Dynamic Acquisition and Retrieval Tool (DART) for Comet Sample Return

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Abstract

The 2011 Decadal Survey for planetary science released by the National Research Council of the National Academies identified Comet Surface Sample Return (CSSR) as one of five high priority potential New Frontiers-class missions in the next decade. The main objectives of the research described in this publication are: develop a concept for an end-to-end system for collecting and storing a comet sample to be returned to Earth; design, fabricate and test a prototype Dynamic Acquisition and Retrieval Tool (DART) capable of collecting 500 cc sample in a canister and eject the canister with a predetermined speed; identify a set of simulants with physical properties at room temperature that suitably match the physical properties of the comet surface as it would be sampled. We propose the use of a dart that would be launched from the spacecraft to impact and penetrate the comet surface. After collecting the sample, the sample canister would be ejected at a speed greater than the comet’s escape velocity and captured by the spacecraft, packaged into a return capsule and returned to Earth. The dart would be composed of an inner tube or sample canister, an outer tube, a decelerator, a means of capturing and retaining the sample, and a mechanism to eject the canister with the sample for later rendezvous with the spacecraft. One of the significant unknowns is the physical properties of the comet surface. Based on new findings from the recent Deep Impact comet encounter mission, we have limited our search of solutions for sampling materials to materials with 10 to 100 kPa shear strength in loose or consolidated form. As the possible range of values for the comet surface temperature is also significantly different than room temperature and testing at conditions other than the room temperature can become resource intensive, we sought sample simulants with physical properties at room temperature similar to the expected physical properties of the comet surface material. The chosen DART configuration, the efforts to identify a test simulant and the properties of these simulants, and the results of the preliminary testing will be described in this paper.

Keywords: comet sampling, DART, penetrator

Introduction

NASA is involved in a continuous work process with the broader scientific community, considers national initiatives, and the results of decade-long surveys by the National Research Council to define a set of space and Earth Science questions that can best be addressed using the Agency’s unique capabilities.
Regarding our solar system planets NASA has defined a set of four questions and the answers to these questions require studies of ancient meteorites, cosmic dust, and comets to provide clues to the processes operating in the early solar system, and actually allow dating of events over 4.5 billion years ago. These objects provide important clues in understanding the components that made up the dust and gas cloud from which the Solar System formed, and the processes that led to the formation of planets because they have changed little since the first few millions years of the Solar Systems existence. The 2011 Decadal Survey for planetary science released by the National Research Council of the National Academies identified Comet Surface Sample Return (CSSR) as one of five high priority potential New Frontiers-class missions in the next decade. The main objectives of the research described in this publication are: develop a concept for an end-to-end system that will collect and store a comet sample to be returned to Earth; design, fabricate and test a prototype Dynamic Acquisition and Retrieval Tool (DART) for collecting 500 cc sample in a canister and eject the canister with a predetermined speed; and identify a set of simulants with physical properties at room temperature that match the physical properties of the comet surface material as it would be sampled.

There have been previous technology demonstrations and missions to collect and return samples to Earth from other Solar System planetary bodies, each one with a different approach and results. In the Stardust mission, particles from the comet Wild 2 were captured at 6.12 km/s using aerogel located in a deployable tray, packaged in a sample return capsule and returned to Earth [Tsou, 2009]. JPL developed and tested the Brush Wheel Sampler (BWS) for surface sampling from primitive bodies [Bonitz, 2012] which has demonstrated up to 2 kg of sample acquisition and is anticipated to be robust in a broad array of anticipated surface conditions. GSFC's OSIRIS-REx SAM is designed to collect asteroid regolith sample and it has demonstrated collection of 60 grams or more of loose material in Earth and micro-g testing. However, it is unknown if it can acquire sample from a comet over the range of anticipated comet surface conditions. The JAXA Hayabusa mission intended to use a projectile and catch container to dislodge and acquire up to 10 grams of sample, but the projectile failed to fire and very few particles were actually collected during its impact with the 25143 Itokawa near earth asteroid. Lorentz led the development of a penetrator to acquire and encapsulate a sample from 20 MPa strength icy material at 190 K using an air gun and was able to collect a sample fraction of 0.5-1 of the expected amount by mass [Lorentz, 2003].

In the research that we are presenting in this paper we propose an architecture for collecting a sample from a cometary surface material while keeping the spacecraft at a prescribed distance away from the sampled body, potentially hundreds of meters. In this architecture a dart would be launched from a spacecraft, penetrate the comet surface, capture and retain the 500 cc of sample (possible 10 cm beneath the surface) in a sample canister that is then ejected from the comet surface into space. The spacecraft would then track and capture the ejected sample canister and store it in a temporary storage tray. The spacecraft would be able to launch multiple DARTs to enable redundancy within the sample collection system and provide for the opportunity to capitalize on varied scientifically interesting sample sites. The DART was developed in two versions: an actuated version and a passive version. The actuated version includes motors, electronic control and potentially a radio beacon. The passive sampler version uses only the inertial energy associated with impact to complete the sample collection process. The
description of the design, working principle, fabrication and test results of the DART prototype will represent the focus of this publication.

System Configuration description

The concept for a comet surface sample return mission that we are considering consists of the following elements: the spacecraft, multiple dart samplers with their associated launcher mechanisms, a canister collection horn, caching carousel, transfer arm, and the Sample Return Capsule (SRC) with internal canister vault, as shown in Figure 1.

The spacecraft is responsible for the proximity operations associated with the sampling system prior to launching the dart and following sample acquisition. Targeting the sampling location relies on the pointing accuracy of the spacecraft combined with accurate control of the vertical and horizontal velocities prior to launching the sampler. The sampler is spin-stabilized prior to launch to maintain orientation of the DART during flight and the spacecraft will follow a trajectory which effectively eliminates any horizontal velocity relative to the target in order to prevent an excessive angle-of-attack during impact. At a distance on the order of hundreds of meters from the comet surface, the DART launcher mechanism will launch the DART at its intended deployment velocity while the spacecraft (S/C) maintains minimal horizontal velocity in relation to the vertical component relative to the DART deployment velocity.

![Figure 1 System configuration architecture](image)

**Figure 1** System configuration architecture

Based on the primary requirements that the DART must be capable of obtaining 500 cc of sample in material approximately 10 cm deep, and also be capable of packaging within a representative SRC vault, the overall size of the dart can be determined based upon the energy relationship governing penetration performance. Using the simple approximation that the energy required to achieve a certain penetration depth is the strength of the material times the volume of material displaced, we were able to configure
the overall dimensions of the DART and estimate the performance within the range of estimated comet surface strength. With an estimated mass of 6 kg and a sampling drive tube sized to be 92 mm OD x 70 mm ID, we estimated full penetration depth can be achieved in the hardest estimated material (100 kPa) with an impact energy of at least 50 J. Conversely, we can dissipate 200 J in the weakest material (10 kPa) by allowing for 100 mm of additional penetration of a decelator flange that is 500 mm OD. A graph showing this design space for a specific geometric configuration is shown in Figure 2.

![Bounding Impact Energy](image)

**Figure 2 Bounding impact energy**

A concept has been developed for the DART launcher consisting of a simple spring-activated deployment system which will spin the sampler prior to release. Based on the energy requirements associated with penetration, the launcher must be capable of firing our 6 kg dart with a relative vertical velocity to the surface approximately 6 m/s, or about 8 m/s absolute with respect to the spacecraft, assuming it is traveling at 2 m/s. The decelator attached to the sampler body includes inertial masses to establish a primary axis about the axis of the sampler drive tube. The launcher is designed to impart the necessary angular momentum to promote stable flight. In this case, stable flight is characterized by the minimum possible wobble angle since wobble about the drive tube axis is the primary additional component to the angle-of-attack during impact. Using conservative assumptions regarding cross-axis angular velocity disturbances during deployment, based on our prototype 6 kg dart, spin rates on the order of 50 rpm are adequate for reducing the wobble angle, or angular deviation, to an acceptable level as shown in Figure 3. Further work is required to validate and refine the estimates of input energy in order to get a
better understanding of the requirements association with penetration into appropriate materials and consequently feed into the design of the launch mechanism.

![Graph showing maximum angular deviation of pointing vector](image1)

**Figure 3** Dart spin stabilization

After the sample is collected, the canister containing the sample is ejected from the dart body using energy stored within a set of compression springs designed to launch the sample canister at a velocity greater than the escape velocity of the comet. Once the canister is ejected, the spacecraft will visually acquire the canister and execute a trajectory to rendezvous with it. It is yet to be determined if a secondary locating radio beacon is necessary, but the sample canister is designed to accommodate a small electronics package that would house such a device. At the time of final rendezvous, the spacecraft acquires the canister by catching it within the body mounted canister collection horn. The horn acts to funnel the cylindrical sample canister into a preferred orientation. A load cell could be used to sense the contact event, at which point the horn captures the sample by way of a series of petals which close upon the canister and force it through the throat into the caching carousel.

![Diagram showing sample canister vault concept](image2)

**Figure 4** Sample canister vault oncept
Since the spacecraft safety can be maximized by creation of a safe flight trajectory for the sampling event and the DART sampler has been designed to minimize cost and complexity, the system can reasonably take multiple samples without adding significant risk to the overall mission. The sampling system will include multiple dart samplers to enable redundancy within the sampling chain as well as providing multiple opportunities to obtain a physically and scientifically acceptable sample. As each sample canister is retrieved it is held in the canister caching carousel until all samples are retrieved. At this point, the best two samples are determined and transferred to the canister vault in the SRC. The transfer to the SRC, will use a robotic arm with simple gripping attachment to move the canister from the caching carousel to the SRC vault (Figure 4). Thermal control of the sample will be provided by phase change material to maintain sample temperatures below the prescribed limit, estimated to be -20 °C, during reentry and final acquisition.

DART

Design description

In a DART architecture, a free-flying sampling device is deployed from the S/C and sampling uses the impact energy of the sampling tool; the sample is collected in a sample canister which is the ejected and rendezvous with the S/C which captures the sample canister. The sampling mechanism needs to be able to penetrate in a 10-100 kPa strength simulant, collect and retain 500 cc material, and eject the sample canister with a predetermined speed larger than the comet escape velocity. The system simplicity and architecture feasibility are attractive for a DART architecture.
The Dynamic Acquisition and Retrieval Tool (DART), shown in Figure 5, consists of an outer structure, a sample canister, an ejection mechanism, and a decelerator. The outer structure is cylindrical in shape with a sharp bottom edge and an upper flange. Its wall thickness houses the sample canister with the sample retention mechanism. This thickness dictates how much material is displaced during the penetration and this in turn will dictate the necessary energy for collecting the desired amount of sample. The outer structure provides interfaces for the sample canister, the decelerator and the ejection mechanism.

The sample canister is a 70mm inner diameter tube with a sample retention mechanism at the lower end and an interface for the locking and ejection mechanism at the upper end (Figure 6). The sample canister also provides the interface to the launching mechanism from the spacecraft. The outer face provides crowned guiding surfaces for sliding inside the outer tube during the ejection. The sample retention mechanism consists of an iris mechanism with a series of blades and two drive rings (Figure 7). The mechanism was adapted from an aperture solution for optical instruments and redesigned for sample cutting and retention. The blades are arc shaped and are housed inside the wall thickness. At both ends they have pins coming out of the blade’s plane in opposite sides. The drive rings include holes or radial slots for housing the blades pins and they need to be able to rotate relative to each other. In our design, one ring is configured as part of the sample canister tube and the other ring is floating. The floating ring is keyed to the outer ring. In this way, when the sample canister is rotated relative to the outer tube, the iris mechanism closes and cuts and retains the sample (Figure 8). Although not
implemented in our current prototype, a design modification has been identified that includes an additional spring which would keep the iris mechanism engaged against a compliant sample or a sample that does not allow the mechanism to fully close. The sample canister includes a gear, a groove and a shoulder at the upper end for interfacing with the ejection mechanism. The volume within this rear portion of the sample canister includes a smaller diameter cylinder for guiding the DART during the launch from the spacecraft, and available space for a simple electronics package containing a radio beacon for easier tracking by the spacecraft and rendezvous after ejection.

Figure 6  Sample canister

Figure 7  The iris sample retention mechanism components
The decelerator is a large diameter disk that prevents the DART from sinking into the comet when launched into a very soft material. In the implemented design configuration it could also be used as a dynamic stabilizer of the DART during the flight from S/C to the comet. The decelerator consists of ribs, balance masses, the web, and an interface ring. The balance mass is mounted on the tips of the ribs such that when this dart is spun and launched by the launch mechanism, the high spin inertia will provide spin stabilization. The decelerator could potentially be a deployable structure that opens after the dart has been launched from the spacecraft.

The ejection mechanism (Figure 9) includes a set of springs and a push plate for ejecting the sample canister and a set of two actuators and avionics for unlocking the sample canister and actuating the sample retention mechanism. The sample canister includes a set of two grooves that have a closed end and an open end in a slot. A roller is located in each one of the grooves and prevents the sample canister from being ejected from inside the outer structure. When assembly begins, the sample canister has the iris mechanism fully closed and has the slots aligned with the rollers of the ejection mechanism. While the sample canister is inserted into the outer tube, its flange presses against a push plate in the ejection mechanism. The push plate acts against a set of compression springs and compresses them.
against the outer structure flange. After reaching the predefined displacement the rollers align with the
grooves in the sample canister and the free floating ring of the iris mechanism engages the keys in the
outer structure tip. At this point the sample canister can be rotated until the rollers reach the closed
end of the grooves. This locks the sample canister inside the outer structure of the DART and
completely opens the iris mechanism.

When penetrating the comet surface the avionics inside the ejection subsystem detect the impact and
command the sample canister ejection. The first step in that sequence is rotating the sample canister by
the two actuators during which the iris mechanism is closed and the locking rollers advance in the
grooves toward the open end. The rollers reach the open end slot when the iris mechanism is closed,
retaining the sample inside the sample canister. The compression springs are now free to push the
ejection mechanism push plate away from the outer structure flange, extracting the sample canister
from inside the outer tube. The motion of the push plate is guided by the sample canister which in turn
is guided by the outer tube. When the springs reach full extension the push plate is retained inside the
ejection mechanism while the sample canister continues its motion away from the DART.

The ejection speed of the sample canister is calculated to exceed the comet escape velocity. In our
design we choose to use a set of small compression springs instead of a single large compression spring
as the single spring would interfere with the actuators and having a larger number of springs allowed us
to adjust the ejection speed by removing some of the springs. Each compression spring is guided on a
Teflon rod to prevent buckling during compression and avoid interference with the other springs. The
ejection mechanism also houses the instrumentation and control electronics for the actuators.

The primary goal of the dart design was to minimize complexity to provide a simple, cost-effective
system that was consistent with the desire to provide multiple, redundant samplers to maximize the
probability of obtaining the desired amount and quality of sample. To achieve this, the dart includes a
simple avionics suite consisting of representative elements that would be included in a flight-ready dart
assembly. A small COTS microprocessor (Pololu Baby Orangutan B-328) and accelerometer
(LSM303DL) provides the capability to monitor the impact acceleration resulting from the sampler
contacting the target surface and, then using that feedback, to activate simple motor driver circuitry to
power the actuators controlling the retention and canister release mechanisms. Power for the system is
provided by (2) Li-ion cells mounted within the housing to maintain a statically-balanced configuration.

Fabrication

Fabrication was started with using rapid prototyping to perform preliminary tests to bound some of the
design parameters values. These values were then used to size the DART prototype and understand the
sensitivities of the design parameters. Two of the parameters that would drive the rest of the design
were the outer diameter of the DART and the shape of the outer structure tip. Tests were proceeded
with two values for the outer diameter of 94 mm (prototype A, in Figure 10) and 124 mm (prototype B in
Figure 10) and two tip shapes: sharp and round (Figure 11). All tubes had the same 70mm inner
diameter. The sharp tips were built in two versions: 30 degrees half angle and 45 degrees half angle.
The radius of the round edges was half the wall thickness. Later, a third test prototype was fabricated
with an outside diameter equal to the full function prototype outer diameter (prototype C in Figure 10). Preliminary tests showed that, for the range of impact speeds necessary to collect 500 cc sample, the sharp tips performed better but the tip angle did not have a conclusive influence on the penetration depth.

![Figure 10 Built test prototypes](image)

![Figure 11 Prototype DART tips](image)

The full function DART prototype, shown in Figure 12, was designed using these design considerations and the ease of fabrication. The inner diameter was the same 70mm and the outer diameter was 106mm, having as the main driver the sample capture and retention iris mechanism. The dimensions of the DART launch guide cylinder in the upper section of the sample canister were driven by the launch mechanism. For ease of fabrication we selected aluminum alloy as the preferred material for the machined parts and Teflon for the sliding and rotating interface components. The number and size of the springs in the ejection mechanism were determined by the mass and the ejection speed of the sample canister and were selected from commercially available springs. The implemented solution to use one set of actuators to unlock the sample canister from inside the outer structure, actuate the iris mechanism and trigger the ejection mechanism determined the rotation of the sample canister under the continuous load of the ejection springs and so a larger torque actuators were required. Also, because the push plate of the ejection mechanism has a large diameter we chose to guide the sample canister /push plate assembly on the outer diameter of the sample canister during the acceleration phase of the sample canister ejection.
Test setup

The chosen simulant for demonstration was a floral foam with a shear strength of 25 kPa - a material readily available and with a strength within the limits that we were proposing to design. Given this material we were able to estimate a necessary impact energy in the order of 100 J and we could vary the test dart mass to accommodate dropping it from a height of up to 3 m. The guiding would be realized inside a 200 mm diameter PVC pipe and loading and releasing the dart would be done using a mobile work platform. In this configuration the decelerator cannot be accommodated but its DART stabilization function is performed by the pipe. The dart would be attached to a sliding sabot that would allow adding additional mass to increase the impact energy and spinning the dart to simulate dynamic trajectory stabilization (Figure 13). Most of the sabot components were fabricated using rapid prototyping. We recorded the tests using a high speed camera recording at 1200 frames per second and measured the penetration depth. After processing the video data we were able to determine the dart speed before the impact and later the sample canister ejection speed.
Test results

The test fixture allowed dropping the DART/carousel assembly from different heights and allowed the addition of more weight inside the carousel to adjust the impact energy level. The prototype versions A and B were meant to bound the design parameters and version C had the same outer diameter as the full function prototype DART. The floral foam simulant has shear strength of 25 kPa and very low compressive toughness. Although the data is scattered, the retained sample volume can be considered to vary linearly with the impact energy, as shown in Figure 14. This data suggests that the full function prototype required slightly more than 100 J of impact energy for collecting a 500 cc sample.

![Test setup](image)

**Figure 13 Test setup**

![Graph](image)

**Figure 14 Retained sample volume**
After assembly the full function DART prototype was tested in consolidated simulant (rectangular floral foam blocks) and unconsolidated simulant (1-5 cm size crumbs of the floral foam). For the 100 J impact energy and consolidated simulant the DART penetrated the predicted depth and collected the required volume of sample. The iris mechanism was able to cut the sample and retain it during the ejection. In the unconsolidated simulant, the DART made use of its decelerator plate to prevent it from completely sinking into the simulant bin. Although in its current configuration the iris mechanism leaves a 4 mm size hole at the center after fully closing, it was able to retain the sample in consolidated and unconsolidated forms.

Passive sampler

Passive sampling tools were also studied, and a prototype for one of the sampling tools was developed and preliminary tests were performed. The passive sampling tools provide mechanical only sampling and ejection of the sample canister. These sampling tools are applicable to both harpoon and dart mission architectures. The passive sampling tools that were studied had two primary architectures, hemispherical canister and square cross-section rectangular prism canister.

![Figure 15](image)

**Figure 15** Square face passive sampler

The rectangular prism canister sampler, called “Square-Face Sampler” here, is a momentum drive tube with segmented doors for closure, as shown in Figure 15. As a momentum drive tube, the sample canister is driven into the comet surface with a sufficient velocity to penetrate the comet surface and fill the sample canister. A decelerator plate (not shown in the figure), as described in the DART design, would ensure that the sampler stopped within a sufficiently short distance from the surface. A free mass would continue moving down relative to the sampler and push against the back of segmented doors which would then follow guides along the sides of the canister and slice through the comet material and close off the bottom of the sample canister. The free mass would then trigger the release
of springs which would eject the sample canister out of the outer canister. This sampler has most potential where the sampling tool is not spin stabilized, either for a Dart architecture where the sampling tool does not need to be spin stabilized, or for a harpoon architecture where the sampling tool does not spin.

Figure 16 Rack and Pinion Hemispherical Sampler

The Rack and Pinion Hemispherical Sampler, shown in Figure 16, acquires a hemispherical sample. Two quarter spheres cut through the comet material and enclose the sample with the top of the sample canister closing the opposite end. A free mass is attached to two rack gears, each of which is mated with a pinion gear on a quarter sphere. A decelerator plate (not shown) would decelerate the sampler when it hits the comet surface and the free mass would continue pushing down and would push the rack gears down which would force the quarter spheres to cut into the comet material and close. After the quarter spheres close, the free mass would then trigger the release of springs which would eject the sample canister out of the top of the outer mechanism. The resulting sample canister would look similar to the sample canister for the Bear-Trap sampler described below. The Rack and Pinion Hemispherical Sampler could be utilized for both spun and non-spun sampling systems. It could therefore be used with a Dart architecture which uses spin stabilization for alignment during transfer to impact with the surface or with Dart and Harpoon architectures which do not utilize a spinning sampling tool. A concern with this sampling tool is that the rack gears push into the comet surface with unknown affect for a spinning sampling tool.
The “Bear-Trap” sampling tool, shown in Figure 17, uses springs to force two quarter spheres to cut through the comet material and retain the sample. This sampler can be used as part of a spin stabilized Dart architecture sampling tool or a non-spin stabilized tool for a Dart or Harpoon system. A decelerator plate, shown at the bottom of the tool in Figure 17 right, decelerates the sampling tool upon impact with the comet. A free mass (brass colored in the figure), continues moving down relative to the decelerator plate and causes a pin to be pulled. The pin releases the two quarter spheres which then cut through the comet, or simulant in the tests, via the force of the internal torsional springs. The motion of the free mass then pulls two cables that pull pins on either side of the canister to release linear springs and push the sample canister out the top of the outer mechanism. The fabricated prototype was dropped from a height of about 1 meter onto comet simulant (floral foam with shear strength of about 25 kPa). The sampling tool worked as designed, with the decelerator plate stopping the motion, the free mass continuing down relative to the decelerator plate and releasing the pin to initiate closure of the quarter spheres for sampling and then releasing the pins to actuate the springs to push the canister out the top of the outer mechanism. For safety reasons, initial testing was done with weaker-than-designed torsional sampling springs so the quarter spheres only closed about 2/3 of the way. With the full-strength torsional closing springs, it is anticipated that the quarter spheres will fully close for comet simulants with properties across the expected range, as may be demonstrated with further testing.

Conclusions and future work

In this paper we present the development of a dart architecture for a possible comet sample return mission. The DART is intended to sample material with 10-100 kPa strength. It would be launched from the spacecraft from hundreds of meters distance from the comet body, penetrate the comet surface, capture and retain the sample in a sample canister, and eject the sample canister with a speed larger than the comet escape velocity. The sample canister is then tracked by the spacecraft and captured upon rendezvous. The spacecraft has the possibility to launch up to four darts and retain the ejected
sample canisters in an intermediate tray. After sample mass measurement two of the sample canisters can be selected and placed in a tray in the sample return capsule for return to Earth.

We performed preliminary analysis and selected a configuration that could be built and tested and be a viable candidate for a potential comet sample return mission. We tested a full function prototype in simulant at room temperature conditions and demonstrated its feasibility. An iris mechanism was selected and implemented as a sample retention mechanism. We demonstrated DART penetration, sample capture and sample canister ejection.

Research is underway for further testing in a wider range of simulants, further iris mechanism development, reduced load from the ejection mechanism on the actuators during the iris closing, and develop a model for estimating the impact energy necessary to collect the necessary sample volume for various sample characteristics and penetrator size.

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