tools can be separated in three parts: a General Drive Unit (GDU), the Frame Gripper and the Cleat Gripper.

[1] STARLIT Project: `https://robotik.dfkibremen.de/en/research/projects/starlit`

4.1.1 General Drive Unit (GDU)

The GDU (Fig. 4) is connected directly to the MPT and uses a ball screw spindle to convert rotational movement into linear movement on the output. The GDU is used for both grippers, which can be attached to the output side. The spindle has end stops that can handle the forces from the MPT and allow only a predetermined distance of linear movement. It is also spring-loaded to always return to its initial position.

All adjustments made in EU-Rise only affected the GDU. The splined shaft that transfers torque from the MPT was replaced with a smaller size that fits into the passive SIROM TE, which was added as an interface to connect to the MPT.

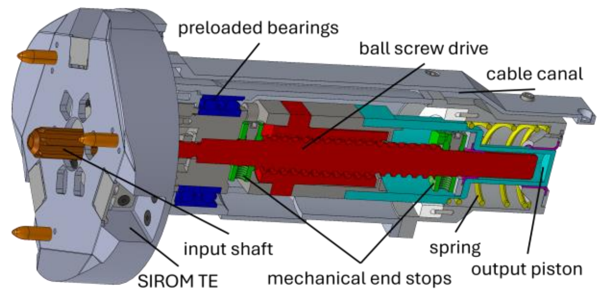

Fig. 4. GDU with updates from EU-Rise

4.1.2 Frame Gripper

The Frame Gripper (Fig. 5) is designed to grip triangular frames. The linear output from the GDU moves two rotating fingers, opening the gripper and allowing it to be placed into the frame. Then, the output piston retracts, and a spring closes the gripper, positioning the rotating fingers into the frame and grasping it with a defined force. This ensures that the gripper closes by default and does not release the grasped object in the event of a failure. Additionally, multiple contact sensors are integrated to detect whether the gripper is open or closed and whether it is grasping a frame.

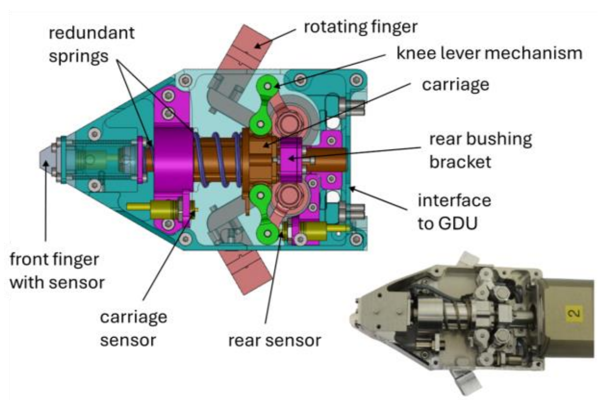

Fig. 5. Frame Gripper design and components [10]

4.1.3 Cleat Gripper

The Cleat Gripper (Fig. 6) is designed to grasp round objects through a combination of form-fit and force. Similar to the Frame Gripper, linear movement opens the gripper, and a spring closes it for fail-safe grasping and a defined grasping force. There are also multiple contact sensors that detect the status of the gripper.

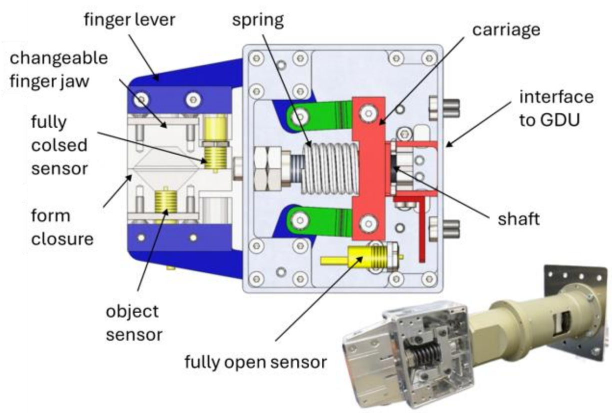

Fig. 6. Cleat Gripper design and components [10]

4.2 Wrench Socket

With the Wrench Socket (Fig. 7), a new tool was developed, which can be used for fastening and loosening special screws for assembly and disassembly tasks.

This socket does not require a GDU, and the MPT's incoming torque can be used directly for screwdriving. However, the torque must be limited to 2 Nm to prevent damage to the socket and to achieve the desired tightening torque for the screws. Similar to the GDU, a splined shaft is used to transfer the torque, and the SIROM TE serves as a modular connection to the MPT. Two static fingers at the tip of the tool act as a counter torque feature. These fingers are fixed in place by a counterpart during the screwing process, ensuring that the torque acts only on the screw and does not transfer back to the source. This would be particularly important under real conditions with zero gravity. The rotating tip has slots on two sides that fit the special screws used in this scenario. The tip is also equipped with a misalignment feature that allows it to tilt by 2.5° in any direction. This compensates for inaccuracies when approaching the screw and helps with an autonomous approach. The tip has a screw detection feature that recognizes when a screw is in place, indicating that the screwdriving process can begin. This feature uses springs connected in series that push a component in front of an inductive proximity sensor when the screw is positioned in the tip. Lastly, a feature that detects the rotational position of the tip has been integrated. A groove was added to the end of the splined shaft to fit an ArUco marker, which indicates the rotational position relative to a second ArUco marker on the SIROM. For redundancy, a second inductive proximity sensor is installed in the tool itself, detecting the rotational position. After docking to the MPT, a calibration run can be performed to move to a defined position. From there on the orientation can then be read out via integrated encoders in the MPT.

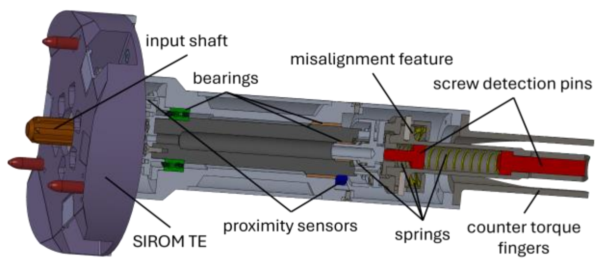

Fig. 7. Wrench Socket design and components

5. Demonstration Scenario

In the end of the project, a scenario will be demonstrated to illustrate the application of modularity and autonomy as a future solution for in-space assembly. This scenario consists of several tasks: assembling an antenna reflector; assembling a boom; and refilling an empty tank in another satellite. The assembly tool is used in different ways for all these tasks. To provide an example of how the tool is used, the task of assembling an antenna reflector will be described.

5.1 Testbench

To perform these different tasks a testbench (Fig. 9) was designed to provide a realistic setting for the demonstration scenario. Therefore, realistic lightening conditions are created, by eliminating all external light sources with a darkening cloak and simulating the sunlight with an array of LED (not shown in Fig. 9 for better visibility). The testbench is equipped with two robotic arms: the VISPA [8], which was developed by Airbus, and a commercially available arm, the KUKA iiwa 14. Both arms are equipped with the MPT and can collaborate to perform various tasks. The VISPA arm is also connected to a spring-loaded gravity compensation feature to enable it to handle higher weights under Earth's gravity. Within reach of both arms is a tool magazine where the various Tool Sockets are stored. Using the SIROM interface on the sockets and MPT, the arms can connect to the required tool socket, pick it up, and return it to the magazine when the task is complete or to change the socket. To perform the antenna reflector assembly task, there is an antenna workbench within reach. The antenna (Fig. 8) consists of six triangular reflector plates, five of which are already mounted, while one is missing and needs to be assembled. The missing piece is stored in a specific storage location, which the arms can access. It should be noted that there are further setups for the remaining assembly tasks. However, these will not be described in more detail in this paper.

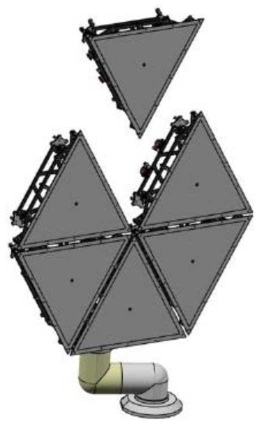

Fig. 8. Antenna reflector with missing piece

5.2 Antenna assembly

The antenna assembly involves multiple operations, such as simple arm movements, software tasks like position detection or the use of the MPT and Tool Socket features. To provide an overview of the antenna assembly and demonstrate how the assembly tool is used, the tasks are briefly described in simple terms without going into detail about the software tasks. The Tool Sockets are divided into the three described tools: the Frame Gripper, the Cleat Gripper, and the Wrench Socket, which are stored in the tool magazine. The process of the antenna assembly is described below.

First, the KUKA arm picks up the Frame Gripper from the tool magazine, followed by the VISPA arm picking up the Wrench Socket, both utilizing the SIROM interface. The Frame Gripper grasps the reflector plate from the storage location. Then the Wrench Socket is used to unscrew the reflector so that it can be lifted with the KUKA arm. The reflector is then moved toward the antenna workbench and positioned in the open space between the other reflectors. The VISPA arm replaces the Wrench Socket with the Cleat Gripper, which is used to preposition the cleats at the reflectors relative to each other so that they can be screwed together. Then, the VISPA arm replaces the Cleat Gripper with the Wrench Socket and uses it to tighten all the cleats. Finally, all sockets are placed back into the magazine, and the arms return to a safe position, completing the antenna assembly.

6. Results and Outlook

A modular tool for autonomous assembly and service tasks was developed using the three presented components. The new SIROM TE, along with three different Tool Sockets, enables modular switching between attachments in the demonstration scenario, thereby changing the function according to the task. The MPT's functions and the sockets built-in sensors enable the entire mission to pursue an autonomous approach.

The next step is to perform the described demonstration scenario at the end of the project. This will involve extensive testing of the tool under simulated conditions and verification of its functions in the scenario. Further qualification of the tool components is possible in the future, increasing the TRL and moving towards a real scenario. The modular approach generally allows for the development of additional Tool Sockets to extend the tool's application possibilities and functions.

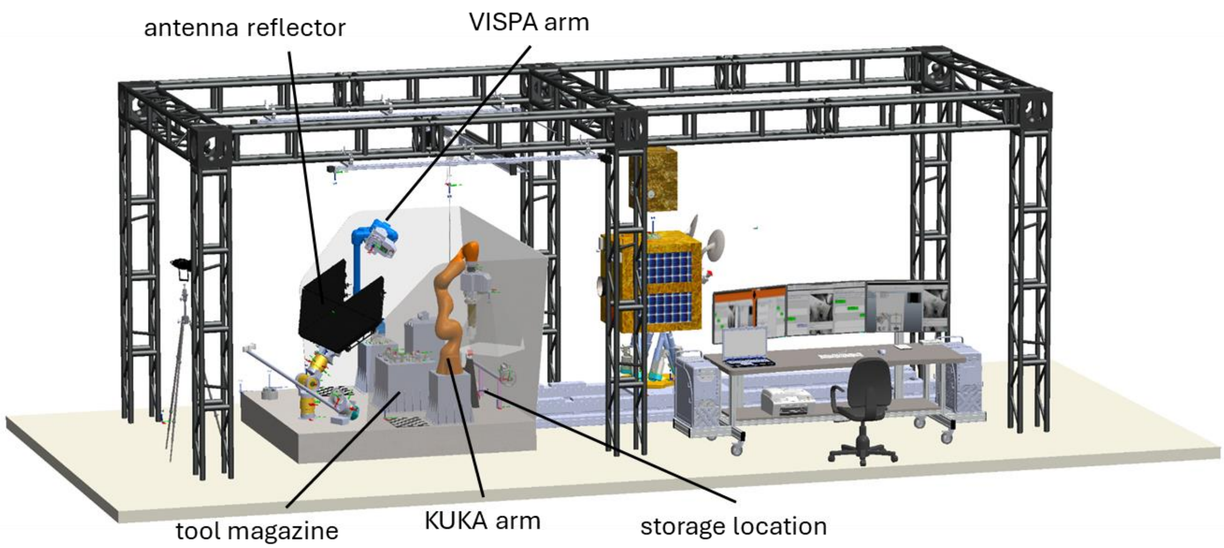

Fig. 9. EU-RISE Testbed with In-Orbit Demonstration (IOD) configuration in a cargo trunk

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References

[1] D. C. Arney, R. L. Sutherland, J. W. Mulvaney, D. M. Steinkoenig, C. J. Stockdale, M. P. Farley. *On-orbit Servicing, Assembly, and Manufacturing (OSAM) State of Play*. NASA public release, 2021.

[2] Z. Xue, J. Liu, C. Wu, Y. Tong. *Review of in-space assembly technologies.* Chinese Journal of Aeronautics. 2021;34(11):21–47.

[3] M.H. Nair, M.C. Rai, M. Poozhiyil, S. Eckersley, S. Kay, J. Estremera. *Robotic Technologies for In-Orbit Assembly of a Large Aperture Space Telescope: A Review*. Adv. Space Res. 2024, 74, 5118–5141.

[4] R. Caujolle et al., *European Robotics for Space Ecosystem - EU-RISE*. 75th International Astronautical Congres, Milan, Italy, 2024, 14-18 October.

[5] C. E. S. Koch et al., *Underwater Demonstrator for Autonomous In-Orbit Assembly of Large Structures*, i-SAIRAS, Virtual Conference, 2020, 19-23 October.

[6] S. Estable et al., *Outcomes of the PERIOD project on In-Space Manufacturing, Assembly and Refuelling Technologies.* In Proceedings of the 12th EASN International Conference on: Innovation in Aviation & Space for opening New Horizons, Barcelona, Spain, 18-21 October 2023.

[7] M. Manz, M. Doermer, S. Gornig, R. Regele, C. Haskamp, I. Ahrns. *Modular Robotics Tools for Space Applications, The Multi Purpose Tool (MPT).* 16th Symbosium on Advanced Technologies in Robotic and Automation (ASTRA), Noordwijk, Netherlands, June 2022.

[8] M. Shilton et al., VISPA URDF, version 0.0.2, https://github.com/AirbusDefenceAndSpace/vispa, (accessed 14.07.2025).

[9] J. Viñals, J. Gala, G. Guerra, *Standard Interface for Robotic Manipulation (SIROM): SRC H2020 OG5 Final Results-Future Upgrades and Applications*. i-SAIRAS, Virtual Conference, 2020, 19-23 October.

[10] N. A. Mulsow, A. Dabrowski, M. Mallwitz, L. Maisch. *Design and testing of mechanical gripping tools for On Orbit assembling.* In Proceedings of the 13th EASN International Conference on: Innovation in Aviation & Space for opening New Horizons, Salerno, Italy, 5-8 September 2023.