GRIPPERS FOR LAUNCH ADAPTER RINGS OF NON-COOPERATIVE SATELLITES CAPTURE FOR ACTIVE DEBRIS REMOVAL, SPACE TUG AND ON-ORBIT SATELLITE SERVICING APPLICATIONS

Jaroslaw Jaworski, Łukasz Dudek, Mateusz Wolski, Artur Mateja, Paweł Wittels, Michał Łabęcki (1), **Brice Dellandréa, Julien Christy, Vincent Dubanchet, Catherine Le Peuvedic** (2)

(1) *PIAP Space*, Jerozolimskie 202, 02-484 Warsaw, Poland Email:{letteroffirstnamelastname}@piap.pl
(2) *Thales Alenia Space - France*, 5 allée des Gabians, 06150 Cannes La Bocca, France
Email:{firstname.lastname}@thalesaleniaspace.com

ABSTRACT

Growing population of space debris is being pointed as an emerging challenge for the space community, especially for upcoming plans of launching several satellites constellations. Analyses showed that removing five critical objects per year, satellites or launcher upper stages, would stabilize the growing number of space debris. System studies made by Clean Space initiative of the European Space Agency (ESA) shown that capturing uncooperative satellite would be the most successful by rigid approach, made by a grasping device on the tip of robotics arm. Due to its features, the preferable grasping point on the unprepared satellite is Launch Adapter Ring (LAR) [1].

Following paper presents design and validation of two grippers prototypes designed to capture two different models of LAR of heavy class satellites.

Figure 1. Chaser approaching to target satellite.

1. STATE OF THE ART

1.1. Grippers

LAR Capture Tool, MDA

The MDA's capture tool is designed to grasp LAR models with various diameters – from 937 diameter up to a straight beam. It consists of two sets of jaws with adjustable angle to fit different diameters. Both jaws contain contactless "trigger" sensors for detecting the target object in the capture envelope as well as a successful or failed capture attempt. The tool operates in two main stages, with two separate mechanisms, one performing a fast acting soft capture and the other a slower operation to seat and rigidize the LAR in the tool. The first stage is achieved by quickly closing the jaws over the target object when the sensors on the jaws are triggered. The key idea of the mechanism is to prevent the target object from escaping from the capture envelope. Once the jaws have closed, the second mechanism pulls the target onto rigidization surfaces until a desired preload is reached in order to obtain a firm grasp [2].

LAR Gripper, OHB

The gripper proposed by OHB is designed to accommodate specifically the Envisat's LAR with its nominal diameter of 2624 mm. The tool is composed of two clamping brackets on both sides of the target object, driven symmetrically by a spindle with right and left thread to perform a first phase enclosing LAR. Each bracket contains a spring driven grip jaw, inclined by 15 deg to vertical, with contact rollers. The second phase begins once the grip jaws have come in contact with LAR.. With the continuous motion of the spindle the jaws start pulling the target object onto rigidization surfaces between the brackets due to occurrence of a horizontal contact force on the rollers. When a nominal gripping force is achieved the motor stops and gripping is finalised by activating a motor break. The design foresees following sets of sensors: micro switches below LAR support for positive LAR capturing indication, "open" and "closed" configuration limit switches at hard end-stops, a motor torque sensor for measuring the nominal clamping force, encoder/resolver for the brackets position determination, inductive proximity sensors for nominal grapple position verification; and optionally: optical markers on brackets and jaws for visual verification of position, light curtain sensors to verify if LAR lower surface is within the alignment tolerance envelope [3].

1.2. Vision system

The rendezvous and docking missions require sensors implemented on the chaser spacecraft for relative navigation. Different kinds of sensors may be implemented to estimate the relative pose (position and attitude): monocular or stereoscopic panchromatic cameras, RF sensor, LIDAR, Time-Of-Flight cameras, infrared and multispectral cameras. Inertial sensors and GPS may also be used for the chaser dynamics measurement, as well as ground Doppler and ranging measurements.

The sensor suite and data fusion are selected and designed with respect to the mission requirements: cooperative or non-cooperative target, model based approach or not, autonomy constraints, redundancy, robustness and accuracy, system impacts, etc.

For e-Deorbit Active Debris Removal mission [4], a set of monocular cameras is foreseen for long range and close range operations [5], with the possible data fusion with a LIDAR at short range [6].

1.3. Control algorithm

The automatic manoeuvres required to perform a rendezvous between two spacecrafts is covered in reference books like [7]. The Clohessy-Wiltshire equations may be used to describe the relative dynamics and then to design control laws and trajectory planning [8] [9] rather focuses on the control of the robotic arm in the last steps of the capture, when the two spacecrafts can be considered floating freely in space, and when the target is within reach of the end-effector, or close to it.

Under these conditions, the control of a space robot may be chosen among two main avenues: the *free-flying* or the *free-floating* strategies. The first one consists of controlling both the base spacecraft and the robotic arm, while the second one is leaving the base free to react to any disturbances produced by the arm motion. Both strategies are discussed in [8] and are usually brought together in a mission scenario. The *free-floating* guidance scheme is especially presented in [9].

2. MAIN REQUIREMENTS (JJ)

2.1. Grippers

The grippers' task is to successfully grasp and release a particular LAR model (described further in [6].). At least three operating states are required: open – jaws open, LAR not within capture envelope; captive – jaws initially closed, LAR loose within capture envelope; closed – jaws closed, rigid LAR grasp. The states shall be autonomously detected by the gripper. The gripper shall contain a set of contactless sensors to indicate when the LAR is located within the capture envelope of the tool due to the fact that any physical interference may cause relative movement between the chaser and the target object. The closed state shall remain rigid under a minimal torque of 20 Nm around all axes to sustain a robotic arm backdrive. Required time of gripper capture and rigidization operation shall be lowest as possible to decrease required capture window. The capture envelope shall include possible positioning errors and therefore at least 5 cm and 5 deg misalignment margin on each axis is required. Last but not least, the grippers shall distribute capture loads on LAR not to damage it at any point – the applied stresses cannot exceed LAR's material yield strength.

2.2. Vision system

The proposed experimental setup performs the HIL validation by using a wide angle camera (97° field of view) on the chaser side. On the target side, a dedicated visual target made of four green dots is mounted on the robot in order to account for the fact that the whole satellite and launcher interface is not represented in the test setup.

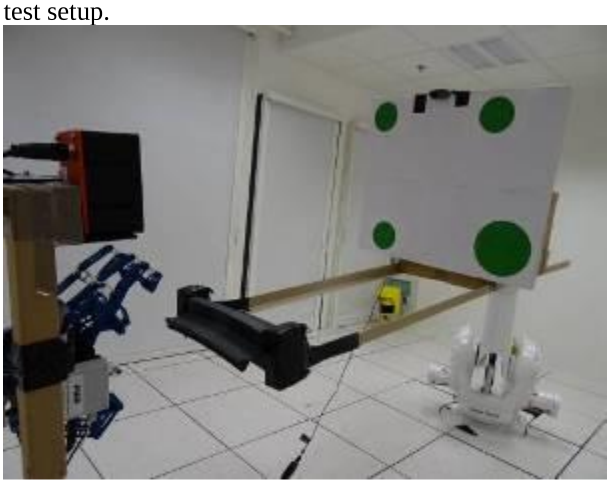

Figure 2: LAR and visual target mounted on the target robot

The image processing algorithms is in charge of measuring the relative position and attitude from the detected dots. This pose measurement feeds a navigation filter with a feedforward loop in order to smooth the pose estimation used by the control algorithm.

2.3. Control algorithm

The objective of the control algorithm is to track the target movement and keep the uncertainty corridor within the gripper tolerance.

The global control scheme for the whole test bench is illustrated in Figure x with the real-time simulation and the integration of a real sensor in the feedback. Therefore, the Simulink model includes a feedback from a communication module to receive and process the camera data before using it in the chaser controller of the *real world*.

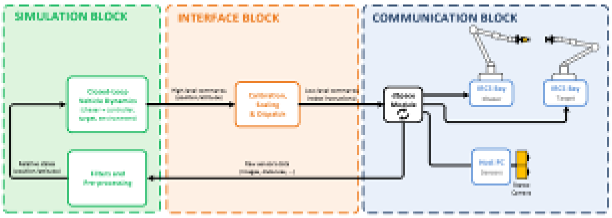

Figure 3: Global HIL structure of the Simulink scheme emulating the on-orbit dynamics of the closed-loop system [7]

The *Simulation Block* propagates the on-orbit dynamics of both the chaser and the target using the classic Newton-Euler algorithm to represent the multi-body dynamics. This block integrated the guidance, navigation and control algorithms. The camera measurement and navigation algorithms are used to estimate the pose of the LAR. The control algorithm uses the estimated pose to compute the torque and force to be applied on the chaser. The real chaser and target states are computed considering their dynamics and the torque/force commands to close the loop.
The *Interface Block* contains the control strategy of the industrial manipulators. The on-orbit motions coming from the simulation are dispatched between the target and the chaser robots.
Eventually, the *Communication Block* stands for the communication setup with the dSpace module. All the protocols and data encoding are implemented inside. The commands and measurements are sent, received and decoded through this block.

3. TARGET DESCRIPTION

Launch Adapter Rings have been chosen as the interface for a gripping tool due to their features: high loads capability since they are designed to withstand launch loads, different LAR models resemble each other in shape and cross section dimensions, their diameter is standardised (usually 937, 1194, 1666 or 2624 mm), tight manufacturing tolerances, relatively easy to be recognised by a vision system, no blankets or coatings, usually no additional external satellite equipment (e.g. solar arrays, antennas) close to LAR, which could interfere with the Chaser's gripper and robotic arm.
Each gripper was designed to capture a particular LAR. Both have the same nominal diameter (2624 mm) and material (Al. 7075-T6), but their cross sections significantly vary.

3.1. LAR 1

The first Launch Adapter Ring does not resemble any standard adapters regarding shape. It has two horizontal ribs, internal and external, with different thickness, position and length as well as a sloped flange which make the model quite complex to capture. Its bottom surface due to being narrow, with two grooves and one small external flange, would not provide stable, rigid interface with the capture tool, hence the model is more likely to be grasped using other geometric features.

3.2. Envisat's PAS-2624 VS

The Envisat's LAR is a standard adapter, which shape is similar to other models with different diameters. Its cross section is "L" shaped, with an internal vertical flange and a horizontal external rib and a small groove. The shape is more regular, has many flat surfaces and thus provides plenty of space for a rigid grasp comparing to the previous model. It is also easier to be supported from the bottom.

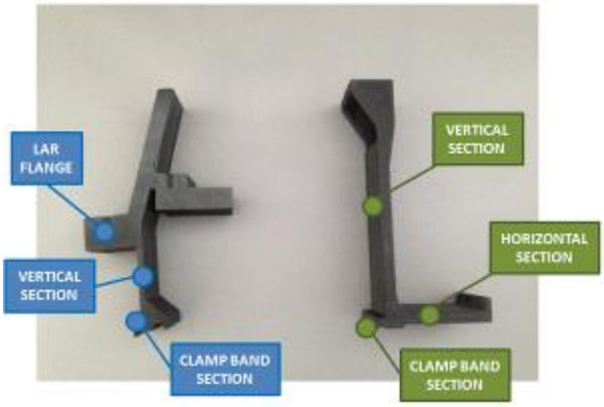

Figure 4: Profiles of LAR model No1 (left) and Envisat LAR model (right)

4. DESIGN

4.1. Overview

Two grippers models have been designed and manufactured. Each is dedicated to capture a particular LAR model. The maturity of both capture tools is Technology Readiness Level (TRL) 4. The corresponding LAR's unique cross section shapes require completely different capturing approaches to optimize performance and functionality, therefore the proposed designs notably vary.

4.2. Gripper B/B No. 1

The gripper dedicated to the first LAR due to its inconvenient shape regarding capture consists of two independent modules: Fast Gripping Module (FGM) and Strong Gripping Module (SGM). The first's role is to quickly enclose the target object under high misalignments and position it in a proper spot. The second module provides a rigid grasp to transfer required loads.
FGM resembles anthropomorphic architecture with three "fingers" – two external and one internal (opposable), driven by a linear actuator, but resulting in a compound motion of the end-effectors due to several links in the mechanism. Both external fingers are identical. They provide contact with LAR on three

surfaces (one on the vertical flange surface and two on both horizontal rib surfaces. The opposable finger interfaces with two internal vertical surfaces. The drive system consists of a DC motor with a lead screw as well as a differential gear and two additional lead screws for each external finger. Such mechanism enables them to adapt to LAR position separately and therefore increase the capture envelope.

SGM is composed of two almost identical jaws, with different shapes of end-effectors due to LAR cross section asymmetry and cylindrical surfaces for vertical contact to distribute clamping loads evenly along entire contact surface. SGM is driven by a linear actuator (DC motor + drive screw) with a gearbox of high gear ratio, to provide sufficient preload and self-locking. Analogically to FGM, the mechanism's links transform a linear motion into a compound movement to accommodate LAR.

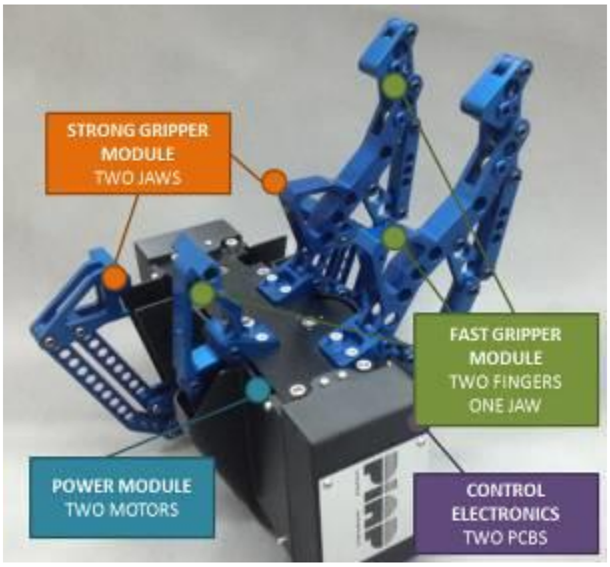

Figure 5: Breadboard Model of the LAR Gripper No1

4.3. Gripper B/B No. 2

The second gripper is dedicated to capture Envisat's PAS 2624 VS adapter model. Unlike the first gripper, it uses a single module that performs capturing, handling misalignments and transferring high loads between chaser and target satellite.

The gripper uses the same drive module, control electronics and control software as the first model, however, its construction has been entirely re-designed to accommodate the particular adapter. It consists of two identical, symmetrically located grasping mechanisms, each comprising an external L-shaped jaw and an internal hook-shaped jaw. When the target object is within capture envelope, the external jaws start being pulled while the internal hook-shaped jaws are being pushed onto LAR. The external jaws interface the target object on vertical cylindrical and horizontal bottom surface. The internal jaws contact LAR with dedicated rollers on jaw tips, which firstly contact the horizontal upper surface and then the inner cylindrical. The module is driven by a single DC motor with an integrated reduction gear, however, each mechanism adapts to LAR separately due to a differential gear between them. A lead screw on each pair is used to transform rotary motion from the differential gear outputs into linear. The L-shape jaws' movement is guided by dedicated rails. The hook-shaped jaws are linked with the drive system by several elements, hence their motion is compound. The movement is not rigid - springs are used to force the inner jaws to contact LAR horizontal surface before being pushed onto vertical cylindrical surface, what improves performance.

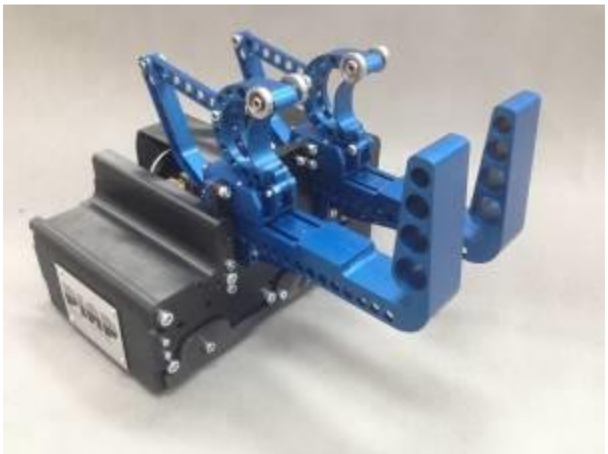

Figure 6: Breadboard Model of the LAR Gripper No2

4.4. Vision system

A series of processing algorithms are applied on the raw images acquired from the camera (Figure 7).

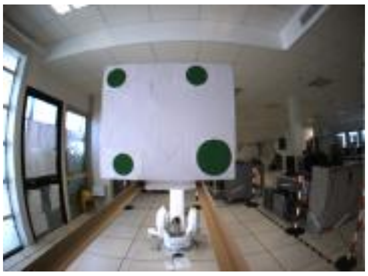

Figure 7: Raw image acquired by the camera

First, pre-processing algorithms are used to correct the raw image: correction of distortion, low-pass filtering, histogram adjustment and thresholding. Then the dots must be detected and measured. Homographic filter and contour detection algorithms are implemented and the resulting image is shown in Figure 8. The circular shapes are then extracted, and their centroids are measured. Finally, a P4P algorithm [10] is applied to measure the relative position and attitude.

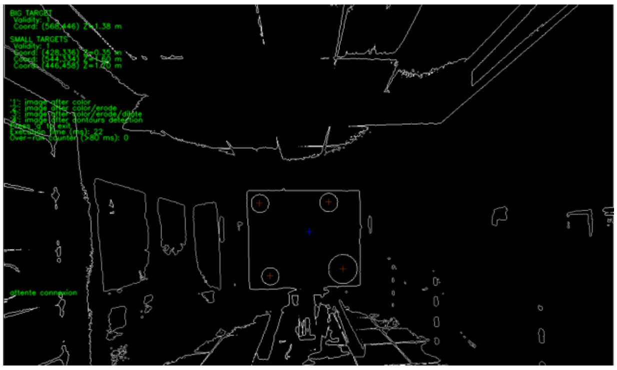

Figure 8: Image resulting from a series of processing

4.5. Control algorithm

To be able to communicate with the gripper, Thales Alenia Space developed a communication interface software dedicated to its test bench needs.
The approach trajectory and the final gripping is commanded by the control software thanks to the pose measured by the vision system.
An estimation filter has also been implemented to improve the closed loop control accuracy. It includes a feedforward action based on the target periodic motion which parameters are estimated inline.
Finally, the gripper closure is commanded when the control algorithm converged to the required accuracy.

5. OPERATION

5.1. Approach

Based on its background on previous rendezvous studies [11], Thales Alenia Space implemented an approach scenario made of three main phases:

- First approach from a 1m range up to 20cm
- Final approach until the LAR is between the gripper jaws
- LAR capture

In each phase, the target is tracked by the vision system and the control maintains the relative attitude and lateral position. At the end of the approach phases, the software is waiting for the control convergence before trigging the next phase.

5.2. Soft capture

When the LAR is detected in the capture envelope, gripper is commanded to closure. Fingers start to enclose LAR profile first, to ensure that the target will not escape as a result of contact forces. After enclosing first contact between LAR and finger tips is made automatically. Gripper is handling static and dynamic misalignments of the LAR using multiple contact points to set up itself in configuration in reference to the LAR, where all internal surfaces of the fingers have contact with LAR at the end of the operation. Gripping force in this phase must be enough high to overcome moment load coming from the robotic arm.

5.3. Rigidization

Rigidization phase starts automatically. The result is rigid connection between robotic arm and a target that allow to transfer different loads for chaser manoeuvrings, de-tumbling and changing target orbit, what also includes deorbitation.

FGM in the gripper B/B No 1 has high abilities to handle misalignments, however due to the anthropomorphic design is not able to transfer loads that would allow any robotic arm re-orientation. For rigidization additional “strong gripper” is use, that shapely jam on the particular part of the LAR.

For the gripper B/B No 2 both phases are performed by the same gripper.

6. VALIDATION

6.1. Open loop tests

Rendezvous test bench overview

Test campaign was made in ESA-ESTEC ORBIT facility, able to emulates microgravity on the ground. Facility consists 5x9m high flat floor with support equipment: VICON motion tracking cameras for position tracking objects located on the floor and three air bearing platforms: ROOTLESS – able for continuous working, payload capacity up to 15kg, MANTIS – able to work up to the 20 min (depending from the weight of the payload), payload capacity up to 75kg., ACROBAT - payload capacity up to 250kg.

During the tests ROOTLESS platform was used (to carry the gripper, battery, control station and mechanical interface) and MANTIS (LAR mock-up and mechanical interface). VICON cameras were used for gripper and LAR tracking, video cameras were installed on the structure outside of the floor to record the tests.

Test Scenarios

The goal of the tests was to validate grippers abilities to capture LAR under different misalignments. Three type of the static tests have been run: angular misalignment in one selected axis, linear misalignment in one selected axis, mixed angular and linear in multiple axis.

Results

Tests allowed to confirm capture envelopes of the grippers. They also underline the importance of suitable high gripping force during the soft phase – for some high multiple angular misalignments gripper No 1 didn’t have enough force to rotate the LAR and set it up to nominal position.

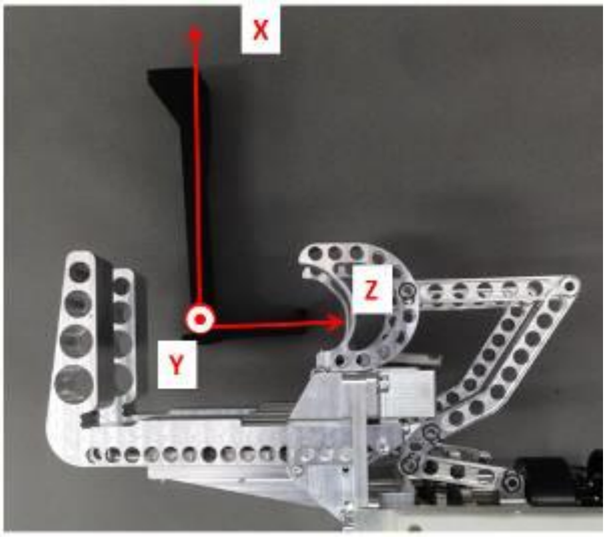

Figure 9. Coordination system for the misalignments definition

	Static misalignments:		
Capture envelope Gripper No 1:	X [mm]	+45,0	10,0
	Y [mm]	+60,0	-50,0
	Z [mm]	+25,0	-25,0
	α [deg]	+12,0	-9,0
	β [deg]	+10,0	-10,0
	γ [deg]	+2,0	-5,0
	Static misalignments:		
Capture envelope Gripper No 2:	X [mm]	+20,0	-20,0
	Y [mm]	+70,0	-70,0
	Z [mm]	+10,0	-10,0
	α [deg]	+10,0	-10,0
	β [deg]	+5,0	-20,0
	γ [deg]	+30,0	-30,0

Table 1: Verified static misalignments

6.2. Hardware In the Loop tests

Rendezvous test bench overview

The test bench used for this experiment is illustrated in Figure 10. Two industrial robots IRB 2400/16 made by ABB are used to reproduce the behaviour of the target from one side, and of the chaser on the other side. This latter is mounted on a base moving on a ten-meter rail, allowing to reproduce the close range approach.

The camera and the gripper have been mounted on the chaser robot with a custom-made mechanical interface support. On the target robot side, the LAR model interface has been fixed with magnets at the end of cardboard rods. Also, four webcams have been placed around the room or on the robots to save a video. Finally, the robotic test bench has been optically calibrated prior to the test campaign.


Figure 10: Thales Alenia Space rendezvous test bench facility

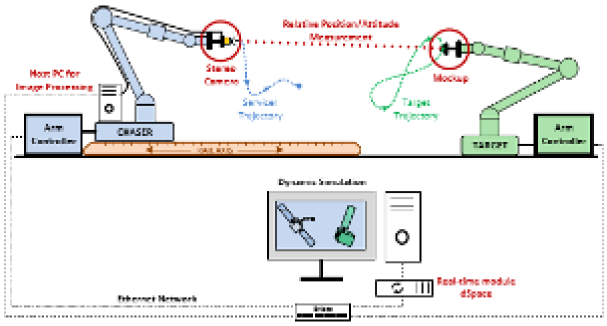

Figure 11: Thales Alenia Space robotic test bench setup to simulate the on-orbit kinematics of a capture

Test Scenarios

Rendezvous tests have been performed on the Thales Alenia Space robotic test bench in order to demonstrate the gripper controllability in real-time environment, its tolerance to dynamic conditions, and the capability to capture the LAR in closed-loop conditions using a camera.
Three closed-loop test have been run on the rendezvous test bench: with a fixed target position and attitude, with a circular translation motion, and with a periodic position/attitude motion of the target.

Results

The main criteria for the test case evaluation are the successful completion of the grip in a simulated dynamic scenario and the compliance to the accuracy requirement. From this point of view, the closed-loop tests have been successful.
As expected, the accuracy is lower with the addition of the attitude motion, since it significantly increases the amplitude of the chaser movement to track the target. Figure 12 and Table 2 illustrate the accuracy of this driving test case.

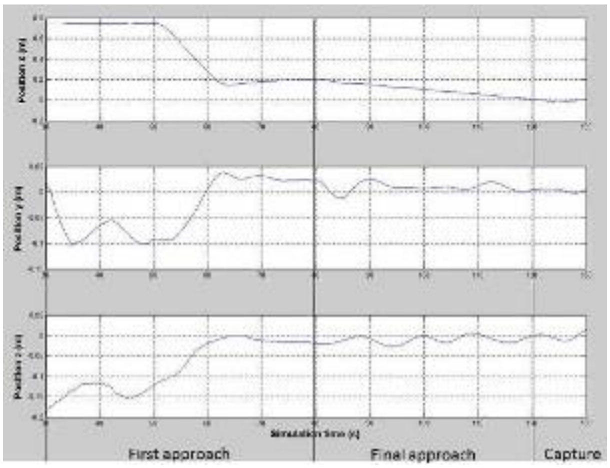

Figure 12: Gripper position in rod frame

Pointing accuracy (cm)	X	0.8
	Y	2.7
	Z	2.6
Attitude accuracy (cm)	X	0.05
	Y	0.80
	Z	0.78

Table 2. Closed-loop final accuracy.

7. ACHIEVED CAPABILITIES

Capture time	Fast Gripper Module: 2,8 seconds Strong Gripper Modules: 20,2 seconds		
Load capability	Mx: 75Nm My: 55Nm Mz: 200 Nm		
Capture envelope / misalignments	Static		
	X [mm] Y [mm] Z [mm] α [deg] β [deg] γ [deg]	+45,0 +60,0 +25,0 +12,0 +10,0 +2,0	10,0 -50,0 -25,0 -9,0 -10,0 -5,0
Dimensions	Gripper wide open		
	X axis: 350mm	Y axis: 280mm	Z axis: 244mm
	Gripper closed		
	X axis: 330mm	Y axis: 280mm	Z axis: 190mm
Mass	3,2 kg		

Table 3. Gripper No1 capabilities.

Capture time	5 s		
Load capability	Mx: 35 Nm My: 200 Nm Mz: 35 Nm		
Capture envelope / misalignments	Static		
	X [mm] Y [mm] Z [mm] α [deg] β [deg] γ [deg]	+20,0 +70,0 +10,0 +10,0 +5,0 +30,0	-20,0 -70,0 -10,0 -10,0 -20,0 -30,0
Dimensions	Gripper wide open		
	X axis: 200mm	Y axis: 190mm	Z axis: 340mm
	Gripper closed		
	X axis: 200mm	Y axis: 190mm	Z axis: 330mm
Mass	2,9 kg		

Table 4. Gripper No2 capabilities

8. CONCLUSIONS

The main goal of this part of LAR grippers development - abilities to capture LARs under static misalignments and to transfer loads were proven. To increase this performance, under next iteration of design gripper's fingers shall be open the widest as it possible during beginning of capturing. Also, width of fingers in open configuration is the main factor determining capture envelope.

The rendezvous tests on Thales Alenia Space test bench allowed to make a first test in laboratory conditions of a satellite collecting a debris with a gripper. The tests were successful, with a reasonable accuracy compliant to the requirement, and ways of improvements.

9. FURTHER DEVELOPMENT

9.1. Grippers

Particular improvements of the gripper design are on-going. Jaws shape is re-designing to reach larger capture envelope. Different motor drive is implementing to allow transfer higher loads. Interface will be adapted to integrate gripper with space dedicated robotic arms. Particular sensors will be added: positioning sensors for jaws position monitoring, contact sensors to detect LAR successfully capturing, torque sensor for loads monitoring, vision system for LAR position identification inside capture envelope. Light source to illuminate LAR will be added. Fully autonomous operations will be tested.

9.2. Rendezvous test bench

Several improvements of the Thales Alenia Space test bench are in progress or foreseen in a next future. First, the room is going to be covered to reproduce a dark background, closer to the space environment. A spot will simulate the sun light coming from only one direction, with limited diffuse reflection on the walls.
Also, more realistic satellite mock-ups are used to represent the target spacecraft, in order to test more advanced image processing algorithms.
The bench will also implement force and torque sensors in the frame of I3DS H2020 study [10].

9.3. Vision system & control algorithm

Thales Alenia Space is testing other types of sensors, either upon internal funding or in the frame of ESA and European Union studies ([10], [11]), especially time-of-flight cameras, LIDAR and infrared cameras.

Besides, Thales Alenia Space is working on more complex algorithms to estimate the relative pose of a target satellite, feature detection and tracking and also limb fitting algorithms for interplanetary navigation. Our objective is to implement the developed algorithms on the dynamic environment of the test bench, with different sensors and target mock-ups.

10. REFERENCES

1. Robin Biesbroek et al. (2012), The e.Deorbit study in the Concurrent Design Facility, Clean Space Industry Days, Workshop on Active Space Debris Removal, ESOC, Darmstadt, Germany.

2. John Ratti (2014) Spacecraft Robotic Capture Tool, e.Deorbit Symposium.

3. Marc Scheper (2016), OHB Gripper Design and Grapple Simulations, Clean Space Industrial Days

4. Marc Scheper (2016), OHB e.Deorbit Phase B1 Overview of Mission and GNC Equipment, ESA Webinar GNC.

5. Stéphane Estable (2016), ADS e.Deorbit Phase B1 Overview of Mission and GNC Equipment, ESA Webinar GNC.

6. W. Fehse (2008), Automated RendezVous and Docking of Spacecraft. Cambridge Aerospace Series.

7. F. Ankersen (2011), Guidance, Navigation, Control and Relative Dynamics for Spacecraft Proximity Maneuvers, PhD thesis, Aalborg University.

8. V. Dubanchet (2017), Modeling and Control of a Flexible Space Robot to Capture a Tumbling Debris, PhD thesis, Université de Toulouse

9. V. Dubanchet et al. (2017), Closed-Loop Validation of a Free-Floating Guidance Scheme for a Space Robot, GNC 2017: 10th International ESA Conference on Guidance, Navigation & Control Systems (to be published).

10. R. Horaud et al. (1989), An analytic solution for the perspective 4-point problem, Computer vision, graphics, and image processing.

11. ESA (2010), Integrated GNC Solution for Autonomous Mars Rendezvous and Capture, SRE-PAP/MREP/GNCRVC-SOW

12. European Union (2016), COMPET-4-2016: SRC - Space Robotics Technologies – H2020 Integrated 3D Sensor.

13. ESA (2011) , RDV and Docking 3D Camera Technology Trade-off and BreadBoard Demonstration, ESTEC AO 1-6975/11/NL/MH

14. P. Roberts, J. White, S. Fisher, R. Rembala, “Spacecraft Capture Mechanism” U.S. Patent: US 2013/0249229 A1, issued date Sep 26, 2013.

11. ACKNOWLEDGEMENTS

LAR Grippers development and validations was made during “Active debris removal demonstration in laboratory condition experiment (ADRexp)” project, founded under 2nd Call For Outline Proposals Under The Polish Industry Incentive Scheme.