Mars Sample Handling End-Effector Breadboarding

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Abstract

A novel End Effector design is presented, developed in the frame of the Mars Sample Return mission preparation. The End Effector is a mechanism that provides manipulation capabilities to the robotic arm onboard the mission lander, and it enables the collection and handling of the sample tubes containing Martian soil specimens, and the ancillary tools onboard the lander. The developed End Effector mechanism operates through the combination of an original passive grasp architecture, and a grasp locking function, which allow for both soft target capture and handling, and high loads application capability. The design and analysis are presented, followed by the integration and test campaign, demonstrating the End Effector performance effectiveness for sample handling, and insertion, extraction and torque application tasks.

Introduction

In the Mars Sample Return mission architecture [1], a Sample Retrieval Lander [2] is equipped with a Sample Transfer Arm (STA), whose primary function is to transfer Martian soil sample tubes, collected by the NASA/JPL Perseverance rover [3] and ESA Sample Fetch Rover from the rovers themselves onto the Mars Ascent Vehicle. The sample tubes collection from Perseverance will be performed either through a dedicated collection tray or directly from the rover bit carousel, according to the latest scenarios.

The STA End Effector (EE) provides the robotic manipulation capabilities to the STA and it is the subject of this paper and of the development and breadboarding activity performed by OHB Italia S.p.A. The activity was conducted by OHB Italia in the frame of the ESA Program STABLE (Sample Transfer Arm Breadboard and Lander Evaluation), with Leonardo S.p.A. as prime contractor of the STA system.

The EE primary function consists in the manipulation of the sample tube containing the collected Martian soil quantity - the Return Sample Tube Assembly (RSTA) - picking it from different locations such as the mission rovers or at different working stations on the lander itself, and handling it through different grip interfaces. This manipulation has to be performed with care, in order not to exceed the force interface limits of the sample tube; nevertheless, the EE is also capable of providing the higher forces required to extract the sample tubes from their storage locations, and insert them at their target location on the orbiting sample canister.

In addition to the sample tube handling, the EE manipulates secondary tools mechanical interfaces, such as a tube collection tray for retrieval from Perseverance, or the lander orbiting sample lid. As reference tool mechanical interface, OHB Italia proposed a custom-designed grapple fixture, which is compatible with the sample tube grip interfaces, but also allows for the application of higher mechanical loads.

The target capture is performed in cooperation with the Sample Transfer Arm, which provides the positioning and the proximity maneuvers to the EE. In this phase, during the target capture sequence, the EE is able to accommodate residual misalignments, simplifying and supporting the overall operation. For this reason, the EE functionality is provided with a soft-capture capability, inherently passive, and a hard-

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capture configuration, which provides the grasp locking after the misalignments are recovered. The passive stability of the capture conditions, also allows for a secure grasp even in the event of a power loss.

Design and Analysis

The EE layout and the sample tube CAD models are displayed in Figure 1. The interaction of the EE with the sample tube can be performed through two different mechanical interfaces: the end-grip, located at the sample tube head, and the body-grip, located at the tube stem. The EE architecture is organized in two sections: the actuator housing, and the gripper mechanism. The housing intergrates the flange for the mechanical interface with the robotic arm, and hosts internally the servomotor assembly, and externally the mechanism control board. On the outer side, the gripper section is made of the target grasp jaws, the mechanical guides to the jaws motion, and the inner mechanical transmission.

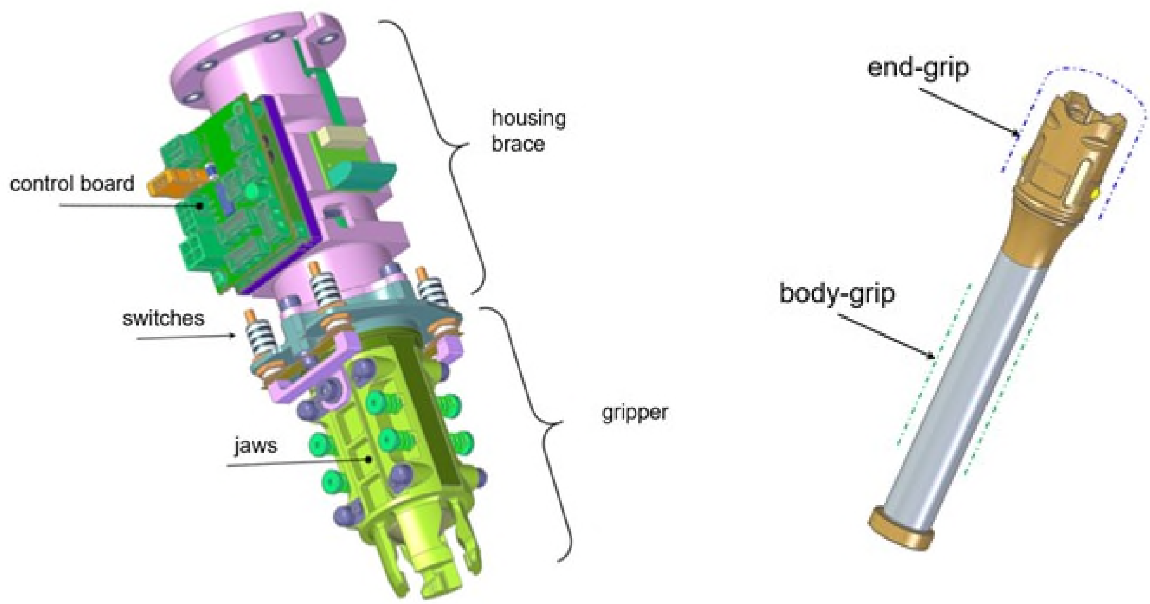

Figure 1. OHB-I End-Effector and JPL RSTA (RSTA model courtesy NASA/JPL-Caltech).

Motor housing.
The EE cross section is displayed in Figure 2. The servomotor actuation and control unit is realized through an aluminum tubular support. The actuator and driver are selected from the Maxon components, and consist of an EC32-flat DC motor, coupled with a GP32 planetary gearhead, 3 stages, controlled through an EPOS4 control board.

The most original setup is embedded in the gripper mechanism section, which core is the cam shaft, providing the opening force actuation to the jaws. A set of 4 microswitches are positioned at the intermediate connection between the two sections, providing the gripper closure signal to the control board. A conical probe element provides the fitting geometry and centering to the sample tube head. The overall envelope of the EE fits in a cylinder of size Ø 70 × 200 mm (0.8 ℓ).

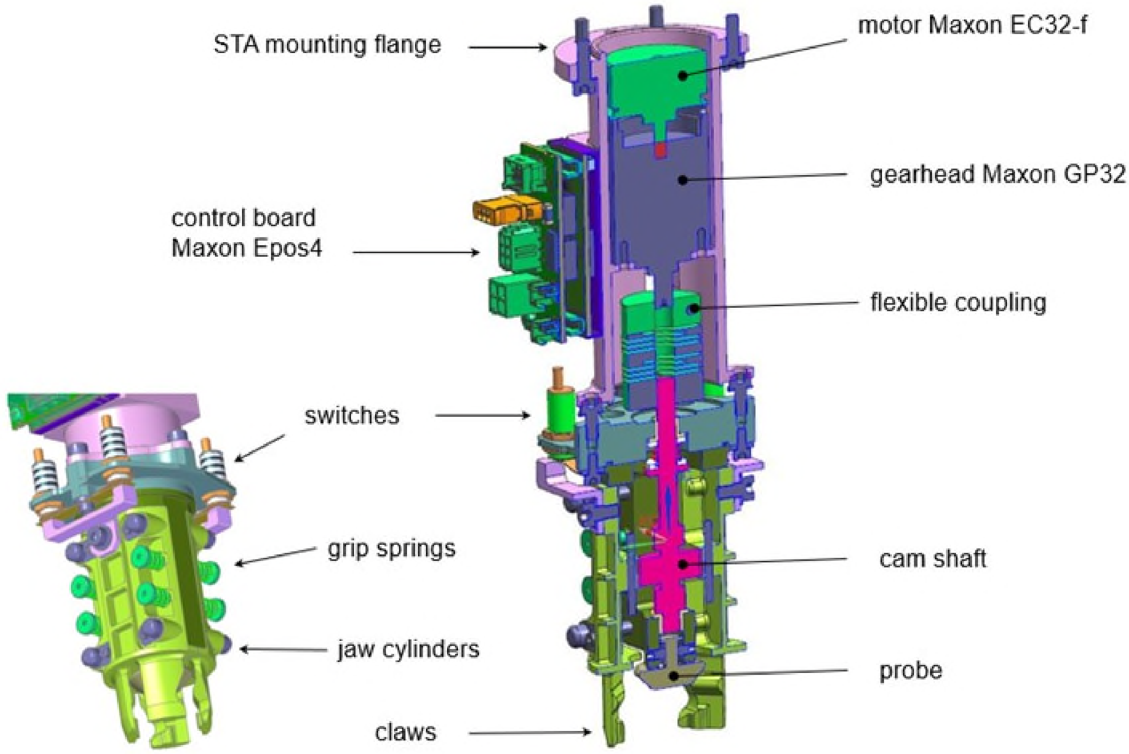

Figure 2. End Effector Cross Section.

Actuation.

The EE actuation and control chain is represented in the block scheme of Figure 3. The control board receives power from the STA electrical interface, commands the motor and receives the motor hall sensors and the microswitches signals. The gearhead reduces the output speed and increases the torque available at the cam shaft.

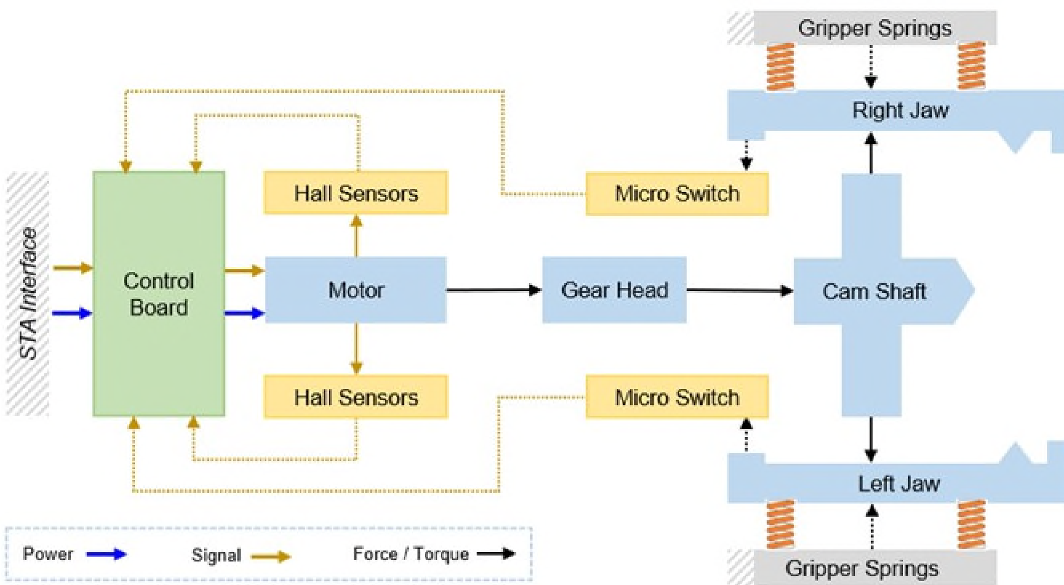

Figure 3. Control, Actuation, and Sensors Chain.

Gripper mechanism.
The gripper mechanism is composed of two grasping stainless steel jaws, which can each displace linearly of 6+6 mm outwards, switching from the closed to the open configuration. The linear displacement is guided by a set of 4 stainless steel pins sliding over PTFE-coated stainless steel bushings (Figure 4).

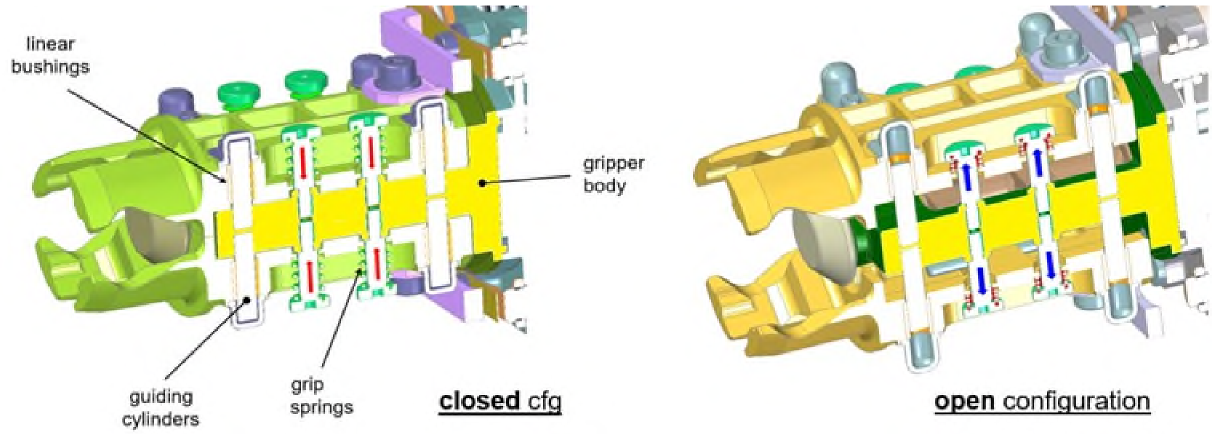

Figure 4. Gripper Springs and Guiding Cylinders.

The jaws are normally closed, thanks to a set of eight helical springs providing the soft compression load between their outer surface and the gripper body part. This load is calibrated in order to provide a contact force below 10 N when manipulating the sample tube. The jaws opening is actuated through a cam profile machined on the cam shaft.

The actuation torque is supplied by the motor gearhead through the interposition of a flexible coupling. The flexible coupling allows for internal misalignments recovery and ensures no undesired bending, normal or shear loads are back transferred to the gearhead.

The stainless steel cam shaft itself is supported in two points through a pair of flanged PTFE-coated stainless steel bushings, and is axially preloaded through a compression wave spring. Diamond-Like Carbon coating is applied to both the cam shaft and the gripper jaws in order to increase the contact hardness for improved cam-contact performance and improved jaws grasping wear resistance.

Laterally to the cam profile, two locking hooks are machined in the cam shaft. The hooks have the function of locking the mechanism at the completion of the grasp.

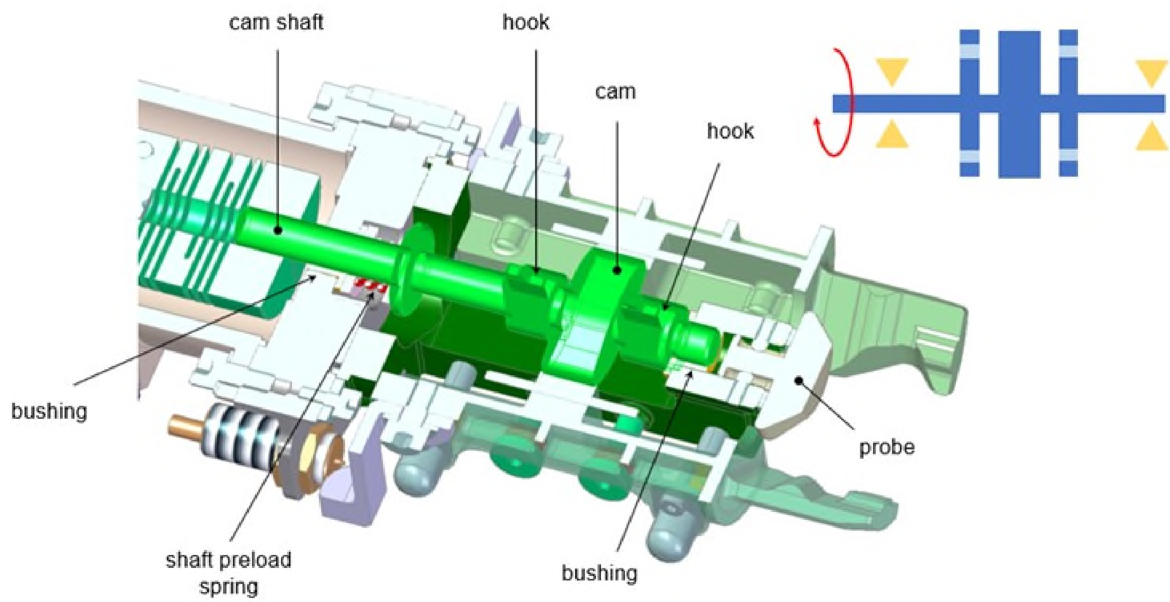

Figure 5. Gripper Cross Section and Cam Shaft Detail.

The jaws opening condition is displayed in Figure 6. The cam profile is rotated up to 90 deg and slides against the flats pushing the jaws internal side; the jaws are then displaced externally sliding along the guiding cylinders, and compressing the gripper retain springs.

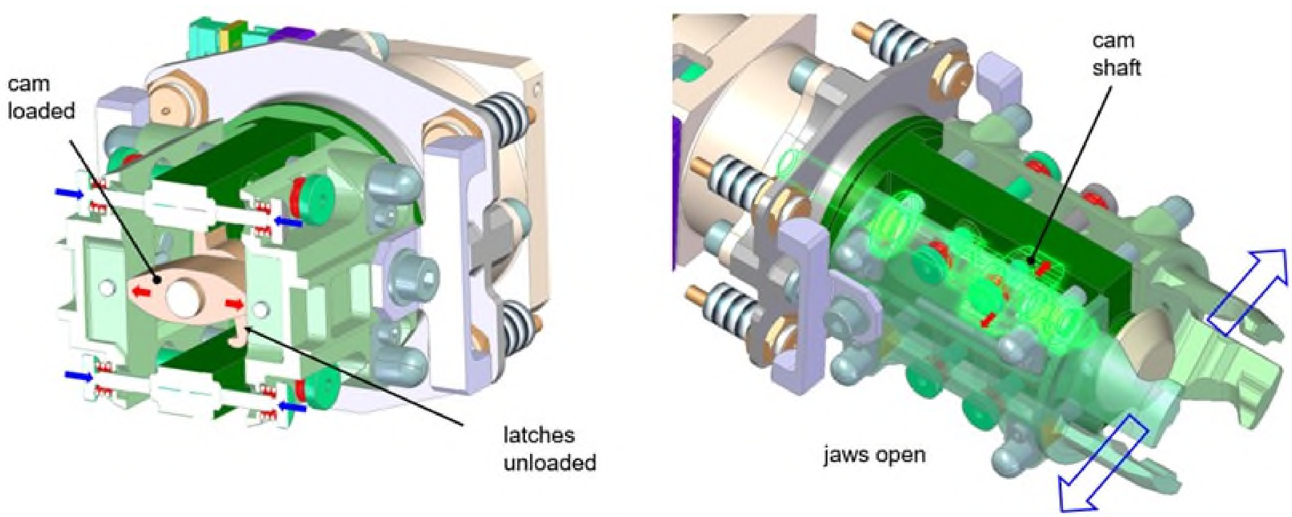

Figure 6. Open Configuration.

In the closure movement (Figure 7), the cam profile is rotated backwards down to 12 deg. At this working angle, the jaws unload the cam profile by reaching their endstops at the gripper body. The grasp closure force is always granted, since it is inherently passive and provided by the gripper springs. Therefore, it does not require electric power and is robust against incidental power losses. The passive closure architecture also allows for the jaws to adapt to the target geometrical constraint, providing roboustness against misalignment and surface uncertainties, such as those due to dust interposition at the grip interfaces. Once the jaws endstop is reached, the microswitches provide the closure signal.

At this moment, the further cam back-rotation can be commanded to the 0 deg homing angle, allowing the engagment of the locking hooks with the two latching stainless steel pins, fixed at the jaws internal side, laterally to the cam flat feature. The engagment of the locking hooks ensures the final secure and rigidized grasp.

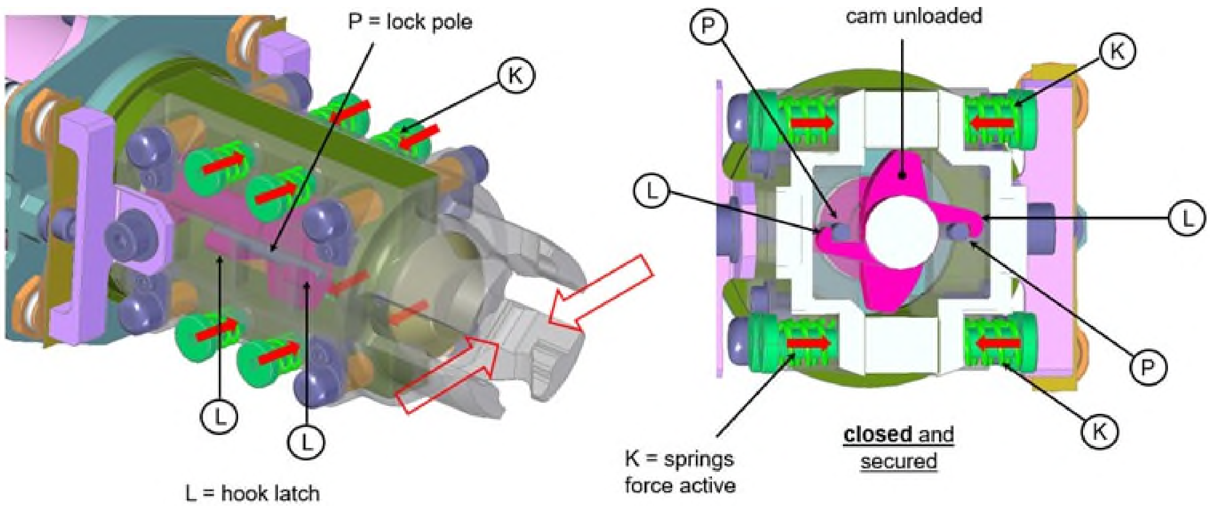

Figure 7. Closed Configuration.

<u>Jaws</u>

The jaws ends are shaped in four claws which comply with the sample tube handling grips (Figure 8). Since both the sample tube body-grip and end-grip present an outer cylindrical shape, the principle of the cylinder-wedge accomodation is implemented, in order to guide the capture of the cylindrical features: a cross-wedge guides the the end-grip capture, while the body-wedge guides the body-grip capture.

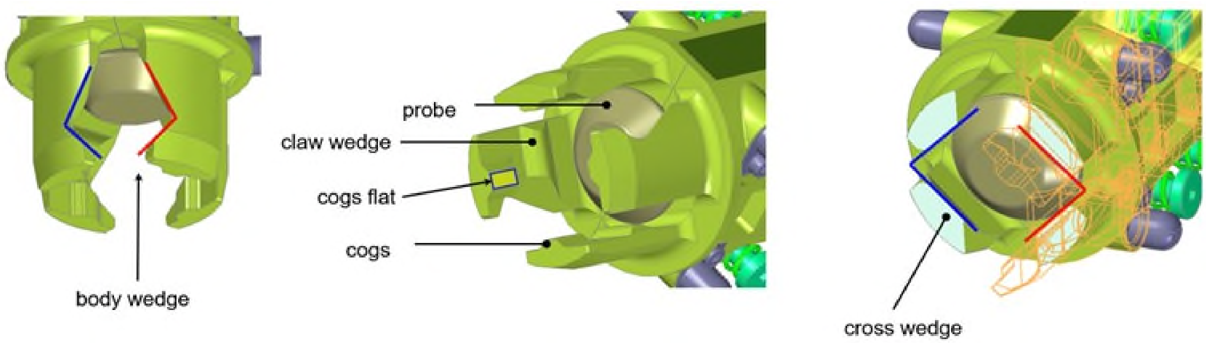

Figure 8. Claws Design.

The sample tube body-grip nominal grasp is displayed in Figure 8. The grasp closes between the jaws body-wedge and the gripper axial probe.

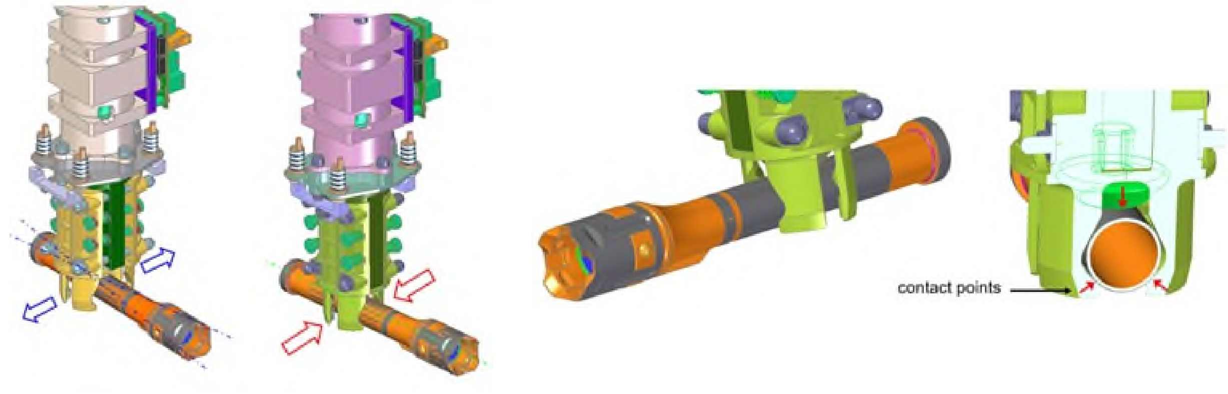

Figure 9. Body-Grip Grasp (RSTA model courtesy NASA/JPL-Caltech).

The grasp of the sample tube body-grip is achieved in subsequent steps (Figure 11). At first the EE is aligned to the sample tube axis through the cross-wedge mating with the tube end-grip cylindrical surface, the axial probe contact provides the alinemnt along the length direction. Only the soft grasp mode is active in these phase, providing the touch of the tube outer surface. Afterwards, the EE is rotated through the arm wrist along the clock direction, until the key protrusions at the claws tips engage with the axial and radial grooves on the sample tube. The engagement is automatic thanks to the action of the gripper soft springs. At this point, the microswitch signals inform of the closure state, and the grasp rigidization can be commanded through the locking hooks engagement.

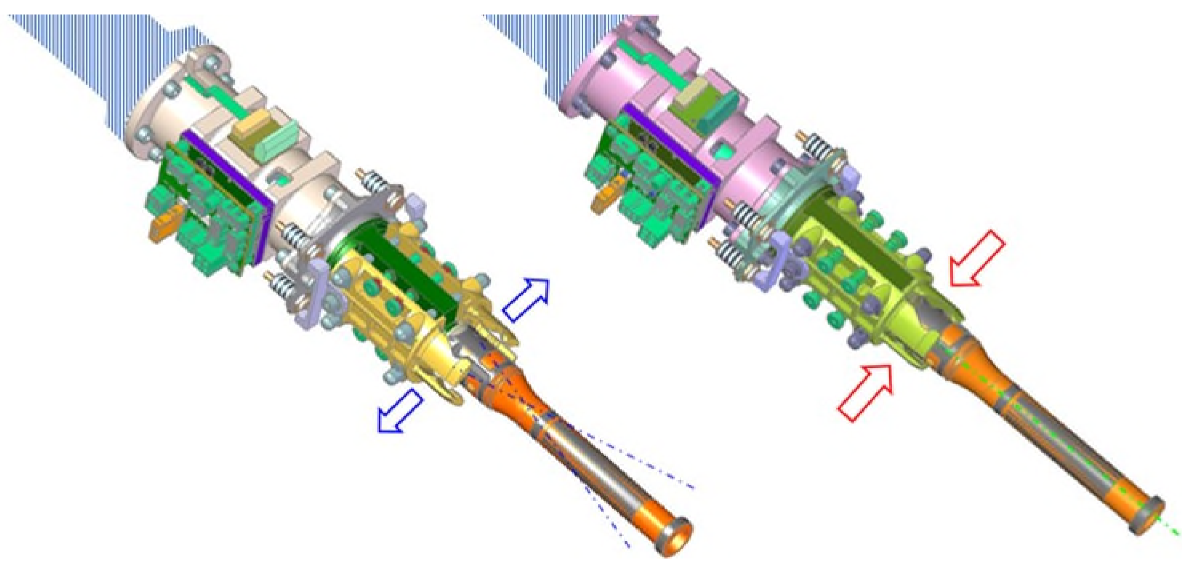

Figure 10. Tilt Alignment (RSTA model courtesy NASA/JPL-Caltech.

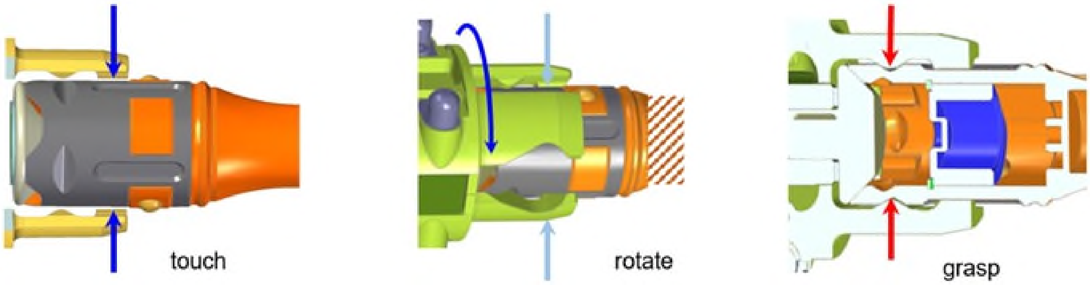

Figure 11. Clock Alignment (RSTA models courtesy NASA/JPL-Caltech)).

Actuation analysis

The actuation torque available at the cam shaft is of 2.3 Nm. This torque guarantees a motorization factor larger than *2* in accordance with the ECSS standards (
Figure *12*).

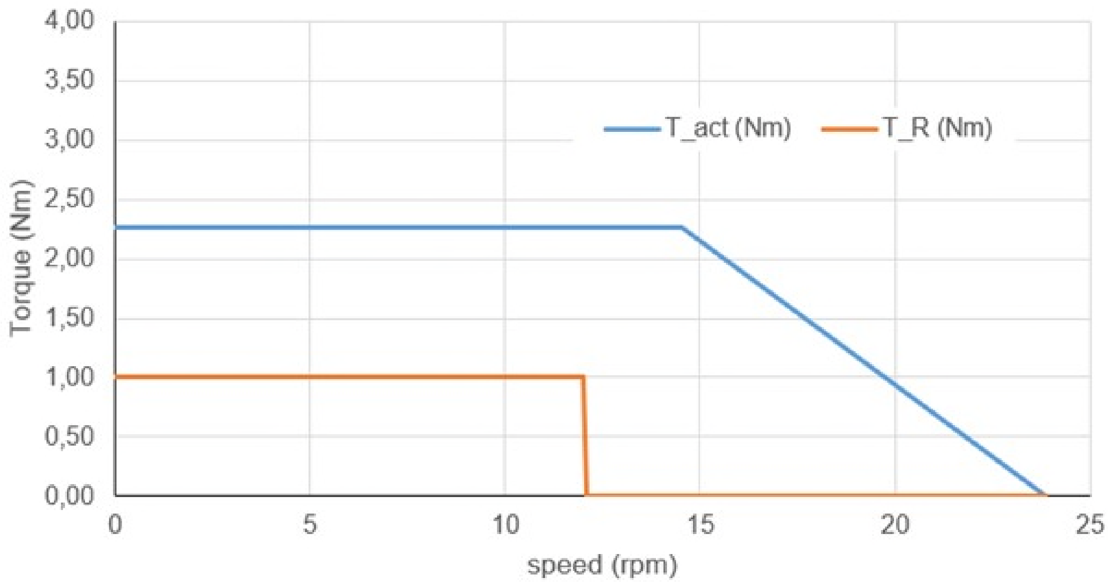

Figure 12. Actuation and Resistant Torques.

Tools Interface

In addition to the sample tube manipulation, the End Effector is capable of handling additional tools which could be adopted in the mission architecture, such as the tube collection tray, and the orbiting sample lid. A design was outlined for the tool interface, named as grapple fixture (Figure 13). The design of the grapple fixture incorporates different grip features for full compatibility with the sample tube grips, and allows for the application of higher mechanical loads. The soft handling is again convenient during the target capture phase, while the full load application can be exerted after grasp rigidization.

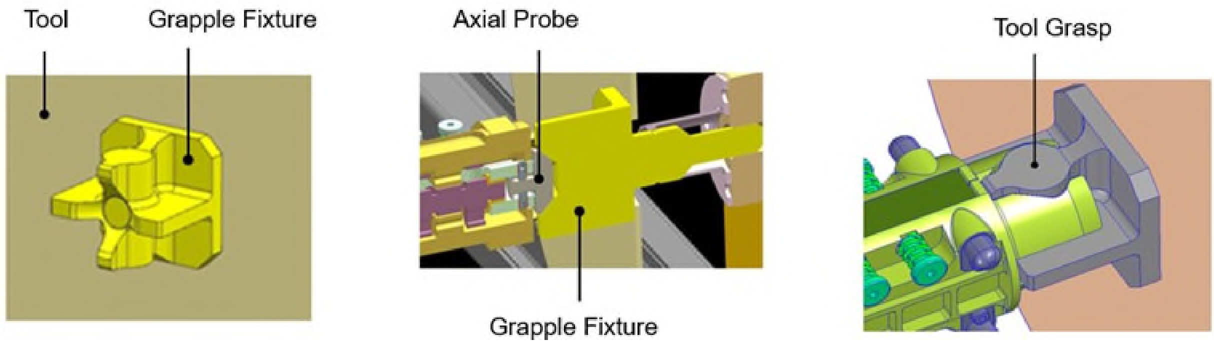

Figure 13. Grapple Fixture Design and Grasp.

It shall be noticed that, once the grasp rigidization is completed, the actuation chain is unloaded, while the load path is absorbed by the EE structural elements.

Integration and Tests

<u>Integration</u>
The integration is carried out in two sub-assemblies. At first the gripper mechanism is integrated, including manual check of the cam operation jaws opening torque measurement through dynamometer read. Then the actuator housing is assembled, including servomotor, microswitches, and control board. Afterwards, the EE is completed by connecting the two blocks (Figure 14). Functional checks are carried out for motor actuation control, and signals acquisition. Motor torque and resistant torque are measured through current acquisition, with confirmation of compliant actuation margins.

The EE overall mass is 1.1 kg, while the peak power absorbed by the motor during the opening maneuver is of 1.40 W. The energy consumption is very low since the torque effort is necessary only for the opening maneuver while the closure and grasp is passively actuated through the gripper springs.

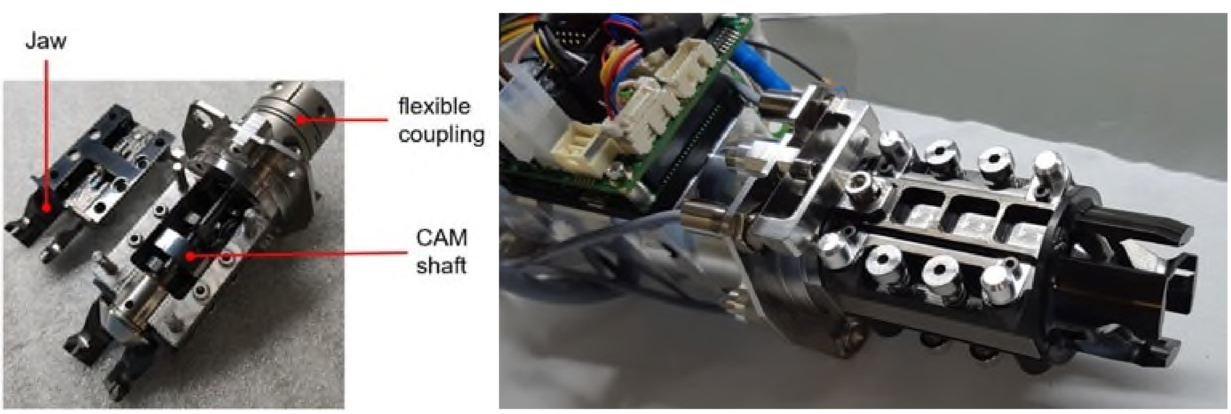

Figure 14. End-Effector at Integration.

<u>Capture tests</u>
Capture tests are performed for the sample tube end-grip and body-grip, and the tools grapple-fixture. The end-grip capture (Figure 15) is carried out considering misalignments up to ±3 mm and ±5 deg. The sample tube dummy is placed in the capture volume of the EE, which grasp soft-closure force aligns the grip to the tube axis. A relative axial displacement allows the axial probe to contact the tube head. Then, a relative

clock rotation is provided until the jaws automatically engage with the tube axial grooves. Microswitch closure signals are detected, and the secure grasp rigidization is commanded to the locking hooks. The correct performance of the end-grip capture and locking operations was verified.

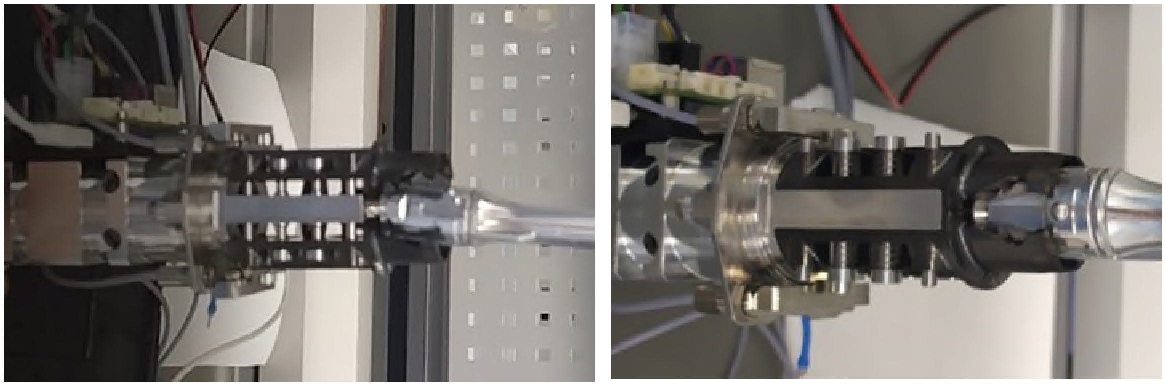

Figure 15. RSTA end-grip capture test (RSTA models courtesy NASA/JPL-Caltech).

The body-grip capture test was then carried out (Figure 16) considering target misalignments up to ±3 mm and ±5 deg. The sample tube dummy is presented to the EE with transverse orientation and residual misalignment; the EE soft-closure then aligns the tube body axis. Microswitches closure signals are detected, and the secure grasp rigidization is commanded to the locking hooks. The correct performance of the body-grip capture and locking operation was verified.

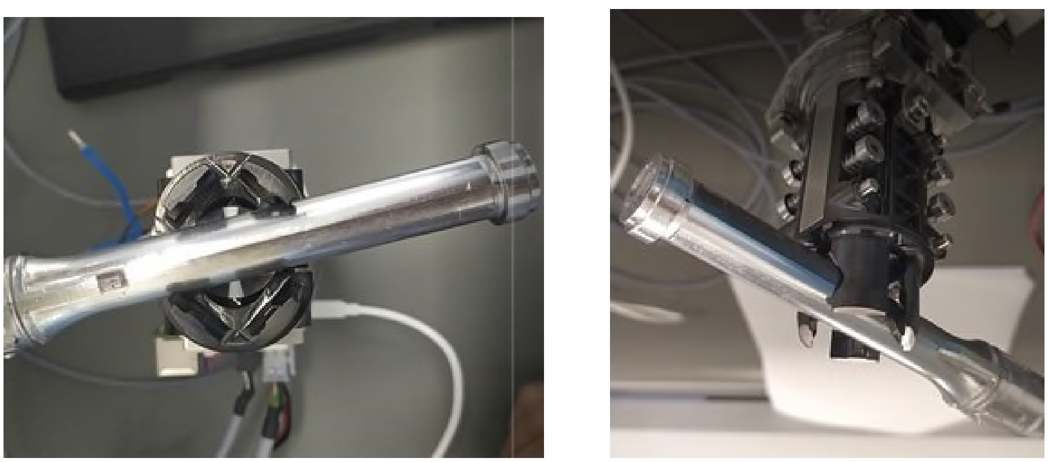

Figure 16. Body-grip capture test (RSTA models courtesy NASA/JPL-Caltech).

Similarly, the grapple-fixture capture was tested (Figure 17), proceeding with the misalignment, capture, and locking sequence. Capture and locking performance were confirmed.

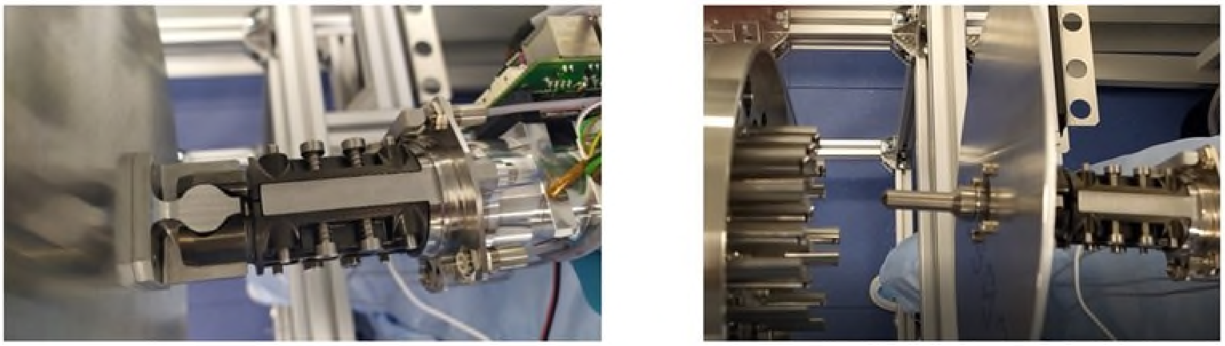

Figure 17. Grapple-Fixture Grasp of the OS-Lid Dummy.

Insertion and extraction tests followed the higher load tests, including: sample tube insertion test, sample tube extraction test, OS-Lid insertion test, and OS-Lid extraction test. The tests were performed against custom-designed ground equipment restaint interfaces. The secure grasp locking confirmed the robust performance of each operation (*Figure 18*).

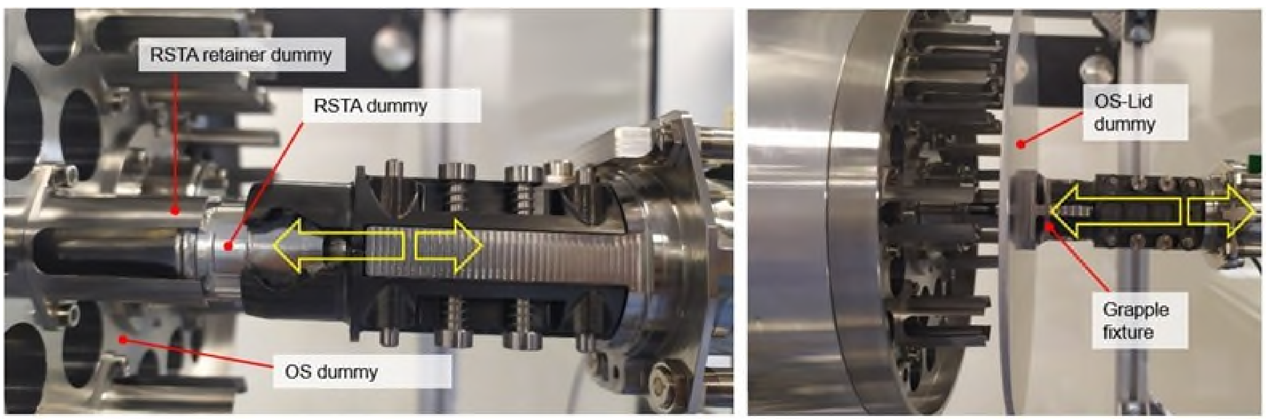

Figure 18. RSTA and OS-Lid Dummy Insertion and Extraction test.

The most significant engineering budget and performance features of the EE breadboard are summarized in Table 1.

Table 1. End-Effector Features.

Quantity	**Value**
EE Envelope	Ø70 mm × 200 mm (0.8 ℓ)
EE Mass	1.1 kg
Peak Power	< 5 W
Soft Capture Grasp	10 N
Secure Grasp Locking	✓
Axial Force Capacity	> 350 N
Shear Force Capacity	> 250 N
Bending Moment Capacity	> 20 Nm
Torque Capacity	> 60 Nm

Conclusions

The sample handling End Effector breadboard design and tests were presented. The system study and development led to a compact End Effector design. The EE is capable of both soft-capture handling and withstanding the higher interaction loads due to insertion, extraction, torque and mass loading operations. The EE is also capable of handling additional tool interfaces, for which a custom design grip interface was designed and tested.

The EE architecture relies on an original passive grasp concept, in which the gripper jaws are normally closed through a set of compression springs. The actuation chain operates a cam shaft opening the gripper jaws against the springs force. The EE architecture is capable of handling target misalignments and is equipped with a mechanical locking feature which secures the grasp once the correct capture is confirmed by the sensor setup.

The design was realized and integrated, and the EE test campaign confirmed the performance with respect to tube sample and the ancillary tools capture, extraction, insertion and release operations.

References

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