



Research Article

Design and Modelling of a Hexagonal Parallel Docking Manipulator for Space Applications

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Abstract

This paper presents a comprehensive analysis and development of a hexagonal parallel manipulator for docking and undocking spacecraft. The combination of Euclidean polyhedral geometry with a parallel kinematic structure and a novel RRS_{CS}-type combined legs provides high spatial mobility, precise relative positioning, and robustness against residual angular velocities and alignment errors. The manipulator's dual-system architecture, incorporating both soft and hard capture systems, enables staged contact formation, reliable mechanical coupling, interface sealing, and the transfer of energy and data between active and passive modules.

Docking and undocking procedures, including off-nominal scenarios, are described in detail, demonstrating the system's ability to safely manage complex multi-body interactions while maintaining structural integrity and operational reliability. The application of graph theory allows formalization of the manipulator's kinematic structure.

The proposed hexagonal parallel manipulator shows significant potential for automated orbital operations, providing accuracy, repeatability, and adaptability.



1. Introduction

Spacecraft docking is a critical operation in orbital missions, playing a central role in the establishment and functioning of multi module space systems. A reliable mechanical connection not only ensures mission success for both crewed and uncrewed operations, but also enables safe transfer of power, data, and other resources between modules (Syromyatnikov, 1984; National Aeronautics and Space Administration, 2016).

Traditional docking systems encounter challenges in positioning accuracy, resilience to residual angular and translational velocities, and tolerance to geometric misalignments during final approach and capture. These limitations can affect interface reliability, increase control system requirements, and potentially jeopardize mission safety (Syromyatnikov, 1984; Sholanov, 2021).

In recent years, parallel manipulators have shown promise for high precision spatial positioning due to their structural stiffness and reduced singularities compared with serial chains (Sholanov, 2021; Alizade, 2019). The integration of geometric methods and parallel kinematics offers potential improvements in interface adaptability and precision. Alizade (2019) advanced the structural synthesis of robotic manipulators using screw theory, which provides insight into mechanism configuration for enhanced motion control and compliance. Alizade and Samedzade (2021) proposed a hexagonal interface docking system, demonstrating improved contact capture fidelity in constrained environments.

Building on these contributions, Alizade et al. (2023) conducted the structural synthesis of Euclidean parallel manipulators for spacecraft docking and proposed corresponding manipulator models.

The present study extends this body of work by developing a hexagonal parallel manipulator designed to meet the stringent requirements of orbital docking operations. The proposed system integrates RRS_{CS} legs and incorporates soft and hard capture systems to enable staged contact, secure mechanical engagement, and effective sealing of the interface. The use of graph theory enables a formal representation of the manipulator's internal structure.

The objective of this work is to propose a comprehensive solution for safe, precise, and repeatable spacecraft docking with high reliability of mechanical and electrical interfaces, as well as the capability for integration into a multi-module orbital infrastructure.

2. Kinematic Limitations of Current Docking Interfaces

Experience with docking devices used in domestic and international space programs, as well as analysis of the design of modern docking interfaces compliant with the IDSS standard, has revealed several fundamental limitations, primarily related to the kinematics of approach and the accuracy of relative positioning of docked spacecraft.

Most existing docking interfaces are based on quasi-axisymmetric ring geometries, with discrete placement of guiding and locking elements along the circumference. This scheme provides a high degree of standardization and enables androgynous docking. However, it is highly sensitive to angular and linear misalignments during initial contact. Ring-symmetric geometries require the simultaneous engagement of a significant number of contact elements, which, in the presence of tilts or offsets, leads to uneven load distribution, localized stress concentrations, and an increased risk of jamming.

Operational experience shows that a substantial portion of off-nominal docking events is caused by misalignment of guiding elements, tilts during contact, and localized impact loads. In some cases, this has led to damage of docking elements, malfunction of locking and latching mechanisms, and even failure to complete the docking procedure. While damping and shock-absorbing devices effectively reduce impact loads, they do not redistribute contact forces or correct the relative positions of the spacecraft during engagement.

Modern docking interfaces compliant with the IDSS standard are characterized by greater standardization and more pronounced geometric symmetry compared to legacy systems. However, they still rely on discrete guiding and locking elements, limiting their ability to compensate for approach errors and achieve high docking accuracy. Consequently, the required precision is largely ensured by spacecraft motion control systems, which increases demands on navigation algorithms and fuel consumption.

In summary, current docking interfaces have inherent limitations due to their axisymmetric ring geometry and simultaneous engagement of multiple kinematic links during initial contact. These constraints cannot be fully

mitigated by local upgrades of individual mechanisms and indicate the need for alternative geometric and kinematic docking concepts focused on staged formation of kinematic links and reduced sensitivity to relative positioning errors.

3. Proposed Concept of a Euclidean Polyhedral Docking Interface

To overcome the limitations observed in existing docking devices, this work proposes a new type of docking interface based on Euclidean polyhedral constructions. In its basic configuration, the interface is formed as a polyhedral geometry, with faces classified as either active or passive. Active faces contain guiding elements and kinematic supports that participate in the formation and transmission of contact interactions, while passive faces serve to spatially separate contact zones and do not carry kinematic loads.

Selecting an appropriate polyhedron with an even number of faces and alternating distribution of active and passive surfaces provides more kinematically determinate relative positioning of the spacecraft than traditional axisymmetric ring-based schemes. The spatially faceted shape of the interface and the staged engagement of contact elements reduce the sensitivity of the docking process to angular and linear misalignment errors without increasing the load on mechanical components.

This geometric concept is particularly relevant for docking operations under conditions of residual angular velocities and limited orientation accuracy. The nature of the contact interaction is largely determined by the shape of the mating surfaces, allowing some of the error-compensation functions to be shifted from spacecraft motion control systems to the interface geometry, thereby reducing the demands on navigation accuracy.

In the developed Euclidean polyhedral designs, traditional limitations are addressed through a different organization of contact interactions. Unlike conventional kinematic chains such as RRP or RRR, a combined RRS_{CS} kinematic support is employed, in which two rotational links form a dyad connected to the central platform through a spatial pair S_{CS} (sphere in a cylindrical slot).

Table 1. Kinematic Pair “Sphere in a Cylindrical Slot”

Name	Symbol	Degree of freedom	Diagram
Sphere in cylindrical slot	S_{CS}	4	

The S_{CS} kinematic pair (Table 1) has four degrees of freedom—three rotational and one translational—providing spatial mobility of the platform without introducing additional constraints. This design enhances the kinematic stability of the docking process and enables precise positioning of the modules even in the presence of residual angular velocities and limited accuracy of orientation systems.

The combination of Euclidean polyhedral geometry and parallel kinematics with RRS_{CS} supports creates a docking interface that:

1. reduces sensitivity to mutual positioning errors;
2. allows stepwise formation of kinematic connections;
3. increases reliability and stability of the coupling under limited guidance accuracy.

The use of a higher kinematic pair “sphere in a cylindrical slot” has led to the development of a new class of Euclidean parallel manipulators with RRS_{CS} -type kinematic structures, characterized by high spatial mobility and symmetrical arrangement. The combination of rotational and spherical-cylindrical joints ensures the required positioning and orientation accuracy of the end-effector within a compact mechanism, making this solution promising for orbital docking and space manipulation tasks.

In the proposed Euclidean docking device, the parallel platform structure is realized by integrating a movable and a passive platform connected through a system of kinematic support chains. This arrangement allows controlled management of the mechanism configuration, uniform load distribution among support branches, and adaptation of the structure to specified docking precision and reliability requirements.

Practical implementation of the concept is based on structural schemes and calculation relations that ensure an optimal combination of links and kinematic pairs in the chosen spatial layout. Therefore, the selection of Euclidean polyhedral geometry and a parallel kinematic structure establishes a fundamental approach to the spatial organization of the docking mechanism and defines its kinematic capabilities.

4. Design of the Hexagonal Parallel Manipulator

To implement the specified kinematic scheme and ensure the required accuracy and reliability of the manipulator's operation, standardized elements are used, maintaining system functionality in space conditions regardless of the number of faces of the polyhedral interface.

The considered docking devices include active and passive modules, which are androgynous: each module can function as either an active or passive docking node. Structurally, the active and passive modules are fully identical.

A docking device of this class consists of two functional systems:

1. Soft capture system
2. Hard capture system

The soft capture system is a movable polyhedral node with inward-oriented guide petals, evenly distributed across alternating active faces. Each petal houses capture latches that engage with striker of the mating docking module.

The soft capture system is connected to the platform of the hard capture system through kinematic chain supports, each comprising two rotational links forming a dyad and a spatial kinematic pair "sphere in a cylindrical slot." One end of the support is fixed to the platform of the hard capture system, while the other connects to the soft capture system. The supports are located on the same faces as the guide petals. The mobility of the soft capture system allows the node to extend to a specified length and retract as necessary. Additionally, spring cables placed on the active faces compensate forces and stabilize the node's position.

The hard capture system is a fixed polyhedral module rigidly attached to the spacecraft structure. It includes locking mechanisms, electrical connectors, guide pins, and corresponding sockets. Each locking mechanism contains a pair of active and passive hooks, and each face houses two pairs of locks, ensuring the formation of a rigid mechanical connection after completion of the soft capture stage.

The geometry of the soft and hard capture systems is determined by the number of faces of the Euclidean polyhedral interface. All devices of this class implement identical functional principles, differing only in the number of repeating elements. Further analysis of the structural elements is conducted using the hexagonal Euclidean docking device as a baseline configuration.

The hexagonal parallel manipulator consists of several key components that ensure its functionality, high precision, and reliability in space applications. Each of these elements plays a crucial role in the accurate positioning and rigid capture of docking spacecraft. The main structural elements of the hexagonal Euclidean parallel robot manipulator include (Fig. 1):

1. **Legs** – Six actuated limbs that provide precise spatial positioning and movement of the manipulator. Each leg can adjust its length, allowing the manipulator to reach desired positions and orientations.
2. **Soft capture system** – The central hexagonal-shaped node connecting all six legs. This junction serves as the main platform for force transmission and coordinated motion control.
3. **Guide petals** – Flexible guiding elements that ensure accurate initial contact and alignment during the approach of the active manipulator to the passive unit, preventing misalignment and mechanical damage.

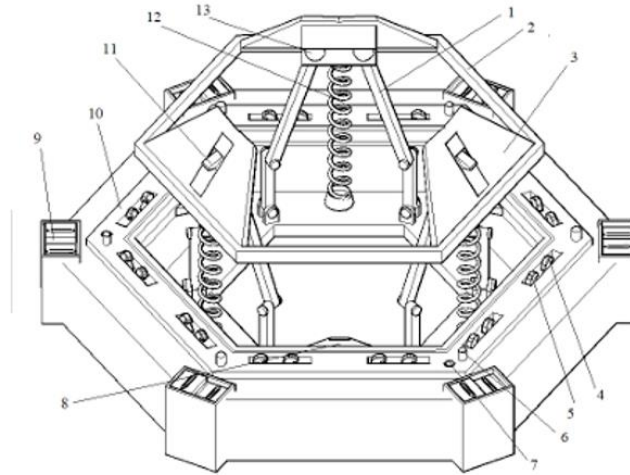


Fig. 1. Constructive elements of the hexagonal Euclidean parallel manipulator (Source: Authors' own work)

4. **Active hooks** – Locking hooks located on the active manipulator side. These engage with the corresponding passive hooks to form a secure mechanical connection.
5. **Passive hooks** – Corresponding hooks on the passive manipulator side designed to engage with active hooks to complete the locking mechanism.
6. **Guide pins** – Pins protruding from the active manipulator that insert into matching holes on the passive manipulator, facilitating precise alignment of the docking interfaces.
7. **Guide pin holes** – Receptacles on the passive manipulator designed to receive guide pins, ensuring accurate alignment and stable mechanical coupling.
8. **Mechanical striker** – A striker mechanism on the passive manipulator that interacts with latches from the active manipulator, securing the initial mechanical engagement.
9. **Power and data plugs** – Electrical and data connectors that engage post-mechanical docking to enable energy and information transfer between spacecraft.
10. **Hard capture system** – A rigid locking assembly that ensures a structurally strong and stable connection between the active and passive manipulators, capable of withstanding operational loads.
11. **Latches** – Deployable locking elements on the active manipulator that engage with the mechanical latch striker on the passive side to secure initial capture.
12. **Spring Cable** – A component that connects various movable elements of the manipulator, serving a dual function: it enables the transmission of control signals or electrical power to the actuators, and it also generates a restoring force during undocking. The cable is designed in the form of an elastic spiral, allowing it to extend and retract in response to the changing positions of the manipulator links without risk of bending damage or failure. During docking operations, the cable remains tensioned, maintaining a reliable connection. Upon undocking, it aids in the safe and controlled disengagement of systems. This design significantly enhances the reliability and fault tolerance of the manipulator, particularly in scenarios involving repeated docking and undocking cycles in the space environment.
13. **Hinge (Sphere-in-Cylindrical Slot)** – A specialized type of kinematic pair that provides four degrees of freedom between the manipulator's structural links. This configuration allows for free rotation of a spherical element within a cylindrical slot, enabling compensation for minor misalignments and angular deviations during the docking process. The use of this hinge ensures both flexibility and sufficient rigidity in the connection between segments, reducing internal stresses and increasing the overall mechanical durability of the system. It is particularly crucial during the final phase of soft capture, where minimal resistance to motion and high precision in self-alignment are required. This hinge allows each leg of the manipulator to adapt to geometric variances and manufacturing tolerances within the docking interfaces.

Thus, the listed elements collectively implement the specified kinematic scheme of the Euclidean parallel docking device and ensure the execution of all docking stages: from soft capture and centering to rigid mechanical connection and data transfer.

5. Docking Process and structural elements of the hexagonal Euclidean parallel manipulator in spacecraft docking systems

Docking of spacecraft is one of the key tasks ensuring the operation and development of orbital infrastructure. The reliability of the mechanical connection directly affects the success of long-duration manned and automated missions, crew safety, as well as the transfer of energy, data, and other resources between modules of complex space systems.

This work considers a possible sequence for performing the docking procedure using a hexagonal parallel docking device - from the approach phase to final sealing and the establishment of a safe passage between the spacecraft.

At the first and highly critical stage of docking - approach and alignment - the active spacecraft, equipped with a hexagonal parallel manipulator, initiates a precisely controlled approach to the passive docking node located on the target platform, such as an orbital station or another spacecraft.

The goal of this stage is to achieve highly accurate alignment of the symmetry axes of the two manipulators within allowable orientation and linear position tolerances sufficient for reliable capture. The passive spacecraft provides three types of targets that assist the active spacecraft in precisely aligning the interfaces for mechanical connection. These targets are accessible at long, medium, and short ranges, with short-range targets used when the active spacecraft is positioned along the docking axis of the passive module. Short-range targets enable the active spacecraft to align itself within the capture zone.

In the final approach stage, while maintaining a safe distance (within a few meters), the active spacecraft reduces its speed and moves along the central axis toward the passive node. All position and orientation corrections at this stage are performed by controlled movement of the six legs of the hexagonal manipulator. This allows the active module to be precisely aligned without maneuvering the entire platform.

Once the approach and alignment phase is completed and the relative position of the active and passive docking nodes is stabilized within specified tolerances, the next critical stage begins - soft capture. This process constitutes the initial mechanical connection between the two spacecraft, serving as the foundation for subsequent rigid structural fixation and sealing of the transitional node. During this stage, the active and passive soft capture systems of the docking devices are aligned, primary connection between the spacecraft is established, dynamic motions between the spacecraft are stabilized, and preliminary alignment is ensured prior to activation of the hard capture system.

In the hexagonal parallel manipulator concept (Fig. 2), the primary mechanical connection is implemented using the soft capture system. This system consists of three inward-oriented guide petals (3) integrated into the hexagonal soft capture system (2).

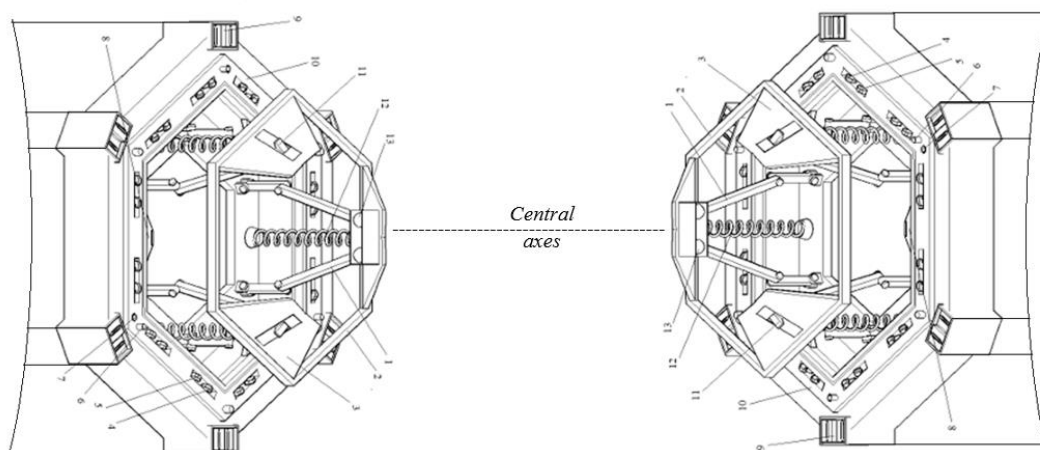


Fig. 2. Approach of spacecraft using a Euclidean hexagonal parallel docking device (Source: Authors' own work)

The docking interfaces of these manipulators have an androgynous design along a single axis, allowing the docking of two identical configurations. During docking, one interface of the soft capture system (2) functions as active, while the other acts as passive, remaining in an extended and fixed position. The active interface controls the sequence of operations during the soft capture stage and prepares the system for subsequent rigid capture.

During the approach phase, the active hexagonal node performs controlled translational motion along the central axis, initiating the engagement of the guide petals (3) with the contact surface of the passive node. The guide petals (3) are connected to the platform via six legs (1), each of which includes dyad and a kinematic pair «sphere-in-cylindrical-slot» (13). Additionally, each leg (1) contains spring cable (12) that generates repelling forces during undocking and compensate for residual interaction forces.

During the approach phase, the soft capture system (2) transitions into a pre-docking state, in which the active interface is maintained in a stabilized configuration and lateral and angular misalignments between the docking interfaces are automatically compensated. This configuration enables the guide petals (3) of the active interface to enter the receiving geometry of the passive interface within allowable tolerances, ensuring a controlled initial contact.

Upon interaction of the guide petals (3) with the receiving geometry of the passive interface, the resulting centering forces actuate the capture latches (11), transferring them from their initial to the engaged state. Simultaneously, this mechanical event is detected by sensors and communicated to the control system, which coordinates the subsequent translational motion of the manipulator along the docking axis.

At the final stage of the controlled axial translation, the capture latches of the soft capture system (2) engage with the mechanical strikers (8) of the passive interface, thereby completing the soft capture phase and establishing the conditions for transition to the hard-mate docking mode.

Once the capture latches (11) engage, sensors embedded in the guide petals (3) detect the successful completion of the soft capture stage. This signal is used by the control system to proceed to the next sub-phase of docking, which includes reducing relative motion, damping residual oscillations, and stabilizing the positions of both modules. This stage minimizes dynamic effects and prepares the system for subsequent rigid capture and interface sealing.

In the following stage, the soft capture system (2) performs precise alignment of the active and passive spacecraft, ensuring coaxial positioning. After alignment is completed, the soft capture system (2) is gradually retracted, freeing the working area and preparing the interface for engagement of the hard capture system (10).

Once the relative positions of the two spacecraft are stabilized, the rigid capture stage begins, aimed at establishing structural fixation, sealing the interface, and preparing for the transfer of energy, data, and atmospheric environment. At this stage, both hexagonal docking elements are maintained in coaxial alignment by the latches (11) of the soft capture system (2). The manipulator's control system adjusts the lengths of the legs (1), ensuring precise geometric coaxiality of the docking tunnels and readiness for activation of the hard capture elements.

After alignment is completed, the active docking node performs a translational approach to the passive node, reducing the inter-flange gap. During this motion, the guide pins (6) of the active node, which are part of the hard capture system (10), engage the corresponding guide pin holes (7) of the passive side, while the guide pins (6) of the passive node interact with the guide pin holes (7) of the active node. This process forms the docking tunnels, which are subsequently rigidly fixed to ensure mechanical strength of the connection.

Once the minimal distance between the docking tunnels is achieved, the structural locking system is activated. In the considered configuration, twelve paired locks with hook elements are evenly distributed around the perimeter of the connecting flange. Each latch consists of active and passive hook elements integrated into the active and passive docking mechanisms. During docking, a cross-engagement occurs: the active hook (4) of the active side engages the passive hook (5) of the passive side, and the active hook (4) of the passive side engages the passive hook (5) of the active side. This ensures synchronous and symmetrical mechanical coupling of the docked modules.

Passive hooks (5) possess elastic compliance, which allows compensation for minor misalignments and geometric deviations during docking. Active hooks (4) move within a limited range, ensuring correct engagement with

passive elements and safe formation of a rigid connection. Overall, the hook system can be considered a sequential assembly of the active hook, passive hook, and structural elements that primarily operate under compression.

The opening and closing of the hook elements are performed via a cable drive powered by a main electric motor mounted on one of the locks. In addition to the primary drive, a backup motor is provided to enable emergency deployment of both active and passive hooks. In the backup system, the cable transmission is replaced by pyrotechnic bolts due to the large number of moving elements, which are sensitive to clearances and deformations. This mechanism has few moving parts and is structurally independent of the main cable drive. To monitor the system status, the locks are equipped with sensors for hook engagement and tension.

The locks of the hard capture system (10) are among the most critical components of the docking device, as their failure could lead to spontaneous release and depressurization of the connection. Therefore, special attention is given to the reliability and strength of these components. Experimental and operational studies have shown that failures such as the breakage of individual parts, rotation of active hooks relative to shafts, eccentric shaft rotation, or issuance of incorrect or spontaneous control commands can lead to unwanted undocking.

To prevent such failures, the strength of a limited number of lock components is of critical importance. The system uses materials designed for space operation, increases the safety factor of the most heavily loaded parts, and employs springs to regulate the force in each lock, ensuring the required preloading of the connection.

Once the system is activated, the locks operate synchronously. Active hooks (4) rotate and engage the corresponding passive elements, forming a closed mechanical loop between the docked modules. This interaction not only eliminates the technological gap between the flanges but also provides a robust structural connection capable of withstanding operational loads and maintaining stability under external forces.

During closure, the hooks compress an elastomeric seal located along the inner flange edge, creating a tight, hermetic contact. This prevents gas leaks when docking pressurized compartments and maintains the reliability of atmospheric separation between modules. The geometry of the docking tunnels and seating surfaces is specifically designed to account for residual micro-deformations, ensuring high contact density and minimizing the risk of reduced sealing even under operational loads and thermal deformations.

After all twelve locks engage, the docking system enters the rigid mechanical capture state. In this mode, the two spacecraft form a single structural system capable of transmitting and withstanding external loads, including those arising from maneuvers, orbital accelerations, and the attachment of additional modules. Rigid fixation ensures stability of the docking interface geometry, prevents relative movement between spacecraft, and provides a foundation for reliable operation of subsequent energy, data transfer, and interface sealing systems.

In the final stage of docking, power and data plugs (9) are activated, enabling the transfer of power and information signals between the mated modules. This provides direct access to power lines, control channels, communication links, and thermal regulation systems, ensuring uninterrupted operation of key systems.

After the rigid mechanical connection is completed, all locks are secured, and the geometric position of the docking interface is stabilized, the system transitions to the final phase - integration of the functional systems of the two spacecraft and preparation of a hermetic transfer tunnel. This phase is critical for maintaining airtightness, crew safety, and the operational readiness of the combined orbital structure.

The power and data plugs (9) perform several crucial functions, ensuring full integration of the docked spacecraft. First, they provide power transfer between the base platform and the attached module, allowing onboard systems of both spacecraft to operate. Second, the power and data plugs serve as channels for data and control signals, including telemetry, diagnostics, and command signals, ensuring coordinated operation of integrated systems. Third, the power and data plugs interface with life-support, thermal regulation, and safety systems, which is critical for maintaining functional and safe operation of crew and equipment.

Thanks to the built-in positioning and self-alignment system, the power and data plugs (9) mate correctly even in the presence of minimal residual deviations between the docked modules. Once mechanical connection is complete, an automatic test of all power and signal lines is performed, verifying the integrity and proper operation of electrical and data channels. This procedure ensures reliable system integration and prevents potential failures in energy and data transfer between spacecraft.

Simultaneously with activation of the power and data plugs (9), the procedure for sealing the transfer volume - the space between the pressurized bulkheads of the docked spacecraft, also called the vestibule - begins. Although the primary seal around the tunnel perimeter is established when the rigid capture hooks are closed, this stage involves additional pressure equalization between the internal volume of one module and the vestibule, leak testing using sensors and redundant measurements, and verification of the absence of residual depressurization or displacement of sealing elements. This comprehensive procedure ensures complete hermetic sealing of the docking interface and prepares for safe crew access and medium transfer between modules.

Only after successfully completing all docking stages can the crew access the transfer vestibule and open the internal hatches. At this point, docking of the two spacecraft is considered fully complete. The connection between modules is comprehensive: mechanical - via locks and latches, electrical and informational - through motorized interfaces, and atmospheric - via the hermetic transfer tunnel. The resulting structure ensures safe crew transfer, movement of payloads, system redundancy integration, and incorporation into a unified orbital infrastructure.

The use of a hexagonal parallel manipulator structure provides high alignment accuracy, reliable mechanical capture, and stabilization of the spacecraft without significant maneuvering of the main platform, creating favorable conditions for subsequent undocking and reuse of the interface.

5.1. Process of Undocking Using the Hexagonal Parallel Manipulator

The undocking procedure is the reverse of the docking process and requires equally high precision and coordination. Its main objectives are to safely separate the active and passive docking interfaces without damaging mechanical or electrical components, maintain the hermeticity of the transfer volume, and prepare both spacecraft for independent operation.

At the start of undocking, the active manipulator's control system receives a command to sequentially disengage all functional connections between the spacecraft. The first step involves disconnecting electrical and data connectors, which provide power, control, and telemetry. These connectors are equipped with self-alignment and contact density monitoring systems, enabling safe disconnection even in the presence of minimal residual misalignments. After successful separation, the system records the status and proceeds to the next phase - relaxation of the mechanical fixation.

The active manipulator initiates the sequential release of all paired hooks that secure the active and passive elements of the flange interface. Each hook pair disengages gradually, relieving pressure on elastomer seals and preventing damage. This step ensures the hermeticity of the transfer volume is maintained for subsequent operations.

Once the hard capture hooks are disengaged, the hard capture system enters a standby state, while the soft capture of the active node extends to a controlled position. Guiding petals of the soft capture begin to withdraw from the passive node surfaces. Retention latches, which held components during docking, return to their original positions under the action of spring cables and secondary automatic release mechanisms. Both hexagonal nodes lose mechanical interlock while maintaining relative alignment within allowable tolerances.

To prevent uncontrolled motion or tilting, the manipulator's legs provide coordinated, smooth retraction of the active node along the central axis. This movement compensates for residual linear and angular offsets, preserving the integrity of guiding pins and guiding pin holes, avoiding shock loads on hooks and latches, and ensuring stable separation of the spacecraft.

At the final stage, the active spacecraft fully retracts from the passive node, leaving the transfer tunnel hermetically sealed by pre-installed seals. Monitoring systems verify the absence of mechanical contact between elements and confirm correct disconnection of connectors. Both modules are now fully autonomous and ready for independent maneuvers, docking with other spacecraft, or autonomous operation.

5.2. Off-Nominal Undocking

In certain cases, undocking may be required outside nominal procedures due to emergencies, actuator failures, or unexpected control commands. Such off-nominal undocking is critical for crew safety, preservation of docking mechanisms, and continued usability of the docking interface.

During off-nominal undocking, the soft capture system with the automatic secondary release mechanism reacts first. It safely separates the active node from the passive node without damaging guiding petals, latches, or strikers. Spring cables of the kinematic supports generate controlled repulsive motion, preventing shock loads. Sensors record the disconnection and relay the information to the control system, completing the primary stage automatically.

Next, the hard capture hooks are disengaged synchronously. Elastomer seals relax, allowing safe exit from the hermetic tunnel. Power and data plugs disconnect correctly due to self-alignment mechanisms, preventing contact damage even with minimal residual offsets. Concurrently, the hermeticity of the transfer volume is verified, and internal pressure is equalized with the atmosphere of one of the spacecraft.

Following the activation of secondary release mechanisms, a re-docking attempt requires inspection of latches, hooks, and connectors before reuse. This safety protocol ensures high reliability while preventing immediate re-engagement without inspection.

The off-nominal procedure is executed in the following sequence:

1. Activation of the soft capture system and secondary release mechanism.
2. Release of active and passive hard capture hooks.
3. Disconnection of power and data plugs.
4. Verification of hermeticity and pressure equalization in the transfer volume.
5. Inspection of system elements to ensure readiness for subsequent docking.

Implementing this procedure within the docking control system increases overall spacecraft reliability and adaptability, ensuring crew safety and minimizing the risk of damage to mechanical elements during emergency undocking maneuvers.

6. Application of graph theory to the modelling of the hexagonal parallel manipulator

Graph theory is a branch of mathematics that examines structures composed of vertices (nodes) and edges (connections), which represent relationships between elements. In engineering, graph models help formalize the architecture of systems and facilitate their structural analysis and optimization.

The hexagonal parallel manipulator can be modelled as a directed graph (Fig. 3), where:

- The central vertex corresponds to the moving platform (soft capture system);
- Peripheral vertices represent the base attachment points of the six legs;
- Each leg is represented by a chain of edges, modelling its joints and actuators.

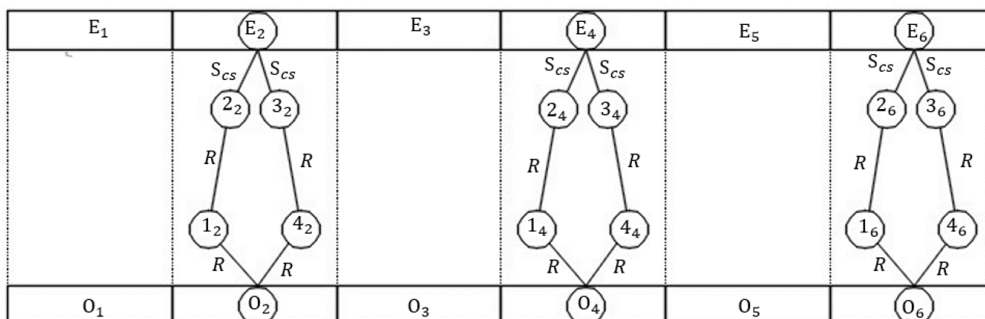


Fig. 3. Design of links of hexagonal Euclidean manipulator by using graph theory (Source: Authors' own work)

This modelling approach allows for:

- Analyzing the transmission of forces and motions within the system;
- Identifying structural redundancy;

- Applying optimization algorithms to improve configuration and control.

A planar graph representation was constructed for all six legs of the manipulator, providing a clear and formalized description of its internal structure.

7. Conclusions

This work presents a comprehensive development and analysis of a hexagonal parallel manipulator for spacecraft docking and undocking. The integration of Euclidean polyhedral geometry with a parallel kinematic structure and the novel RRS_{CS} legs provides high spatial mobility, precise relative positioning, and robustness against residual angular velocities and geometric misalignments. The two-system architecture, comprising soft and hard capture systems, allows controlled step-by-step docking, ensuring reliable mechanical connection, interface sealing, and the transfer of energy and data between modules.

The developed docking and undocking procedures, including emergency scenarios, demonstrate the capability for safe and controlled separation, minimized risk of damage, and the potential for repeated interface reuse. Formalizing the kinematic structure using graph theory provides an analytical tool for structural assessment and system optimization.

The proposed approach combines geometric and kinematic innovations, delivering high reliability, repeatability, and flexibility in automated orbital operations. Although the concept is currently at an early stage and has not yet been implemented in practice, the analysis confirms the potential of parallel manipulators for future spacecraft docking applications.

Abbreviations

R	: Revolute
S _{CS}	: Sphere in cylinder slot
IDSS	: International Docking System Standard

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