BREADBOARD TESTING ACTIVITIES OF THE ARM AND GRIPPER SUBSYSTEM FOR MARS SAMPLE RETRIEVAL

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ABSTRACT

The Mars Sample Return mission aims at collecting samples from Martian soil and bringing them back to Earth for the first time.

In the frame of this mission, the Sample Fetch Rover will collect the sample tubes by means of the AGS (Arm and Gripper Subsystem). Critical units for the development of the AGS have been identified in the Gripper – the mechanism that physically picks the RSTAs up from the Martian surface – and the RSTA Re-Grip Bracket, which holds the RSTA while the Gripper is repositioned in order to re-acquire the RSTA in preparation to the insertion in the storage assembly.

For these two mechanisms, a Breadboard has been designed, manufactured and tested both stand-alone and installed on a representative robotic arm. In this paper, the main outcomes and lessons learned of the breadboarding activity are reported and discussed.

1. INTRODUCTION

The Mars Sample Return mission aims at collecting samples from Martian soil and bringing them back to Earth for the first time. The campaign, led by NASA and the European Space Agency, is made up of three phases.

The first one started with the launch of NASA's Mars 2020 Perseverance rover. Its objective is to explore the surface of the red planet, select and collect rocks and dust in sample tubes, some of which will be retained on Perseverance for direct delivery to a future lander and the rest will be laid down on the Martian surface in order to be retrieved by a subsequent mission.

In the second phase, NASA will deliver on the Martian surface the Mars Ascent Vehicle and the ESA-provided Sample Fetch Rover. The Sample Fetch Rover will collect the sample tubes (called RSTA, Returnable Sample Tube Assembly) left by Perseverance. The Sample Transfer Arm, mounted on the surface platform, will then transfer the samples from both rovers to an Orbiting Sample container, which will be launched in orbit by the Sample Retrieval Lander through the Mars Ascent Vehicle. The container will be captured by the Earth Return Orbiter, launched in the third phase and composed by an ESA spacecraft and the NASA-supplied and operated Capture/Containment and Return System. The Earth Return Orbiter is expected to come back to Earth with the Martian samples in 2031.

The Sample Fetch Rover is developed by a European industrial consortium led by Airbus Defence and Space UK. Once deployed to the surface, the rover will traverse on the Martian surface. The Arm and Gripper Subsystem (AGS) will collect the sample tubes and store them onto the RSTA Storage assembly on board the Rover. The Rover will then return to the lander.

Leonardo S.p.A. is in charge of the development of the AGS, which is composed by:

- Robotic Arm: includes six revolute joints and structural elements;
- Gripper: is the end-effector which can grasp and hold the RSTA in the two grips (body and head);
- RSTA Re-grip Bracket (RRB): holds the RSTA while the grip is changed from the body grip to the head grip;
- 2 Hold Down Release Mechanisms (HDRMs): fix the AGS during launch and provide a safe accommodation to the AGS during SFR traverse;

- RSTA Detection Camera (RDC): is mounted on the arm and provides images of the RSTA, just before pick-up, to the Visual Based Detection System (VBDS), which can provide a more precise estimation of the RSTA location and orientation relative to the arm, in order to update the arm pose before pick-up.

In 2021, in the frame of Advance B2 phase, a comprehensive breadboarding activity was performed. The activity included design, manufacturing and testing of two of the most critical items of the AGS: Gripper and RRB. Added Value Solutions (AVS) was selected to design and manufacture the Gripper for the project and performed the breadboarding activity for this item as well. The development of the RRB breadboard was carried out directly by Leonardo.

This paper presents the activities performed in the breadboarding phase including the design of the gripper and RRB, the test setup, the results and the main lessons learned.

The testing comprised a first phase where the Gripper and the RRB were tested with the aid of dedicated Mechanical Ground Support Equipments (MGSEs), the purpose of which was to establish the performance in "controlled" conditions.

After this phase, they both were integrated and tested with the aid of the DELIAN robotic arm, which was developed by Leonardo in the frame of the relevant ESA R&D activity [1]. This robotic arm has some very interesting similarities with the anticipated SFR robotic arm, such as:

- Six degrees of freedom;
- Similar kinematic configuration and limb length;
- Similar rotary joint architecture, including a brushed motor equipped with relative encoder, planetary gearbox and Harmonic Drive at the output;
- Similar stiffness of limbs and joints.

The differences between the DELIAN and SFR arm were analysed in the frame of the scope of the testing, in order to confirm they did not have significant impacts on the performed tests. In particular, the main difference at architecture level is the use of incremental encoder as joint output sensors in DELIAN, in place of the resolvers foreseen in SFR arm. This turned out to be a worst case for the operations, as it is explained in the next sections.

Remarkably, the testing phase including DELIAN, which was used as a sort of test equipment and was not an item under test, turned out to be very informative on the Gripper and RRB.

2. GRIPPER BB DESIGN AND TESTING

2.1. REQUIREMENTS AND DESIGN

The Gripper is a 2-jaw 1-DoF robotic system which shall capture the RSTA and release it into the storage system on board the Sample Fetch Rover.

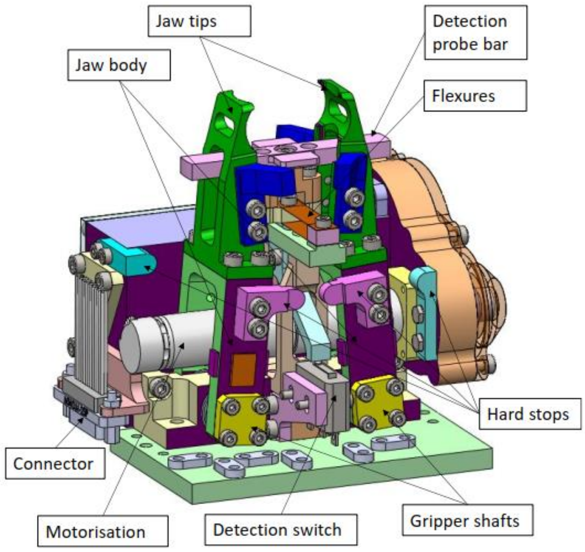

Figure 1. Gripper overview (courtesy of AVS)

Notably, the Gripper key and most challenging requirements concern the interaction with the RSTA, especially the ability to successfully acquire it even when subject to the positioning errors, which are due to both the accuracy of the target position with respect to the RSTA position, which depends on the vision system performance, and the accuracy of the robotic arm itself, which depends on the sensor accuracy and the control performance. To evaluate the performance, a suitable MGSE was designed and built in order to enable the placement of the Gripper with controlled misalignments, both linear and angular. In order to detect when the Gripper is in the correct position to close the jaws, a switch connected to a "detection probe bar" is triggered by the contact with the RSTA during the downward approach motion; when the switch is triggered, the arm motion is commanded to stop.

Moreover, the Gripper shall maintain the grip of the RSTA when the sample tube is subject to an external force. This is necessary during the insertion and extraction of the RSTA to and from the RRB, in order to ensure a correct re-grip. The maximum force allowed to be exerted on the RSTA is limited; to ensure that the limit is not exceeded, two strain gauges are mounted on the jaws.

The Gripper BB also includes a Force Torque Sensor mounted between itself and the Robotic Arm, in order to get more informative results from the tests.

The Gripper shall be compatible with those requirements in both areas of the RSTA allowed for grip, namely the "body grip" area and the "head grip" area. The former is used during pick-up from the Martian soil, the latter is used for the insertion in the storage assembly.

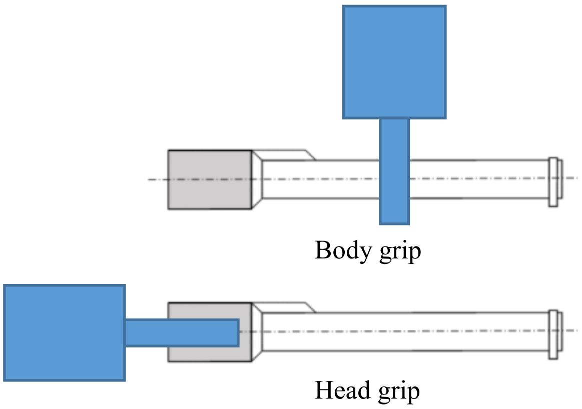

Figure 2. Definition of Body and Head grip of the RSTA.

Volume and mass are also critical because the Gripper is mounted on a Robotic arm. In particular, a too high volume can reduce the dexterity of the arm and make more difficult to reach all the locations without colliding with the surrounding units. The volume requirement drove the design of the transmission chain, where the motor is mounted transversally with respect to the Gripper axis and the motion is transmitted using a series of worm screw and spur gear, which drive the two jaws that grasp the RSTA.

2.2. TEST PLAN

The first phase included testing at Gripper level, performed by AVS. The testing included several aspects which are critical to a successful sample collection.

The tested requirements included:

- Maintain grip: the Gripper shall be able to hold the RSTA when subjected to an external force, in case of both absence and presence of dust. In the nominal operation, the external force arises during the insertion and extraction in/from the RRB. Therefore, respecting this requirement is fundamental to ensure a correct re-grip.
- Operation simulation: it was verified that the Gripper can successfully acquire the RSTA even in case of misalignments, both linear and angular, that in the real case are originated from the inaccuracy of the system arm plus the RDC. This was tested both in body grip and in head grip. This performance can determine the success of the RSTA grasping from the Martian soil (body grip) or from the RRB (head grip).
- Terrain cases: the capture has been verified also in 19 terrain geometric scenarios proposed by JPL, and designed as test cases to ensure and verify that the capture capabilities of the integrated system is not limited by the kinematics and geometry of the Gripper. Compliance to these scenarios was verified without introducing misalignments.
- Residual error: the purpose was to measure the linear and angular misalignment of the RSTA within the Gripper after capture. This is critical to allow a good insertion in the RRB and in RSA.
- Non-nominal conditions: the Gripper test campaign verified also some required non-nominal functions, such as RSTA capture through Radial head grip, capture of the RSTA with a pebble in the proximity, and sudden loss of power.
- A dedicated test campaign regarding dust has been performed in order to find out if the baseline solution for sealing is adequate. In these tests, Mars dust simulant and additional Gripper test pieces purposely built to replicate the parts most sensitive to dust were used.

3. RRB BB TESTING

3.1. REQUIREMENTS AND DESIGN

The RSTA Re-grip Bracket (RRB) shall hold the RSTA while the Gripper is repositioned to switch from body grip capture to axial head grip capture. The RRB BB has been designed as a fully passive item with compliant devices that can compensate the arm positioning inaccuracy. The insertion is performed in two consecutive motions of the arm, a vertical and a sliding motion, each one terminating when a switch is triggered and the RSTA has reached the correct position.

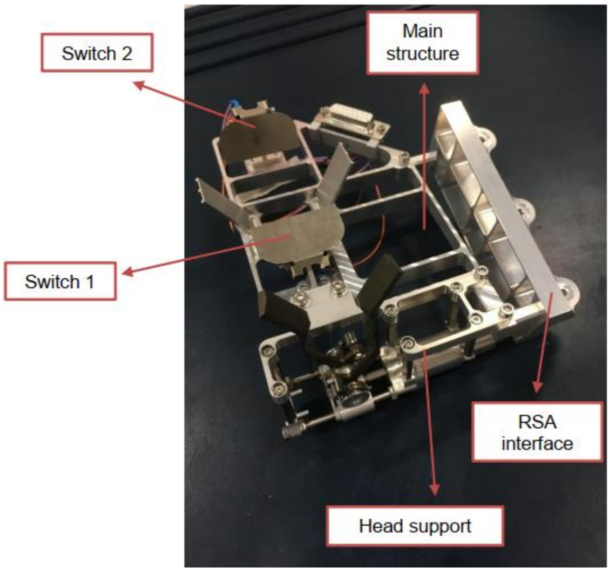

Figure 3. RRB design overview

Main design drivers are:

- The head and body grip interfaces of the RSTA shall be accessible to the gripper in order to enable a correct re-gripping operations;
- The RRB BB shall be able to compensate positioning inaccuracy of the arm while limiting the contact forces on the RSTA, assuming the arm and the gripper are rigid and ensuring, at the same time a solid grip;
- The re-gripping operations shall be successfully performed with any possible body-grips performed by the gripper. Indeed, the gripper could grasp the RSTA in any location inside the body grip area (due to the inaccuracy of the vision system and the robotic arm).

3.2. TEST PLAN

Testing at RRB level were performed by Leonardo. For most of the tests, the Gripper BB was used and was installed on a suitable MGSE, designed specifically for this testing campaign. The MGSE was capable of positioning the Gripper with controlled misalignments w.r.t. the RRB. In such a way, controlled testing conditions to verify the RRB insertion and extraction performances were guaranteed.

The tests included:

- Residual error: the purpose was to measure the linear and angular misalignment of the RSTA after insertion in the RRB. This is critical to allow a good capture of the Gripper by means of the RSTA head grip without using the vision system, but relying on pre-computed trajectories.
- Inadvertent contact with RSTA while captured by RRB: it was verified what is the highest force that can be applied to the RSTA without modifying its position after the force has been removed. This is to verify the “robustness” of the grip in case non-nominal contact on the RSTA
- Insertion and extraction tests: it was verified that the RRB allows the insertion and the extraction of the RSTA without exceeding the maximum allowed forces on the RSTA itself and providing the necessary compliance to compensate for the arm positioning error. The tests were performed with and without dust (i.e. mars simulant poured over the exposed parts of the unit)

4. TEST RESULTS AND LESSON LEARNED

4.1. GRIPPER BB

Thanks to the tests performed, several interesting results were collected.

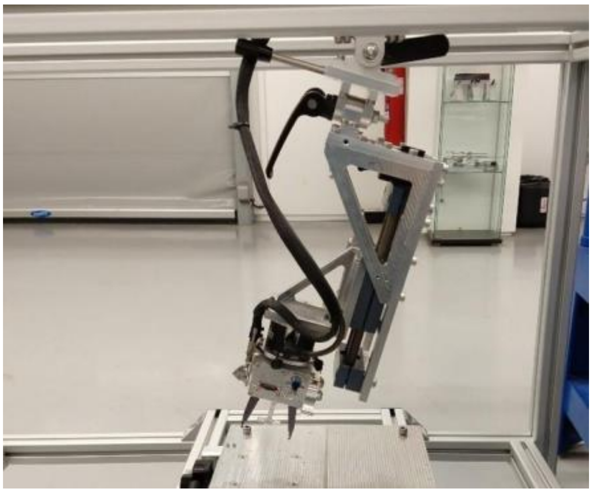

Figure 4. Gripper testing with the MGSE (courtesy of AVS)

- Maintain grip capability has been successfully verified, with only one case of sliding between the RSTA and the jaws. Although this result has been achieved, it has been noted that, initially, the Gripper was not able to apply the expected preload to the RSTA due to a transmission issue. During the breadboarding activity, a mitigation has been implemented to partially fix the problem. Note that possible solutions for the flight model have been already identified.
- Compatibility with terrain cases has been confirmed via test, after the kinematic analysis performed during the design phase. In this regard, the design of the jaws has been changed during the development: the final configuration features longer jaws, in order to be compatible with one of the most critical terrain scenarios.
- Non-nominal capture scenarios have also been successfully tested, especially grasping the RSTA in presence of pebbles or accumulated dust.
- Nominal Capture with maximum misalignments have been performed in this phase with the MGSE positioning the Gripper. The MGSE does not introduce any compliance in the system, unlike the actual system, and thus it is considered a worst case. It turned out that the Gripper was able to cope with a maximum angular misalignment of 12 degrees instead of the initially required 16 degrees. A more updated accuracy budget analysis, including the arm and vision system accuracy, showed that the resulting performance of the Gripper can be considered satisfactory.
- The dust testing campaign has highlighted that the behaviour of the selected static seals and dynamic seals has been satisfactory and ingress of dust has been prevented, and constant tribological

performance has been observed. Regarding the bushing, it has been evaluated that the split-design body is not a viable solution since it can provide a direct path for the dust ingress. Switch performance is considered successful with some minor deviations that will be fixed for the next models.

- Excessive Transmission backlash has been identified. This is mainly due to the usage of COTS parts, limiting the available options, but it is believed that this has not significantly affected the test results. Moreover, for the flight model, the possibility to use the potentiometer for the gripper control instead of the motor-side encoder is currently under investigation. In this latter case, the backlash would be completely compensated.
- Detection bar mechanism is based on a relatively long support mounted on a flexure spline system. During testing, this has proved not fully reliable: sometimes, the bar was stuck and was not triggering the switch at RSTA contact. This item was initially developed for the shorter fingers and then adapted for the longer ones, once selected as baseline during the breadboard campaign. Therefore, it is expected that optimization of the design can be carried out for the flight model in order to solve the issue.

4.2. RRB BB

The main lesson learned thanks to the tests on the RRB BB are listed here below.

- The switches are triggered by a flexible plate which goes into contact with the RSTA. In the BB testing, the plates turned out to be so stiff that they are able to displace the RSTA position from its nominal one. This introduces an uncertainty in the RSTA position, and as such it can make the re-grasping more unreliable, although in the tests the re-grasping was performed successfully. To solve the issue, the plates should be made less stiff , but taking into account dynamic requirements during launch
- The RRB is equipped with two compliance systems, one linear and one rotational. The tests have proved that the rotational compliance system seems less sensitive to dust than the linear system, which can get stuck because of small particles. For the next models, it will be evaluated, as a solution, the possibility to remove this system and only rely on the rotational system, given the fact that this was introduced mainly to limit the forces applied on the RSTA and that such forces have been in almost all cases below the requirement even with the linear mechanism stuck.

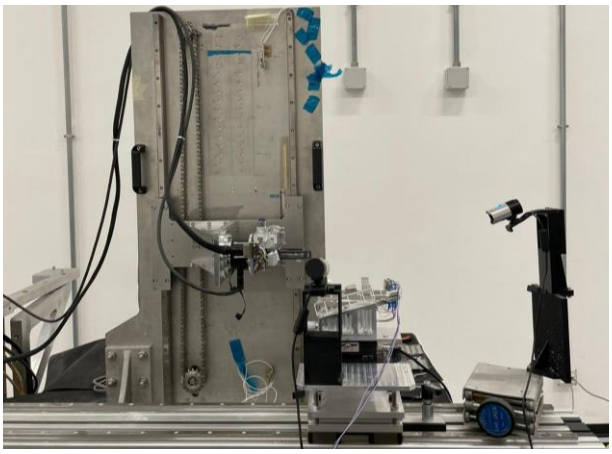

Figure 5. RRB testing with the Gripper installed on the MGSE

4.3. Tests with Gripper Integrated on Delian And RRB BB

In the final testing phase, the Gripper was installed on the DELIAN arm (see Figure 6), and an operation simulation was performed, including the following tasks:

- RSTA grasping by body-grip from a box with Mars simulant
- Transfer the RSTA from the pick-up location to the RRB
- Perform insertion into the RRB by body-grip and open gripper to release the RSTA
- Reposition the Gripper to approach the RSTA by head-grip
- Acquire the RSTA by head-grip and extract it from the RRB

This constitutes the bulk of the AGS fetching cycle, apart from the RSA insertion. The tests were very useful to highlight possible issues related to the design.

Figure 6. Testing of RRB with Gripper installed on the DELIAN arm

The performed tests have highlighted the following points:

- Once the Gripper was lifted after acquiring the RSTA, the preload decreased from 20 N to about 10 N due to the fall of the accumulated dust between the jaws. In this case, it has been verified that the preload can be restored sending a second “closure” command.
- An attempt to grasp the RSTA in the presence of a pebble between one finger of the Gripper and the tube has been performed. Even in this case, a successful grasping was performed, even though the jaws closed asymmetrically due to the mechanical backlash. The presence of the pebble can be detected in telemetry by monitoring the jaws preload and the measured finger position: the preload reached the nominal value, while the jaws position was not the nominal one.
- Ground detection function, based on the Force Torque Sensor, was not fully reliable, probably due to the very small threshold fixed. It is considered that a possible solution is the implementation of an “offset reset” step for the FTS before the pick-up, which was not implemented in the Gripper BB system
- The Gripper is not always able to maintain a stable grip when the extraction from the RRB is performed. This may be improved with a modification in the shape of the detection bar system or a partial modification of the jaws geometry.
- The flexibility of the arm, combined with the non-constant friction generated by the interaction of the RSTA with the RRB, causes discontinuous movements during the insertion. This aspect will be further investigated in the next phases.

Figure 7. Gripper installed on the DELIAN arm

Several lessons learned were captured, both for the interaction of the arm with the RRB and for the Gripper design as well and they will be investigated in the next Development Model based on the breadboard refurbishment.

5. CONCLUSION

An overview of the breadboarding activity performed on the Gripper and RRB has been presented, showing the main results of the testing and the main lesson learned.

Indeed, the goal of the activity has been to validate design choices and, on the other hand, identify as many potential problems as possible in this early phase of the program; to achieve this purpose, several tests were performed in different conditions. The results were encouraging for the most part; in some aspects, it is clear that improvements are possible, especially for the following:

- Design of the Gripper and RRB
- Testing methodology
- Key performance characteristics of the robotic arm

The next activities to be performed for the program are the manufacturing and testing of the Gripper and RRB Development Model (DM), based on refurbished BB items, to allow the progress of the project. In parallel, the preliminary design review cycle will be initiated later this year. The mission will be launched in 2028.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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