Low Risk Technique for Sample Acquisition from Remote and Hazardous Sites on a Comet

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Abstract

This paper describes a mission comet sampling strategy, known as CORSAIR (COmet Rendezvous, Sample Acquisition, Investigation, and Return), which was proposed for NASA New Frontiers 2017. The proposal was led by Applied Physics Lab (APL) with partners Goddard Space Flight Center (GSFC) and Deutsches Zentrum für Luft- und Raumfahrt (DLR).

The mission concept is to launch a projectile from a satellite that is capable of gathering a 300 cc sample. The projectile is tethered and is reeled back to the spacecraft after gathering the sample. Once back at the spacecraft, a robotic manipulator extracts the sample cartridge and places the cartridge into an earth return vehicle (ERV). This method has the following favorable characteristics:

1. Places the mission at minimal risk by isolating the spacecraft from the comet
2. Allows access to remote and otherwise inaccessible locations
3. Permits deep penetration into the surface

1. Introduction

CORSAIR's basic tenet is to deliver a projectile (SARP) of sufficient kinetic energy that it will penetrate the surface regardless of regolith properties. A tether (TRAC boom) deploys with the projectile and provides a means to return the sample to the spacecraft. Upon returning to the spacecraft, the sample cartridge is extracted by a robotic arm (RA) which in turn transfers the sample to a storage container inside of an ERV. The storage container keeps the sample secure and cold while in transit back to earth. The ERV provides utilities to protect the sample against shock and thermal loads that would be anticipated at the re-entry phase of the mission. The following gives details of the previously mentioned favorable characteristics. Figure 1 illustrates a concept overview.

1.1 Risk Reduction

Previous attempts to gather science at a comet put the vehicle in intimate contact with the surface. As the material properties at any landing site are not fully know, this strategy places the spacecraft at high risk. The dynamics of landing a spacecraft on the surface of a comet is complex and risky even when there is some estimate of surface properties in a perceived low risk landing area. By keeping the spacecraft 10 meters above the surface, CORSAIR maintains a low risk profile to the spacecraft while permitting sample operations that otherwise would pose a much higher risk.

1.2 Accessing High Value Locations

Sample site locations at a comet are selected based on compromises between scientific interest and perceived mission risk. If the sampling location is based on the highest possible scientific value without regard to risk, the possibility of truly break through discoveries increases dramatically. Compelling sights may present themselves in locations that are too risky for missions that rely on a more intimate connection between the spacecraft and the comet. Sending a projectile that is tethered permits site selection that is most attractive for scientific reasons even when other acquisition methods would render the site inaccessible. In this regard, scientific inquisition would determine the overall value of the mission and not compromises made to minimize risk. CORSAIR minimizes risk to the mission while permitting sampling operations from most scientifically compelling locations by isolating the spacecraft from the comet.

1.3 Deeper Penetration

Unlike other methods, this strategy is capable of penetrating deep below the surface. Deeper material has the benefit of radiation shielding provided by upper layers. Components in the sample that are sensitive to the effects of radiation are protected and preserved in this manner. Material deeper down also has an increased probability of being less processed due to top evaporation and condensation cycles that are typical of materials near the top surface. Missions that focus on gathering only materials towards the top miss the opportunity to gather the older less processed, more scientifically compelling materials that lay as close as 10 centimeters below the top surface. Accessing the deeper material at a lower risk would present the opportunity for a very compelling mission.

2. System Trades

As part of the CORSAIR proposal, a few key decisions had to be made in order to develop a sample handling sequence. A Tagucchi analysis was used to prioritize design points in order to assemble a sensible mission layout.

2.1 Pointing

Use the spacecraft navigation system to point the sampling system. This implies mounting the Sample Acquisition System (SAS) directly on the spacecraft with no secondary pointing system. The imparted energy on the spacecraft can be mitigated through passive shock absorption. Any torque imposed on the spacecraft due to an offset from the center of mass can be corrected by an on board reaction system.

2.2 Propulsion

Use a chemical propellant versus either a cold or hot gas. This eliminates the need for gas storage containers as wells as complicated gas transfer lines. The energy density of a chemical propellant has the added benefit of minimal mass. Means would be taken to capture any residual gases from contaminating the sample.

2.3 Redundancy

Provide four separate sample acquisition systems that are independent. The SAS assemblies are robust and relatively inexpensive. A distributed layout of the SAS collection provides options for spacecraft layout and transfer access. Providing four systems provides redundancy in case any sampling operation is not able to complete its function.

2.4 Sample Transfer

Use a robotic manipulator (RA) that can transfer the sample from each SAS to the ERV. The manipulator work volume allows mission components to be laid out without regard to transfer operations. There are several options for space qualified manipulators that would be appropriate for this application. Using existing proven technologies negates the need to develop an entirely new mechanism system for sample handling.

2.5 Off-Nominal Protection

Provide a means to abandon a SAS in case an off-nominal condition puts the mission at risk. This can take the form of a cable cutter that can sever a stuck TRAC boom, or of a release mechanisms that can eject an entire SAS.

3. Sample Acquisition System (SAS)

The SAS is illustrated in figure 2 (RA not shown) and has these major components

3.1 Launcher

3.1.1 Expansion chamber and piston

This launcher is a propellant-driven device developed by DLR in Munich, Germany [1]. The launcher uses a NASA Standard Initiator (NSI) to ignite a pyrotechnic charge that propels the SARP towards the comet. The launcher consists of an expansion chamber with a sliding piston that captures energy from the propellant expansion and transfers that energy to the SARP. The design was validated through a test program at DLR shown in Figure 3. An intermittent structure, known as the bird cage, transfers energy from the piston to the projectile, while permitting access to the center of the SARP. Because the TRAC boom connects to the center of the SARP, clear access to this area is critical.

3.1.2 Bird cage

The bird cage accelerates with the piston and transfers the energy to the projectile. The elements in the bird cage have to withstand the acceleration during the first part of travel and the rapid deceleration at the end. Mechanisms are used to slow the bird cage down in a progressive manner to minimize risk of damage. Once stopped, the bird cage is locked to mechanical ground. This provides a stable base for the returning sample cartridge to settle.

3.1.3 Variable Pressure Gas Launcher (ViPR)

To facilitate testing of the SAS, a simulator designated ViPR was built and tested at Goddard. ViPR uses compressed helium that is dumped into an expansion chamber also with a sliding piston. The piston transfers the energy to the projectile via a bird cage simulator. Using compressed gas for testing is cheaper and in general is easier to handle when compared to pyrotechnic means. As the SAS ground testing is not mass limited, the ViPR system facilitated testing by reducing risk and expediting resetting the test setup. See Figure 4.

3.2 Sample Retrieval Projectile (SARP)

The SARP is a mechanically robust sampling projectile that tolerates the shock involved in sampling operations. The electronics on board are simple designs to trigger actuation at certain times during sampling. The SARP contains batteries that supply the actuators with power. Figure 5 illustrates the major parts in the SARP.

3.2.1 Sample Cartridge, Door and Release

The cartridge is a hollow shell with a square cross section that allows for a sample 10 centimetres deep. Once the SARP comes to a stop, a mechanism closes the front door and captures the sample. A second mechanism releases the outer sheath once the door mechanism is triggered.

The SARP door is a spring loaded mechanism with a leading edge that behaves like a cutter. The door is released by a pin puller actuator that is triggered by onboard electronics. Design consideration is given to handle the expected cold temperatures at the comet surface and testing has verified the door shuts properly when cooled with liquid nitrogen. Specific design elements minimize the chances of the door getting stuck or hung up on components in the regolith.

3.2.2 Outer Sheath and Release

Once the door is closed, a second mechanism is actuated that releases the outer sheath from the SARP. As the SARP contacts the surface, the outer sheath gives the SARP more momentum (via additional mass) to penetrate deeper. The outer surface of the outer sheath is cylindrical with a tapered nose to funnel material into the cartridge. Several protrusions on the nose aid in fracturing the surface of the comet to facilitate deeper penetration. The sheath release mechanism is in the rear of the SARP and is based on a fast acting pin puller. Once released, the outer sheath stays in the comet giving a clear exit path for the cartridge.

3.2.3 Inner Sheath, Hinge, Latch and release

The cartridge returns to the spacecraft inside of the inner sheath which protects the assembly. The inner sheath also provides structure for a hinge that allows the cartridge to be flipped over. The hinge has a torsional spring to open the joint and a latch to hold it open. The hinge is held closed by a release that, once at the spacecraft, is triggered to allow the hinge to open. This action flips the cartridge over and exposes a set of features on the back side of the cartridge which have been shielded from contamination up to this point. These features on the cartridge, known as the KINEE, provide a place for the robotic actuator (RA) to grab and extract the cartridge. See Figure 6.

3.3 Boom Retraction and Deployment (BRAD)

The BRAD is an assembly that keeps the SARP connected to the spacecraft via the TRAC boom. The TRAC boom connects to the SARP on one end and to the spacecraft, via a drum, on the other. See Figure 7.

3.3.1 Triangular Rollable and Collapsible Mast (TRAC Boom)

Several designs were considered for the tether that keeps control of the SARP during sampling operations. Requirements are

1. Capable of deploying at high velocities

2. Capable of being stored in a space efficient manner.

3. Capable of becoming stiff when deployed in order to protect the spacecraft from contact.

Selecting the appropriate design for the tether required the help of Air Force Research Lab (AFRL) in New Mexico. AFRL has been involved in the design and development of deployable booms for spacecraft instruments. A design developed at AFRL, designated as a TRAC boom [2], has similar application requirements as those needed for this application. By combining two leaves into an assembly, a TRAC boom can be wrapped around a drum yet become stiff when deployed.

A baseline design, TRAC V5, was decided on as a compromise between the efficiency of the storage envelope and the deployed stiffness. This design choice affects the design of the BRAD drum, the launcher and the attachment devices between the SARP and the bird cage. The boom length was selected to ensure a minimum 10 meter deployment, taking into account variants such as the comet surface texture and spacecraft height. A commercial partner, Roccor, was employed for test article fabrication as well as in-depth internal study of the assembly.

3.3.2 Drum

The drum provides a way to stow the TRAC boom and manage it during deployment. The drum has to accommodate properties of the TRAC V5 design. Special consideration is given to how the drum attaches to the boom to react all load cases.

A mechanism attaches to the drum that arrests the residual momentum in the system after launch. The design of this arrestor took into account the range of expected conditions that would exist due to various interactions at the comet surface. The arrestor design also served to mitigate the shock to the spacecraft upon stopping the drum.

After the sample is gathered, a retraction actuator on the drum reels the TRAC boom back to retrieve the cartridge. Once back at the spacecraft, the cartridge is received by the grounded bird cage. Features on the cartridge and the bird cage lock the two pieces together with the aid of preload. This preload comes from the drum actuator continuing to apply torque to the drum. Once the cartridge has fully seated in the bird cage and preload has been applied, a brake on the drum maintains that load such that the power can be removed from the drum motor. This preload keeps the assembly stable.

If the comet surface does not stop the SARP, the momentum arrestor in BRAD will absorb the energy in the system and prevent the TRAC boom from spooling off the drum.

The drum design minimizes inertia that would otherwise rob the projectile of energy. The design provides sufficient structure for stowing the TRAC boom and handling the load associated with the launch process. The momentum arrestor acts through the structure of the drum so that load condition was the primary design driver for the structure.

3.3.3 Retraction system

A retraction actuator is attached to the drum to reel the boom back to the spacecraft. The actuator is coupled to the drum though a clutch that allows free rotation at deployment and full engagement during retraction. Once the SARP is back at the spacecraft, this actuator applies a torque to the drum that preloads the assembly to mechanical ground. The actuator has a spring-loaded brake which can maintain that tension after power is removed. Holding the SARP tight to mechanical ground is critical to enable the robot actuator (RA) to extract the cartridge.

3.3.4 Boom cutter

A device is placed on the BRAD assembly that is similar to a cable cutter. This actuator provides mission protection if the SARP or TRAC boom were to become stuck or enmeshed in a dangerous configuration. Several mission level checks would have to be tripped in order to trigger this event. By cutting the boom at the spacecraft, the entire boom and SARP assembly would be severed from the mission and present no further risk.

3.4 Robotic Actuator (RA)

The RA is a sophisticated robotic manipulator that uses force feedback to overcome issues of compliance and accuracy. The design offered as part of the CORSAIR proposal is designed and built at DLR in Munich, Germany. This manipulator is made of rotation joints that are configured in a serial manner mimicking the human arm. Although it lacks the full dexterity of a human arm, the DLR RA does have the capacity to very accurately measure applied torques when load is applied to the arm. This information is used to plan trajectories and avoid applying too much force. The capability gives intimate knowledge of loads applied throughout the process of locating and grabbing the cartridge.

Although never flown as an assembly on a space mission, components of the RA have been qualified for space use by experiments on ISS. This testing demonstrated the basic components in the RA assembly can operate for extended periods in space. The complete RA assembly uses these components throughout. Performance as a full 6 degree of freedom actuator would be expected to be similar. The actuators use many industry standard parts used in instrument pointing systems such as brushless DC motors, harmonic drive transmissions, and position encoders. Actuator electronics are laid out in a distributed architecture that facilitates closed-loop control.

As part of the CORSAIR proposal, a ground based simulation was assembled using a commercial version of the RA made by Kuka. Simulators of the SAS and storage container were assembled inside the working range of the RA. Testing demonstrated the RA could successfully interact with the various parts of the sampling system and the earth return vehicle. The RA was able to remove the cartridge from the inner sheath and transfer it to the storage container. See Figure 8.

3.5 KINEE (Kinematic End Effector)

The KINEE is a set of components designed to provide a robust interface between the RA and the cartridge. The device consists of the target and the gripper. KINEE is designed to minimize complexity, mass and volume. Packaging efficiency is especially important in the SARP as internal volume is limited. Features on the target and gripper lock the two pieces together once actuated. See Figure 9.

The gripper has a centralized conical feature intended to provide a reference surface that can be used to locate a round pocket in the target. The robot arm would use the conical surface to probe around the edges of the target pocket to locate a coordinate frame on the target. Once the location of the target center is established, there are three balls on the gripper that are mated to a surface on the target that has three vee shaped cavities. The robot can rotate the gripper around the center of the cone until the balls engage the vees. This will establish the coordinate frame orientation of the target.

Once the location and orientation of the target are known, the gripper can be fully inserted and mated. At this stage, the robot actuates the gripper to apply a load that pulls the gripper and target together. This locks the gripper and target together mechanically, so that forces and torques can now be applied without the pieces separating. This is necessary for the robot to extract the cartridge from the inner sheath. A detent feature retains the cartridge to the inner sheath and requires approximately 20 Newtons to overcome. The same detent feature holds the cartridge in the storage container until a proper lid is closed.

4. Figures

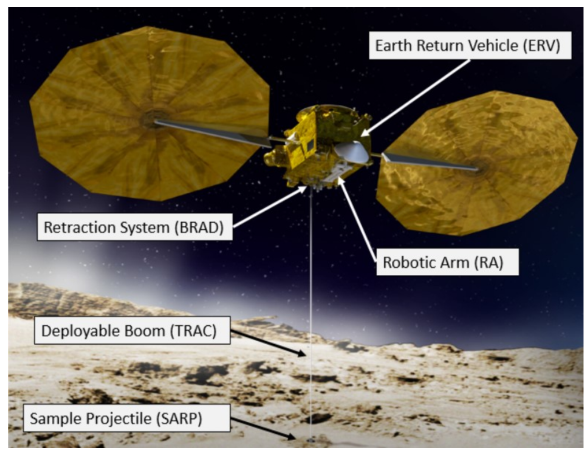

Figure 1: Concept Overview

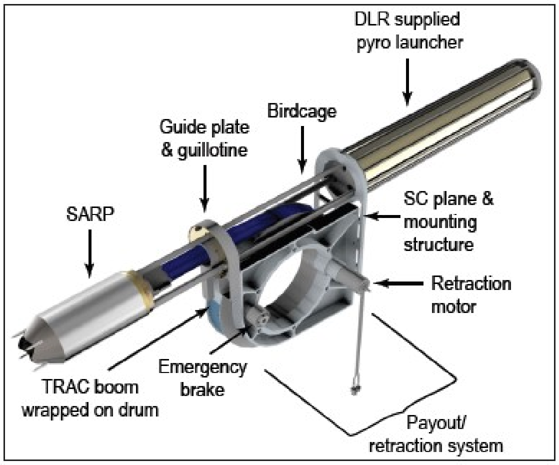

Figure 2: SAS (RA not shown)

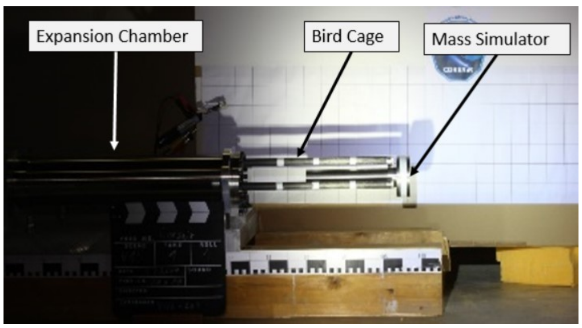

Figure 3: Launcher at DLR

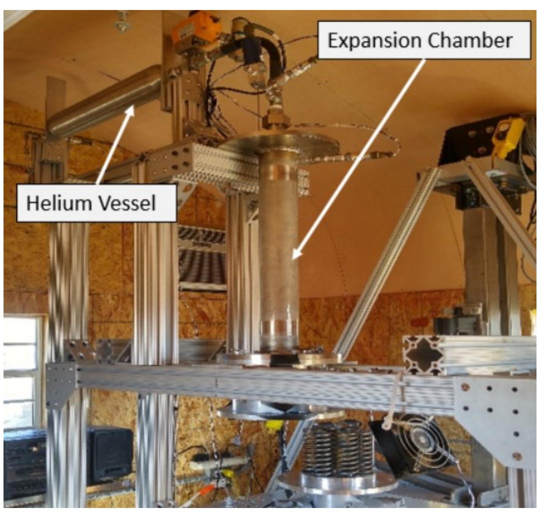

Figure 4: ViPR at GSFC

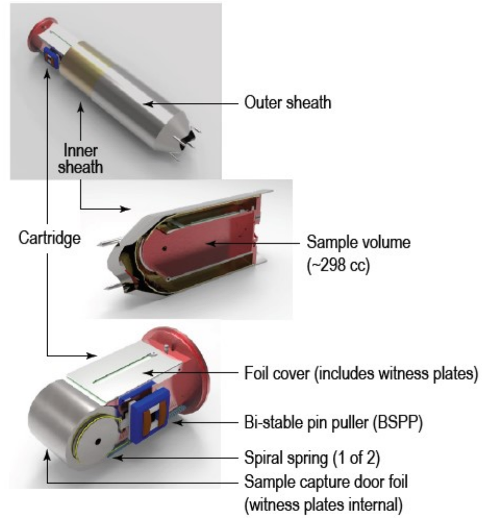

Figure 5: SARP Components

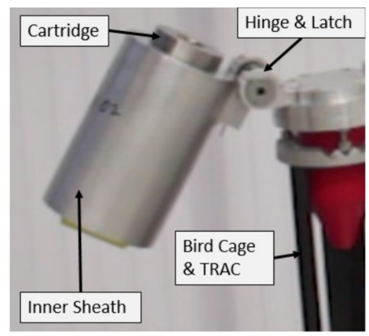

Figure 6: Inner Sheath, Hinge and Cartridge

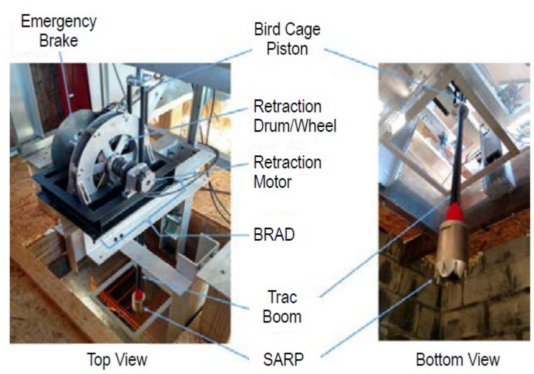

Figure 7: BRAD test setup at GSFC

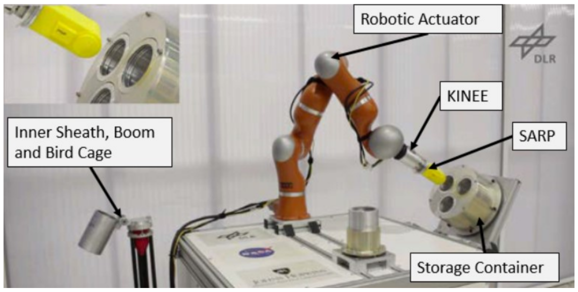

Figure 8: RA test setup at DLR

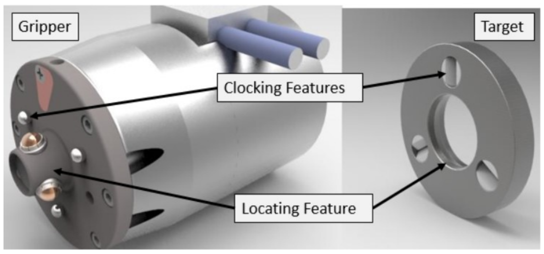

Figure 9: KINEE Components

5. Summary and Conclusions

The CORSAIR sampling technique provides a low risk means to acquire a sub-surface comet sample of high scientific value. Work done for this proposal validated the concept through testing. Continued development would allow design weaknesses to be explored and solved which would strengthen the concept.

Although not selected for NF17, this proposal is still worthy of consideration for future scientific investigation. The work presented in this paper represents at least 4 years of development and testing between APL, GSFC and DLR. All the various trade studies and many exceptional contributions from the team members could not be detailed herein. Hopefully, continued support for this concept can give the opportunity to expand on and document the exceptional work done on this proposal.

Acknowledgements

APL led the CORSAIR proposal effort and supplied development support throughout. GSFC provided IRAD funding to develop and test BRAD, SARP and KINEE. DLR provided development and testing of the Launcher and RA simulator working with all the parts of the system.

References

[1] Volk, et. al., **Development and testing of a pyro-driven launcher for harpoon-based comet sample acquisition,** 68th International Astronautical Congress, Adelaide, Australia, IAC-17-A3,4B,5,x39772.

[2] Banik and Murphey, 2010, **Performance Validation of the Triangular Rollable and Collapsible Mast**, 24th Annual AIAA/USU Conference on Small Satellites, August 9 – 12, Logan Utah, SSC10-II-1

[3] Purves, L. and Nuth, J. A., **Development and Testing of Harpoon-Based Approaches for Collecting Comet Samples**, 2017, https://ssed.gsfc.nasa.gov/harpoon/SAS_Paper-V1.pdf