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Research Article

Multifaceted Euclidean Manipulators of Spacecraft Docking System

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Abstract

The new spacecraft docking system with new Euclidean support-guide legs provide free relative motion of spacecraft and its docking unit are proposed. For the first time, Euclidean hexagonal and octagonal manipulators of docking system are applied. Structural and constructive synthesis of hexagonal and octagonal Euclidean parallel robot manipulators of spacecraft docking system are described. Information on previously and currently used manipulators of docking system and station is presented. Manipulators of these type include "pin-cone" type manipulators and androgynous peripheral manipulators. Systems of links for new Euclidean interface manipulators of docking system and station is designed by using graph theory and theory of structural synthesis.

1. Introduction

In scientific literature there are various descriptions of cylindrical parallel mechanisms of extension, retraction and motion of spacecraft docking system (Syromyatnikov, 1984). The first spacecraft docking devices were pin-cone type devices. The transition of astronauts from one spacecraft to another is made through open space. Devices of 'pin-cone' type carried out precise connection of spars between two spacecraft, and also carried out multiple docking and undocking of spacecraft (Afanasyev, 2003).

The docking process began with the bar head hitting the receiving cone, into which the pin of the docking mechanism entered, which in turn entered to the guide pin holes. Once the bar head entered the receiving cone, the latches went into the slots and clamped down. In the event of a successful coupling, the docking mechanism drive was engaged to tighten and levelling was carried out by a lever mechanism. During undocking, the bar was extended and held in the forward position, springs of the shock absorber were compressed and under the action of springs, the bar head moved forward and separated the spacecraft (Golubev & Yaskevich, 2020; Syromyatnikov, n.d.; Yaskevich, 2007).

In a subsequent device on the principle of 'pin-cone' was to ensure the tightness of the tunnel by means of locks of rigid connection and transition of astronauts through it. These mechanisms were not only androgynous, but could also perform androgynous coupling, which later became the basis for the creation of androgynous peripheral units. The docking process started with coupling and then the actuator of the docking spar locks was engaged. With the closing of the spar locks, the docking mechanism rod unhooking process took place. The docking mechanism actuator allowed the latches to tip forward under spring action, and pulled the head out of guide pin hole and retracted the bar. During undocking, spring pushers were used to disengage the spar joint (Bolotnik & Shmatkov, 2007; Efimenko, 1984; Akimenko et al., 1975).

Further androgynous-peripheral docking devices were developed, which belonged to the 'androgynous type' devices. Androgynous type of docking mechanism is located at the periphery of the docking spar, for this reason such a docking devices is called a peripheral docking devices. Androgynous-peripheral docking devices consist of two units: active and passive. Docking devices that fulfil the functions of both active and passive units are called androgynous docking devices. The most important reason for creation of docking device of new type was liberation of the central part from a pin and a receiving cone. An important element of this mechanism was a ring with three guide petals. The coupling was carried out by latches when the end faces of the rings of both units were aligned. Then the docking spars were aligned with pins and guide pin holes, and the rigid connection that formed the tunnel was provided by locks with active and passive hooks. Undocking was accomplished by unhooking the latches and pushing back the active unit using springs (Mount & Mikhalkin, 1974; Efimenko, 1995; Yaskevich, 2018).

The next modification of androgynous-peripheral docking devices differed from the previous one in the design of guiding petals. The petals were located not outside but inside the docking ring, which led to a reduction in the internal diameter of the transition tunnel (IDSS, 2016). The use of androgynous-peripheral docking devices freed cosmonauts from the work involved in freeing the transition tunnel from the docking mechanisms ("Androgynous Peripheral Attach System", n.d.).

Kinematic structures with different structural parameters of Euclidean docking robot manipulators with three, four and five legs were described (Alizade, 2019). The other one as hexagonal interface Euclidean manipulators of passive and active docking units were represented (Alizade & Samadzade, 2021). In order to reduce the number of links in the four active planes of the support-guide legs, new octagonal Euclidean interface docking units with joints "sphere in cylindrical slot" are created (Alizade et al., 2022). The main advantage of Euclidean parallel robot manipulators is the usage of 4DoF kinematic pair "sphere in cylindrical slot" and RR pairs in each leg (Alizade et al., 2024, June). Euclidean octagonal parallel robot manipulator has four legs insread of six that is benefit of octagonal manipulator and significantly reduces the weight of the structure (Alizade et al., 2024, May).

Using the Euclidean system instead of Cartesian gives the possibility of modelling four kinematic chains instead of six, which is an important advantage. Using the 4DoF kinematic pair "sphere in cylindrical slot" reduces the number of links, which reduces the weight of the structure.

The capture latch system is improved by adding a new mechanism which allows the latches to release quickly enough in the event of failed coupling that helps to prevent structural damage.

For the first time, the vector spaces R2 and R3 are combined and the new Euclidean hexagonal manipulator with three closed kinematic circuits 5R create flat five-link mechanism is received. The connecting coupler point of this mechanism is connected to the 4DoF kinematic pair "sphere-in-cylindrical slot".

2. Structural synthesis of Euclidean hexagonal and octagonal parallel manipulators

Let the octagonal junction generates the motion (RRRPPP) in space with general constraint $d = 0$. Parallel manipulator can be obtained by taking an appropriate structural group ($M = 0$) and adding the reqired number of actuators (M). According to the formula of F. Freudenstain and R.I. Alizade (IDSS, 2016):

$$M = \sum_{i=1}^{j} f_i - \lambda L \tag{1}$$

where: M – mobility of manipulator;
λ – mobility number of independent close loops of manipulator;
L - number of independent loops;
f_i – the DoF of kinematic pairs;
j – the number of joints.

The number of independent loops L is equaled:

$$L = c - B \tag{2}$$

The kinematic chains on moving platform equal:

$$c = c_l + c_b + c_j \tag{3}$$

where c_l –the total number of legs;
c_b –the total number of branches;
c_j –the total number of jointing up of mobile platforms.
Structural groups for Euclidean hexagonal and octagonal parallel manipulators (Fig. 1) have the following form:

1. Hexagonal manipulator

$$0 = \sum_{i=1}^{j} f_i - \lambda(c - B)$$

$$\sum_{i=1}^{j} f_i = \lambda(c - B)$$

$$\lambda = 6;\ c_l = 6; B = 1$$

$$\sum_{i=1}^{j} f_i = 6 \cdot (6 - 1)$$

$$\sum_{i=1}^{j} f_i = 30$$

$$j_i = \frac{\sum_{i=1}^{j} f_i}{c_l} = \frac{30}{6} = (5,5,5,5,5,5)$$

2. Octagonal manipulator

$$0 = \sum_{i=1}^{j} f_i - \lambda(c - B)$$

$$\sum_{i=1}^{j} f_i = \lambda(c - B)$$

$$\lambda = 6;\ c_l = 4; B = 1$$

$$\sum_{i=1}^{j} f_i = 6 \cdot (4 - 1)$$

$$\sum_{i=1}^{j} f_i = 18$$

$$j_i = \frac{\sum_{i=1}^{j} f_i}{c_l} = \frac{18}{4} = (4,4,5,5)$$

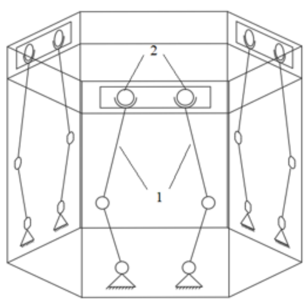
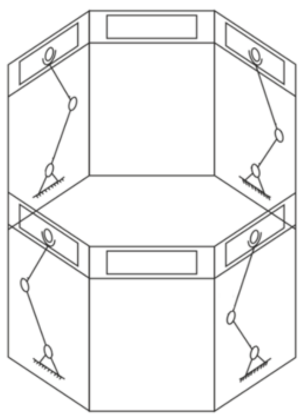
	Hexagonal	Octagonal
Class	6	4
Type	6	4
Kind	0	0
Order	6	4
		

Fig. 1. Structural groups for Euclidean manipulators

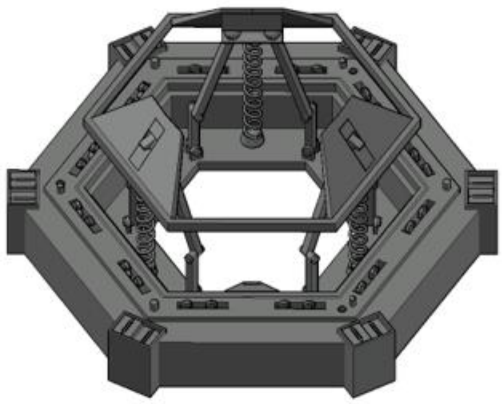
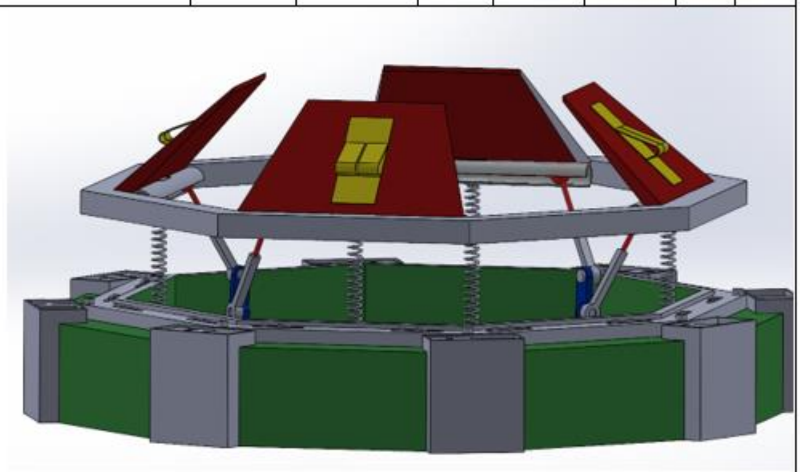
Definitions for structural classification:

- Class of a structural group with the single-platforms equal to the number of platform's joints (J_B).
- Type of a structural group expressed by number of joints on each of the mobile platforms (j_B).
- Kind of a structural group expressed by number of branches (c_B) and platforms connection joints (c_j) .
- Order of a structural group expressed by the number of legs (c_l).

3. Structural synthesis of Euclidean interface manipulator

Existing spatial mechanisms move in vector space R3. Consider the new layout of spacecraft and space station docking mechanism by designing Euclidean four legs manipulator in vector space R3. From this point of view, a octagonal manipulator is considered, which support chains (legs) are at four active planes. The support chains (Fig. 2(b)) are represented as flat dyads with two links and two rotating pairs are connected to the octagonal junction by means of 4DoF of kinematic pair "sphere-in-cylindrical slot".

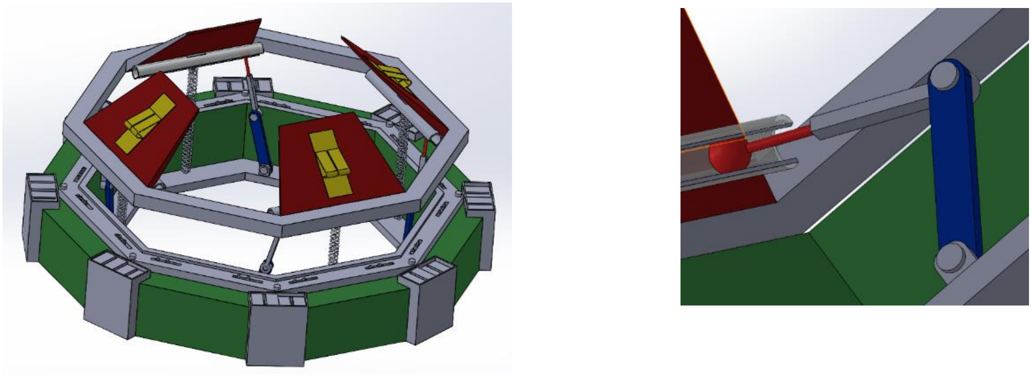
Table 1. New 6DoF parallel robot manipulators of spacecraft

Structural bonding	Illustration						
	Motion of platform	Angle between Euclidean planes	λ_l	c_l	$\sum f_i$	m_p	M
1	2	3	4	5	6	7	8
$\underline{\overline{R}}\overline{R} - [S_{ts}S_{ts}S_{ts}] - \overline{R}\underline{\overline{R}}$, $\overline{R}\underline{\overline{R}}$	$R_x, R_y, R_z, P_x, P_y, P_z$	120°	6	6	36	6	6
1	2	3	4	5	6	8	9
1							
1	2	3	4	5	6	7	8
$\underline{\overline{R}}R$; $\underline{\overline{R}}\overline{R} - [S_{ts}S_{ts}S_{ts}S_{ts}] - \overline{R}\underline{\overline{R}}$; $R\underline{\overline{R}}$	$R_x, R_y, R_z, P_x, P_y, P_z$	90°	6	4	24	6	6
2							

Using four active faces of the docking unit by means of supporting kinematic chains, a new Euclidean manipulator of the form 4RRScs is obtained (Table 1).

Euclidean docking manipulator with $\lambda = 6$; $L = 3$; $\mathrm{M} = 6$; $c_l = 4$ is represented (Fig. 2(a)).

Using the formula (1) and input data, the mobility of docking manipulator is equal: $6 = \sum_{i=1}^{j} f_i - 6 \cdot 3$; $\sum_{i=1}^{j} f_i = 24$.



a) Constructive structure

b) Constructive leg

Fig. 2. New design of octagonal spacecraft docking manipulator

The advantage is the combination of planar structures with spatial ones is applied. The platform itself, which connects to the space station platform, makes six movements in space, both translational and rotational.

The manipulators developed so far use Cartesian system while the proposed manipulator uses Euclidean system. The manipulators used so far have six legs. The proposed Euclidean hexagonal manipulator also has six legs and the octahedral manipulator has four legs. It is the use of the Euclidean system that makes it possible to model a manipulator with four legs. Despite the reduction of the support chains, the manipulator is able to perform the same movements as the current manipulators. This feature is an advantage of the newly proposed Euclidean spacecraft and station docking manipulators.

4. A hexagonal Euclidean manipulator with the form 3(5R)Scs

The present docking manipulators are controlled by a spatial parallel structure manipulator with six degrees of freedom. All these structures, along with those previously proposed in this paper, are spatial mechanisms that are in vector R3 space. A new modification of the hexagonal Euclidean manipulator for docking spacecraft and stations is proposed, which differs from the previously proposed ones. The difference consists in that here two vector spaces R2 and R3 are combined. By combining of these vector spaces has led to a new design of manipulator of docking system and stations. The proposed manipulator is a hexagonal joint with six degrees of freedom, whose support chains are on three alternating active planes. Legs of the proposed hexagonal Euclidean manipulator are three closed kinematic circuits 5R create flat five-link mechanism with two degrees of freedom M=2, the connecting coupler point of which is connected to the hinge "sphere-in-cylindrical slot". Using three active faces of the docking unit by means of legs, a new Euclidean hexagonal manipulator of the form 3(5R)Scs is obtained (Fig.3).

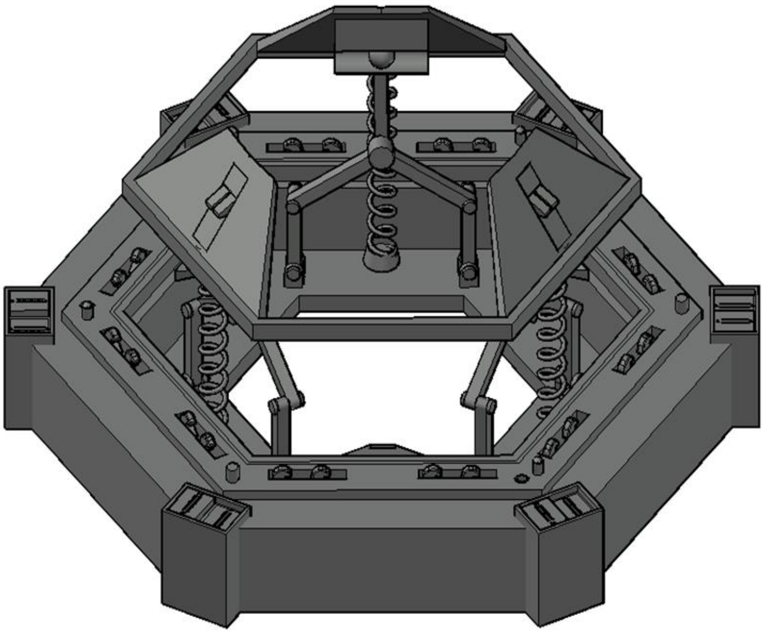


Fig. 3. Design of a hexagonal Euclidean manipulator 3(5R)Scs with six DoF

For the purpose of determining the number of mobility of this manipulator, structural synthesis is performed. This manipulator also differs from previously proposed manipulators in that this one contains mixed independent loops with variable general constraint.

Mobility equation for manipulators which contain mixed independent loops with variable general constraint can be calculated as

$$M = \sum_i^j f_i - \sum_{k=1}^L \lambda_k + q - j_p \tag{4}$$

Where: M – mobility of manipulator;

λ_k – the dimension of the active motion space;

L – the number of independent loops;

f_i – the degree of freedom of kinetic pairs;

j – the number of joints;

q – the excessive over closing constraints;

j_p – the number of passive degree of freedom in kinematic pairs.

The number of independent loops of the hexagonal Euclidean manipulator is five, three of which are in the vector space R2, and the remaining two are in the vector space R3. As a consequence, the dimension of the active motion space is defined as follows

$$\sum_{k=1}^5 \lambda_k = 3 \cdot 3 + 6 \cdot 2 = 21$$

The sum of degree of freedom of kinetic pairs is defined as

$$\sum f_i = 5 \cdot 3 + 4 \cdot 3 = 27$$

Due to the absence of the excessive over closing constraints and the number of passive degree of freedom in kinematic pairs, the mobility of this manipulator is equal

$$M = 27 - 21 - 0 - 0 = 6$$

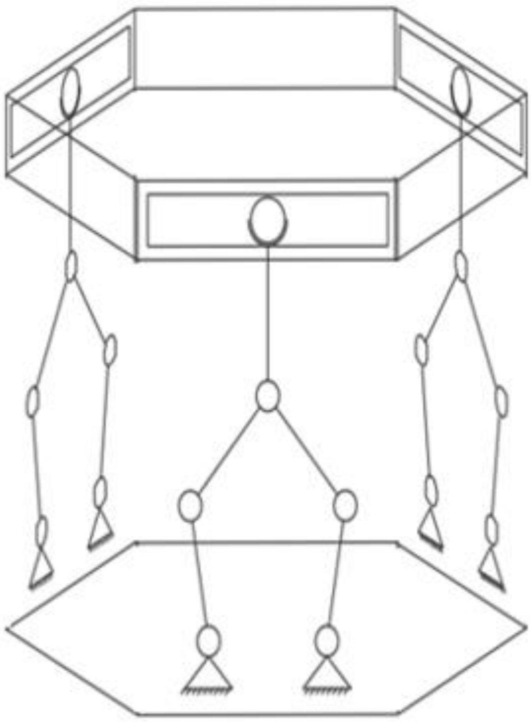


Fig. 4. The structural form of a hexagonal Euclidean manipulator 3(5R)Scs

The structural form of the proposed hexagonal Euclidean manipulator 3(5R)Scs is shown in Fig. 4.

5. Constructive synthesis of Euclidean interface manipulator

Coupling or initial contact is an important part of the docking process. For its implementation, the spacecraft manipulators have a system called the soft capture system.

A soft capture system is a system used during the initial contact between two spacecraft in order to align them. The soft capture system of the hexagonal Euclidean manipulator is a hexagonal joint with three guide petals 5 and three capture latches 1 located on each of them. The soft capture system is used during docking, after the direct approach of the two spacecraft. By means of six legs, the soft capture system extends its full length and is guided directly to the passive manipulator.

The initial contact is made by means of the capture latches entering the corresponding strikers 2 on the passive hexagonal docking system 3. After that, sensors 4 installed in the soft capture system signal that the connection between the spacecraft is held by the latches and it is necessary to start the alignment of the spacecraft. After the completion of the alignment of the two spacecraft, the hard capture system is applied. After successful hard capturing, the capture latches are released and the soft capture system is retracted.

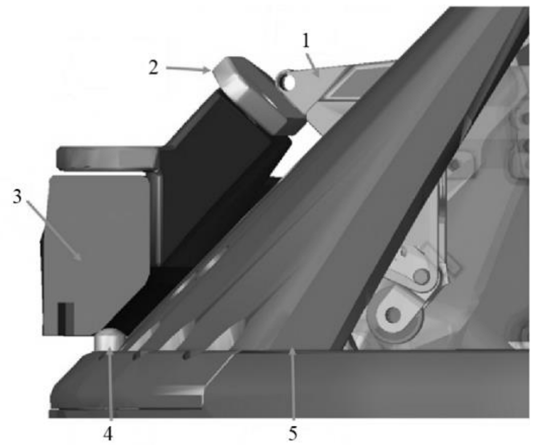


Fig. 5. Capture latch system

Fig. 5 represents such elements as 1 – capture latch; 2 – striker; 3 – passive docking system; 4 – sensor ; 5 – guide petals.

The soft capture system of the hexagonal Euclidean manipulator differs from previous versions. The capture latches in this system are enhanced and have a number of improvements that were not previously available. In the improved version, the latches are capable to release under significantly higher loads, and is also equipped with a mechanism for automatic secondary release, allowing the latches to release quickly enough so that in the event of a failed coupling, the two spacecraft can disengage without damage to the docking mechanisms.

The main elements of the device of capture latch (Fig. 6) are motor 1, latch pawl 3 and automatic secondary release mechanism 4. The latch pawl is used for latching, responsive to the load from the striker 2, located on the passive manipulator to realise the capture of the two docking systems. This mechanism also includes a spring that provides the force required to extend the secondary release mechanism. The lever mechanism system transmits torque from the motor to the latch pawl, thereby holding the catch in the desired position. The principle of operation of the automatic secondary release mechanism is as follows. In a first step, the capture latch is in a position to capture and hold the locking plate located on the passive space docking vehicle. In the event of a failed coupling, the latch is released and releases the striker by means of a motor drive system. A secondary release mechanism allows the striker to be unlocked in the event of failure of the capture latch system. This mechanism is actuated by the actuating mechanism, releasing in turn the spring pusher. When the mechanism is actuated, docking cannot be realised by means of the latches.

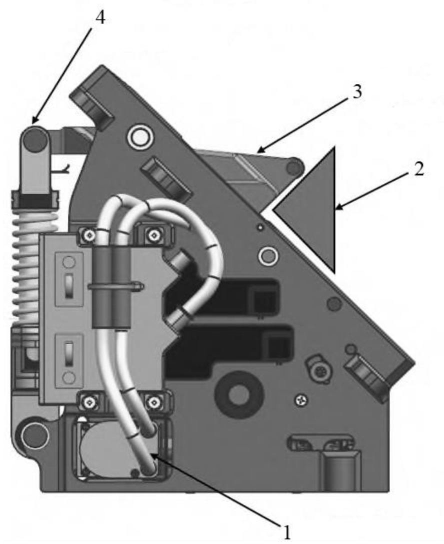


Fig. 6. Device of capture latch

Fig. 6 represents such elements as 1 – motor; 2 – striker; 3 - latch pawl; 4 - automatic secondary release mechanism.

Once the soft capture system is complete, the hard capture system is used to seal and complete the docking process. The hard capture system of a hexagonal Euclidean manipulator includes locks, guide pins, guide pin sockets, and strikers. Each lock includes two hooks, one of which is passive and one of which is active. Two locks are located on each plane of the hexagonal Euclidean manipulator and hence twenty-four hooks are mounted on one docking spar, twelve of which are active and the remaining twelve of which are passive.

When the hard capture systems of the active and passive hexagonal Euclidean manipulator are in close proximity, the locking system is actuated, thereby actuating the hooks. After that, the active hooks engage the passive hooks on the opposite docking manipulator, thereby, along with the sealing, ensuring a tight docking between the two spacecraft. The opening and closing of the hooks by the closed tether is ensured by means of a main motor mounted on one of the locks. In addition to the main motor, there is also an additional motor for redundant opening of the active and passive hooks. The additional cable link has been replaced in this case by pirobolts, due to the large number of gap-sensitive moving parts.

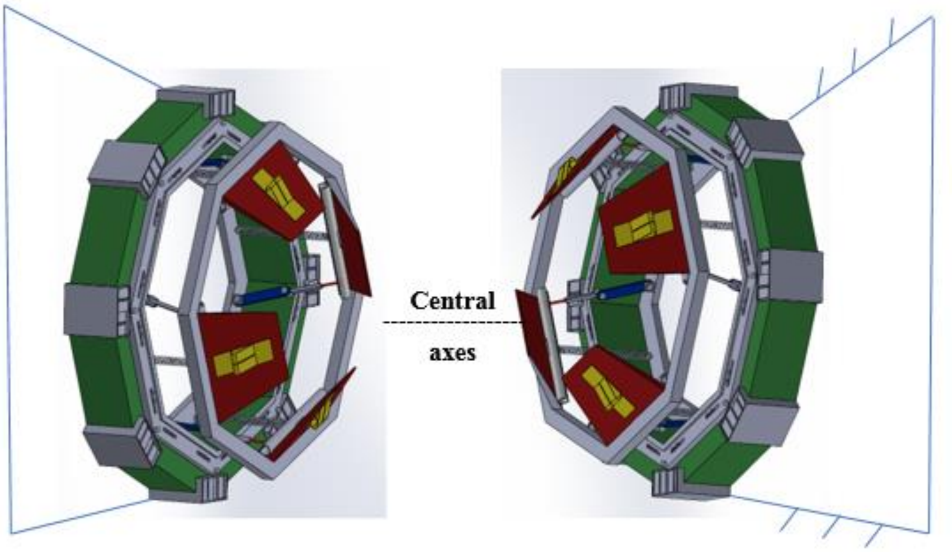
This mechanism has a small number of moving elements and is completely independent of the cable drive. The locks are also fitted with special sensors to monitor hook engagement and tightening. Spar locks must have sufficient reliability and strength to prevent component failure. To prevent or minimise the risk of possible spontaneous opening and depressurisation of the joint, the locks of the hard capture system shall generate a pre-tightening force that exceeds all external forces as well as internal loads tensile to the joint.

6. Constructive synthesis of Euclidean interface manipulator

The docking of active and passive Euclidean manipulators of spacecraft and station (Fig. 7) is a rather complex process, which consists of several stages. This paper provides a detailed description of these stages.

The initial stage of docking of active and passive Euclidean manipulator of spacecraft and station docking begins directly with their approach. After reaching a certain proximity of the two spacecraft, the speed of the active spacecraft is reduced to a certain level. The active spacecraft then moves along the centre axis towards the passive spacecraft. This continues until the distance between the two spacecraft is sufficient to perform docking.

In a second step, the hexagonal junction 2 of the active hexagonal Euclidean manipulator (Fig. 7(a)) performs what is referred to as a "Lunge", wherein the hexagonal junction 2 approaches and enters the passive manipulator (Fig.7(b)) using the six legs 1 to reproduce the first contact.



a) Active docking manipulator b) Passive docking manipulator

Fig. 7. Docking of Euclidean manipulators of spacecraft and station docking

The first contact is reproduced by means of the guide petals 3 of the active Euclidean manipulator. If the "Lunge" is successful, the latches 11 which are arranged on the guide petals 3 of the active manipulator extend and strike the mechanical latch striker 8 which is arranged on the passive Euclidean manipulator. In the next stage, the job of the active hexagonal junction 2 now is to attenuate the relative motion between the two vehicles and to align the active and passive hard capture system 10. For this purpose, all six legs 1 of the hexagonal Euclidean manipulator are brought to an equal position for the same length. In this position, the hexagonal junction 2 will be parallel to the hard capture system 10 relative to the centre axis.

These legs 1 then begin to retract to bring the active and passive hard capture systems 10 together, and the guide pins 6 of the active and passive systems enter their corresponding guide pin hole 7, thereby forming tunnels. When the two tunnels are next to each other, a set of twelve structural locks 14 are actuated. Each lock 14 comprises an active and a passive hook, where the active hooks 4 engage the corresponding passive hooks 5 on the opposite unit.

The structural hooks close the remaining gap between the tunnels, compressing the elastomeric seal and creating a tight connection. Once the hard grip is complete, a power and data plugs 9 engage, allowing energy and data to be transferred between the docked spacecraft.

The docking process is completed that the area between the hatch on the spacecraft and the hatch on the space station called the vestibule needs to be pressurized. Once this is done and leak checks are performed the hatchways can be opened up and astronauts can move between the visiting spacecraft and the space station.

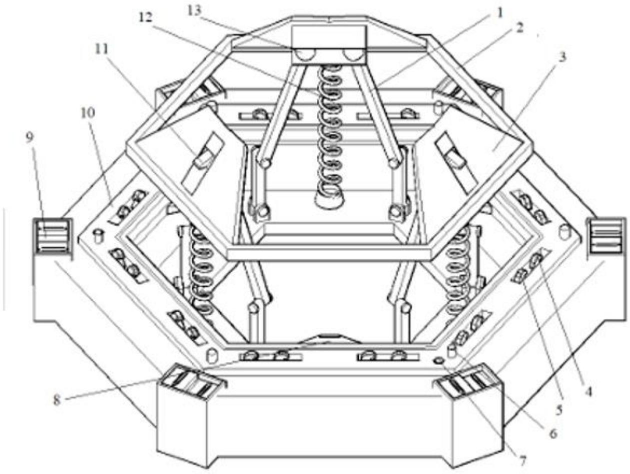


Fig. 8. New design of hexagonal spacecraft docking manipulator

Fig. 8 represents constructive elements of octagonal Euclidean parallel robot manipulator of spacecraft docking system such as 1 – legs; 2 – octagonal junction; 3 – guide petals; 4 - active hook; 5 - passive hook; 6 - guide pin; 7 – guide pin hole; 8 – striker; 9 - latch a power and data plug; 10 - hard capture system; 11 – latch; 12 – spring cable; 13 - hinge (sphere in cylindrical slot).

7. Conclusion

- Based on the analysis it becomes clear that androgynous-peripheral docking manipulators have a number of advantages over the pin-cone design, the main of which is to free astronauts from the complicated work of disassembling the transition tunnel after docking.
- The new manipulator 6RRScs was presented as a hexagonal structure with support chains (legs) on three active planes.
- The soft and hard capture systems of new types of Euclidean manipulators is described.
- The improved version of capture latch system of the Euclidean manipulator is proposed. All improvements of capture latch system is described.
- The developed scheme of the docking mechanism, clearly shows the arrangement of dyads on three active planes, which are connected to the docking element by 4DoF kinematic pairs "sphere-in-cylindrical slot".
- By arranging the support chains on four active planes, it is possible to free up the docking space that is occupied in current designs. The support chains are presented as four flat dyads, which consist of two links with a rotating pair. The connection of the dyads to the octagonal docking element is realised by means of 4DoF of kinematic pair "sphere-in-cylindrical slot".
- Reducing the number of links in the four active planes of the docking manipulator by means of use of a new kinematic pair "sphere-in-cylindrical slot". The new 6DoF octagonal manipulator 4RRScs with four legs on four active planes is presented.
- The structural and cotructive synthesis of the hexagonal and octagonal manipulators are described.
- By combining vector spaces R2 and R3, a new modification of the hexagonal Euclidean manipulator with three closed kinematic circuits 5R create flat five-link mechanism with two degrees of freedom, the connecting coupler point of which is connected to the hinge "sphere-in-cylindrical slot" is obtained.
- For the purpose of determining the number of mobility of the hexagonal Euclidean manipulator 3(5R)Scs, structural synthesis is performed and by using formula for manipulators which contain mixed independent loops with variable general constraint, the number of mobility is calculated.
- Structural form the hexagonal Euclidean manipulator 3(5R)Scs was presented.

- A hard capture system was also presented, with twelwe locks, containing one active and one passive hook each, located on six faces of the docking spar. The spar locks are one of the most critical mechanisms in docking as they are the ones that provide the tightness of the joint.
- The additional cable link has been replaced pirobolts because this one has a smaller number of moving elements and also because of its independence of the cable drive.
- The description of the docking process of the active and passive Euclidean manipulator for docking spacecraft and stations provides an opportunity to review all elements of the Euclidean manipulator design and get their purpose.

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