DEVELOPMENT OF A NOVEL ACTIVE DEBRIS REMOVAL INTERFACE FOR ROBOTIC CAPTURE

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ABSTRACT

Due to orbital debris proliferation, Active Debris Removal (ADR) missions will play an important role in the future. Several methods to de-risk an ADR mission were identified during a past GSP study, called Design for Removal (D4R). The activities identified covered different areas for technology improvement, [1]. A more recent ADR for the mega-constellation ESA study, also highlighted the need of target preparation. Such activity eases potential future removal operations and mitigates the risk of rendering part of the orbits unusable, thereby affecting the services offered by constellation operators. ADR also can be considered as a technology precursor for future, more complex servicing missions. In general, optimal mission profiles may look rather different depending on the use case. Nevertheless, synergies exist in a number of areas. ADR poses a number of technical challenges and risks in terms of rendezvous and capture of a non-operational satellite, such as accurately tracking and performing rendezvous; achieving the desired attitude for capture, considering Target tumbling motions; and performing physical capture.

To this end, NTUA-CSL and TASF have developed a novel capture Interface (I/F), focusing on the Passive mechanical I/F part, while at the same time proposing initial design options for the Active mechanical I/F part. To assist a Chaser identify Target distance and attitude, the design of the Passive I/F includes appropriate markers. The Passive I/F has been designed and developed both in 3D printing and aluminium as a mockup, while the markers have been constructed also. Simulation tests took place for both the mechanical I/F and the markers, in an effort to examine the working envelope of the designs. Important results have been developed, which included among other, the analysis of the performance under the effects of certain parameters like Active I/F motor torques and the relative velocity between Chaser and Target during capture. Emulation tests have been performed both for the mechanical I/F and the markers; the former on NTUA-CSL's Space Robotic Emulator (SRE), an air-bearing facility designed for the execution of similar tasks for robotic systems, and the latter at the ROBotic FacilitY for orbital rendezvous demonstration (ROBY) of TASF. In this paper, important details on the mechanical I/F will be presented.

1 PROJECT OBJECTIVE AND REQUIREMENTS

The main objective of the PRINCE activity was to design and verify (up to TRL 3) a mechanical interface (I/F) with integrated rendezvous/ navigation aids (named PRINCE), which will enable the safe capture and removal of a non-operational/ non-cooperative satellite for uncontrolled re-entry (i.e. no high thrust manoeuvres/ loads as a result of controlled re- entry burns). PRINCE included the following elements: (a) Passive interface on the Target satellite including the mechanical I/F to facilitate capture and the navigation supports (e.g. 2D/ 3D markers); (b) Mechanical I/F on the space servicing vehicle (e.g. the gripper at the end of a robotic arm). Within this activity, the Passive I/F had to be constructed as a breadboard and the Consortium to demonstrate the capture process including the mechanical I/F.

It is important to mention also, that PRINCE had to minimize the impact on the Target satellite (power, mass, and volume), and the risk, cost and/ or complexity of a Chaser, which will perform the capture of the non-operational satellite after end-of-life. Therefore, the design had to take into account degradation due to long-term exposure to the space environment.

To this end, a set of requirements have been defined for the execution of the project. A summary of the most important ones is presented in Table 1.

2 DESIGN PROCESS

Initially, NTUA-CSL and TASF developed four basic conceptual designs. Except from the necessary requirements, main design drivers were also: Minimum impact on the Spacecrafts (S/Cs) and the complexity of the system which had to be kept to a minimum, without however losing any of the necessary functionalities.

Table 1: Requirements for PRINCE as set by ESA.

Important Requirements Description
The PRINCE system shall enable capture of an uncooperative Target satellite by a Chaser.
The capture operation of the PRINCE system shall be a repeatable operation.
The passive interface of PRINCE on the Target satellite shall not require any activation e.g. power, data.
The linear misalignment between passive part and active part at the beginning of the capture are within: 0 mm < in plane offset XY < ±20 mm
The angular misalignment between passive part and active part at the beginning of the capture are within: 0° < in plane angle XY < ±3°
The Z angular position between the passive part and the EE is within: 0° < out of plane angle Z < 360°
The mass of a passive part shall not exceed 2 Kg.
The mass of an active part shall not exceed 6 Kg.
The passive interface of PRINCE integrated grasping fixtures shall fit within a 70mm diameter and 50mm height cylinder. The keep out zone shall be a circle with diameter less than 100mm, with its center at the center of the Passive I/F.
The gripper of PRINCE shall be within a volume of 70x35x150 mm^3
The PRINCE system shall be designed to operate in conditions typical of an Earth Observation satellite in LEO.
The passive fixture of PRINCE located on the target satellite shall be designed for operation after 15 years on orbit, considering degradation due to environmental effects typical of an Earth Observation satellite in LEO.
The passive interface of PRINCE integrated grasping fixtures shall have an approach frustum of 70mm TBD diameter in small base 0.5m TBC height and 140mm TBC in large base
The gripper should be able to retract if the capture fails
The PRINCE system shall make use of materials and processes compatible with ECSS-Q-ST70.

Then, the two entities of the consortium, following discussions between them and with ESA, marked each concept versus a set of criteria in order to choose the concept which would be designed in greater detail, Figure 1, each with different relative weight. A Trade-Off (T/O) procedure took place, with goal to retain a single design on which a detailed design would then be performed. Finally, and based on the results, a final design which encompasses the best design parameters of the conceptual designs have been developed. Important elements are presented in this work, while further details on the PRINCE concept are presented in the related ICD document [2].

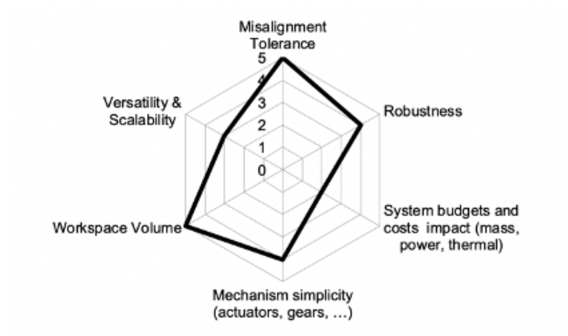


Figure 1: Final six criteria for the T/O (ESA Key Value Attributes).

3 SELECTED CONCEPT

The PRINCE I/F can be seen in Figure 2 and the Passive I/F in particular in Figure 3. The central pin is connected with a continuation of its geometry (black part, light blue part) with a linear spring (not always visible in CAD).

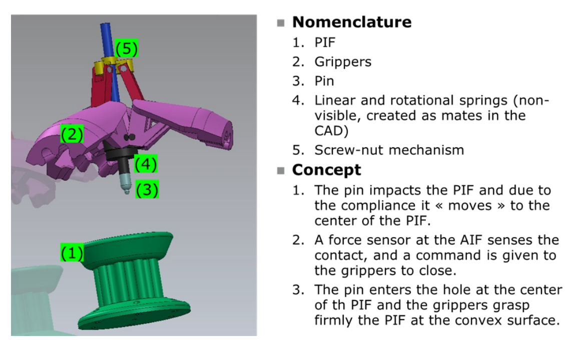


Figure 2: PRINCE concept.

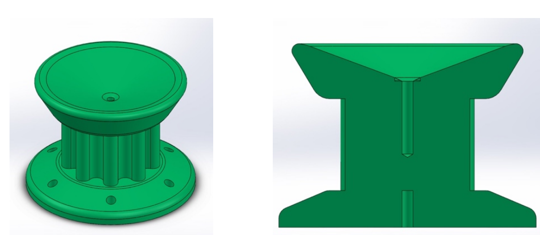


Figure 3: Passive I/F of PRINCE concept

The capturing process follows the following phases:

Soft capture: The fingers envelop the conical geometry at the top of the Passive I/F and the spring starts getting compressed, Figure 4. The actuation of the fingers takes place, as soon as the guiding pin touches the Passive I/F with the use of a sensor. The fingers are moved with a single rotary actuator, which transmits movement to the fingers with the use of a screw-nut mechanism and slide-crank mechanisms, screw being the blue part and nut being the yellow part.

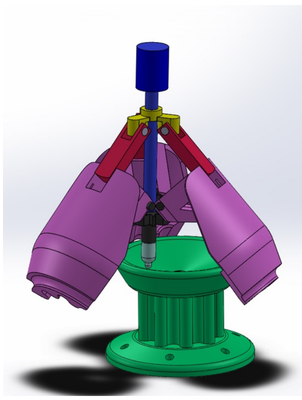


Figure 4: Start of Soft Capture.

Hard capture: The guiding pin with the compressed spring is led to the central hole at the top of the passive part, while the fingers start enveloping the complex geometry of the passive interface with their complex geometry, Figure 5. The complex geometry of the fingers is gradually reaching the equivalent geometry of the Passive I/F. During capture an indentation of a finger can envelope an indentation and a bump of the Passive I/F's complex geometry, so the more the gripper gets to close, the more the rotation around the vertical axis is being locked, while the grasp is gradually rigidized. The process is shown in Figure 6. As the fingers close and fit the geometry of the passive part, the spring decompresses a little and pushes the Passive I/F (and eventually the Target) on the top surface of the grasping volume of the fingers.

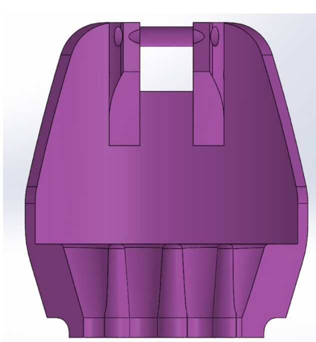
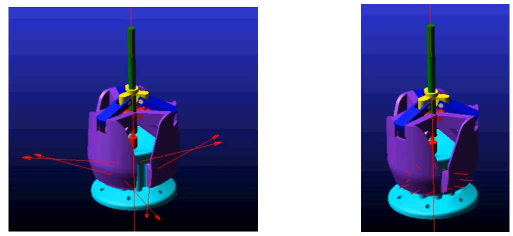


Figure 5: Complex geometry of the finger of the Active I/F.



(a) (b)

Figure 6: Hard capture of PRINCE I/F from simulations in MSC ADAMS. With red arrows the contact forces are presented.

Release: When the fingers open, the spring decompresses completely and pushes the target.

The screw has a blocking geometry. In Figure 7 a 3D printed version of the passive mechanism is depicted. The version was printed in NTUA-CSL

Figure 7: 3D printed version of PRINCE Passive I/F.

In Figure 8 the Active I/F's workspace for a scenario with the maximum angular and linear displacements (according to the requirements) has been calculated; the span is less than 127mm.

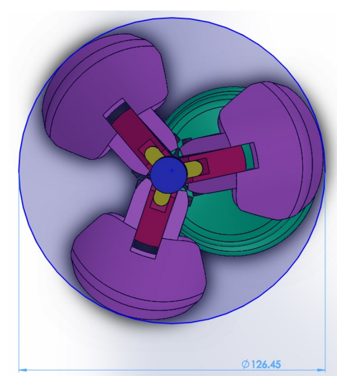


Figure 8: Active I/F's workspace top view.

4 STATIC ANALYSIS, MATERIAL AND MANUFACTURING

Several static analyses have been performed for both the Active and Passive I/Fs using Solidworks. No large stresses were presented, which were far below the yield strength of typical aerospace materials. In order to identify the necessary materials for the Passive and Active I/Fs, while taking into consideration the requirements, as well as ESA's suggestions, the following parameters had to be taken into account: (a) The material of the Passive I/F shall withstand the space environment for at least 15 years; (b) The material of the grippers of the Active I/F shall not create Cold Welding due to Impact or Fretting under Vacuum when in contact with the material of the Passive I/F; (c) According to best practices and recommendation from the mechanisms ECSS [3], using two hard dissimilar metals with a coating on one of them is optimal; and (d) It is recommended not to use any type of coating on the Target side due to the long exposure to LEO environment, soft and hard coatings may have problems with ATOX and thus, it is better to apply the coating on the mechanism (Active I/F).

Having in mind the abovementioned information, the following material selection was proposed for the Passive I/F, as well the grippers of the Active I/F:

- For the Passive I/F, Stainless Steel 18/8 300 Series;
- For the Active I/F Titanium Alloy Ti6Al4V with Keronite coating.

Regarding the manufacturability, the design can be manufactured in one block under specific directions. Otherwise, the complex geometry of the passive interface would possibly lead to the breaking of cutting tools, due to the need for a perfect ball end nose contouring tool to penetrate perfectly the metal, or the use of an extremely thin cutting tool with a cutting length greater than 3.5 mm, which is not practically feasible. Alternatively, the Passive I/F could be manufactured as a two-part assembly as is. For this reason, minor modifications to the original design of the Passive I/F have been performed after discussions with a dedicated workshop, which did not lead to further modifications at the Active I/F due to the gradual change of geometry on the fingers, that can envelope the bigger radius of the bumps on top of the complex geometry. The final metallic item has been manufactured and can be seen in *Figure 9*.

(a) (b) (c)

Figure 9: (a) Modified Passive I/F for manufacturing at one block, (b) and (c) Metallic Passive I/F, manufactured as one piece.

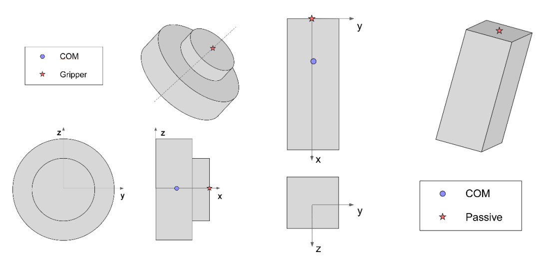
5 SIMULATIONS

A successful grasp comprises of two distinct parts: The first part is the geometric compatibility of the Chaser's Active I/F and Target's Passive I/F, which can be achieved by carefully designing the two parts and introducing geometric features that cooperate to enable capture. The second part is the grasp I/F dynamics, where the approach conditions between the Target and the Chaser give rise to contact forces that heavily depend on the two bodies' inertias as well as other parameters like friction. Both these parts were investigated using a dynamic simulation developed in MSC Adams. The purpose of each dynamic simulation was to close a design loop, enabling the optimization of the grasp I/F's design and its functional parameters.

The model under study included the Chaser and the Target S/Cs in space: there is no gravity field or friction force acting on their bodies. The Chaser and Target inertial parameters used for the simulations are listed in Table 2, with respect to the body-fixed axes shown in Figure 10a for the Chaser, and Figure 10b for the Target. In particular, the Chaser has been inspired by the characteristics of the S/C under development by ESA CDF for the particular ADR mission, while the Target has been inspired by the characteristics of Sentinel 3.

Table 2: Chaser and Target inertial parameters. Body-bound axes as shown in Figure 10.

	Chaser	Target
Mass, m	1100 kg	1050 kg
COM position in x-axis, x_{COM}	0.628 m	1.617 m
COM position in y-axis, y_{COM}	0	0.245 m
COM position in z-axis, z_{COM}	0	0.01 m
Moment of Inertia around x-axis, I_{xx}	562.7 kgm^2	1500 kgm^2
Moment of Inertia around x-axis, I_{yy}	458.3 kgm^2	1200 kgm^2
Moment of Inertia around z-axis, I_{zz}	548.3 kgm^2	2400 kgm^2



(a) *(b)*

Figure 10: (a) Chaser and (b) Target schematics.

As shown in Figure 10, the developed Active I/F has been placed on the Chaser S/C, while the Target S/C has been equipped with the Passive I/F, at the center of the Launch Adaptor Ring (LAR). The two I/Fs, each mounted on their respective S/C, in ADAMS, are shown in Figure 11.

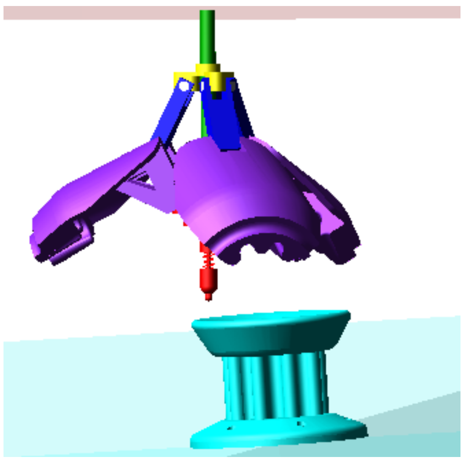


Figure 11: Active and Passive I/Fs, mounted on the Chaser and the Target S/C respectively.

The two I/Fs were imported to the simulation software MSC ADAMS through the SolidWorks Motion Study. In this manner, most of the functional constraints of the mechanism, which were initially introduced in the form of mates in SolidWorks, were automatically configured as either connections or constraints.

5.1 Assumptions

According to the information from ESA, the Active I/F is expected to be installed directly on a Stewart platform ("hexapod") which has some controlled motion capacities. Alternatively, the Active I/F can be installed as an End Effector to a robotic manipulator. No matter which of the two cases is chosen, the important issue is that the Active I/F will be installed on another mechanism which has its own kinematics and control and not directly on the Chaser. Therefore, in both cases, the controller of this mechanism (i.e. hexapod or manipulator in general) will be able to allow for some compliance, which in turn will allow for a better control of the capture process. More specifically, due to the compliance of the mechanism, some forces that are exerted during contact will be even lower than in the case of no existing compliance.

In the simulations, the assumption that the hexapod (or the manipulator) is rigid, i.e. without compliance, was made. This way, worst-case scenarios were examined, and this ensured that if the capturing process worked as requested, then it would work also with the compliance of the mechanisms, and in fact it will be subject to lower forces/ torques. Furthermore, this assumption allowed for a better understanding of the effect of each parameter of the S/Cs, the Active and the Passive I/Fs on the capturing process. On the other hand, the Passive I/F was assumed to be rigidly connected at the centre of the LAR area in all cases.

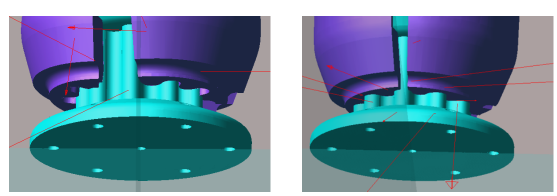
5.2 Suitability of Geometric Design

An important part of designing the capture I/F is creating two geometries that will optimally cooperate to achieve a successful grasp of the Target, followed by an alignment of the two bodies. This part of the design process is independent of the capture dynamics; however, it is imperative to evaluate the efficiency of the geometric design of the Active I/F and the Passive I/F in the fine-tuned model, mainly to ensure that the friction forces of the grasped contact can be overcome to allow for relative motion. For this reason, the two S/C bodies were set in the misaligned positions and their gradual alignment was observed.

The results presented have been obtained with a coefficient of friction $\mu = 0.3$, which is a good estimate for most contacts between metallic surfaces. It can be seen in Figure 12 that the successful capture that has been analysed ultimately results in perfect alignment of the two bodies. In Figure 13, a close up of the interlocking mechanism is presented for two instances: (a) right after the closing of the Active I/F's fingers around the Passive I/F, where the relative position is random and an alignment is not yet achieved, and (b) after the gripper's closing force overcomes the contact friction, forcing a relative motion in the contact and ultimately leading to aligned geometries.

(a) (b)

Figure 12: (a) Initial misalignment of Chaser and Target and (b) final alignment.



(a) (b)

Figure 13: (a) Random positioning of the matching geometries right after closure of the fingers and (b) successful interlock after relative motion for alignment.

These results show that the selected geometries are suitable for achieving an alignment after capture, and that the geometric interlock is possible even when starting at a random closed position. Once again, it must be noted that if the hexapod's compliance was accounted, this closure process would be easier.

5.3 Investigation of Parameter Ranges

The geometry of the Active and Passive I/Fs can safely be considered to remain constant after their manufacturing and during their operation, as has been shown in the relevant stress analysis study that the expected loads did not exceed the yield stress of any of the materials. However, this is not the case for the operational parameters of the Active I/F, as these can change for various reasons. In this section, an investigation of parameter ranges, as well as of parameter combinations is presented, to obtain an insight in the operation of the capture mechanism. The set of parameters studied together was selected based on the observed mechanism behaviour during the early design and fine-tuning processes.

In the following tests, various designs were evaluated with respect to their ability to perform a successful capture, along with the capture's suitability with respect to the requirement for the maximum force exerted on all Active and Passive I/Fs parts to be lower than F_c = 250 N.

5.4 Approaching Velocity and Spring Stiffness

During the initial fine-tuning process, it was observed that the relative approach velocity between the Active and Passive I/Fs affects the optimal spring stiffness selection for the contact sensing mechanism. Together, these two parameters can greatly influence the outcome of the grasping process.

Figure 14 presents the results of a parametric design analysis on the gripper, performed by changing the relative approach velocity and the stiffness of the sensing pin within some specified limits. The figure plots the maximum force applied on the mechanism during the capture process, from initial impact until rigidization. The margins of successful capture cases were also plotted in this figure: for small relative approach velocities, the capture is unsuccessful, as the force exerted on the pin is not enough to exceed the sensing threshold and trigger the closure of the grippers.

It can be observed that there is a large area where the capture is successful, and the loads are within the specified limits of F_c = 250 N. However, there are some areas where the loads exerted on the mechanisms exceed this maximum allowed value. This is the case for large relative velocities between the Active and Passive I/Fs, as the impact force is increased with increased approach velocities.

Therefore, it can be observed that for the relative velocities that lie within the specifications the capture is successful, and the loads are within the specified limits. The region where there is no successful capture can be minimized by minimizing the sensing pin's force detection threshold, or altogether eliminated by using a different proximity detection technology.

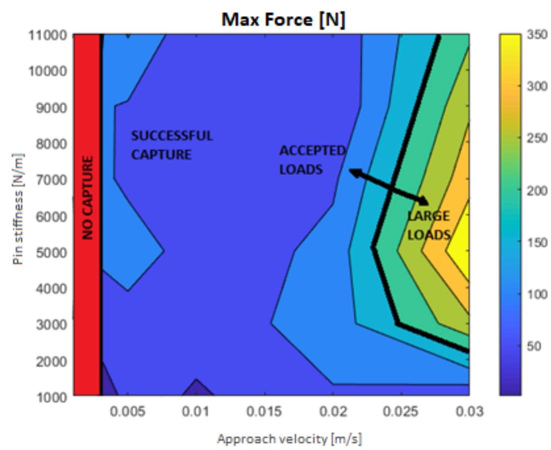


Figure 14: Approach velocity and sensing pin stiffness investigation.

5.5 Motor Target Velocity and Pitch

Another set of parameters that work in cooperation with each other in determining the success of a capture attempt are the motor control system's target closure velocity ω_t, as well as the pitch of the screw-nut mechanism. Figure 15 presents the results of an investigation regarding these two parameters. The simulations performed were evaluated with respect to the maximum recorded forces as well as their success at performing capture.

As it can be expected, for large closure velocities ω_t the fingers' impact with the Passive I/F leads to larger loads which might exceed the limit F_c = 250 N. The same holds for large pitch values, as for a certain ω_t, the actual descent velocity of the fingers increases even further with a larger pitch. Therefore, the top-right corner of the investigative chart should be avoided in the design process.

On the other hand, a slow ω_t in conjunction with small pitch values would lead to a smaller descent velocity for the Active I/F's fingers, which would not be effective in grasping the Passive I/F in the time available for the capture. Therefore, the bottom-left corner of the chart should also be avoided.

In conclusion, a large portion of the graph in Figure 15 corresponds to successful combinations for the motor velocity and the screw-nut pitch. Any one of the corresponding designs could be safely implemented in the Active I/F.

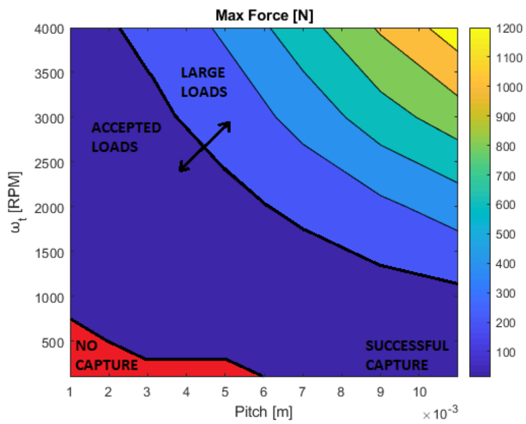


Figure 15: Motor target velocity and screw-nut mechanism pitch investigation.

5.6 Discussion

In conclusion, the system was shown to successfully perform captures even at the worst of the cases studied. The geometries of the grasping interface were proven to be efficient in ensuring a gradual geometric interlock of the Chaser and Target. The fine-tuning process provided useful guidelines regarding the Active I/F's design.

Another point of interest is that it is concluded that for the set of S/C parameters used, a solution for the Active I/F parameters can be found; during the analysis, other dummy S/C parameters have been tested and different sets of Active I/F parameters were necessary. However, again solutions could be reached.

6 HARDWARE TESTS

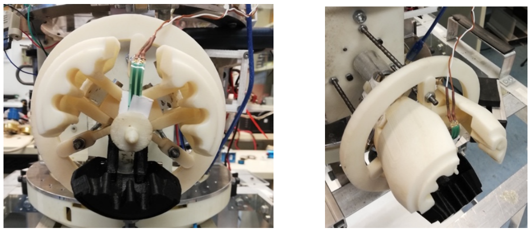
The functionality characteristics of the PRINCE I/F were examined in the experimental test that took place on the Space Robot Emulator (SRE) in the NTUA-CSL facilities, [4]. The main goal of the test was to examine whether the Chaser can capture the Target, as the simulations show. Additionally, it examined the capability of the coupled I/F to maintain the Hard Capture phase grasp, while the Chaser and Target move. Regarding the tests, the control of the Chaser robot was done in ROS, and the overall movement of both the Chaser and the Target was monitored by a PhaseSpace mocap system.

During the initial tests, an initial design has been developed in a 3D printer. The grasping procedure worked almost as expected from the concept and the simulations, however some issues were identified: Due to the roughness of the ABS material, a small eccentricity between the Active and Passive I/Fs, as well as a small flexibility of the Active I/F mounting system, existed, which led to some occasions in which the two I/Fs were jammed during the grasping process. Note, that the SRE is a 2D emulator, and the robots cannot roll (neither a mechanism for rolling compliance existed), which would solve the issue by design; This is however not the case in a 3D system, which can have compliance in the roll axis (e.g. by installing it on a manipulator), and by design would compensate for such small inaccuracies.

Furthermore, after some tests, it has been noticed that some joints of the screw-nut system of the Active I/F mechanism break relatively easily; after analysing the issue, it was concluded that the initial design used for the 3D printer, appeared to have configurations which were located near singularities during the final steps of the motion; although the stresses were not extreme at these joints, they were just enough for the ABS material to crack (however for a metallic I/F the stresses would be still relatively low compared to the yield strength).

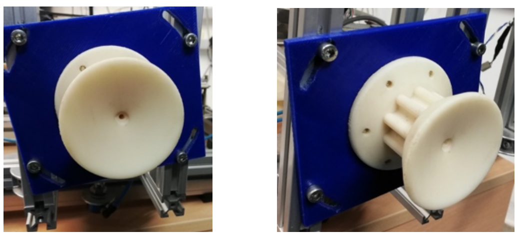
To address the issues a small design change of the Active I/F mechanism took place, regarding the lengths of the links of the screw-nut mechanism, without affecting the workspace of the Active I/F. However, and in order to decrease both the flexibility of the mounting system (of the Active I/F) as well as to further decrease erroneous motions that would stress the ABS, a ring has been implemented; This decreased a little bit the opening of the fingers (i.e. the 2 cm misalignment requirement was difficult to be achieved in the experiment), however the functionality remained the same. Naturally, this ring will not exist in a metallic Active I/F. Simultaneously, another adaptor for the Passive I/F has been developed which allowed to minimize to the extent possible, the inaccuracies along the roll plane. Additionally, a pin with force sensor has been installed, in order to initiate the grasping upon impact. The final design can be seen in Figure 16 and Figure 17, while in Figure 18 an instant after capture is shown.

Several functionality tests for capturing took place, and a characteristic set of plots can be seen in Figure 19 and Figure 20. As it can be seen, the grasping was successful (no jams) even with the roughness of the ABS material, the relative velocity during the impact was about 10cm/s, the relative angle during the impact about 3.1^{o} and after the grasping, both systems moved together without losing the grasp (no relative motion between them).



(a) (b)

Figure 16: Various views of the Active I/F after modifications.



(a) (b)

Figure 17: Various views of the Passive I/F with its adaptor.

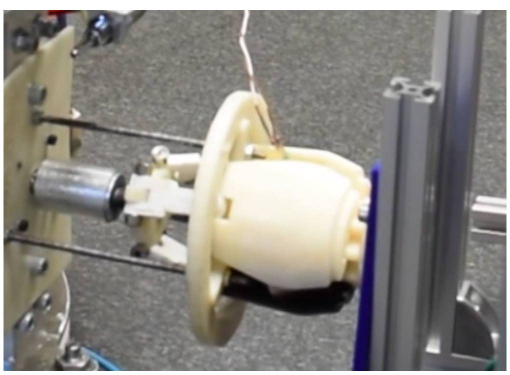


Figure 18: Grasping during experimental tests.

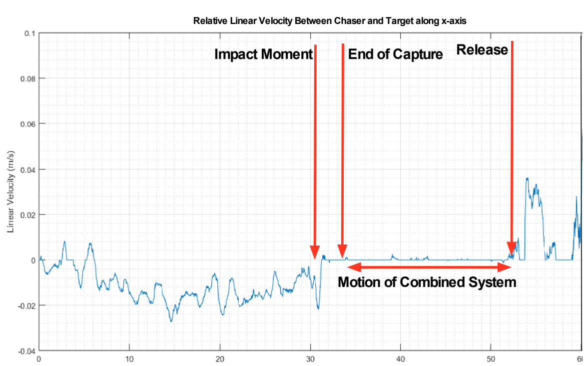


Figure 19: Relative Linear Velocity between Chaser and Target.

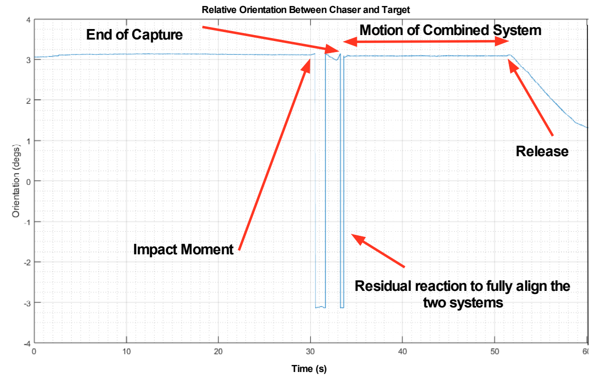


Figure 20: Relative Orientation between Chaser and Target.

7 CONCLUSION

The PRINCE project has been successfully concluded by NTUA-CSL and TASF, and a novel I/F has been presented, reaching TRL 3, [5]. Suggestions, lessons learned and various issues for discussion for future activities have been derived, and were presented in this work. Design choices and characteristics were discussed; the simulation and experimental approach were analyzed and results were shown; finally, the ESA's requirements has been achieved.

Acknowledgement

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