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THE THOR SPACE STATION AT EML2: ANALYSIS AND PRELIMINARY DESIGN OF AN INNOVATIVE ADAPTABLE DOCKING SYSTEM.

Mr. Crescenzio Ruben Xavier Amendola
ISAE/SUPAERO, France, crescenzio-ruben-xavier.amendola@etu.isae.fr

Mrs. Stéphanie Lizy-Destrez
ISAE/SUPAERO, France, stephanie-lizy.destrez@isae.fr

Mrs. Régine Leconte
ISAE/SUPAERO, France, regine.leconte@isae.fr

This paper reflects the effort of the ISAE University of Toulouse to conform with the Global Exploration Roadmap (GER): it is focused on the analysis and the preliminary design of the innovative universal docking system of the THOR (Trans-lunar Human explORation) station located at the second Earth-Moon Lagrangian Point. The Roadmap brings under light a way of exploring a large array of destinations situated beyond low-Earth orbit by following a 'Moon', 'near-Earth asteroids' and 'Mars' pathway.

The THOR station consists of seven cylindrical (whose dimensional reference is the ATV) and two spherical modules: each part, with a specific role, will be launched separately. Nowadays, the dynamics of the docking is still in development: one option is to assembly the modules at LEO and another one is to have the spacecraft put together at EML2. By coping with design criteria imposed by the deep-space environment, the docking system has been designed. The aim is to have an 'universal type of junction' between the stations and the re-supply, manned or unmanned, shuttles.

At first, a detailed analysis of the kinematics of the rendezvous has been conducted, in order to identify the optimal time windows for the orbital transfer at EML2. The docking system must be able to perform a structural connection between the hubs and the cylindrical modules or external vehicles, to allow fuel, power and data transfer and, moreover, to function as passageway for crew and materials. It will be fitted on the spherical hubs in order to anchor the modules and the visiting vehicles in safe conditions. Thanks to movable surfaces and adaptable pins, this innovative system will allow diverse kind of modules to safely dock on the spherical hubs. Because of the severe constraints, the functioning of the docking system has been improved in order to consent the control of the trajectory in the critical phases of the mission. Taking as reference the kinematics of the ATV and all the previous docking/berthing systems, the structural design of the subsystem has been performed and, adding up the kinematic analysis, a realistic video of the rendezvous has been produced.

This innovative system presents at the same time all the benefits of the docking systems and of the robotic arms: its adaptability to several visiting vehicles and the passive functioning are strong points that can pave a new road for the future of docking systems.

I. INTRODUCTION

The goal of this project is to come up with the design of an innovative docking system. This docking and berthing system is included in the design of the THOR (Trans-lunar Human explORation) space station which intends to widen the human presence in the Solar System: as stated in the Global Exploration Roadmap[10], the next step will be the exploration of a large array of destinations situated beyond Low Earth orbit by following a "Moon"-"near-Earth asteroids" and "Mars" pathway. The purpose of the mission developed at ISAE University is the future perspective of a deep space habitat in an Halo orbit around EML2.

Each module of the station will be sent into space separately: one of the most difficult challenges posed by the design of the spacecraft is the docking between the different modules.

At first, a detailed study of the rendezvous configuration and different docking systems is performed: the milestones for the project are the ATV (Automated Transfer Vehicle) docking system, the Progress, the ESA International Berthing Docking Mechanism (IBDM) and the inflatable anchoring system (IDS).

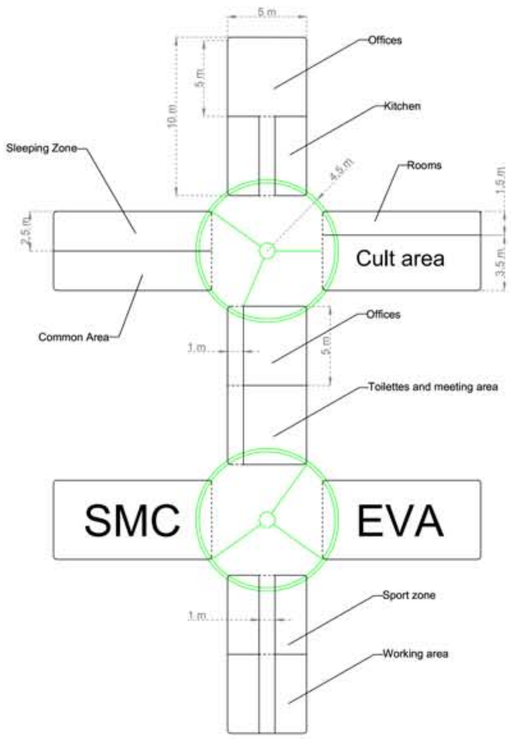


Figure 1: THOR layout.

The analysis of the different components of the docking systems is placed side by side with the environment investigation of the rendezvous to reproduce as similar as possible the real docking process through an experiment in the laboratory. In fact, an important output of the project is the simulation of the rendezvous between the spherical and the cylindrical module, by using a scaled down mock-up and engines/sensors of the LEGO®MINDSTORMS®EV3.

Clearly, the position of the docking system and its configuration influences the architecture of the space station: every single characteristics has been analyzed and the final design is optimized in order to deal with both the structural and human constraints posed by the environment and to optimize the final design.

Thanks to this new method of researching, it will be possible to deeply understand the real behavior of the components implied in the docking system during the rendezvous. Once the docking is completed, it will be possible to improve the structure of the mock-up through data acquired by sensors and to optimize the programming, in order to be alike as much as possible with the zero-g environment.

The aim of the project is to demonstrate that the adaptability to several visiting vehicles and the passive functioning are strong points that can pave a new road for the future of docking systems.

II. ASSEMBLY STRATEGIES

Space agencies projects participating to ISEGC clearly highlight the importance of Lunar Lagrangian points in the solar system exploration roadmap. Operating a space station located at EML2 could generate numerous benefits to strengthen international co-operation in science and technology and guarantee a safe and permanent human presence in space outside the Earth cradle. As a consequence, it is interesting to deploy an inhabited space station at EML2, to re-supply it and to transport crew. This space station would support others missions en route to the Moon, Asteroids and Mars. The three-body problem refers to the motion of a particle of a negligible mass, traveling in the gravitational field of two massive bodies. In the Earth-Moon system, they are named EML1 to EML5.

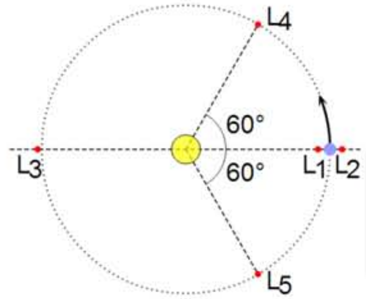


Figure 2: Earth-Moon Lagrangian system [15].

Three of them (EML1 to EML3) are collinear and located on the Earth – Moon axis. The two equilateral last points are positioned at 60^o leading and 60^o trailing on the Moon orbit (as smaller primary body). Thor mission analysis led to the conclusion that the optimal location for the THOR station could be a Halo orbit around EML2 point. The station deployment phase consists in transporting the seven modules and the two spheres from earth surfaces to the EML2. In this case, the return is not considered, but the main challenge is to find the optimal assembly scenario: is it better to integrate the module in LEO, at EML2 or somewhere else.

Since the most expensive leg is the transfer (from LEO to EML2), the best scenario is the one that minimize the transfer number. As a consequence, the optimal one is to integrate all the modules in LEO and transfer the station to EML2 through Weak Stability Boundary strategy.

This scenario drawbacks are:

- to increase the LEO activities duration. By consequence, the modules will be longer exposed to LEO environment;
- to require LEO station keeping maneuvers;
- to postpone Thor station delivery in EML2.

III. THE RENDEZ-VOUS

Rendez-vous in EML2 is mandatory for module integration, cargo delivery and crew rotation. Rendezvous strategy is based on a Halo to Halo heteroclinic connection. The THOR space station is already orbiting on Halo orbit. The chaser (cargo, crew vehicle) will arrive from Earth, traveling on the interplanetary superhighway and then orbits on its own Halo orbit. When rendez-vous starts the chaser leaves it orbit through an unstable manifold until it crosses the stable manifold of the Thor station halo orbit. It will then glide on the stable manifold to reach the station orbit. When distance between chaser and Thor is low enough, proximity operations start to conduct the chaser to the physical contact with the station. A mechanical, electrical and communication merging will then take place.

IV. DESIGN OF THE DOCKING SYSTEM

The docking system will be fitted on the spherical modules, because their shape allow to have better possibility of storage of materials and it is optimal to house the visiting shuttles. An additional idea is to equip some cylindrical modules with a docking system, in order to allow visiting space vehicles to anchor the spacecraft: during the life of the station, several supplies will be needed, and the additional docking systems must be equipped to allow the loading and unloading form the cargo shuttles. Furthermore, the docking system must satisfy all the safety requirements to be able to dock the shuttles in all the environmental conditions.

IV.I Background

The design of the coming docking system are based on the prospect of having 'universal' type of joint. For saving time and financial resources, the various national space agencies are developing a docking system that can fit all the future spacecraft: thus, with the collaboration of all the companies, the final goal will be a unique type of connection between the stations and all the re-supply - manned or unmanned - shuttles[20]. The aim is to avoid to have different interconnection for different docking systems and to have, eventually, a unique architecture for all the spacecraft.

Clearly, there are few examples of the docking in the history of the space and, moreover, no so far away from the ground bases on the Earth. The reference for this project will be the Russian Docking System (RDS) of the ATV (Figure 3) and the IBDM.

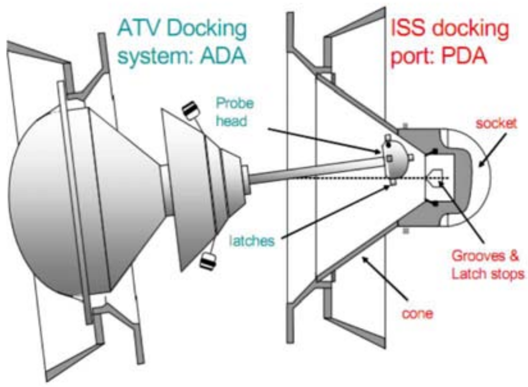


Figure 3: ATV docking system [4].

Its basic design requirements, in addition to mechanical, electrical and functional, will be redundancy and safety: different technical cultures and standards must be taken into account. The main functionalities in the attached phase will be, as for the ATV, the following ones [4]:

- mechanical connection between ISS and ATV;
- passageway for pressurized cargo transfer in both direct;
- transfer of ATV fuel to ISS tanks;
- transfer of ISS power to the ATV;
- communication between ATV and ISS computers.

The main differences between the new docking system and the one of the ATV are: maneuverability and larger doors. In fact, as the visiting vehicles for this space station will be manned, there will be less safety requirements and the possibility of correcting the trajectory in the most critical phases of the mission - as docking is. Obviously, the astronauts must be hardly trained in order to be able to accurately *drive* the shuttles. However, an automatic docking procedure can be realized, in case of emergency.

Since the ATV is unmanned, and there is no strict need to have huge space for astronauts' transfer, the gates between itself and the ISS are as small as possible. The modern spacecrafts will be designed with wider spaces, in order to allow easier movements within the different modules. It is important to highlight that, while the ATV is eventually undocked, most of the vehicles of the space station - at any rate, in the first part of the mission - will remain as permanent modules of the spacecraft.

Even so, the ATV docking system still remains the reference one for the overall development of the design of the THOR station. Moreover, as above mentioned, all the requirements must be satisfied, in order to get the final design for future rendezvous.

The other reference element utilized in this study is the IBDM [6]. This mechanism is compatible with the future ISS docking ports. It captures the vehicle in proximity of ISS and it damps the residal relative motion between the space vehicle and the International Space Station. This innovative berthing and docking system allows also berthing of a vehicle due to a robotic manipulator. Moreover, it will allow docking of two free-flyer shuttles in LEO and in deep-space missions.

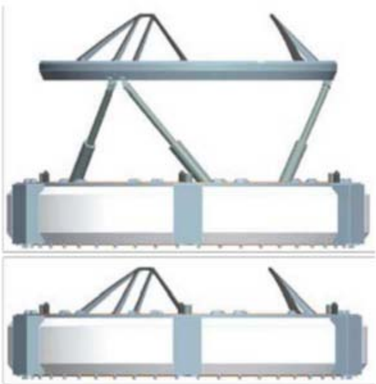


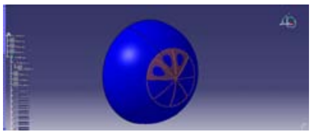
Figure 4: The new ESA IBDM [6].

As the space station will be a reference point for the human space missions to Mars, other docking points - in the cylindrical modules - must be provided in order to allow visiting vehicles to anchor and to use the spacecraft as a spaceport.

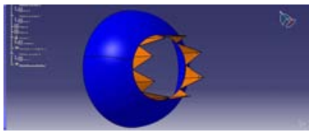
IV.II THOR docking system

In the first part of the project, two kinds of docking system have been presented for the THOR space station.

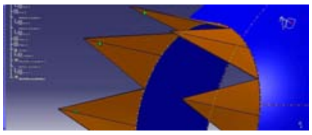
The first system is an universal docking system with adaptable pins that allow to fit every visitor spacecraft that must be attached at the spherical module (hubs) of the space station (Figure 5).



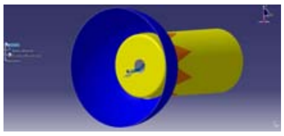
(a) Closed docking system.



(b) Open docking system.



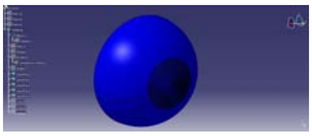
(c) Particular: adaptable docking pins



(d) Conceptual picture of a rendezvous.

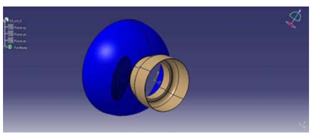
Figure 5: First idea of an *universal* docking system: the size of the pins can be adapted to the different visiting vehicles/modules.

Another conceptual idea can be the opportunity to build the docking system by using inflatable materials. Their features allow to save space and cost, and the characteristic of being flexible and adaptable are advantages for their purpose. In fact, these materials can be easily stored in low volumes, and then deployed in the void.

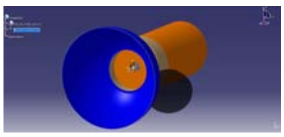


(a) Closed docking system; the black gate can be designed as a solar array.

(b) Open docking system.



(c) Sphere and inflatable docking system



(d) Conceptual picture of a rendezvous, with an inflatable docking system.

Figure 6: Alternative idea of an *universal* docking system: the inflatable materials is stored in the sphere and open just before the anchoring between the cylindrical module and the sphere.

As above mentioned, the kinematics of the rendezvous is still under development. The assembly of the station in Low Earth Orbit, at this stage, has many more advantages respect to an eventual one at EML2. In fact, the assembly at LEO enables to save space and money for the engines: while considering the rendezvous at EML2, an engine on each module is needed, and a huge amount of fuel must be transported on board. Moreover, the dock at LEO allows us to have some docking systems also on the cylindrical modules, in order to permit other space vehicles to dock on the THOR space station.

Docking and Berthing system

'Docking is when one incoming spacecraft rendezvous with another spacecraft and flies a controlled collision trajectory in such a manner so as to align and mesh the interface mechanisms'[5]. The mechanisms typically is composed by two systems: soft capture, followed by a load attenuation phase, and hard docked position which establishes a structural connection between two parts or modules of the spacecraft.

'Berthing, by contrast, is when an incoming spacecraft is grappled by a robotic arm and its interface mechanism is placed in close proximity of the stationary interface mechanism'[5]. Typically, the processes are: capture, coarse alignment, fine alignment and then structural attachment.

Indeed, the main constraint of the modern docking systems is to comply with the IDSS (International Docking System Standard) and, at the same time, to be universal: they must allow the link between all the type of the space vehicle existing. The purpose is to provide a basic common design parameter to allow having compatible docking systems[8].

During the space exploration history, many systems have been developed and utilized in order to connect different modules of the spacecraft, of the space stations or to allow the anchoring of space vehicles to the space stations. So, the docking system is one of the fundamental part of each spacecraft and its evolution is the consequence of the space program (Global Exploration Roadmap).

Nowadays, the wide presence of the man within the spacecraft have posed some new constraints on the docking system architecture and new solutions are being examined by several companies in collaboration with the space agencies. For this project, many systems will be taken as reference, taking into account that the corridors must allow both items and people passing through.

Today, the docking system used or nowadays in development are:

- ERA (European Robotic Arm);
- Russian Docking System (Soyuz and ATV);
- NASA Dockyng System (NDS);
- Inflatable Docking System;
- ESA IBDM.

In the Table 1, a general analysis on the pros and cons of the different docking systems have been carried out in order to place the THOR adaptable docking system in the panorama of the all docking system (real or prototypes).

	ERA	**RDS**	**NDS**	**IDS**	**IBDM**
Passageway	×	✓	✓	✓	✓
Crew passage	×	✓	✓	✓	✓
Support	✓	×	×	×	×

Table 1: Panorama of characteristics for the docking and berthing systems.

The advantages of each system are:

- multi-function: possibility to perform many activities (Docking, EVA);
- reliability: very high performance and safety during the docking;
- adaptability: possibility to dock different space vehicles;
- inflatable: structures that can be used only when necessary.

Thanks to the table above, it is possible to summarize the most performing docking system: the possibility of have an high reliable, inflatable and adaptable docking system can pave the road to a new future in the rendezvous. This can be combined with the possibility of the EVA and of the space rescue. Furthermore, the goal is to have as less mass as possible: so, thanks to the inflatable structures and/or the adaptable surfaces, it will be possible to save mass and cost, in order to cope with all the constraints of the deep space environment.

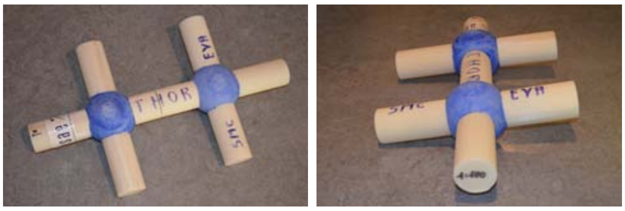
IV.III 3D printer and LEGO mock-ups

In order to better analyze the docking system and the dynamics of the rendezvous some mock-ups have been built. This new approach to the study, can allow to reproduce in a real way the docking between a cylindrical module and a spherical one. By making use of the LEGO *MINDSTORMS*® EV3 sensors and engines, it has been possible to move and to give a target to the cylindrical modules: to enter in the spherical hubs and to stop when the docking is complete. Moreover, it has been possible to analyze the problems and constraints that came out during the rendezvous.

The mock-ups have been built either by the 3D printer and the Lego bricks. Further more, a mock-up of a entire station has been implemented, in order to give a physical verification to the project.

<u>THOR Space Station mock-up</u>

The station mock-up has been built through the 3D printer (Figure 7).



(a) Lateral view (b) Front view

Figure 7: THOR Space Station mock-up.

The scale of the model is 1:100. On each module, it is indicated its particular function. Moreover, due to the 3D printer dimension, the model is split into two parts and it can be assembled trough a pin.

<u>Mock-ups of the docking system</u>

The docking system is composed by two parts: the spherical hubs and the cylindrical module. The half sphere is fixed on a wood panel that will be hung up to a wall. The dimensions of the hub are: $\phi = 22.5mm$ and the thickness is $2mm$.

The cylindrical module has been built by making use of both 3D printer and Lego bricks. Both modules have a scale of 1:40, as well as for the sphere. The 3D model has been built in two parts, in order to put the sensors in it and to make the rendezvous as much realistic as possible. It has a hole on one of the face, that allows the sensors to scan the path and to stop the engines when the docking is complete.

The Lego model has the same dimensions, but both the sides are void, in order to make the structure as lighter as possible. Thanks to the hole in the bricks, is has been easy to attach the module on the engines and, at the same time, to put the sensors in the module.

In order to comply with the aim of light structures, the LEGO model has been chosen. In fact, it is lighter, and the presence on the holes on the bricks enables to better link the module with the engines.

Figure 8: Spherical hubs mock-up.

(a) Top and bottom view (b) Complete view

Figure 9: Cylindrical module mock-up (3D printer).

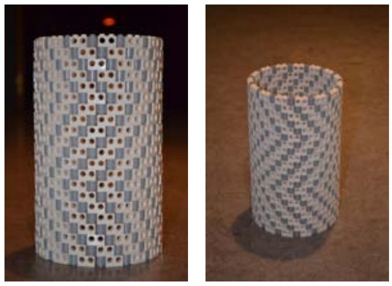


Figure 10: Cylindrical module mock-up (LEGO).

<u>LEGO *MINDSTORMS*® EV3.</u>

This robotic kit has been used to move the cylindrical module during the docking. By making use of the two engines and three sensors, it has been possible to perform the rendezvous. The module has been mounted on an 'intelligent brick' (named EV3 brick) that will be the central processing unit (cpu) of the mock-up. Moreover, the module is equipped with the engine and 2 sensors used to allow the detection of the hole of the hubs; other two sensors have been utilized to stop the engines when the docking is complete.

The components of the robotic kit are:

- EV3 brick: used as support for the programming and for the connection of the sensors/engines;
- 2 servomotors (max speed: 160 round per minute; precision: 1^o)
- contact sensor;
- infrared distance sensor (range: 1-70 cm; allow the remote control of the sensor);
- ultrasonic sensor (range: 1-250 cm; precision: 1 cm);
- light and color.

The infrared and ultrasonic sensors allow to search for the spherical hubs during the docking, while the color and touch sensor are used to stop the engines when the cylindrical module goes in the sphere.

<u>Sensors and Engines</u>

The sensors have been used all at the same time, even if each one performs a specific task depending on the phase of the rendezvous. Thanks to the Lego software, each block corresponding to a sensor can be modified and a special assignment can be set.

Figure 11: Color, touch, infrared and ultrasonic sensors used for the rendezvous.

The Infrared Sensor can detect the approximate position of the Remote Infrared Beacon (IR Beacon) in front of the sensor. The sensor can you the beacon's Proximity (relative distance from the sensor) and its Heading (angle from the direction the sensor is pointing). Of course, the presence of some disturbances will influence the performances of each sensor.

The big servomotors for MINDOSTORMS EV3 robots are specifically designed to actuate the wheels of the Lego modules. They have a power of 20 N/cm of running torque and 40 N/cm stall torque, and has a angle sensor with a precision under 1^o.

<u>Rendezvous</u>

This chapter focuses on the real rendezvous between the spherical hub and the cylindrical module and on its analysis. Finally, the rendezvous has been performed by making use of: 3D spherical hubs, Lego cylindrical module, 4 sensors (distance, angle, color, touch) and 2 engines.

In order to respect the space environment constraints, some devices and strategies have been used. To simulate a space dock is not simple, so, thanks to some expedients, it has been made as much real as possible.

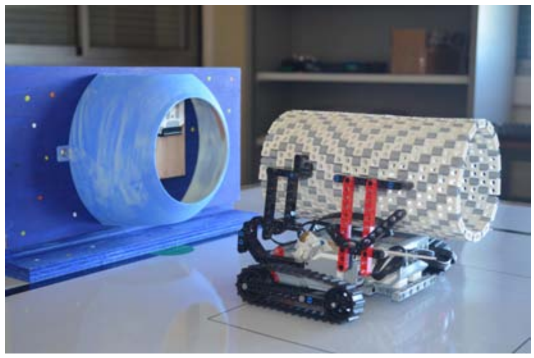


Figure 12: Module and hub on the slippery surface.

<u>Hub and module</u>

The two tools implied in the rendezvous are the hub and the cylindrical module. The first one has been built by using the 3D printer and it has been fixed on a wood support (painted as a starry sky). In the internal part of the module, a special piece allows the Infrared Beacon to be mounted on it, in order to be used as reference for the docking approach.

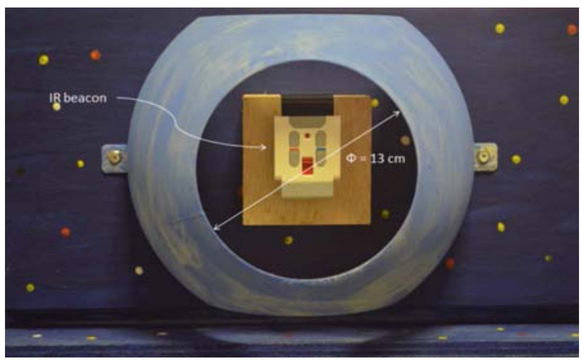


Figure 13: The hub for the docking.

The cylindrical module has been mounted on the Lego intelligent, with 2 caterpillar wheels that allow the module to slide on the ground. This particular wheels reflect (with some disturbance) the behavior of the module in the space. The surface on which the rendezvous will be performed very slippery, so the friction between it and the modules is very low.

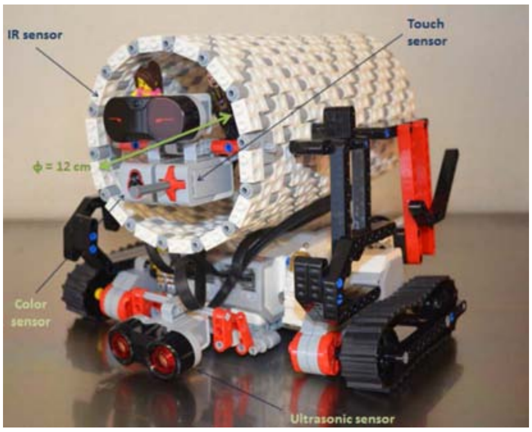


Figure 14: Cylindrical module with sensors.

The rendezvous has been programmed thanks to the Lego software. The docking has a similar kinematics of the ATV-ISS rendezvous. In a first step, there is the approach of the cylindrical module to the hub. The modules checks at the same time the distance to the hub thanks to the Ultrasonic sensor and the angle through the Infrared beacon. Later then, when the distance between the parts is less than 8 cm and the angle is 0^o, a probe goes out and the docking finishes when there is the double check of contact and light sensor.

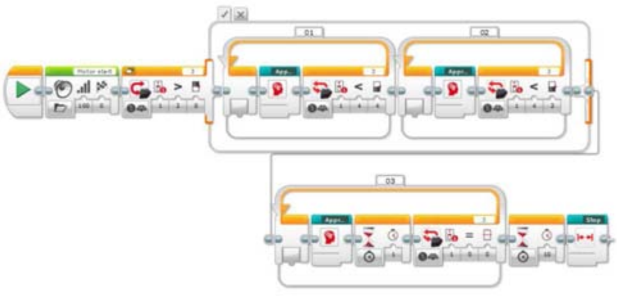


Figure 15: Docking - block diagram.

In order to make the block diagram easier, the rendezvous has been divided into different phases:

- Approach: it is divided into other 3 phases;

  Approach I: approach up to 20 cm from the hub and an angle of $\pm 4^o$;

  Approach II: approach up to 15 cm from the hub and an angle of $\pm 2^o$;

  Approach III: approach up to 8 cm from the hub and an angle of 0^o;

- Docking: it starts 10 seconds after the end of the previous phase, in which the contact with the hub is performed.

Because of structural vibrations due to the motion of the structure, at the end of each phase, before evaluating the angle, a time break of 2 seconds is imposed, in order to calm down the vibrations of the sensors.

Approach

In all the three phases there is a double control performed by the ultrasonic (distance) and the infrared sensor (angle). Because the Lego module can be positioned, at the beginning, both at right and left of the hub, there are two different path taking into account the initial relative position. When the module has a fixed distance and an angle less then a threshold, the new phase can start.

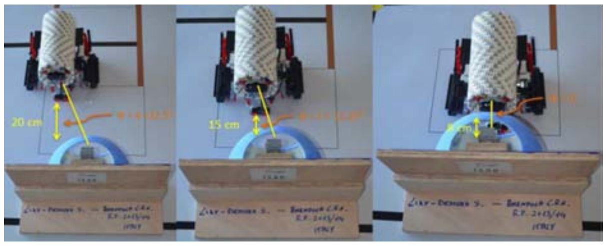


Figure 16: The three different approach phases.

The 'Approach I' (Figure 17) begins from an undefined distance and angle and ends when the angle between the IR sensor and IR beacon is less then 4^o. During this phase there is a check about the sign of the angle (right and left respect to the hub): depending on the position, one or other path will be followed. Thanks to the motion of the engines, the module tends to progressively align with the hub, keeping its perpendicular position.

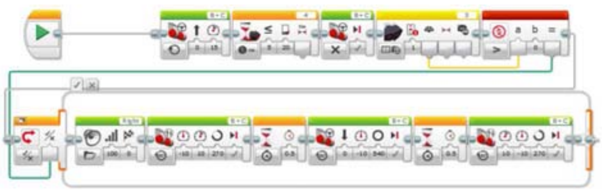


Figure 17: Approach I - block diagram.

As the first phase, the block diagram of the second enable to further approach to the hub. In this case, the distance and the angle becomes more precise (15 cm and $\pm 2^o$).

Figure 18: Approach II - block diagram.

Finally, the last phase ('Approach III') of the approach ends when the distance is less than 8 cm and when the IR sensor and the beacon are aligned (angle of 0^o).

Figure 19: Approach III - block diagram.

Docking

When the approach phase is finished, there is a break of 10 seconds that enable to deploy the probe. At this stage, the probe will be added by hands. In this phase, the color and touch sensors have been used: in fact, in order to complete the rendezvous, a double check must be performed. The docking is complete when both there is a touch and when the color sensor detect the color of the wood piece (brown).

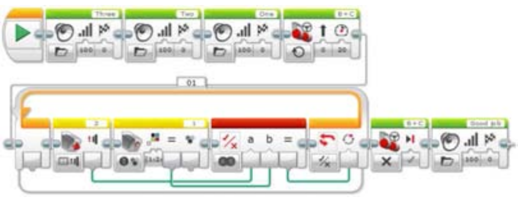


Figure 20: Contact - block diagram.

The final part of the rendezvous depends on the choice about the type of the docking system. In fact, as first step of the project both adaptable pins and inflatable materials have been analyzed. In the case of the inflatable materials, the structures (Figure 21) will catch the module and will fix it on the hub.

On the other hand, if the adaptable surfaces docking system is chosen (Figure 22), some pins will fix the module on the hub. Thanks to the mobility of the pins and the surfaces, it is possible to dock every type of visiting vehicles, independently form their size.

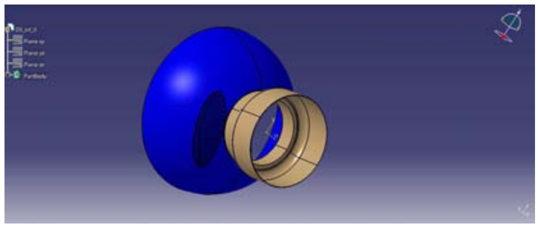


Figure 21: Inflatable Docking System.

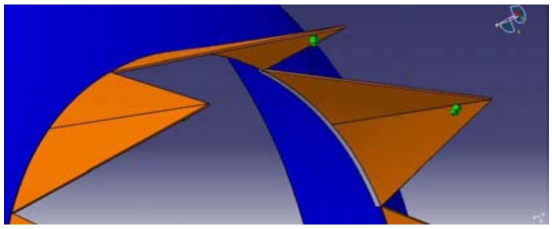


Figure 22: Adaptable pins.

The multi-threading

The docking system must be now tested in an environment with more constraints to verify that the general strategy can be adopted. The programming language JAVA for Lego is an adaptation to exploit all the sensors capabilities, the multi-threading. For the final phase, it is important to take care of the power in order to finalize the docking: at this step it is not possible to verify the alignment of the elements, and there are possibility of misalignment. Thanks to the use of JAVA, it possible to ensure the alignment.

V. RESULTS AND OPTIMIZATION

So the rendezvous is performed at very low speed - as in the real case - starting form the Proximity Operation B (100m to 10m). Thanks to the progressive alignment in distance and angle, it is possible to perform the rendezvous

The conditions of the rendezvous does not perfectly reflect the deep space dock. In fact, on the Earth, it is not always possible to have the zero-g conditions except in the Bremen Drop Tower and in the A300 Zero-G. Nevertheless, it has been possible to generally reproduce the conditions thanks to the slippery surface and the caterpillar wheels.

Moreover, because of the quality of the sensors and the engines, the rendezvous can be easily influenced by the environment during the performance. Nevertheless, the system analyzed, represents at research level a good milestone for the future projects. All the simulations have ended with a docking even if, occasionally, it has taken more time then the expected. Because of the angle sensors that does not return an angle value, it is not possible to have an optimal performance of the rendezvous.

Furthermore, because of the lack of the sensors, the cylindrical module must be kept such as the sensors will be perpendicular to the hub. Whenever more sensors will be used, it will be possible to connect the motion of the wheels with the relative position of between the module and the hub. The average time of the docking is about one minute, and the longest phase is 'Approach III'. In fact, it involves no play neither in angular rate or the distance, so the Lego module must be perfectly aligned with the hole. As already said, the play between both tools is 1 cm (0.5 cm at left and 0.5 cm at right); this characteristic, along with the range of the sensors, makes the rendezvous complex. Fortunately, the measures of the sensors are performed at $1kHz$ that ensures 1000 measurement at second.

The velocity of the module depends on the phase, as such as the angular rotation of the module. The average velocity is:

- 15% of the power of the engines, $\sim 4cm/s$;
- 10% of the power of the engines, $\sim 2cm/s$;
- 5% of the power of the engines, $\sim 1cm/s$;

In order to further develop the docking system, some optimizations can concern:

- use of JAVA development tool in order to increase the accuracy;
- use of smaller and more precise angles in the 'Approach III' phase;
- use of more sensors in order to link the position (distance and orientation) of the module to the engines;
- use of movable wheels in order to horizontally move the module;
- use of retractable probe in the last phase of the docking;
- use of third engine to vertically move the module and align it to the hole of the hub.

In the Table 2, a schematic of the result compared with the ATV is presented.

Furthermore, this table reflects the function that can be implemented on the project. The possibility of using more sensors and programming in JAVA will help to improve the docking system and to better analyze the behavior of the rendezvous.

Characteristic	**ATV**	**IBDM**	**THOR D.S.**
Deep space environment	✓	✓	✓
Reaction control system	✓	✓	✓
Ultrasonic sensor	✓	✓	✓
Infrared sensor	✓	✓	✓
Color sensor	✓	✓	✓
Touch sensor/probe	✓	✓	✓
Longitudinal control	✓	✓	✓
Pitch/yaw control	✓	✓	✓
Roll control	✓	✓	x
Adaptability	x	✓	✓
Habitability	x	x	✓
Inflatable structure	x	x	✓

Table 2: The THOR docking system vs. ATV and IBDM.

VI. CONCLUSION

The design of a whole spacecraft is a complex project. All the subsystems must be integrated and all the respective constraints must be satisfied. It is very complicate to focus the attention on the complete architecture of a spacecraft, on its systems and on its configuration. However, the design of the whole space station is out of the scope of this research project.

This innovative system presents at the same time all the benefits of the docking systems and of the robotic arms: its adaptability to several visiting vehicles and the passive functioning are strong points that can pave a new road for the future of docking systems.

The hypothesis at the basis of the research project come from an accurate analysis on the human aspect of the mission: the goal of Deep Space exploration must comply with the well-being of astronauts (scientists, engineers, mathematicians, artists, etc.). So, at first, all the constraints that might be satisfied were linked to the human field.

In order to take benefits form the lessons learnt, the general architecture of the spacecraft has characteristics similar to the ATV. Due to its good performances and overall qualities, this cargo-shuttle represents the reference for the study and the analysis of the station. So, the dimensions, the mass, the natural frequency must not be deeply examined, because of their similarity with the European transfer vehicle.

During the project, the constraints relative to the structural perspective have been analyzed into details, thanking into account the different working environments in which the manned vehicle should work during its lifetime. The ground loads, the LEO and the EML2 establish all the structural and thermal restrictions that must be satisfied in the accurate internal and external design of the docking system.

By coping with design criteria imposed by the deep-space environment, the docking system has been designed. The aim is to have an 'universal type of junction' between the stations and the re-supply – manned or unmanned – shuttles.

The docking system must be able to perform a structural connection between the hubs and the cylindrical modules or external vehicles, to allow fuel, power and data transfer and, moreover, to function as passageway for crew and materials. It will be fitted on the spherical hubs in order to anchor the modules and the visiting vehicles in safe conditions.

Thanks to movable surfaces and adaptable pins, this innovative system will allow diverse kind of modules to safely dock on the spherical hubs. Because of the severe constraints, the functioning of the docking system has been improved in order to consent the control the trajectory in the critical phases of the mission.

In order to further develop the architecture of the rendezvous and of the docking system, a deeper study must be performed so to cope with the more stringent constraints of the deep space. Once acquired the complete analysis and design, it will be possible to develop in depth all the structure of the docking system and, at the same time, to study the integration between the structure and the sensors.

Here in after, several hints on the possible future analysis are listed:

- development of the docking system adjustable as function of the mission;
- in-depth study of the structure of the docking system;
- subsystem integration (fuel tank, solar panels);
- JAVA programming of the rendezvous;
- the use of the inflatable docking system as reference for space debris removal;
- performance of the rendezvous on a zero-g environment (Spin Your Thesis, Drop Tower);
- study of the rendezvous with more performing sensors and engines.

The rendezvous is one of the most critical parts of a mission. The application on the THOR space station is a first approach on a project that can go further behind with diverse applications. In the future, this innovative design could turn out to be the essential basis for further developing the detailed design and sizing of the universal docking system.

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