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Sampling System Concepts for a Touch-and-Go Architecture Comet Surface Sample Return Mission

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Three sampling tools were developed as candidate tools for use in a potential Comet Surface Sample Return mission for a touch-and-go mission architecture. In a touch-and-go mission architecture, a spacecraft would maneuver to several meters from the surface of a small body and deploy a sampling tool to the surface using a manipulator. A sample would be acquired in a few seconds and the spacecraft would thrust away from the surface of the small body. The tools would acquire 500 cc samples. The Reactionless Drive Tube tool would minimize the reacted force to the spacecraft due to the sampling event. The Clamshell sampler would acquire and encapsulate the sample in the same sampling action. The BiBlade sampler would also acquire and encapsulate the sample in the same sampling action but with the advantage of acquiring sample from greater depth than the Clamshell sampler.

I. Introduction

THE NASA Decadal Survey identified a Comet Surface Sample Return (CSSR) mission concept as a high priority mission for the next decade[1,2]. In the work presented here, three sampling tools were developed and tested as candidate tools for a potential CSSR mission with a touch-and-go (TAG) mission architecture. In a TAG mission, a spacecraft would maneuver to several meters from the surface of a small body and then extend a robotic arm which would have a sampling tool. The arm would deploy the sampling tool to the surface and a sample would be acquired in a few seconds and the spacecraft would thrust away from the surface of the small body. The CSSR mission concept and expected science requirements were described in the Decadal Survey and associated mission study[1,2]. Comet surface strength has been estimated to be within the range of 1 – 100 kPa, with the range of 1 – 10 kPa being most likely, similar to lightly packed dry snow[3,4,5]. The preliminary CSSR requirements associated with sampling are listed below.

Group 1: Required, science floor
- Return a single ≥ 500 cc sample from the surface of any comet nucleus
- Preserve sample complex organics (sample using a “soft” technique)
- Prevent aqueous alteration of the sample at any time (maintain at ≤ -10^{o}C)

Group 2: Baseline Mission, budget was scoped to potentially be able to include these
- Capture evolved gases from the sample
- Return material from depth >= 10cm, and maintain sample stratigraphy

Various sampling techniques have been proposed for small body missions. The sampling techniques are associated with mission architectures: lander, harpoon, dart, and TAG. These mission architectures and sampling tools for them are described below.

In a lander architecture mission, a spacecraft would land and anchor to the surface and then a sampling tool would be deployed to the surface to acquire a sample. A lander mission would allow for the sampling process to

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take longer than for other mission architectures. The Rosetta mission is a lander architecture in-situ sampling mission to comet 67P/Churyumov-Gerasimenko[6]. The mission was launched by the European Space Agency in 2004 and is scheduled to arrive at the comet in August 2014. Its Philae robotic lander is planned to separate from the Rosetta orbiter spacecraft and land on and anchor to the comet and then deploy a drill to acquire samples for in-situ analysis. The sampling drill, SD2, weighs 5 kg and can penetrate up to 250 mm and acquire samples at predetermined depths inside its drill bit. The samples, up to tens of mm^3, can be transported to a carousel with 25 ovens[7]. The drill was designed to penetrate material with strength ranging from fluffy snow to materials with a strength approaching a few MPa.

In a harpoon architecture mission concept, a spacecraft would maneuver to the proximity of a small body surface, perhaps 10 m to 1 km from the surface, and a sampler would be shot to the surface with a tether connecting it to the spacecraft. The momentum of the sampler would embed it into the surface driving the material into the sampler and then the sampler would be ejected from the surface and it would be reeled back to the spacecraft with the tether. NASA Goddard Space Flight Center developed the RApid SAmple Retrieval System (RASARS) for harpoon architecture small body sample return missions[8]. They developed a sample collecting projectile that would be fired from a spacecraft and then would embed in the surface of the small body. The projectile would have an outer sheath for penetrating the small body material and an inner sample cartridge that would collect the sample. A garage-door type mechanism would be used to cut through the material at the front of the sampler and retain the sample.

A dart architecture mission concept is similar to a harpoon architecture mission concept except there is no tether connecting the sampler to the spacecraft. The sampler would be shot to the surface and its kinetic energy would be used to drive the sampler into the surface, and then the sample canister would be ejected from the surface and the spacecraft would rendezvous with and capture the sample canister. The dart architecture would eliminate the problems associated with controlling a tether but would add the complexity of tracking, rendezvous, and capturing the sample canister. A penetrator for a dart mission architecture was developed at the University of Arizona[9]. A rocket motor would accelerate a projectile sampler at a small body and imbed itself in the small body. A flared body shape would decelerate the sampler as it embeds in the surface to minimize the sensitivity of penetration depth to the strength of the material. To retain the sample, four sections of a cone would be pushed forwards and inwards to close the front of the sample chamber. A sample canister would be ejected out of the back with a spring at about 5 m/s. For testing, an air gun was used to shoot a prototype sampler into simulant with target simulant material between 550 and 750 kg/m^3 bulk density. Sampler impact speeds were about 17 m/s and penetration depths were about 40cm. The samples were flaked ice mixtures with strength up to about 20 MPa. They demonstrated successful sampling of the simulants, but the sample retention and ejection steps had issues that indicated further work would be needed for those capabilities. JPL developed the Dynamic Acquisition and Retrieval Tool (DART) for a dart architecture small body sample return mission[10]. The DART tool would be fired from the spacecraft and its kinetic energy would drive it into the small body surface. A decelerator plate would prevent the sampler from embedding too deep into the surface for softer materials. An iris type mechanism cut the material at the front of the sampler and the inner sample canister would be ejected out the back at greater than escape velocity of the small body.

In a touch-and-go (TAG) architecture mission concept, a spacecraft would maneuver to within a few meters of the small body surface and a robotic arm would deploy a sampling tool to the surface and the sample would be acquired quickly and the spacecraft would then thrust away. The sample would be transferred to the spacecraft using the robotic arm.

The Hayabusa mission of JAXA had a TAG mission architecture and returned samples from asteroid Itokawa. The Hayabusa sampler was designed to fire 5 gram tantalum pellets at 300 m/s into the surface of the asteroid to cause asteroid surface material to be ejected and subsequently acquired using a 1 meter long horn which guided the sample material into sample chamber[11,12]. Unfortunately, various spacecraft problems prevented the sampler from being used as planned. The spacecraft was able to have the sampler contact the surface and a small amount of material travelled through the horn to the sample chamber.

The OSIRIS REx mission is a TAG architecture sample return mission to an asteroid scheduled to launch in 2016[13]. OSIRIS REx is a NASA New Frontiers program mission and is planned to acquire surface samples from asteroid 101995 Bennu and return samples to Earth in 2023. The Touch-and-Go Sample Acquisition Mechanism

(TAGSAM) would acquire and store samples. A robotic arm would deploy the TAGSAM sampler to the surface of the asteroid and it would acquire at least 60 grams of surface sample. Upon contact with the surface, nitrogen gas is released from the circumference of the sampler to lift loose regolith from the surface and drive it into a sample filter that would capture the sample. The sampler is designed to support three sampling attempts. After sampling is complete, the robotic arm would transfer the sampling tool to the Sample Return Capsule and release the sampling tool head there. The sampling tool head would be returned with the sample.

The Brush-Wheel-Sampler (BWS) was developed at Jet Propulsion Laboratory for TAG architecture small body sample return missions[14]. The BWS has two or three counter-rotating brushes which would capture surface material and drive it up and into a sample canister. The robotic arm that deployed the BWS to the surface would transfer the sample canister to a sample chamber in the Sample Return Capsule where it would be released. The BWS had the benefit of quickly capturing a large volume of sample.

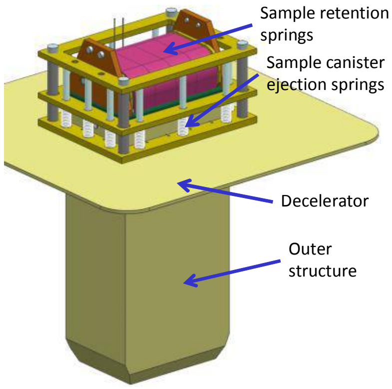
Honeybee Robotics developed the Touch and Go Surface Sampler (TGSS)[15]. The sampling head has counter-rotating cutters that rotate at speeds of 5000 to 8000 rpm and consumes 20 W to 30 W of power. The prototype weighed 450 grams and had a volumetric envelope of 50 mm x 75 mm x 150 mm. The TGSS was demonstrated to sample unconsolidated regolith at a rate of 30 cc/sec and consolidated chalk with strength of 10 MPa at a rate of 0.5 cc/sec. The TGSS was demonstrated in microgravity tests to be able to acquire samples from both consolidated and unconsolidated material.

A drive tube has a constant cross section and would be driven into the comet surface. The dart architecture tools are generally drive tubes. Since drive tubes have an open face, they require separate steps and mechanisms to cut the material and retain the sample. These mechanisms are placed in the walls of the sampler which increases the width of the sampling tool walls and the required sampling energy.

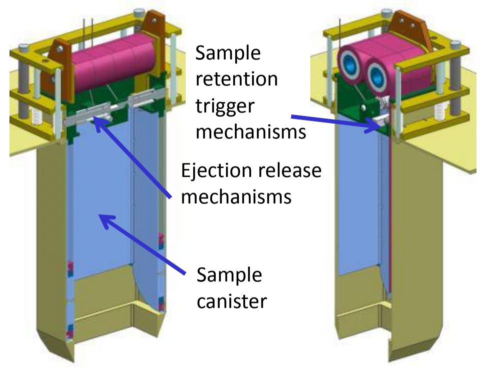
Prior robotic sample return missions have not used autonomous sample measurement. NASA's Genesis and Stardust robotic sample return missions successfully returned samples to Earth without an in-situ sample acquisition verification system on board the spacecraft[16,17]. JAXA's Hayabusa mission also did not have an in-situ sample acquisition verification system; as a result, positive confirmation of successful sample acquisition and transfer could only be done after the return of the sample capsule to Earth[18]. The OSIRIS-REx mission, currently under development, uses two methods for sample measurement. The TAGSAM sample head can be imaged to see if it is dirty indicating that any sample is present. The primary OSIRIS-REx sample measurement approach is to measure the change in inertia of the arm/sampler due to the increased sample mass as induced by spacecraft motion. Jet Propulsion Laboratory developed sample canister embedded capacitance mass sensors with 50 g resolution for potential lunar sample return missions[19]. This concept assumes an unconsolidated sample, which is not assured for comet samples.

II. Reactionless Drive Tube Sampler

The Reactionless Drive Tube (RDT) was developed with the objective of developing a sampling tool that acquires the desired sample to 10 cm depth while maintaining stratigraphy, but also while minimizing reacted force to the spacecraft. The concept was to eject a sacrificial mass that would provide the reacted force for an impulsive sampling event. The design of the RDT is shown in Figures 1, 2, and 3, and the sampling scenario is shown in Figure 4. The sampler would have an outer shell structure, an inner sample canister, a decelerator, sample retention mechanisms, and sample canister ejection mechanisms.

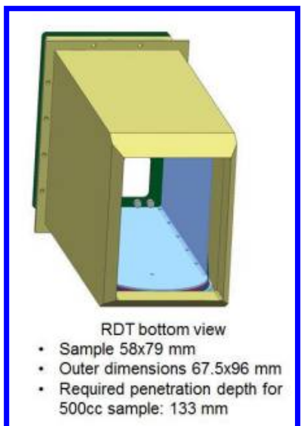


a) RDT components

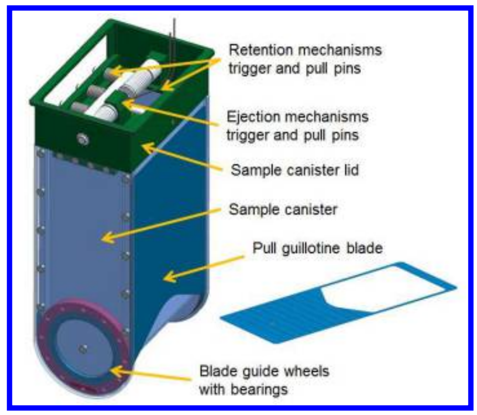


b) RDT cross sections

Figure 1: Reactionless Drive Tube components

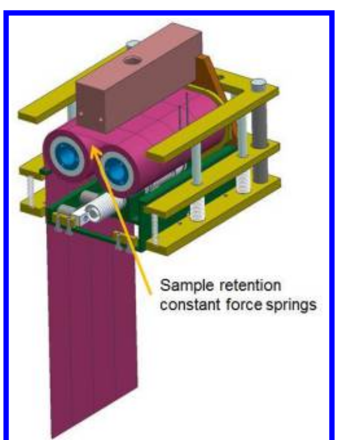


a) Outer shell

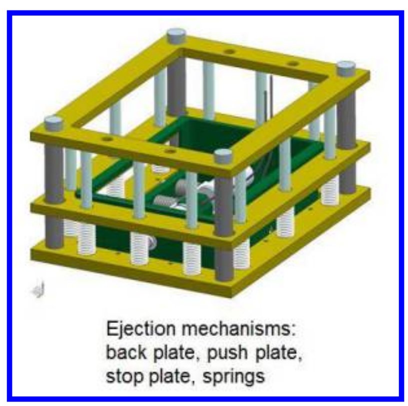


b) Inner shell

Figure 2: Reactionless Drive Tube outer and inner shells

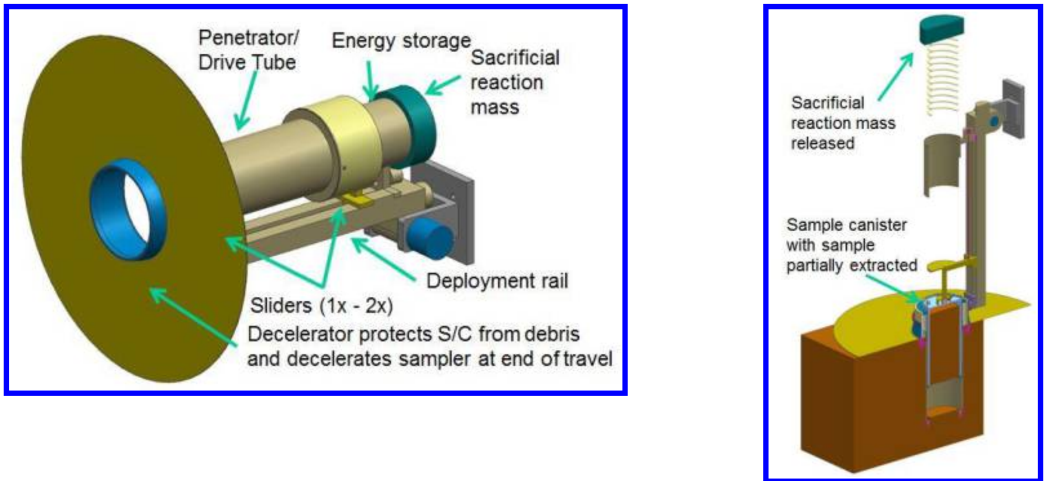


a) RDT retention mechanism



b) RDT sample canister ejection mechanism

Figure 3: Reactionless Drive Tube retention and canister ejection mechanisms



a) RDT before sampling b) RDT after sampling

Figure 4: Reactionless Drive Tube before and after sampling

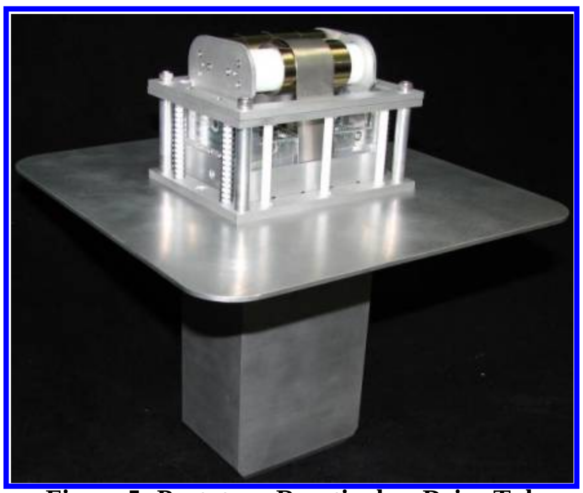
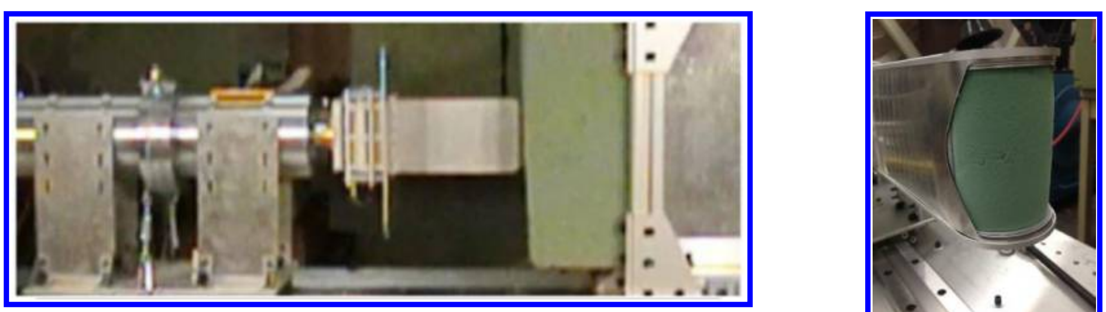


Figure 5: Prototype Reactionless Drive Tube



a) Test setup b) Test results

Figure 6: Reactionless Drive Tube test results

The sampler is attached with sliders to a deployment rail. The energy source, e.g. a spring, drives the sampling tool down a rail and into the comet which drives the sample into the inner canister. The energy source accelerates the sampler toward the sampling media while accelerating a sacrificial mass in opposite direction. After full penetration, a pull-guillotine door then slices through the sample to cut and retain the sample in the inner canister. The inner canister with the enclosed sample would then be ejected from the outer structure.

A prototype of the RDT was built and tested as shown in Figure 5 and Figure 6. The RDT prototype worked as designed. The tests were conducted with floral foam simulant of shear strength 75 kPa.

III. Clamshell Sampler

The Clamshell Sampler would acquire a surface sample by driving two quarter-sphere buckets into the small body surface. A linear piston, or slider, drives a linkage that causes the two buckets to rotate about a common axis to close the buckets into each other, as shown in Figure 7. The sampler could be built as a reactionless sampling tool by using a single release device, in this case a pair of ball-lock cams, to simultaneously release the piston slider and a sacrificial reaction mass, which allows the stored energy in the actuation spring or other energy source to drive the linkage to close the buckets. The large reaction forces of the actuation spring and sampling event are reacted against the sacrificial reaction mass, while the forces to retard any residual forward motion into weaker surfaces are reacted against the decelerator plate at the front of the device. A benefit of the Clamshell Sampler is that one action with one actuator is used to acquire and retain the sample. The tool has three pivot points (at two ends of the pushrods and at the bucket rotation axis) and one slider joint that are all driven by the single energy source. The thin walls of the sampler buckets result in minimum sampling energy due to the minimal displaced volume of material during the sampling event. Since the sampling action results in a retained sample, there is no need for additional retention mechanisms within the sampler walls as would be the case for drive tube sampling tools. Due to the geometry of the buckets, the aspect ratio of the sample has a depth that is half the width of the sample.

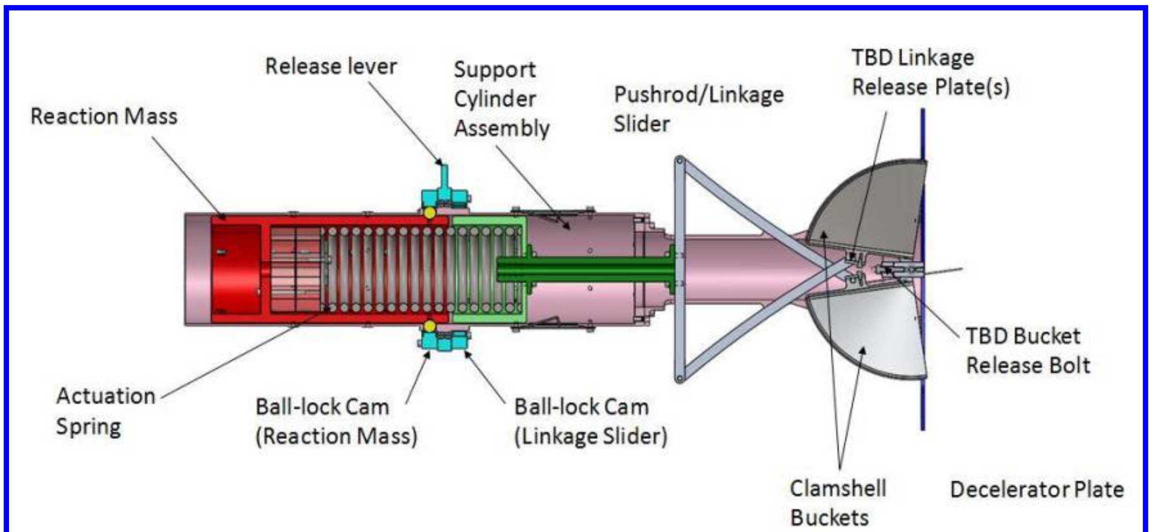


Figure 7: Clamshell design

Once the sample is obtained, two torsion springs keep the buckets closed while the buckets are detached from the tool body in order to minimize the amount of volume that is stored in the return capsule. A single separable bolt, such as a frangibolt type device, along with a mechanism to detach the links from the bucket, would release the buckets and retained sample from the remainder of the device, as depicted in Figure 8.

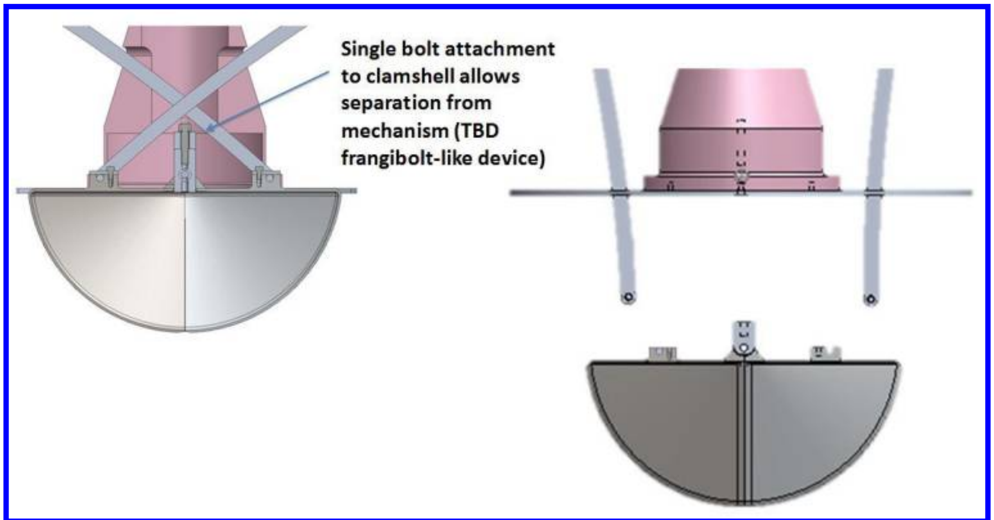
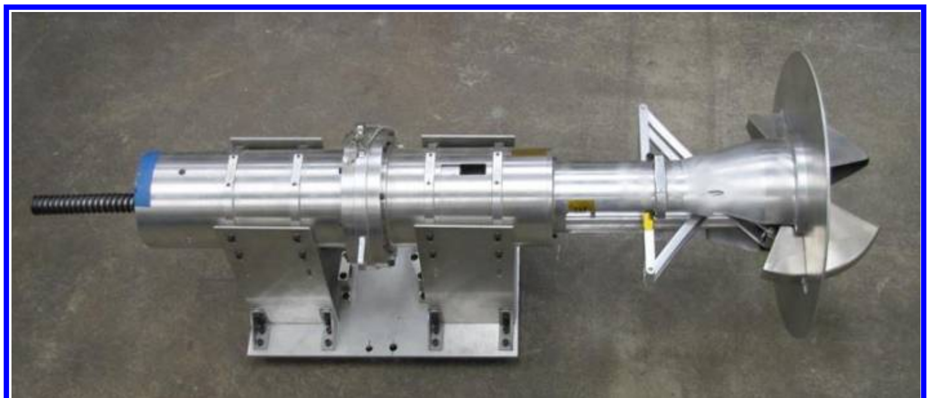


Figure 8: Bucket release for SRC insertion



a) Clamshell prototype

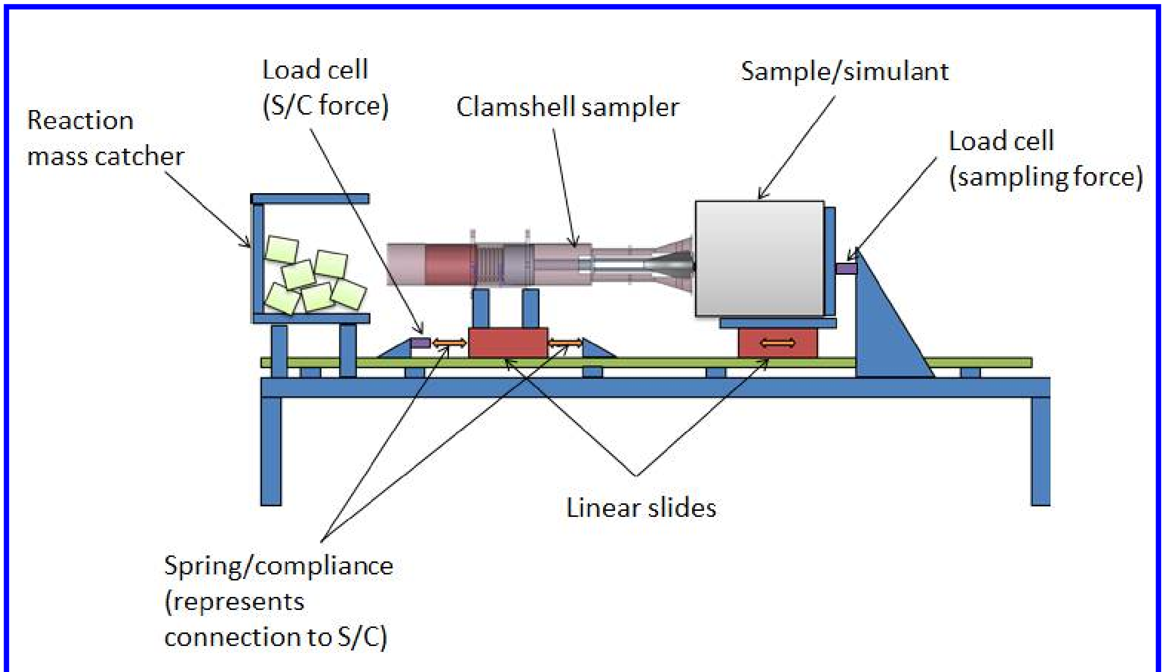
b) Clamshell blades

c) Clamshell sample

Figure 9: Clamshell prototype and example sample

A prototype Clamshell Sampler was fabricated, as shown in Figure 9a and Figure 9b, with the resulting sample shown in Figure 9c. A spring was used to provide the energy for the prototype sampler so that a variety of different stored energy levels could be tested to validate the functional performance of the design in a variety of simulants. By varying the spring rate and the amount of preload, the prototype was able to provide an initial stored energy from 87 J to 188 J for these different tests.

A horizontal test bed was developed to evaluate the Clamshell Sampler prototype. A cartoon of the setup is shown in Figure 10a and the implemented testbed is shown in Figure 10b. The tool and simulant block were both mounted on a linear slide rail to simulate the action of the device in micro-gravity conditions, while a catch tube filled with foam was used to constrain the free reaction mass as it ejected out the backside of the tool. Two load cells installed on the fixture were used to measure the reaction forces at the comet surface and the forces reacted at the interface to the sampling device (i.e., at the robotic arm).

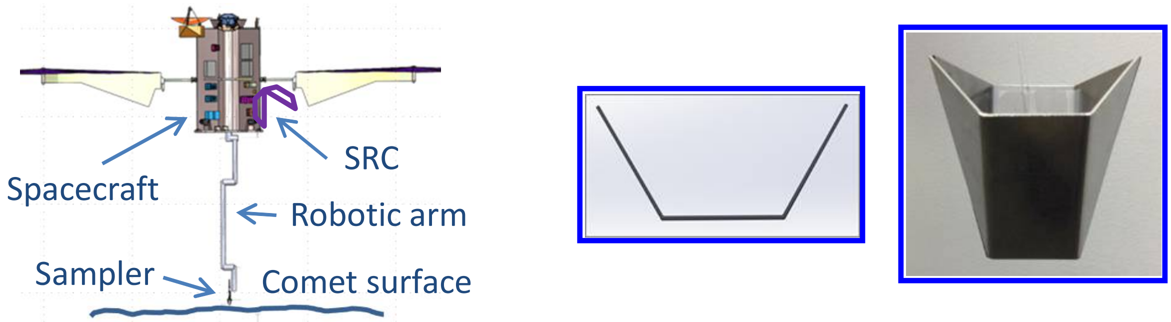


a) Testbed design

b) Testbed implementation

Figure 10: Clamshell Sampler testbed

Tests were performed with the system in both reactionless and non-reactionless configurations. Complete samples were acquired during tests that were performed on a range of simulants including 25 kPa and 75 kPa floral foams and 300 kPa grill brick. The stronger grill brick required the highest sampling energy, 188J.

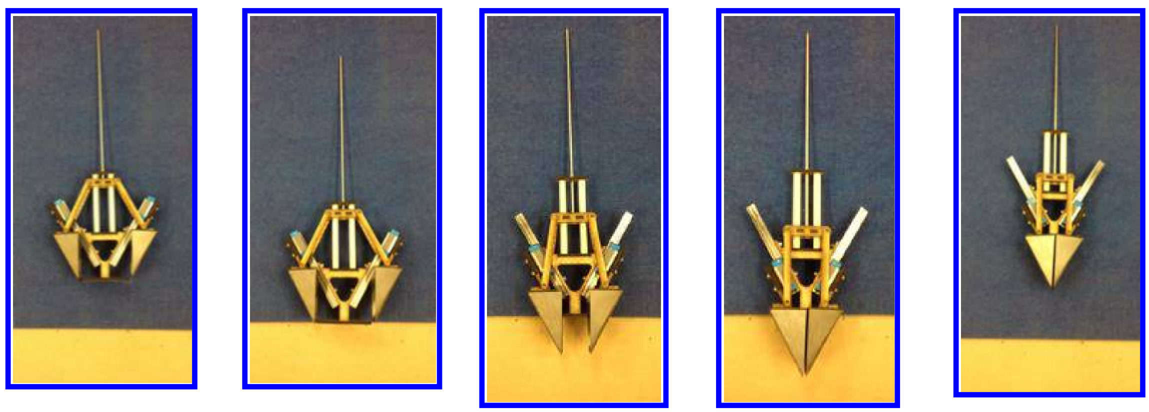


a) Touch-and-Go mission architecture

b) Thin blade cross section minimizes sampling energy

c) BiBlade tapered closed blades

Figure 11: Touch-and-Go (TAG) mission architecture and BiBlade blades



Approach | Contact | Sampling | Sampled | Retract

Figure 12: Sampling process

IV. BiBlade Sampler

The BiBlade sampler is designed for use in a touch-and-go (TAG) mission architecture, where it would be deployed to the surface of the small body using a robotic arm (Figure 11). In the baseline design, two blades would be driven into the surface using springs, with the sampling action completed in about 0.1 seconds, and the spacecraft would thrust away from the comet immediately upon initiation of the sampling action. While closed, the blades would temporarily encapsulate the sample before sample measurement and final deposit in the sample chamber. The robotic arm would transfer the sampler to a sample measurement station where the sample would be measured using a multi-fiberscope sample imager system and then the sample would be transferred to a sample chamber in the Sample Return Capsule (SRC). A lid stored on the sampler would then be released over the SRC sample chamber to encapsulate the sample. It is anticipated that a three degree-of-freedom (DOF) robotic arm would deploy the BiBlade sampler to the surface of the comet, and transfer the sample to the measurement station and the SRC. The arm would be attached such that reacted forces during sampling would react through the spacecraft center of mass so sampling forces safely push the spacecraft away from the comet during the sampling event. Sample measurement could be done in either the SRC sample chamber or in a separate sample measurement station.

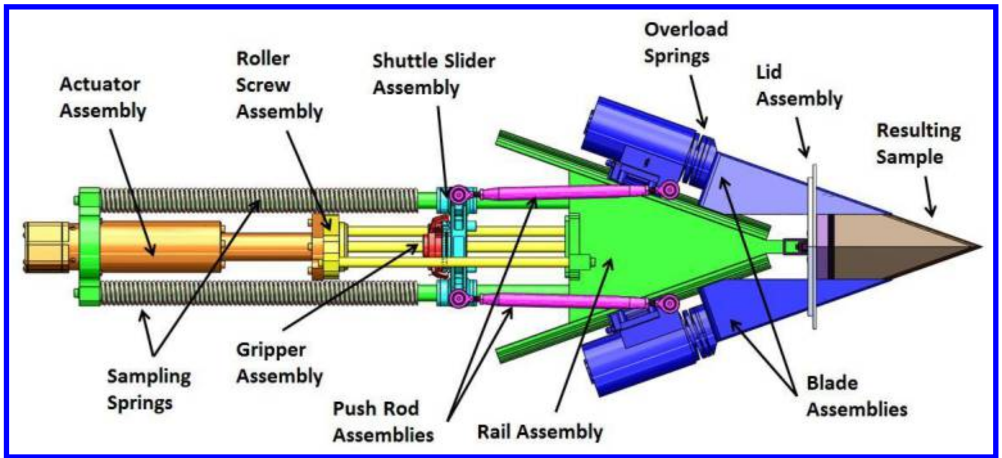
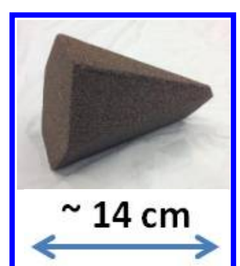


Figure 13: BiBlade Sampler Subassemblies

Figure 14: BiBlade prototype including sampling tool (left), simulant and acquired sample (middle) and sample chamber (right)

a) BiBlade prototype



b) Acquired sample

Figure 15: BiBlade sampling test setup and acquired sample

A. Sample Acquisition

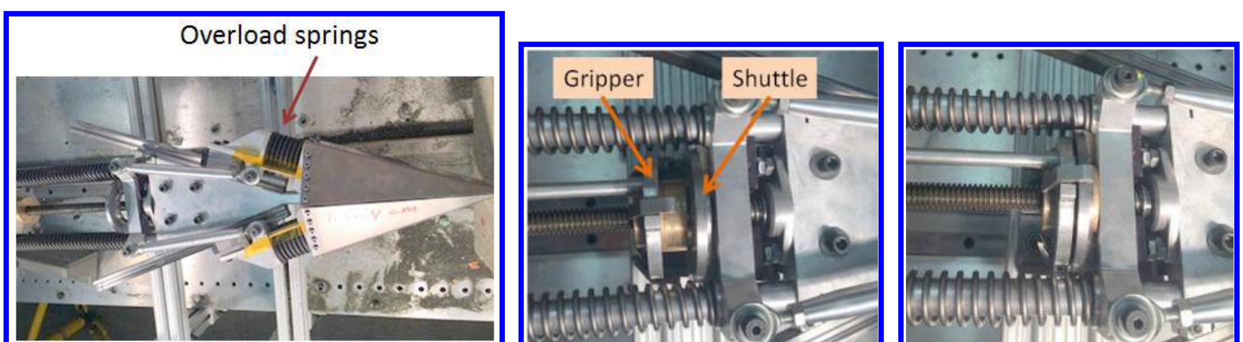
Two blades would be used to acquire and retain the sample. With a fast linear motion of the blades, the blades would both acquire and retain the sample, and the resulting shape formed by the two closed blades would be tapered in all directions (Figure 11). The tapered blades would facilitate removal of the sampler from the comet surface since any linear motion away from the comet would release the closed blade volume in all directions.

The sampling process (Figure 12) would start with the BiBlade being deployed to the surface of the comet using a robotic arm. Upon contact, the BiBlade blades would be driven into the comet surface with springs in less than 0.1 seconds. When the sampling process is initiated the spacecraft would immediately thrust away from the comet, thus retracting the sampler from the comet.

The subassemblies of the BiBlade sampler are shown in Figure 13. Two blades are attached to linear rails by blade sliders. The blade sliders are connected to a shuttle slider using pushrods. The shuttle slides on two linear rails between two compression springs and a hard-stop. The shuttle is grasped or released by a gripper that is attached to the nut of a roller screw. The roller screw is driven by a rotary actuator. The nut is prevented from rotation using two additional rods. The gripper is passive, able to grasp the shuttle when it is driven to the bottom end of the roller screw, and able to release the shuttle when the nut reaches the top end of the roller screw, closer to the actuator.

In preparation for sampling, the gripper release hooks would be attached to the shuttle and the actuator would pull the gripper back along the roller screw drive shaft. Full retraction of the actuator would cause the gripper release hooks to release the shuttle and the sampling compression springs would push the shuttle down its rail, the shuttle would transfer motion through the push rods which would push the blades down their canted rails and into the comet material. For later release of the sample, the gripper would be driven down the roller screw until the gripper hooks grab the shuttle, as depicted in Figure 16 b) and c). When the sample is released later in the SRC sample chamber, the shuttle would be pulled back by the actuator as the sampling springs are compressed.

A prototype of the BiBlade was built and tested, as shown in Figure 14 and Figure 15. A test program validated the design for extreme conditions including internally absorbing sampling energy (i.e. sampling in air), hitting solid surfaces, and acquisition of soft and hard simulants. The prototype successfully sampled 25 kPa shear strength weak simulant. The strongest simulant sampled was 300 kPa shear strength grill brick and the grill brick was acquired with significant margin. The resulting sample from grill brick is shown in Figure 15. The tests showed that the sampler would sample materials ranging from the weakest to strongest expected for a comet.



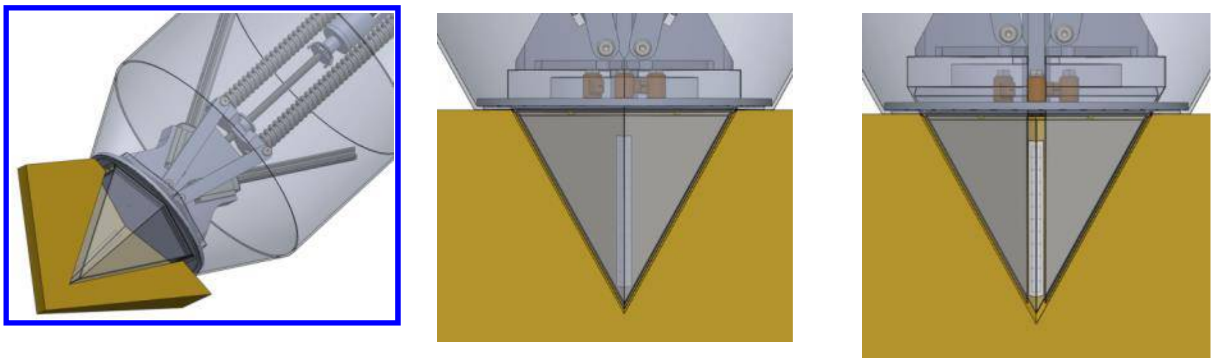
a) Overload springs absorb energy and protect mechanism when hitting hardest of material

b) Gripper just before grasping shuttle

c) Gripper grasped to shuttle

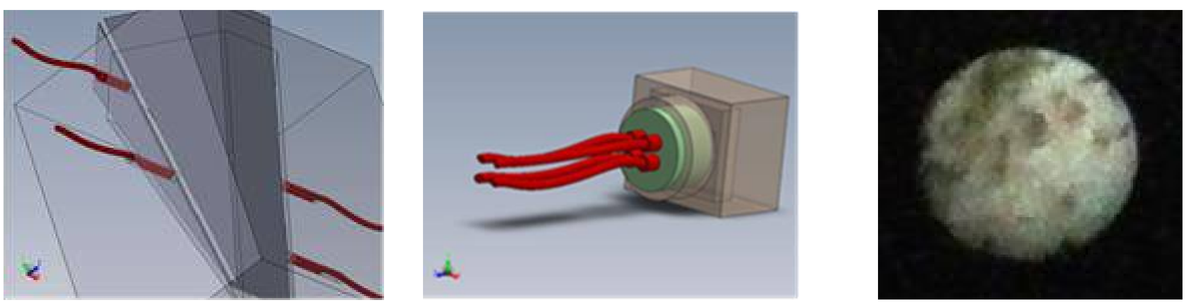
Figure 16: BiBlade prototype with overload springs, and grasping of shuttle

Extreme test cases were conducted with the prototype. First, the sampler was fired in the air to show that the tool could absorb the sampling energy if it was triggered accidentally before reaching the comet surface or if it sampled very weak non-cohesive material. Second, the sampler was fired at a cinder block to simulate hitting the strongest possible material (> 10 MPa). In all cases the sampler was undamaged. No sample was acquired from the cinder block, as expected, but the tests show that the sampler would not be damaged for any operational scenario and it could be used for subsequent sampling attempts.



Insert blades into sample measurement station chamber

Partially retract blades exposing the sample through slits



Capture images of the sample using fiberscopes

Transfer fiberscope images to a common camera

Image of salt and pepper captured with a 2.6 mm diameter, 6000 pixel resolution fiberscope

Figure 17: Sample measurement process using Fiberscope Sample Imager

B. Sample Measurement

The Fiberscope Sample Imager (FSI) system was developed to directly measure the sample. The robotic arm would insert the closed blades enclosing the sample into the sample measurement chamber on the spacecraft, as depicted in Figure 17. The blades would then be pulled back slightly, exposing the sample in the slits between them about 5 mm wide. Multiple (four shown here) fiberscopes along the walls of the measurement chamber would passively transfer views of the surface of the sample to a common camera which would acquire one picture that includes images from the fiberscope locations. The fiberscopes are highly flexible and robust to the thermal environment, and transfer the images to a camera which could be in a warm electronics box away from the measuring chamber. The sample would be illuminated by light emitted around the perimeter of the fiberscope optical elements. After sample measurement is complete, the blades would be closed and the robotic arm would remove the sample enclosed in the blades from the sample measurement station. If sample measurement is done in SRC sample chambers, then the sample would be immediately deposited there.

The acquired images provide direct measurement of the surface of the sample. It is assumed that there would be material internal to the sample. With the surface measurement and the assumption of material internal to the sample, the volume measurement would be made.

Fiberscopes of 3-mm diameter with integrated illumination would be implemented. These use custom-designed lenses with 5-mm to ∞ focus, FOV of 55° and 8X magnification. The fiber resolution would be 30,000 pixel elements with resolution equivalent to 170 x 170 pixel focal plane array (FPA). The images from all fiberscopes would be sent to a common camera via optical fibers of about 1 m length and with stainless steel (SS304) or polyimide jacket material. Fiberscopes of 3 mm diameter would be integrated with a single 12 mm x 12 mm image sensor to cast the partitioned images on the same FPA.

Measurements made using COTS fiberscopes of 2.6 mm diameter and 6000 pixel resolution optical fibers showed that the concept worked inside a cold refrigerator held at -50° C, a typical temperature that could be encountered inside the sample measurement chamber during a comet sample return mission. A calibration chart was imaged in three different conditions to evaluate the robustness of fiberscope to cold temperatures. Figure 18 shows three images of the same SFR (Spatial Frequency Response) chart at room temperature, -50°C, and back at room temperature. It can be seen that the images are almost identical with very slight blurring at cold temperature. This blurring is because of the unsuitability of lens holding epoxy used in these COTS fiberscopes. The custom fiberscopes would be made using low-temperature compatible lens cements. The SFR image shows that the scope is able to resolve 4 lp/mm or 250 μm line-space pattern.

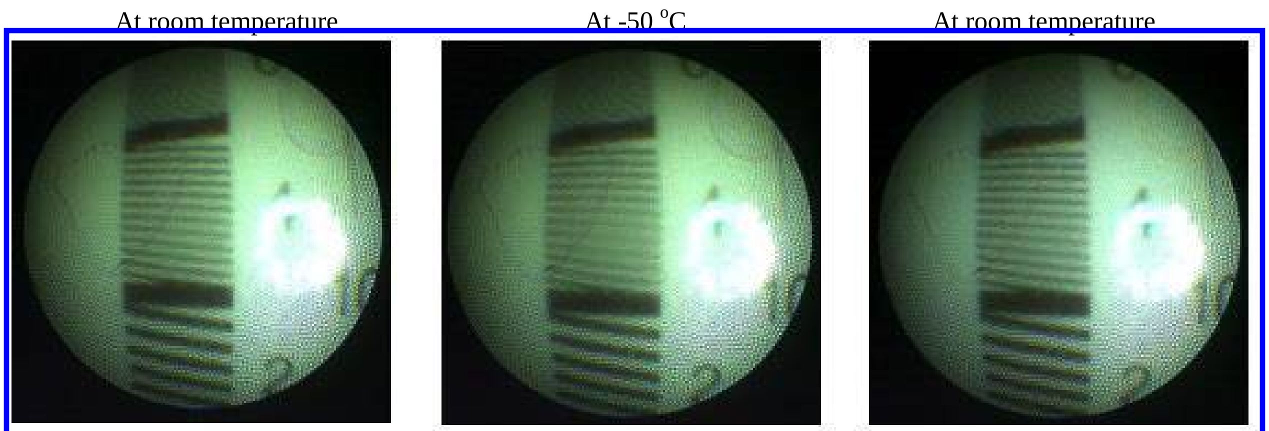
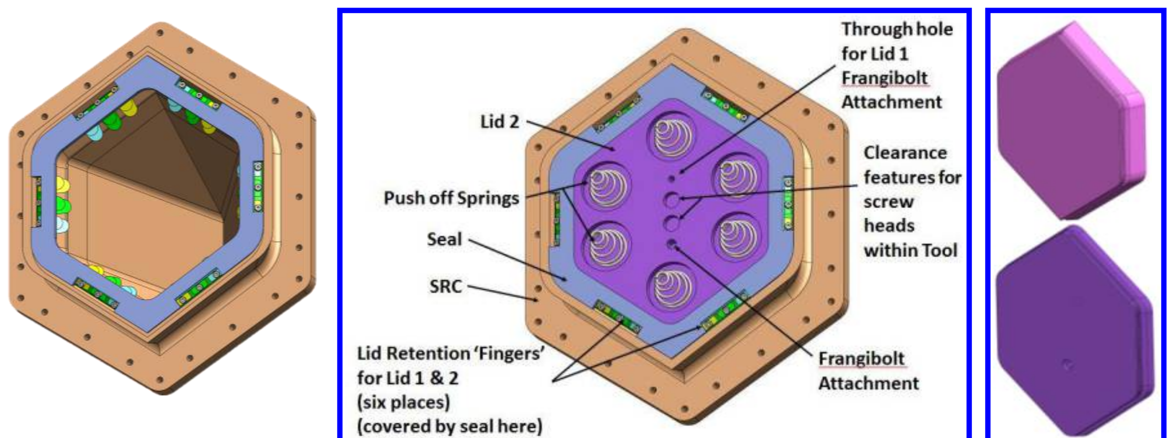


Figure 18: SFR chart image at room temperature, -50°C, and at room temperature again, as captured by a COTS fiberscope to show the possibility of resolution and use in cold temperatures of sample measurement chamber during sample collection.

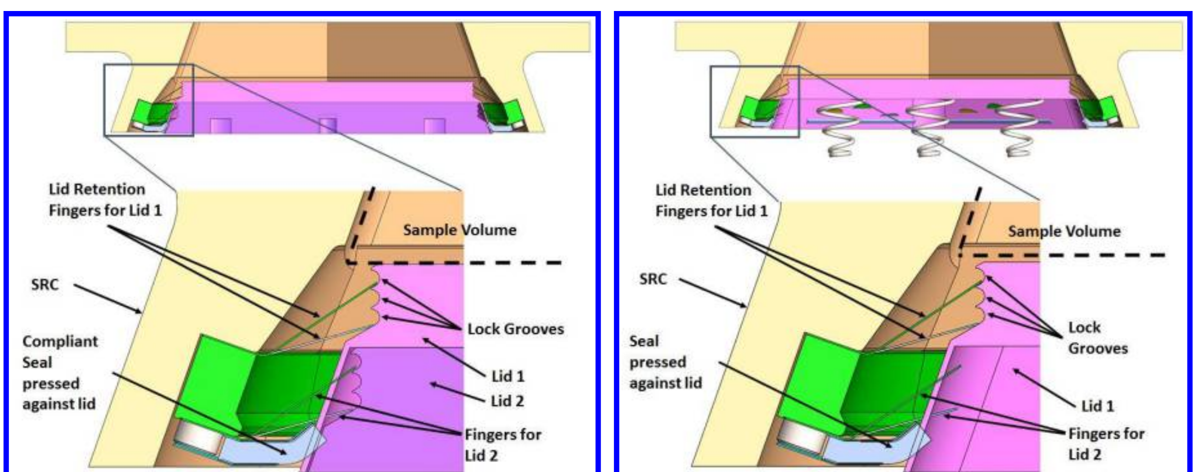
Lid release from sampler   Lid capture by SRC sample chamber

Figure 19: Sample transfer and retention in Sample Return Capsule sample chamber



Empty SRC sample chamber (one of two)   SRC sample chamber with lid 2   Lids 1 (top) and 2 (bottom)

Figure 20: Concept of Sample Return Capsule (SRC) sample chamber and lids



Inserting lid 1 into SRC sample chamber   Lid 1 released into SRC sample chamber

Figure 21: Inserting a lid into an SRC sample chamber

a) Approach SRC sample chamber
b) Insert sample into chamber
c) Fully retract blades
d) Trigger frangibolt to release lid (simulated with a screw in prototype)
e) Retract arm
f) Fully retract arm

Figure 22: Sample transfer into an SRC chamber using BiBlade prototype

C. Sample Transfer

To store a sample for return to Earth, the robotic arm would transfer the sample enclosed in the blades to the Sample Return Capsule (SRC) and insert the closed blades into an SRC sample chamber. The blades would then be retracted leaving the sample behind in the sample chamber. A lid attached to the sampler would be released and retained by the sample chamber lid retaining clips, thus retaining the lid as well as the now encapsulated sample in the SRC sample chamber, as depicted in Figure 19. The sampler would hold as many lids as there are sample return chambers. The nominal mission design is for return of two samples, so two sample chambers and two lids would be used. The lids are designed to be in a nested configuration so that either lid could be used with either of the sample chambers. The baseline design for releasing a lid from the sampling tool would be to use a frangibolt and a separation spring, as depicted in Figure 20 and Figure 21. There would be a set of separation springs between the first and second lids as well as between the sampler and the second lid. When the blades are inserted into a sample chamber, retention clips attached at the top of the chamber would be deflected out of the way by the BiBlade blades. The blades would then be retracted and the retention clips would spring back against the lid locking features, fully retaining the exposed lid (the tool would be stationary except for the blade retraction). A frangibolt would then release a lid from the sampling tool and a spring would separate the lid from the sampling tool. The lid would then be retained at the top of the sample chamber, also retaining the sample. The lid clips would be all around the perimeter of the lid to ensure that sample material could not escape from the sample chamber. A second seal would further prevent any sample material from leaking out of the sample chamber. The sample transfer process, demonstrated using the BiBlade prototype, is shown in Figure 22. In the prototype, the lid was released by unthreading a screw in place of using a frangibolt.

A sample could be rejected rather than stored when using the BiBlade sampler. To reject a sample, the robotic arm would extend the sampler away from the spacecraft and the blades would be fully retracted to expose the sample while the spacecraft thrusts away from the direction of the exposed sample. The spacecraft would then move

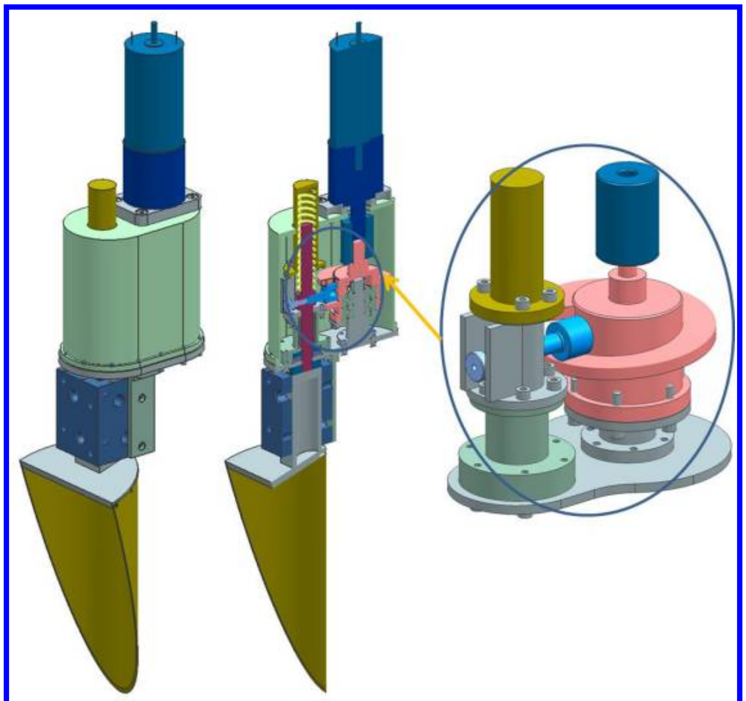


Figure 23: Design of the BiBlade percussive mechanism unit: isometric view (left), cross section (middle), and detail of the helical cam percussive mechanism (right)

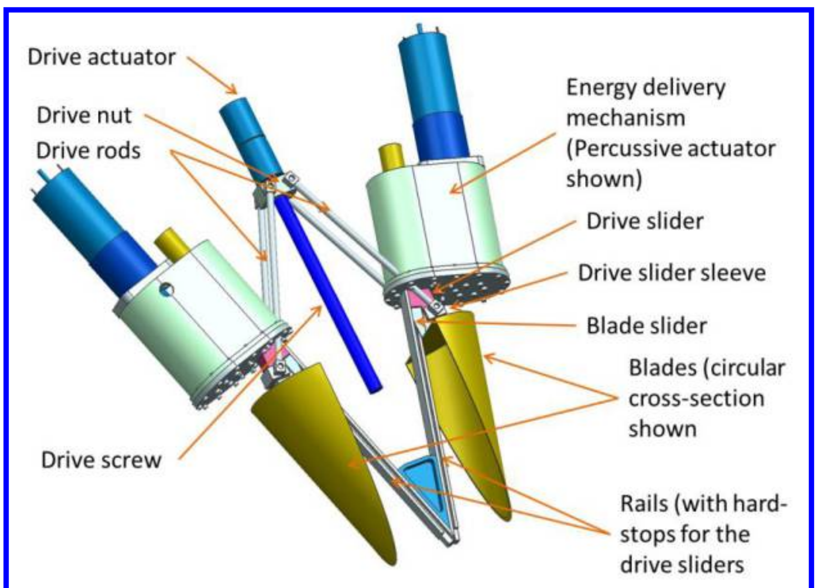


Figure 24: Preliminary design of the sampling tool using two percussive mechanism units and a linear drive actuator

away from the sample and then the blades would be closed. Any material that remained with the sampler would be combined with the subsequent sample.

D. Alternative BiBlade Designs

An alternative implementation of the BiBlade sampler concept was designed that would use percussive hammering as a penetration energy delivery method. The integrated tool with a preliminary design, shown in Figure

23 and Figure 24, is similar with the compression springs driven BiBlade sampler except that the compression springs have been replaced with two percussive mechanisms. The percussive mechanism uses a constant impact energy helical mechanism similar to that used in the drill developed for the Apollo missions. A set of sliders are

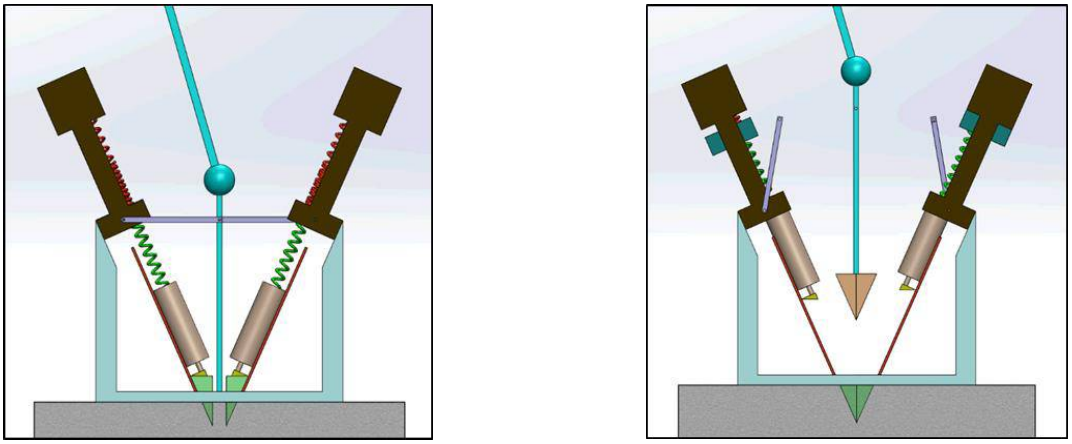
Figure 25: Percussive single blade unit

Figure 26: Percussive single blade unit testbed

attached to rails and controlled by a linear actuator using push rods. The blades and percussive actuators are attached to these sliders using an interface that allows limited axial motion to the blade. For sampling, the linear actuator preloads the blades against the sampling media and the percussive actuators hammer the back of the blade, significantly reducing required axial preload. A single blade unit is shown in Figure 25. One unit was fabricated and tested using the same blade as the spring driven BiBlade sampler implementation (Figure 26). Blade preload was 33 N, impact energy was 1.5 J per impact with a frequency of 12 Hz. The test media was the grill brick with about 300 kPa shear strength. The penetration time was 3 seconds and the sample volume was 275cc (550 cc per sampler which uses 2 blade units).

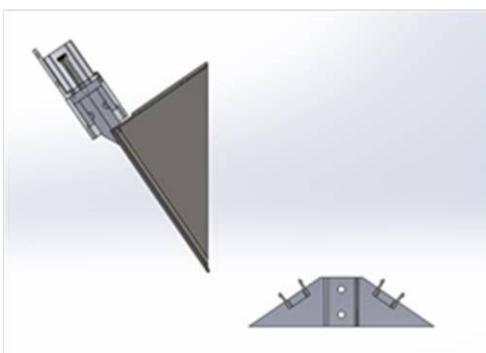
A dual-shell configuration of the BiBlade was also designed, built, and tested. The Dual-shell BiBlade has an inner and outer shell for each blade. During the sampling event, depicted in Figure 27 and Figure 28, the blades would be driven into the comet surface. At the completion of the sampling motion, the outer blades would be attached to a skirt that is initially attached to the sampler body, nominally using a ratcheting capture mechanism. The inner blades are attached to a lid, also via a ratcheting mechanism. After the sampling action is completed, the drive mechanism and skirt would be released from the deployment arm and the inner blades would be pulled away, attached to the robotic arm by the lid. The dual-shell configuration has the benefit that the motion of the sample canister, made up of the inner blades, is only relative to the outer blades and not relative to the comet surface, thus potentially improving the robustness of removal of the sample from the comet surface relative to the single blade BiBlade design.

A prototype of the dual-shell BiBlade was built and tested, as shown in Figure 29 and Figure 30. A passive ball-lock connected the inner and outer shells when they were driven into the sampling material. For the prototype, pneumatic cylinders were used to drive the blades into the simulant material; a different drive mechanism would be used for a flight implementation. After sampling, the ball-locks were retracted which passively released the inner and outer shells so that the inner and outer shells were no longer connected. The inner shells were attached to the lid via a ratcheting mechanism with spring steel in a circular pattern on the shell attaching to a ribbed post on the lid. The outer shells were attached to the skirt with a ratcheting mechanism. The integrated lid and inner shells with sample were then raised up by the simulated robotic arm.

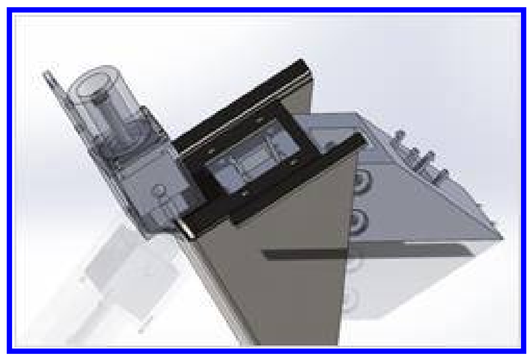


a) Dual-shell BiBlade during sampling b) Removal of inner sample canister

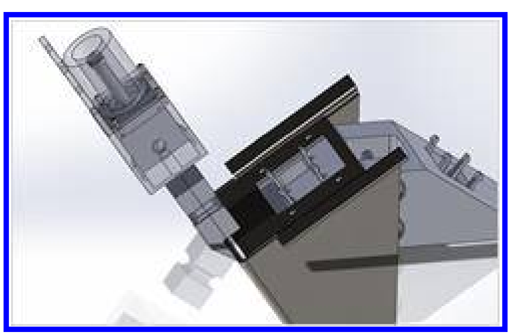
Figure 27: Dual-shell BiBlade concept during sampling and removal of inner sample canister



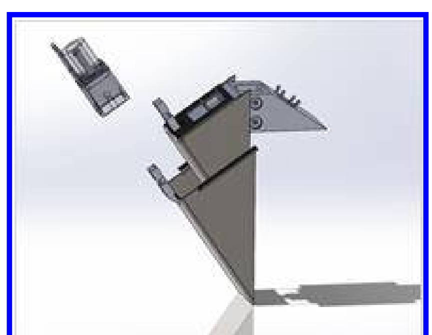
a) Sampler contacts surface



b) Blades drive into surface along linear rails; inner blades connect to lid, outer blades connect to skirt



c) Pull back and release ball-lock

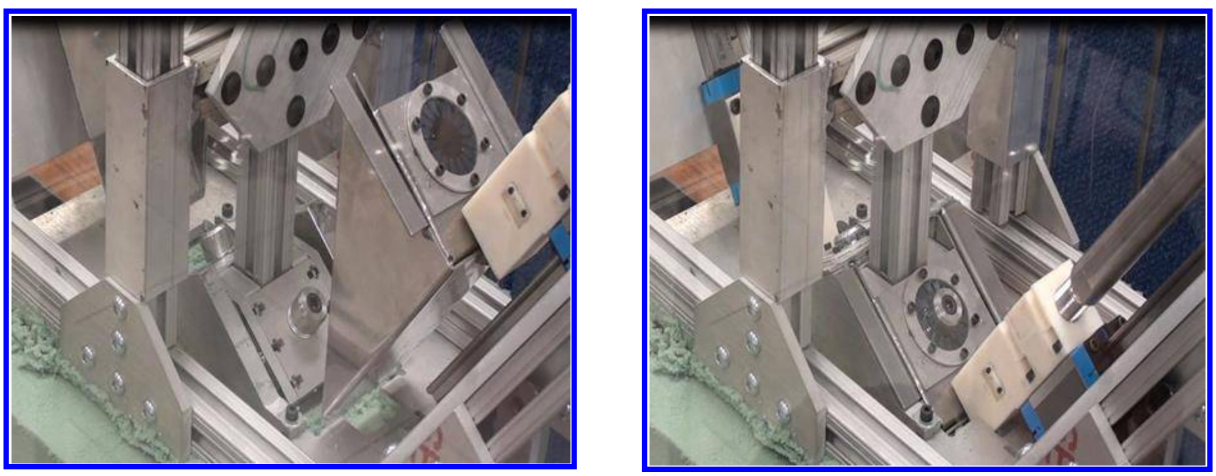


d) Pull sample canister (two inner blades attached to lid) up and out of outer shells

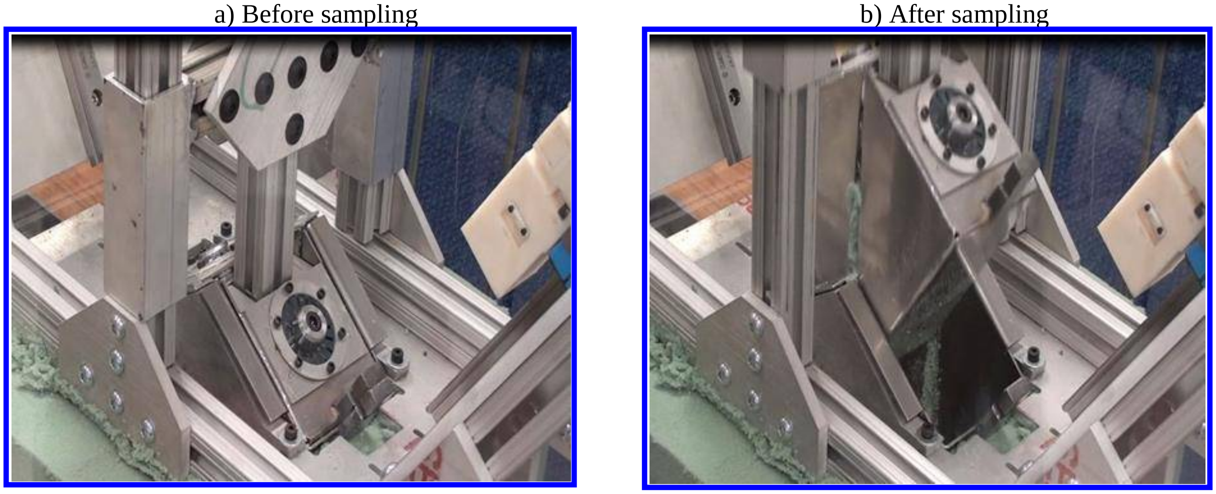
Figure 28: Dual-shell BiBlade operational steps

a) Test setup	b) Nested inner and outer shells	c) Acquired sample

Figure 29: Dual-shell BiBlade prototype



a) Before sampling	b) After sampling



c) Ball-locks retracted	d) Remove inner shells with sample

Figure 30: Dual-shell BiBlade sampling test

V. Conclusions

Three sampling tool concepts were described that are candidate sampling tools for a Comet Surface Sample Return mission in a touch-and-go mission architecture. The Reactionless Drive Tube provides a uniform cross section sample and minimized reaction force to the spacecraft. The Clamshell sampler provides a reduced complexity mechanism that acquires and retains the sample in one action. The BiBlade sampler also allows for low complexity and acquires and retains the sample in one action. Alternative configuration options were presented for the BiBlade concept and the Fiberscope Sample Imager concept was described that could provide direct sample measurement for a BiBlade sampler.

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References

[1] Vision and Voyages for Planetary Science in the Decade 2013-2022, Committee on the Planetary Science Decadal Survey, National Research Council, The National Academies Press, 2011.

[2] G. H. Fountain, et al., “Comet Surface Sample Mission Study”, SDO-11998, prepared for NASA’s Planetary Science Division, April 30, 2008.

[3] J. Richardson, H. Melosh, “An Examination of the Deep Impact Collision Site on Comet Tempel 1 via Stardust-NExT: Placing Further Constraints on Cometary Surface Properties,” Icarus 222 (2013) 492-501.

[4] J. Biele, et. al., “The Strength of Cometary Surface Material: Relevance of Deep Impact Results for Philae Landing on a Comet,” Eso Astrophysics Symposia 2009, pp 285-300.

[5] J. Biele, et. al, “The Putative Mechanical Strength of Comet Surface Material Applied to Landing on a Comet,” Acta Astronautica 65, 1168-1178 (2009).

[6] K-H Glassmeier, H. Boehnhardt, D. Koschny, E. Kuhrt, I. Richter, “The Rosetta Mission: Flying Towards the Origin of the Solar System,” Space Science Reviews (2007) 128: 1-21.

[7] Finzi et al., “SD2 - How to Sample a Comet,” Space Science Reviews (2007) 128: 281-299.

[8] D. Wegel, J. Nuth, “Rapid Sample Retrieval System (RASARS) for Comet Nucleus Sample Return,” International Workshop on Instrumentation for Planetary Missions, 10-12 October 2012, Greenbelt, MD.

[9] R. Lorenz, et al, “Demonstration of Comet Sample Collection by Penetrator,” Proceedings of the 5th IAA International Conference on Low-Cost Planetary Missions, pp. 387-394, 2003.

[10] M. Badescu, et al. “Dynamic Acquisition and Retrieval Tool (DART) for Comet Sample Return”, IEEE Aerospace Conference. 978-1-4673-1813-6/13, 2013.

[11] O.S. Barnouin-Jha et al. “Sampling a Planetary Surface with a Pyrotechnic Rock Chipper.” Proc. IEEE Aero Conf., 2004.

[12] Yano et al. “Asteroidal Surface Sampling by the MUSES-C Spacecraft.” Asteroids, Comets, Meteors, (2002).

[13] L. Lim, “OSIRIS-REx Asteroid Sample Return Mission,” 7th Meeting of the NASA Small Bodies Assessment Group, July 10-11, 2012, Pasadena, CA.

[14] R. Bonitz, “The Brush Wheel Sampler - a Sampling Device for Small-body Touch-and-Go Missions,” Proc. IEEE Aerospace Conference (2012).

[15] Drilling in Extreme Environments: Penetration and Sampling on Earth and Other Planets, Editors Y. Bar-Cohen and K. Zacny, 2009, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany.

[16] D. S. Burnett, B. L. Barraclough, R. Bennett, M. Neugebauer, L. P. Oldham, C. N. Sasaki, D. Sevilla, N. Smith, E. Stansbery, D. Sweetnam, R. C. Wiens "The Genesis Discovery Mission: Return of Solar Matter to Earth", Space Science Reviews, Vol. 105, pp. 509-534, 2003.

[17] D. E. Brownlee, P. Tsou, J. D. Anderson, M. S. Hanner, R. L. Newburn, Z. Sekanina, B. C. Clark, F. Horz, M. E. Zolenski, J. Kissel, J. A. M. McDonnell, S. A. Sandford, A. J. Tuzzolino, "Stardust: Comet and Interstellar Dust Sample Return Mission", J. of Geophys. Res., Vol. 108, E10, 8111, doi:10.1029/2003JE002087, 2003.

[18] J. Kawaguchi, H. Kuninaka, A. Fujiwara, T. Uesugi, "MUSES-C, Its Launch and Early Orbit Operations", Acta Astronautica 59, pp. 669-678, 2006, doi: 10.1016/j.actaastro.2005.07.002.

[19] R. Toda, H. Manohara, C. McKinney, S. Jackson, M. Mojarradi and A. Trebi-Ollennu, “Development of Sample Verification System for Sample Return Missions,” Proc. IEEE Aerospace Conference (2011).