Experimental Results with the BiBlade Sampling Chain for Comet Surface Sampling

Paul Backes, Scott Moreland, Harish Manohara, Jacklyn Green, Jesse Grimes-York, Mircea Badescu, Peter Vieira, Risaku Toda, Elizabeth Carey, Gregory Peters
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
Paul.G.Backes@jpl.nasa.gov

Abstract— **The BiBlade sampling chain has been developed for use in a potential Comet Surface Sample Return mission in a touch-and-go mission architecture. This paper describes the BiBlade sampling chain, an implementation of the system and experimental results. The system includes a BiBlade sampling tool, a robotic arm, a sample measurement system, a sample transfer system, and simulants.**

TABLE OF CONTENTS

1. 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] The BiBlade sampling chain was developed for use in a possible CSSR mission. This paper describes the BiBlade sampling chain, an implementation of the sampling chain, and experimental results with the system.

The BiBlade sampling chain was developed for use in a touch-and-go (TAG) mission architecture where a spacecraft would maneuver to several meters from the surface of a small body and deploy a sampling tool at the end of a robotic arm. The spacecraft would continue descent to the surface until sample tool contact when a sample would be acquired quickly and the spacecraft would thrust away from the surface of the small body. The BiBlade concept and several other TAG sampling tools were described in an earlier publication [3]. The CSSR mission concept and expected science requirements were described in the Decadal Survey and associated mission study [1,2].

The preliminary CSSR requirements from the Decadal Survey 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 ºC)

The CSSR mission study identified Group 2 Baseline Mission requirements which would be desired from a CSSR mission.

Group 2: Baseline Mission

- Capture evolved gases from the sample
- Return material from depth >= 10 cm, and maintain sample stratigraphy

Prior to results from the Rosetta mission, comet surface strength was estimated to be within the range of 1 – 100 kPa [4,5,6,7]. Rosetta mission results suggest that the comet 67P/Churyumov-Gerasimenko may have areas with surface strength as weak as on the order of 1 kPa compressive strength to as strong as above 2 MPa crushing strength [8,9].

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 take longer than for other mission architectures. The Philae lander of the Rosetta mission represents a lander mission architecture [7]. The Philae lander sampling drill, SD2, weighs 5 kg and was designed to 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 [10]. The drill was designed to penetrate material with strength ranging from fluffy snow to materials with a strength approaching a few MPa.

978-1-4673-7676-1/16/$31.00 ©2016 IEEE

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 [11]. 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 [12]. 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 [13] 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 would 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 a sample chamber [14,15]. Unfortunately, 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 [16]. 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 a 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 potential TAG architecture small body sample return missions [17]. 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 a Sample Return Capsule where it would be released. The BWS had the benefit of quickly capturing a large volume of sample.

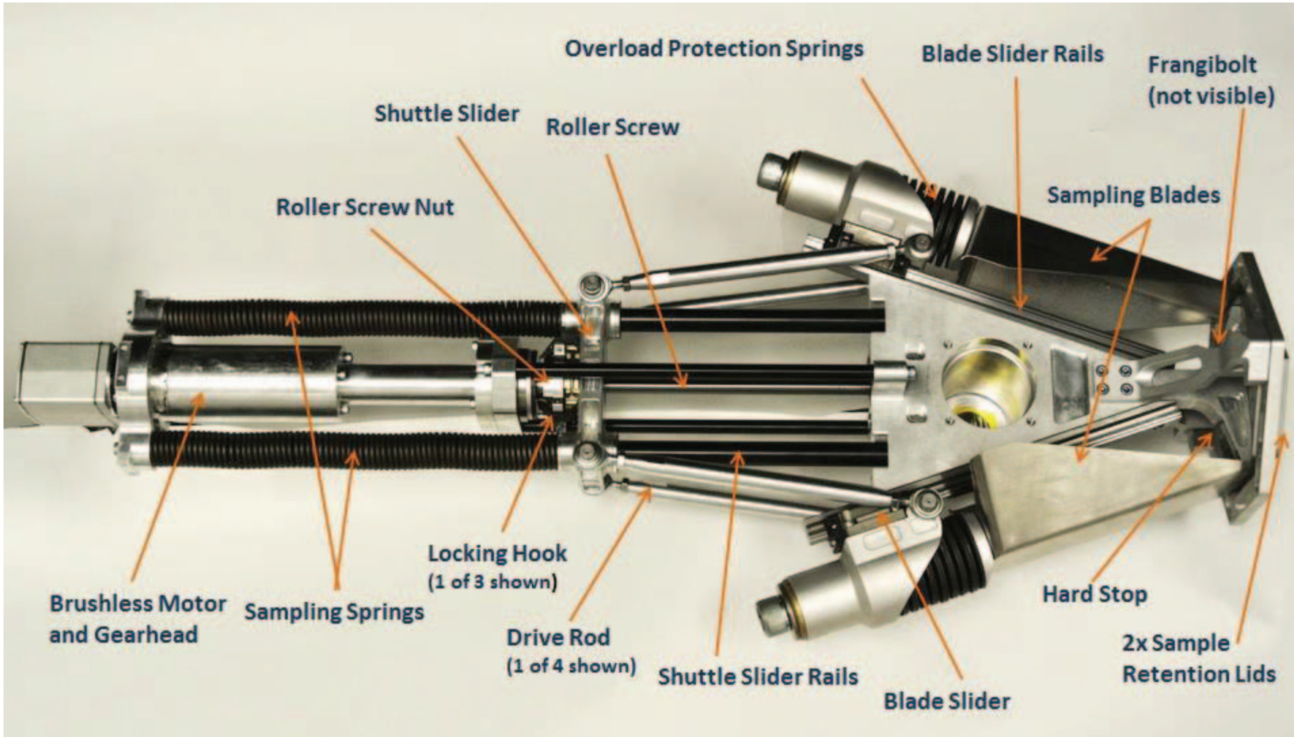


Figure 1. BiBlade design

Honeybee Robotics developed the Touch and Go Surface Sampler (TGSS) [18]. 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 leading to additional volume of material that must be displaced or crushed and the corresponding required sampling energy.

This paper describes an end-to-end implementation of the BiBlade sampling chain and experimental results using the system. Section 2 describes the BiBlade sampling tool. Section 3 describes the approach for sample measurement, and Section 4 describes experimental results with the end-to-end sampling chain.

2. BiBlade Sampling Tool

The BiBlade sampling tool is shown in Figure 1. Two blades would be driven into the surface using springs, with the sampling action completed in about 30 ms, 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 volume would be measured using a multi-fiberscope sample imager system and then the sample would be transferred to a sample chamber in a Sample Return Capsule (SRC). A lid stored on the sampler would then be released over a SRC sample chamber to encapsulate the sample. It is anticipated that a three degree-of-freedom (DOF) planar robotic arm would deploy the BiBlade sampler to the surface of the comet, and transfer the sample to the measurement station and a SRC sample chamber. The arm would be attached such that reacted forces during sampling would react through the spacecraft center of mass so sampling forces push the spacecraft away from the comet during the sampling event. The sample measurement process could be performed in either a SRC sample chamber or in a separate sample measurement station.

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. The tapered blades would facilitate removal of

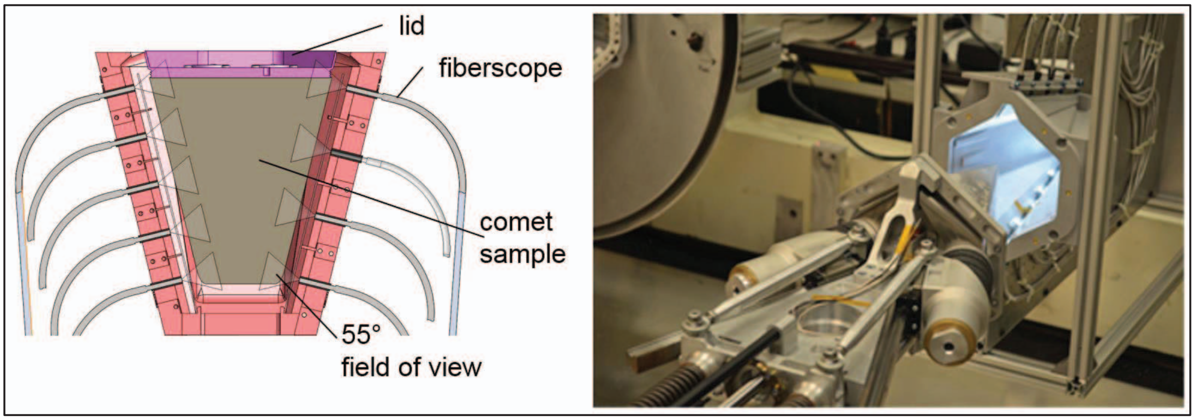


Figure 2. Sample measurement chamber design (left) and prototype implementation (right)

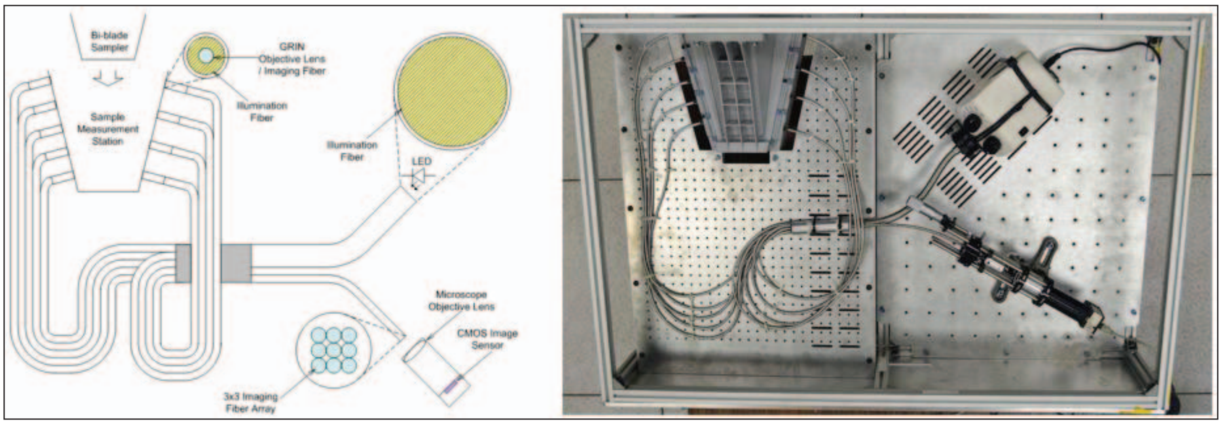


Figure 3. Sample measurement system design (left) and implementation for testing (right)

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 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 about 30 ms. 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 1. Two blades are attached to linear rails by blade sliders (ball bearing carriages). The blade sliders are connected to a shuttle slider using pushrods. The shuttle slides on two linear rails via bushings between compression springs and a rest location dictated by the blade hard-stops. 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 an additional rod. 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 travel, closer to the actuator.

In preparation for sampling, the gripper locking hooks would be connected to the shuttle and the actuator would pull the gripper with the shuttle back along the roller screw drive shaft. Prior to sampling, the roller screw would hold position of the shuttle just before end of travel with the springs in a fully compressed state. Upon sampling, full retraction of the actuator would cause the gripper locking 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 locking hooks grab the shuttle. When the sample is released later in the SRC sample chamber, the shuttle would be pulled back by the actuator, compressing the sampling springs as the blades open.

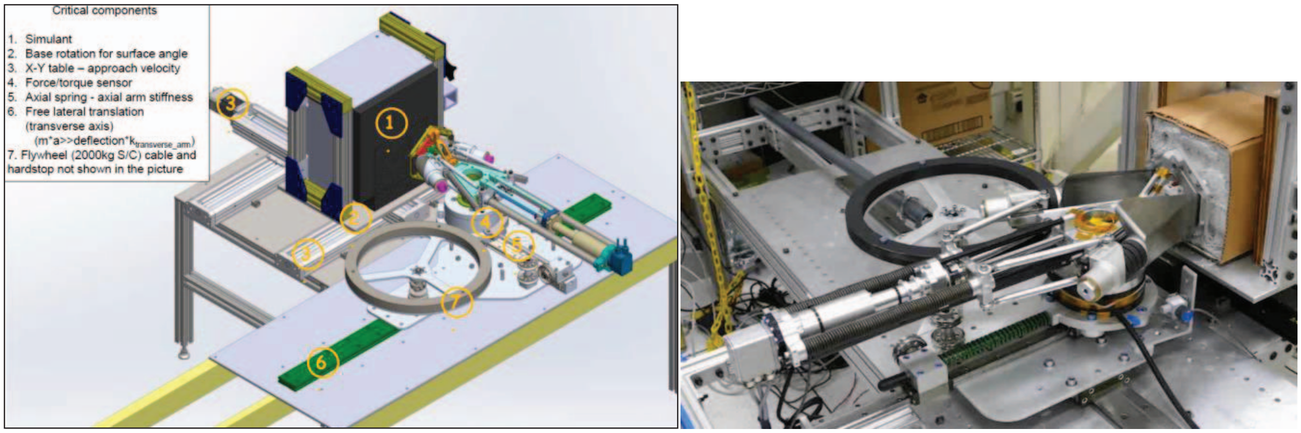


Figure 4. Sample acquisition testbed design (left) and implementation (right)

3. Sample Measurement

The Fiberscope Sample Imager (FiSI) system was developed to directly measure the sample. The robotic arm would insert the closed blades enclosing the sample into a sample measurement chamber on the spacecraft, as shown in Figure 2. The blades would then be pulled back slightly, exposing the sample in the slits between them about 5 mm wide. Nine 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 all of the fiberscope locations. The fiberscopes would be in a parallelized configuration enabling a single camera and light source. The fiberscopes are designed to be 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.

4. Experimental Results

Three testbeds were developed to test the sampling chain. The sample measurement testbed is shown in Figure 3. The sample acquisition testbed is shown in Figure 4, and the end-to-end sampling chain testbed is shown in Figure 5.

Performance results of sample measurement are presented in a companion paper [19]. The sample measurement testbed

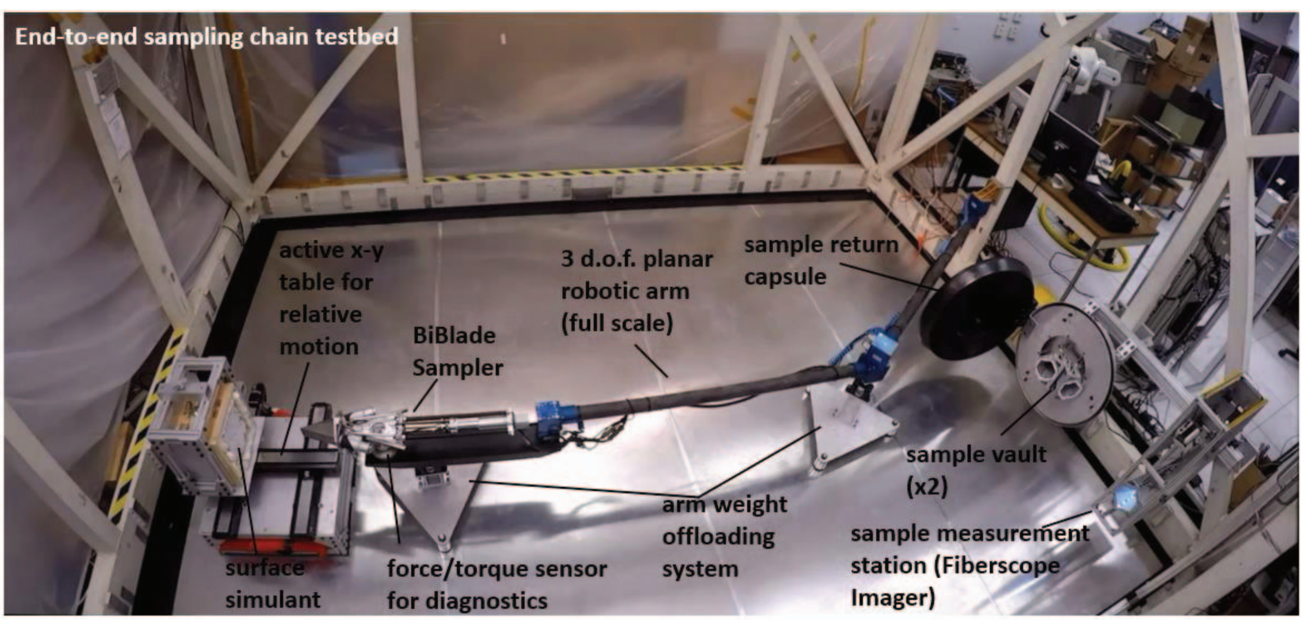


Figure 5. End-to-end sampling chain testbed

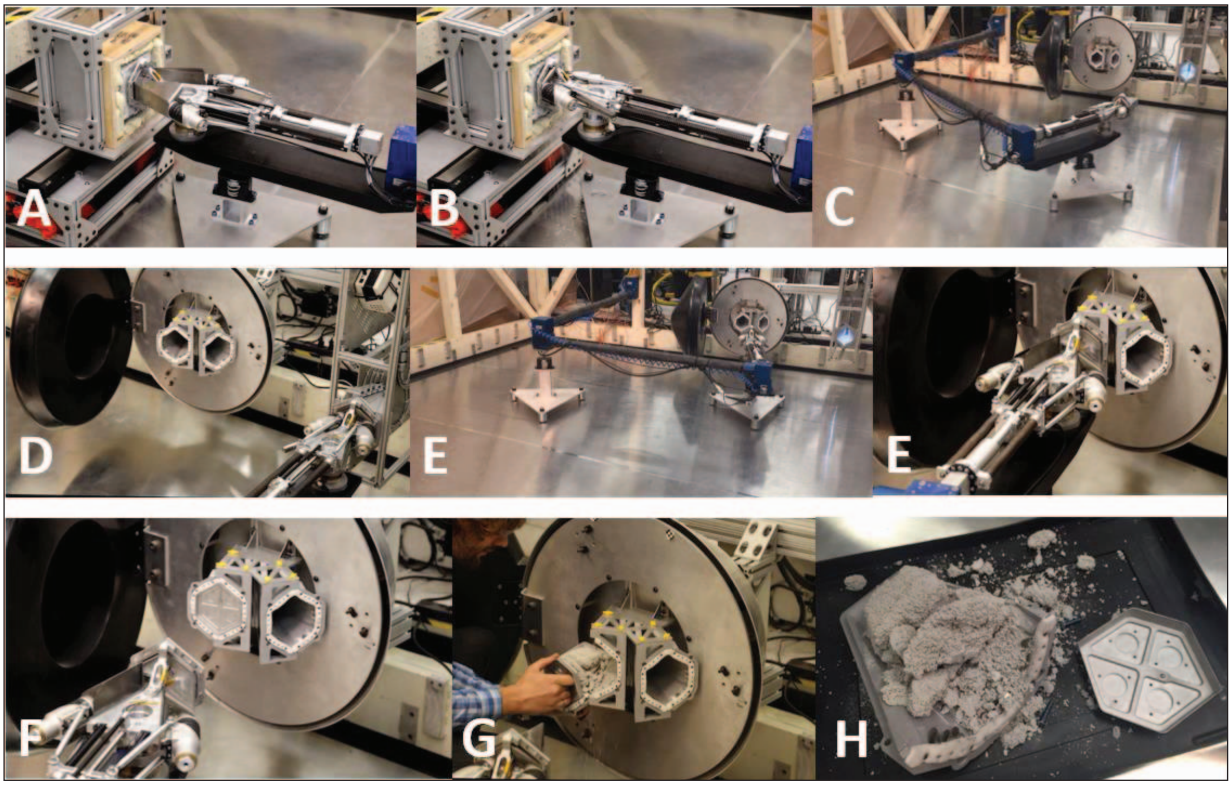


Figure 6. End-to-end sample chain sequence. (A) Sampler approach simulant with blades retracted (sampler springs energized). (B) Sampler blades triggered and rapidly close (~30ms) enclosing surface sample. (C) Robotic arm retract and insert BiBlade into Fiberscope Imager. (D) Image of sample inside blades acquired to verify fullness. (E) Robotic arm insert BiBlade into Sample Return Capsule (SRC) sample vault. (E) Blades retract leaving sample in vault and Frangibolt bolt breaker releases lid to seal sample. (F) BiBlade move away from SRC. (G) Opening of sample vault to show acquired sample. (H) Full sample of MPACS simulant acquired displayed.

was used for sample measurement performance testing. The sample measurement testbed was mounted in the end-to-end sampling chain testbed where the sample measurement step was performed, as shown in Figure 5.

The sample acquisition testbed (Figure 4) was constructed for the characterization of the BiBlade acquisition performance over a range of parameters expected to affect sampling. Parameters represented included simulant strength, surface angle, spacecraft approach velocity (axial and transverse) and tool mounting interface properties (reaction mass, axial & transverse arm stiffness). The

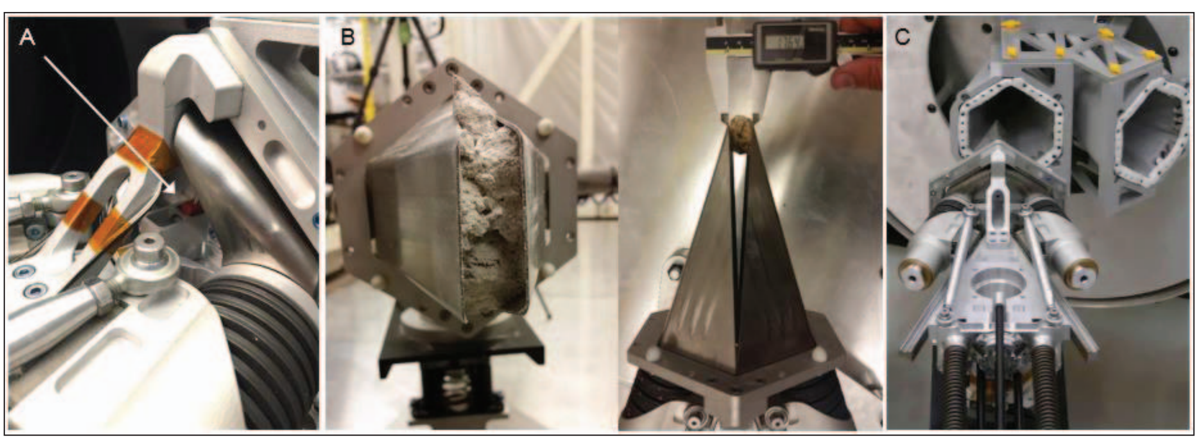


Figure 7. Robustness testing of sample transfer process/hardware. (A) Frangibolt actuation is included in the sample lid release. (B) Off-nominal samples are forced to test insertion and stowage robustness to extreme scenarios. (C) Positional error was intentionally commanded to evaluate limits of self-alignment during tool insertion.

testbed was equipped with a force-torque sensor to measure tool reaction loads and tool position/blade position transducers. A pulleys and wire rope driven fly-wheel was included to represent the reflected full spacecraft mass with respect to sampler reaction loads. A spring was included behind the tool base to represent robotic arm stiffness along the tool axis.

A suite of simulants were developed to represent a range of potential comet properties. A mix design called Manufactured Porous Ambient Comet Simulant (MPACS) was developed using Portland cement and pumicite combined and added to water and Varimax foaming agent. Strength properties were varied by changing the amount of Varimax added to the mixture. The MPACS material was developed for 4-inch cubic boxes or 8-inch cubic boxes for the BiBlade test program. Batches of comet surface simulant material were also produced for the purpose of testing their mechanical properties. Blocks of the simulant were cut into 2-inch cubes. Density, cone penetration resistance (CPR), uniaxial compressive strength (UCS), shear strength, and porosity were measured.

In support of the BiBlade test program, 110 eight-inch cubes of MPACS materials were manufactured. In addition, 50 eight-inch cubes, 50 four-inch cubes and 100 tubes of 1.5-inch diameter and 3-inch height were produced for mechanical testing purposes. The MPACS materials produced for the BiBlade test program were then installed in wooden boxes via expanding foam for easier handling and mounting in the testbed. Cone penetration resistance and density data were obtained on each test article before mounting them into the wooden boxes. This serves as a strength measurement reference for every simulant block produced. The MPACS materials suite used contains four strength ranges of materials from ~45 kPa UCS and ~0.5 MPa CPR of MPACS simulant A to 800 kPa UCS and ~22 MPa CPR.

The sample acquisition testing completed 50 tests, utilizing an MPACS simulant block in each test. Key findings of the Sample Acquisition test program are as follows. (1) The BiBlade sampling tool functioned as designed, demonstrating robustness to operational scenarios. (2) Arm stiffness and approach trajectory do not appear to affect sampling within the range tested. (3) Surface angle does not lead to increased sampling resistance but reduces sample volume. (4) Graceful degradation was observed while sampling in hard materials.

The end-to-end sampling chain was validated by performing end-to-end sampling chain tests as depicted in Figure 6. The BiBlade sampling tool was attached to a full-scale three degree-of-freedom planar manipulator arm. The simulant was mounted to the X-Y stage of the sampling testbed and the sample measurement testbed was mounted next to a representative Sample Return Capsule (SRC) which had two sample chambers. The arm positioned the sampler in the sampling configuration and then the X-Y table moved the simulant to the sampler, representing the spacecraft approach to the comet. Upon contact, the BiBlade blades were released and driven into the simulant by the sampling springs. The arm then transferred the sample in the blades to the sample measurement station (the sample measurement testbed) where it was measured, and then the arm transferred the sample in the blades into an SRC sample chamber. The blades were retracted to deposit the sample in the SRC sample chamber and a Frangibolt bolt breaker activated to release a lid from the front of the sampler and fixing it over the sample chamber.

Tests were performed to validate the robustness of the sample transfer process, as shown in Figure 7. Off-nominal samples were forced into the blades to test insertion and stowage robustness to extreme scenarios. Blade positional error of several centimeters was intentionally commanded to evaluate limits of self-alignment during tool insertion into the sample measurement station or SRC sample chamber.

Two additional types of tests were performed to validate end-condition functionality. The tool was successfully fired in the air validating that it could absorb the sampling energy without damage to the tool hardware. The tool was fired into a cinder block to validate that it would survive without damage when sampling the hardest possible material.

5. SUMMARY

The BiBlade sampling chain was validated in each of the end-to-end sampling steps in a laboratory environment. The sampler was mounted on a full-scale three degree-of-freedom manipulator to deploy it to the sampling, sample measurement, and representative Sample Return Capsule (SRC) sample chamber locations. Sampling was accomplished across a suite of simulants and operational conditions. Sample measurement was conducted in a sample measurement station. Sample transfer to the SRC was shown to be robust to positioning errors of several centimeters. The results indicate that the BiBlade sampling chain is a viable candidate approach to sampling for a potential Comet Surface Sample Return mission.

ACKNOWLEDGEMENTS

The research described in this publication was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA).

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] P. Backes, C. McQuin, M. Badescu, A. Ganino, H. Manohara, Y. Bae, R. Toda, N. Wiltsie, S. Moreland, J. Grimes-York, P. Walkemeyer, E. Kulczycki, C. Dandino, R. Smith, M. Williamson, D. Wai, R. Bonitz, A. San Martin, and B. Wilcox, "Sampling System Concepts for a Touch-and-Go Architecture Comet Surface Sample Return Mission," AIAA Space, 4-7 August 2014, San Diego, California.

[4] 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

[5] 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.

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

[7] 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.

[8] J. Biele, et al., "The Landing(s) of Philae and Inferences about Comet Surface Mechanical Properties," Science. 2015 Jul 31; 349(6247).

[9] T. Spohn, et al., "Thermal and Mechanical Properties of the Near-surface Layers of Comet 67P/Churyumov-Gerasimenko," Science. 2015 Jul 31; 349(6247).

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

[11] 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.

[12] 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, 24-26 September, 2003.

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

[14] O.S. Barnouin-Jha et al., "Sampling a Planetary Surface with a Pyrotechnic Rock Chipper." Proceedings IEEE Aerospace Conference, 2004.

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

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

[17] R. Bonitz, "The Brush Wheel Sampler - a Sampling Device for Small-body Touch-and-Go Missions," Proc. IEEE Aerospace Conference, 2012.

[18] 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.

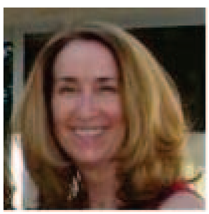
[19] R. Toda, et al., "FiSI: Fiberscope Sample Imaging System for Robotic Comet Surface Sample Return Missions," 2016 IEEE Aerospace Conference, March 5-12, 2016, Big Sky, Montana.

BIOGRAPHY

Paul Backes, Ph.D. *is the Group Supervisor of the Robotic Manipulation and Sampling group at Jet Propulsion Laboratory, California Institute of Technology, where he has been since 1987. He received the BSME degree from U.C. Berkeley in 1982, MSME degree from Purdue University in 1984, and Ph.D. in Mechanical Engineering from Purdue University in 1987. Dr. Backes received the 1993 NASA Exceptional Engineering Achievement Medal for his contributions to space telerobotics, 1998 JPL Award for Excellence, 1998 NASA Software of the Year Award Sole Runner-up, 2004 NASA Software of the Year Award, and 2008 IEEE Robotics and Automation Award. He has served as an Associate Editor of the IEEE Robotics and Automation Society Magazine.*

Scott Moreland, Ph.D. *received his B.S. degree from University of Toronto and his M.S. and Ph.D. degrees in Mechanical Engineering from Carnegie Mellon University. He joined JPL in the fall of 2013 as a member of the Robotic Vehicles and Manipulators Group. His work typically involves systems that interact with the ground either for mobility or sampling purposes. Of particular interest to Dr. Moreland is the development of traction devices for extreme surface materials and micro-gravity environments. His experience includes the design and fielding of robotic vehicles, mechanism/machine design and mechanical systems testing.*

Harish Manohara, Ph.D. *received the Bachelor of Engineering degree in instrumentation technology from the Bangalore University, India in 1989, followed by an M.S. degree in nuclear engineering in 1992, and a Ph.D. degree in engineering science in 1997 from the Louisiana State University, Baton Rouge, Louisiana. He joined the Center for Advanced Microstructures and Devices (CAMD) at the Louisiana State University as a Research Associate in January of 1997. In 1998, he became the Assistant Professor of Research at CAMD, and an Adjunct Faculty Member of the Department of Electrical Engineering. While at CAMD, he developed new X-ray microfabrication techniques. In November of 2000 he joined the Jet Propulsion Laboratory to develop advanced silicon and vacuum electronic devices for THz applications. Since 2005, he has been leading the Nano and Micro Systems (NAMS) group at JPL and has developed carbon nanotube field emitters, nanoelectronic devices, miniature spectroscopic instruments, and MEMS for space, defense, medical, and commercial applications.*



Jacklyn Green, Ph.D. *joined JPL as a planetary scientist, specializing in the thermo-mechanical properties and behavior of cometary nuclei. She received her Ph.D. from The University of Texas at Austin. She developed the Extraterrestrial Materials Simulation Laboratory at JPL, a one-of-a-kind laboratory for the research and development of planetary materials analogs. Additionally, she is a leader and systems engineer for advanced studies in space exploration. Currently, she leads the Advanced Design Engineering Group at JPL to conduct studies and model-based systems engineering for advanced mission concepts and technology developments in the Team X and A-Team environments.*

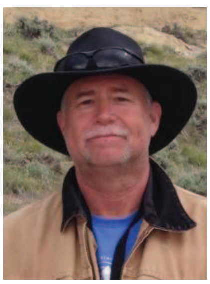
Jesse Grimes-York *joined the Mobility and Robotic Systems Section of JPL in 2013. He received his B.S. and M.S. degrees from Oregon State Univ. in 2011 and 2013, respectively, in mechanical engineering with an emphasis on machine design and robotics. His graduate work focused on the design, production, and assembly of a human scale biped robot with series compliant actuators for research into legged mobility with high energy economy while robustly walking and running. His undergraduate work focused on a robotic arm for a six wheeled, teleoperated rover that competed in, and won an international university level competition.*

Mircea Badescu, Ph.D. *is a Technologist at the NDEAA lab of the Jet Propulsion Laboratory. He joined JPL in February 2005 after serving as a Caltech Postdoctoral Scholar for a year. He received the Ph.D. degree in robotics in mechanical and aerospace engineering, from Rutgers University, in 2003. Prior to graduate school he worked for the Romanian Navy on the design of underwater diving equipment. He has experience on design integration of power ultrasonic piezoelectric devices, planetary and low gravity sampling systems, extreme environments devices, instruments for planetary exploration, optical components for telescopes, and optimal design of self-reconfigurable robots using parallel platforms as modules. He has experience in organizing and conducting field tests including glaciers, Antarctica, and desert. He has expertise on designing haptic devices for vehicular instruments control and automotive smart clutches. He is coauthor of 91 publications, 11 patents, 57 NTRs, and recipient of 39 NASA awards.*

Peter Vieira *joined the Robotic Manipulation and Sampling group at JPL in August 2014. Prior to joining JPL he completed his Master of Science in Electrical & Computer Engineering at Georgia Institute of Technology where he held a Graduate Research Assistantship, during which he was a main team member of their DARPA Robotics Challenge team, Hubo, and co-operated the robot during the semi-finals in Miami, FL. The focus of his Masters was robotics software and control systems. He gained significant hands-on experience with whole robotics systems which he applies in his current roles.*

Risaku Toda, Ph.D. *received a B.S. degree in Applied Physics and a Ph.D. degree in mechatronics and precision engineering from Tohoku University, Sendai Japan. He also received a M.S. degree in materials science and engineering from University of California Los Angeles. Prior to joining Jet Propulsion Laboratory, he worked for Ford Motor Company Japan Ltd. and a semiconductor/MEMS startup company in Texas. Since 2003, he has been with Nano and Micro Systems group at JPL. His research interests include fabrication of MEMS sensors, actuators and nanotechnology devices for aerospace applications. He holds several US patents.*

Elizabeth Carey *is a member of the Planetary Ices group at Jet Propulsion Laboratory. She joined JPL in August 2013 after completing a Master of Science degree in Physics from California State University, Northridge. Her graduate work focused on the morphology of vapor deposited ice into regolith under Martian conditions. Currently, she is the Research Lead of the Geo Analogs task for Mars2020 and is also involved with multiple laboratory experiments studying the thermal and mechanical properties of ices. Prior to joining Jet Propulsion Laboratory, she worked as a research assistant in the Mars Simulation Laboratory at California Institute of Technology while pursuing her B.S. Degree in Astrophysics from California State University, Northridge.*



Gregory H. Peters *is a member of the Geophysics and Planetary Geosciences Section at the Jet Propulsion Laboratory. Currently he is a Surface Sampling and Science (SSS) Scientist for the Mars Science Laboratory Mission and the Cognizant Engineer of the Geo-Analogs task for the Mars2020 Mission. Greg began working in the mining industry where he helped identify mining locations and managed the operations of mining and production facilities. In 1996 Greg founded Native Soil Research (NSR) where he created comet simulant materials for Comet Nucleus Sample Return (CNSR) under contract to JPL. In 2001, he became a JPL employee. Greg's work at JPL is centered on the development of planetary sample acquisition systems as well as the development of relevant planetary simulants. Among Greg's accomplishments include the development of the Mojave Mars Simulant Suite and he invented the RASP Tool used on the Mars Phoenix Mission, which allowed the historical first sampling of ice-laden permafrost on another planet. Greg holds two US patents and seven NTRs.*