Chapter 12
Asteroids: Anchoring and Sample Acquisition Approaches in Support of Science, Exploration, and *In situ* Resource Utilization

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12.1 Introduction

The goal of this chapter is to describe technologies related to asteroid sampling and mining. In particular, the chapter discusses various methods of anchoring to a small body (a prerequisite for sampling and mining missions) as well as sample acquisition technologies and large scale mining options. These technologies are critical to enabling exploration, and utilization of asteroids by NASA and private companies.

12.1.1 Types of Near Earth Objects

The term "asteroid" refers to any of a small class of solar system bodies that are in various orbits around the Sun. These include asteroids within the asteroid belt between Mars and Jupiter, asteroids co-orbital with a moon or planet (such as Jupiter's Trojans), and Near Earth Asteroids. In order to be more inclusive in this chapter, we also consider comets, and icy bodies with a wide range of orbital periods, ranging from a few years to hundreds of thousands of years. Comets are made up mostly of water, ice, and some dust particles, while asteroids are classified by their characteristic spectra, with the majority falling into three main groups: C-type (carbon rich), S-type (stony), and M-type (metallic). Both asteroids and comets fall within the larger category of "small bodies".

Near-Earth Objects (NEOs) are comets and asteroids that have been pulled by the gravity of nearby planets into orbits close to Earth. NEO asteroids are also referred to as Near Earth Asteroids, or NEAs in order to distinguish them from asteroids within the Asteroid Belt or Trojan asteroids. What makes NEOs very enticing is that they come close to Earth and could be within relatively easy reach for access by spacecraft. That is quite an important consideration given that traveling from Earth to the Asteroid Belt could take several years.

12.1.2 Motivations for Taking Samples from NEOs

NEOs are of interest to us for two reasons: for scientific study, and as a source of resources (Tsiolkovskii 1903; Lewis 1996). So far, all missions to NEOs were motivated by scientific exploration (Veverka et al. 2001; Yano et al. 2006; Glassmeier et al. 2007). However, given recent advancement in various space technologies, their value for resource mining is becoming of more interest. A significant portion of that value is derived from their location; the resources contained in NEOs do not need to be lifted from the surface of the Earth in order to be utilized in space. To help represent this, a new term was coined: *In situ* Resource Utilization (ISRU). ISRU facilitates planetary exploration by drawing needed resources, such as water, from the local environment. Comets and asteroids are therefore of great interest as a source of raw materials. Currently, the economics of extracting resources from these bodies, processing them *in situ*, and bringing the valuable material back to Earth is speculative. Whether this would be profitable or not depends on a number of assumptions which themselves are only based on expert opinions and not concrete data. Alternatively, there might also be some economic value in processing the resources *in situ* and using these processed resources in space rather than bring them to earth, but this is also quite speculative.

Assuming it will one day be profitable to mine, process, and use materials in space, asteroids can provide a great deal of resources. Raw materials from M-type asteroids could be used in developing various space structures. Water and carbon-based molecules from comets and C-type asteroids could be used to support life and in generating liquid hydrogen and oxygen for chemical propulsion to enable further exploration and colonization of our solar system. In addition, water offers shielding against galactic cosmic rays. Although the exploitation of asteroids has been discussed for a long time, only recently have private companies such as Planetary Resources and Deep Space Industries announced they aim to do this (Wall 2013).

Transporting water from the Near Earth Objects (NEOs) could be very profitable given that launch costs to Lower Earth Orbit (LEO) are on the order of $3,000-40,000/kg (Wilhite et al. 2012). Some major markets for water could include human consumption (e.g. International Space Station, Space Hotels) or refueling of spacecraft and satellites, but the only real sustainable market for water in space would be for chemical propulsion (LOX/Hydrogen). Water for human consumption can be mostly recycled, while water for fuel is a consumable.

Extracting water on Asteroids is much easier than processing metals. To extract precious metals in space new technology has to be developed that works in micro-gravity, and even potentially in vacuum. Terrestrial methods of mineral extraction require water, various chemicals, and gravity, and hence cannot be easily adapted to the space environment. Extracting water, however, only requires heating ice-bound regolith and capturing the produced water vapor – hence it is quite feasible to achieve with modest technology investment (Zacny et al. 2012a). From the resource extraction standpoint, the carbonaceous C-type asteroids are most desirable; as they contain a mixture of volatiles, organic molecules, rock, and metals (Gaffey et al. 2002; Lodders 2010).

There are at least two exploitation options for mining asteroids: either an entire asteroid could be captured and brought back to the Earth's or Moon's vicinity, or the desirable resource could be extracted and processed *in situ*. Whether to bring an entire asteroid or to process resources *in situ*, will depend on the size of the target asteroid. Smaller asteroids would be easier to capture, de-spin and bring to earth's vicinity while large asteroids would either have to be entirely processed *in situ* or only a fraction of the asteroid could be returned. In addition, very large asteroids or smaller M-type asteroids are more likely to survive atmospheric entry and impact earth because they are less likely to break up in the atmosphere. A recent study found that it is feasible to capture, de-spin, and bring to high lunar orbit, a 7 meter diameter asteroid weighing in excess of 500 metric tons. Such a mission would cost approximately $2.6B and would not require any new technology development (Brophy et al. 2012). Another study concluded that it is also possible to retrieve a 2 meter diameter asteroid to the International Space Station (Brophy et al. 2011).

A capture and return mission is attractive as an early asteroid resource exploitation mission. Having an asteroid in Earth's proximity would allow testing and verification of various material processing technologies. In addition, visits by astronauts could be conducted on a weekly, rather than annual basis and various autonomous or telerobotic technologies could be further demonstrated and improved upon. Once all the required technologies for an industrial scale asteroid mining operation have been developed and validated it might be more cost effective to send asteroid miners and refiners to various targets and only bring back the processed material.

In addition to private investment, national priorities also influence the pace of asteroid exploration. In 2010, President Obama directed NASA to get astronauts to a NEA by 2025, and then on to the vicinity of Mars by the mid-2030s. To reach these destinations, NASA has been developing the largest rocket since Saturn V called the Space Launch System, as well as a crew capsule called Orion. The SLS-Orion system is scheduled to begin launching astronauts in 2021 to a yet to be determined asteroid. This heavy launch capability will also enable launching larger asteroid mining missions.

12.2 Past Missions

Table 12.1 summarizes space missions to small bodies to date, including their cost (where available), and science returned. Missions highlighted in the table are missions which included surface operations. It can be seen that science returned per dollar is relatively low and after spending billions of dollars we still do not know much about the majority of asteroids. In addition, out of over a dozen missions to asteroids and comets, only two managed to touch the surface: the Near Earth Asteroid Rendezvous (NEAR) and Hayabusa missions. These two missions are described in more detail in the sections following. Three other missions: Rosetta (en route), Hayabusa 2, and OSIRIS-Rex (currently under development), also plan to perform *in situ* operations.

Table 12.1 Overview of small bodies missions to date, along with mission cost and results

Mission and Body visited	Agency, Launch Date	Mission Description (relevant to small bodies)	Cost, if readily available.
International Cometary Explorer (ICE)	NASA, 1978	Carried an X-Ray spectrometer and a Gamma burst spectrometer. Flew through the tail of the Giacobini-Zinner comet, and observed Halley's Comet from afar.	$3 Million ops-only add-on to an existing mission.
Vega 1 and Vega 2	SAS, 1984	Gathered images of Halley's Comet after investigating Venus.	
Sakigake	ISAS, 1985	Carried instruments to measure plasma wave spectra, solar wind ions, and interplanetary magnetic fields. Made a flyby of Halley's Comet.	
Suisei	ISAS, 1985	Carried CCD UV imaging system and a solar wind instrument for a flyby of Halley's Comet.	
Giotto	ESA, 1985	Carried 10 instruments to explore Halley's Comet, and provided data despite taking damage. Went on to explore comet Grigg-Skjellerup as well.	
Galileo	NASA, 1989	Carried 10 instruments. Flew by 951 Gaspra and 243 Ida, discovered Ida's moon Dactyl, and witnessed fragments of the comet Shoemaker-Levy 9 crash into Jupiter.	$1.6 Billion

Table 12.1 (*continued*)

Mission and Body visited	Agency, Launch Date	Mission Description (relevant to small bodies)	Cost, if readily available.
Near Earth Asteroid Rendezvous (NEAR) Shoemaker	NASA, 1996	Characterized asteroid Eros using imagers, spectrometers, a magnetometer, and a rangefinder. Although not originally planned to do so, NEAR-Shoemaker landed on Eros.	$220.5 Million
Deep Space 1	NASA, 1998	Carried technology experiments. Flew by asteroid 9969 Braille and comet 19P/Borrelly.	$152.3 Million
Stardust	NASA, 1999	Carried instruments for imaging and dust analysis. Flew by asteroid 5535 AnneFrank, comet Wild 2, and comet Tempel 1. Returned sample material from comet Wild 2.	$199.6 Million
Comet Nucleus Tour (CONTOUR)	NASA, 2002	Carried instruments for imaging, spectrometry, and dust analysis. Spacecraft was lost.	$135 Million
Hayabusa	ISAS, 2003	Landed on the asteroid Itokawa and returned sample material to Earth.	$170 Million
Rosetta	ESA, 2004	Flew by asteroid 2867 Steins and 21 Lutetia. Observed Deep Impact. Mission plans to put a lander on comet 67P/Churyumov-Gerasimenko.	~$1.2 Billion
Deep Impact	NASA, 2005	Carried instruments for imaging and spectrometry. Hit the comet Tempel 1 with an impactor and observed the collision. Will continue to study comets and asteroids as the EPOXI mission.	$330 Million
Dawn	NASA, 2007	Carries an imager, spectrometer, and gamma ray and neutron detector. Currently observing the asteroid Vesta, plans to move on to the asteroid Ceres.	$446 Million

Table 12.1 (*continued*)

Mission and Body visited	Agency, Launch Date	Mission Description (relevant to small bodies)	Cost, if readily available.
Hayabusa 2	JAXA, 2014 (planned)	Plans to create an artificial crater on asteroid 1999 JU3and return samples that have not been exposed to sunlight and solar winds.	$367 Million
OSIRIS-Rex	NASA, 2016 (planned)	Plans to study C-type asteroid 1999 RQ36 and bring >60 grams of surface sample back to Earth.	$750 Million

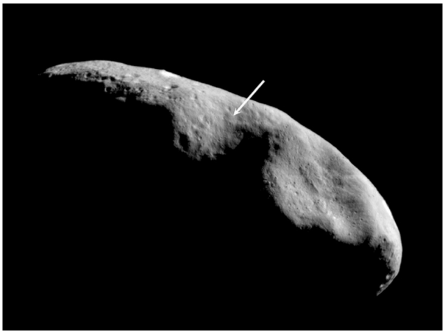
Non-contact instruments provide great scientific value, but they are no substitute for contact instruments, or a returned sample. So much more can be learned if the mission can land a spacecraft and analyze samples *in situ,* or even more importantly, bring the samples back to Earth. Terrestrial laboratories allow far more analysis capability than can be packed into a spacecraft's payload. In addition, these returned samples can be studied by future generations with technology that has not been invented yet. Anchoring and sample acquisition are critical technologies enabling *in situ* exploration of small bodies.

12.2.1 Near Earth Asteroid Rendezvous (NEAR) Shoemaker

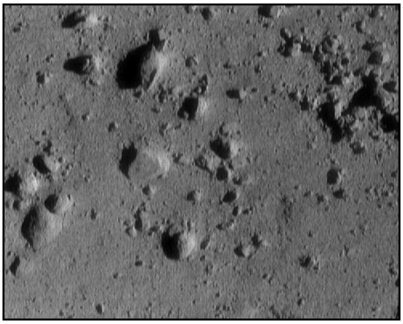
The Near Earth Asteroid Rendezvous (NEAR) Shoemaker spacecraft (Veverka et al. 2000) was not originally planned to make physical contact with an asteroid. It was at the end of its life when the mission team decided to take the risk of making a soft landing on the surface of *433 Eros.* If something went wrong (i.e. the spacecraft crashed, or damaged its fragile solar panels and protruding antennae) there would have been relatively few negative repercussions since the mission had already completed its intended goals.

The spacecraft was successfully brought to a 1.9 m/s touchdown on the rocky surface and demonstrated that soft landing on an asteroid is possible (Veverka et al. 2001). Fig. 12.1 shows the final resting place of the NEAR Shoemaker spacecraft on asteroid *433 Eros*. Note that from a distance of 200 km, it is very difficult to resolve any surface details. The second image taken from a distance of only 250 m above the surface revealed the surfaces covered in fine regolith with protruding rocks.

This lack of *a priori* knowledge of the surface conditions presents a significant challenge to missions intending to touch down or sample asteroids. For known surface conditions, the sample acquisition equipment can be tailored to deliver the highest probability of success within the mass, volume, and power constraints of the spacecraft. For unknown surface conditions, the sample acquisition equipment cannot be as effectively tailored. If the NEAR Shoemaker mission had required landing and surface operations (e.g. sample acquisition) as part of its baseline, it would have been quite difficult to decide which anchoring system to use. Selecting and developing an anchoring system that would work in any formation is extremely difficult. If a harpoon were to be used, there is some chance that it might have hit one of the rocks, bounced back and impacted the spacecraft, damaging its solar panels, antennae or structures. If the anchoring system used some type of grippers, they would have been unsuitable for loose soil.



The location of NEAR Shoemaker's landing site from an orbital altitude of 200 kilometers (see the tip of the arrow). Mosaic of images 015246034-015246840. Courtesy NASA/JHU/APL.



NEAR Shoemaker's image of the surface taken from a range of 250 meters. The area imaged is 12 meters (39 feet) across. The cluster of rocks at the upper right measures 1.4 meters (5 feet) across. Image 0157417133. Courtesy NASA/JHU/APL

Fig. 12.1 Images of the asteroid 433 Eros taken by the NEAR Shoemaker spacecraft

12.2.2 Hayabusa

The second asteroid landing was performed by the Japanese Aerospace Exploration Agency's (JAXA) Hayabusa spacecraft. Its target was the S-type asteroid 25143 Itokawa. Hayabusa was launched towards its destination in 2003, rendezvoused, landed, and collected samples in 2005, then returned samples to Earth in 2010 (Kawaguchi et al. 2008). The spacecraft did not perform a sustained landing, but rather performed touch-and-go surface operation. During the brief surface encounters, the sampling system acquired approximately 1500 grains, mostly smaller than 10 microns.

Hayabusa also carried a tiny mini-lander named "MINERVA" (MIcro/Nano Experimental Robot Vehicle for Asteroid). However, MINERVA was released at a higher altitude than intended while the Hayabusa spacecraft was ascending. As a result, the MINERVA lander escaped Itokawa's gravitational pull and tumbled into space (Normile 2005).

Currently JAXA is developing a follow-on mission named Hayabusa 2 to investigate and sample asteroid 1999 JU3.

12.3 Current and Future Missions

Table 12.1 includes two missions that are currently under development: Hayabusa 2 and OSIRIS-Rex. These two missions share a common goal: Acquire sample material from an asteroid, and return that material to Earth. Another sampling mission is the Rosetta mission. The spacecraft already been launched and will acquire subsurface samples from a comet for *in situ* analysis. These missions are further described in the sections that follow.

12.3.1 Rosetta

The objective of the Rosetta mission is to rendezvous with comet 67/P Churyumov-Gerasimenko and acquire scientific data via an orbiting spacecraft and Philae lander (Biele et al. 2002). The 96 kg Philae lander will be the first spacecraft ever to make a soft landing on the surface of a comet nucleus. When it touches down on the comet, the Rosetta lander will use three different techniques to absorb the impact of the landing and secure itself to the surface. As shown in Fig. 12.2 and 12.3, these three techniques are self-adjusting landing gear, harpoons, and ice screws in the landing pads (Ulamec et al. 2006). These three techniques are employed in rapid succession: First the self-adjusting landing gear absorbs the energy of impact, then the ice screws engage the (possibly soft) surface, and finally the harpoons engage the (possibly hard) surface.

Initial fixation of the lander to ground will be achieved by deploying three passive “ice screws”, or one in each foot of the spacecraft. The initial impact energy from the <1.5 m/s descent should be sufficient to push the screws into ground. Each of the ice screws is coupled via a cable mechanism to the two feet of the self-adjusting landing gear in such a way that half of the impact force is led to the ice screw and the other half is equally distributed to the two feet, that can move independently (up or down) of each other.

Upon touchdown, the default harpoon will fire automatically and penetrate up to 2.5 m into cometary surface. Immediately after the firing, the cable will be tightened up to 30 N in 8 seconds. The 30 N is well below the rewind cable system strength of 100 N and the anchor cable breaking strength of 330 N. An identical second harpoon is used as a back-up in case the first harpoon fails to secure the spacecraft to the surface.

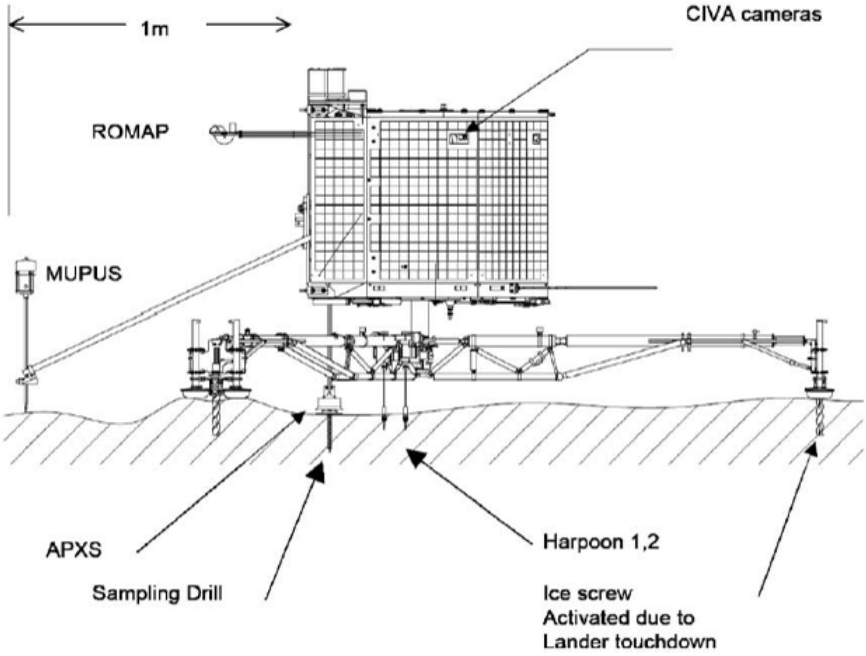


Fig. 12.2 Rosetta Philae lander (Biele et al. 2009)

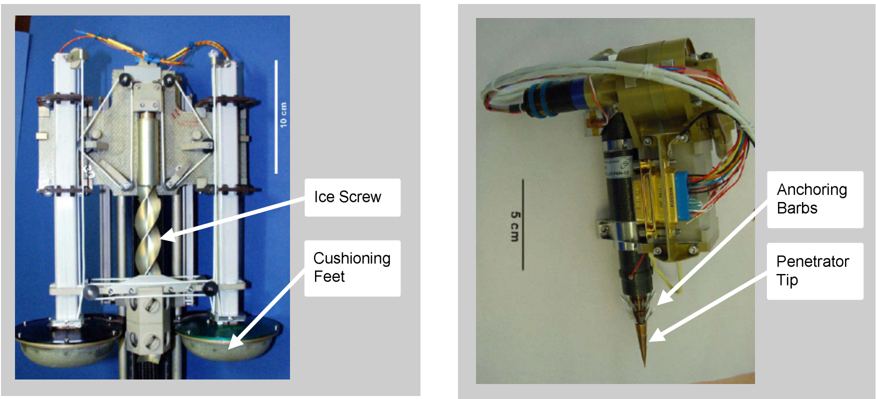


Fig. 12.3 Philae ice screw (left) and harpoon (right). (Biele et al. 2009).

The harpoon design uses both a sharp point and shovel flukes in order to ensure acceptable anchoring in surfaces that have both high tensile strength and low density. The point can penetrate the icy surface of the comet, which is expected to have high tensile strength, and the shovel flukes will develop holding power in the low-density material beneath this crust.

It should be noted that ice screws will not be able to penetrate hard material, while harpoons' anchoring effect will be negligible in very soft material. This dual anchoring approach aims to address the challenges associated with a lack of knowledge of comet surface properties by including anchoring mechanisms suitable to a range of surface types.

12.3.2 OSIRIS-REx

Figure 12.4 shows the Apollo asteroid 1999 RQ36. The asteroid is a potential Earth impactor with a mean diameter of approximately 500 meters. Data acquired from observations by the Arecibo Observatory Planetary Radar and the Goldstone Deep Space Network suggest that the asteroid might impact the Earth during one of its 8 close encounters between 2169 and 2199, with a probability of an impact of 0.07% or less (Andre et al. 2009).

This asteroid is the target of the OSIRIS-REx mission (OSIRIS-REx 2012). The goal of the mission is to return surface samples to Earth for further study. Asteroid 1999 RQ36 has been selected as the mission's target not because of its relatively high probability to impact the Earth, but rather due to the low ΔV required to reach it. The spacecraft is scheduled to launch in 2016, reach the asteroid in 2019, and return samples to Earth only in 2023, 7 years after the launch.

The mission will not land on the asteroid. Instead, the sampler will be deployed from a long and slender robotic arm, approach the surface at 0.1 m/s, fluidize regolith using gas and collect sample in approximately 5 seconds. The pneumatic sampler looks like an automobile air filter; a minimum of 60 grams will be trapped inside the filter part while some powder will also get stuck to the sticky surface of the sampler. After acquisition, the sampler will be inserted into the earth return capsule – the same design used on the Stardust mission.

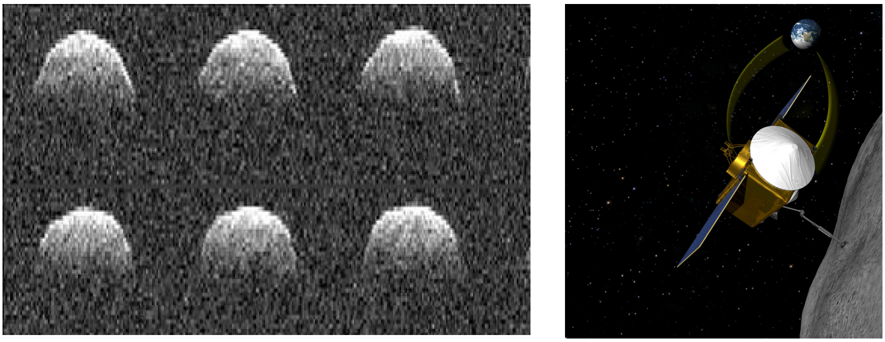


Fig. 12.4 OSIRIS-REx asteroid sample return mission. Left: Doppler imagery of the asteroid target: 1999 RQ36 (NASA's Goldstone Radar). Right: OSIRIS-REx spacecraft. The spacecraft will employ a "touch and go" sampling approach.

It is interesting to note that $750M is being spent to go to an asteroid about which relatively little is known. That is quite risky of course, but this is a reality of Asteroid missions: we do not know much until we get there. The sampling mission must to be able to perform successfully on a range of potential surface materials.

12.3.3 Hayabusa 2

Hayabusa 2 is a successor spacecraft to Hayabusa, with a similar goal of bringing samples back to Earth from asteroid 1999 JU3, a carbonaceous or C-type asteroid (Kawaguchi 2008; Campins et al. 2009). Hayabusa 2 would launch in 2014 or 2015, arrive at the asteroid in 2018, conduct a series of investigations and operations as shown in Fig. 12.5, and then return to Earth towards the end of 2020. Hayabusa 2 will create an artificial crater by striking the asteroid with a copper plate accelerated by explosives, and then sample the freshly exposed material from the floor of the crater. This more pristine material is scientifically valuable in that it has not been exposed to sunlight and solar winds.

Hayabusa 2 is more ambitious than the original Hayabusa mission. It will carry three landers to the asteroid instead of one carried by Hayabusa. The first two are based on the detachable MINERVA lander that was developed and built for the first Hayabusa mission, but missed the asteroid surface and drifted off into space. The third lander is called MASCOT (Mobile Asteroid Surface Scout). It is a standalone lander developed by the German Aerospace Center (DLR).

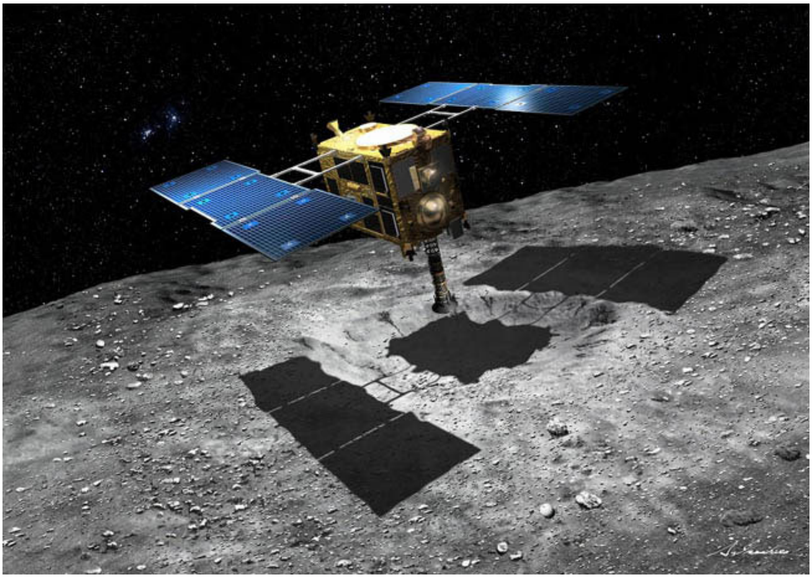


Fig. 12.5 Concept of Japan's Hayabusa 2 spacecraft. Hayabusa 2 would hurl an impactor into the asteroid 1999 JU3, sample the exposed crater material and bring it back to earth. Credit: JAXA/A. Ikeshita. http://www.space.com/14759-asteroid-sample-mission-hayabusa-2.html

Hayabusa 2's copper impactor will be deployed from the spacecraft and slam into the asteroid to create a large crater. To prevent potential damage of the spacecraft by the crater ejecta, Hayabusa 2 will hide on the other side of the asteroid during the impact, while a deployed standalone camera will record the impact. Two samples will be acquired prior to the impact event, then Hayabusa 2 will attempt to land at the fresh crater and acquire a third sample for transport back to Earth.

12.4 Small Bodies Surface Environment

Due to the close proximity required to detect surface features, most of the information we have about surface features and surface properties of small bodies comes from the past missions that visited these small bodies. In particular, from the Deep Impact (DI) mission we learned that the surface of the comet Mathilde is highly porous, with porosity estimated to be around 60% (Figs. 12.6 and 12.7). The shear strength of the surface soil was also found to be very weak, in the range of 1-10 kPa (Richardson et al. 2007). That presents a challenge to any anchoring system, since the spacecraft has to anchor itself to something that has consistency of fluffy snow or flour.

The Rosetta mission's Philae lander is tasked with anchoring itself and then sampling a comet 67P in 2014. It will use its harpoons and ice screws to anchor itself in an environment where a local gravity on the surface is of the order of 3×10^{-4} m/s^2. It has been estimated that the nominal bulk density of 67P is 100-370 g/cc with an upper limit of 500-600 g/cc. (Hilchenbach et al. 2004). For comparison purposes, the density of freshly fallen snow is 160 g/cc and that of compacted snow is 480 g/cc.

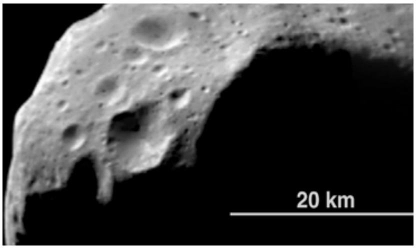


Fig. 12.6 hock dissipation is evident in craters formed in porous materials. The large craters on the porous asteroid Mathilde (a C-Type Asteroid) are packed closely together with little evidence of shock-induced disturbance of adjacent craters. (Images courtesy NASA).

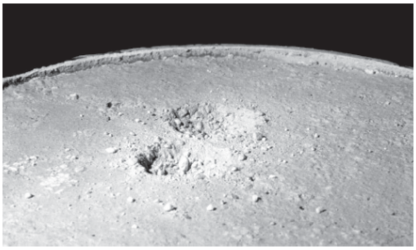


Fig. 12.7 material with porosity of 60%. Images of the first crater (furthest from camera) before and after the second impact showed no noticeable damage caused by the second impact, even though the crater rims were nearly touching. This means that the porous material efficiently damps the shock pressure (Britt et al. 2002).

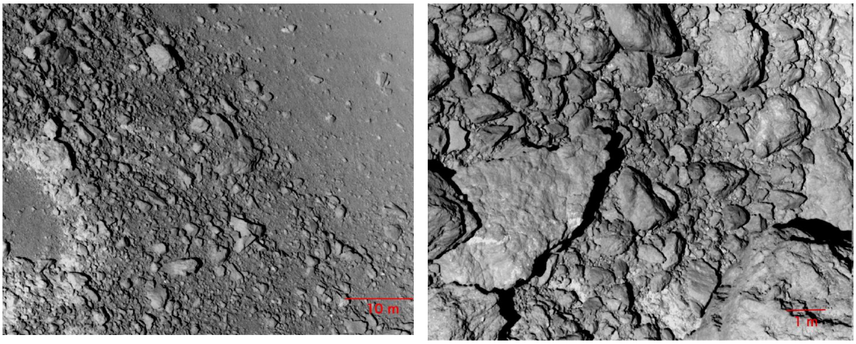


Fig. 12.8 Itokawa (S-type asteroid). Note the scale bars in bottom right. (Images courtesy of JAXA).

The Hayabusa spacecraft took pictures of the Itokawa S-type asteroid as shown in Fig. 12.8. This example demonstrates that the surface properties of asteroids are quite variable: ranging from fluffy powder, and loose gravel, all the way to solid rock. Itokawa is now considered to be a "rubble pile" body because of its low bulk density, high porosity, boulder-rich appearance, and shape. The presence of very large boulders points to the early collisional breakup of a preexisting parent asteroid (Fujiwara et al. 2006). It is quite clear that due to the high variability of the surface terrain, a spacecraft attempting to anchor itself to the asteroid Itokawa would face different challenges depending upon its actual landing site.

12.5 Anchoring Concepts for Small Bodies

For an anchoring system to be effective and low-risk, there are a number of criteria it must meet. Firstly, the main purpose of the anchor is to react all forces and torques caused by the movement of the robotic arm or other deployment or sampling systems on the spacecraft. Since there will be little to no prior knowledge of surface properties, the anchoring system must be able to function in a range of surface types, including powder, gravel piles, and rocks. If the mission requires sample return, the anchor must provide the capability to free the spacecraft, either by detaching from the surface or detaching from the spacecraft. If the mission requires multiple landings, the anchor must be reusable or lightweight and simple enough that multiple sets of anchors could be integrated with a spacecraft.

Landing on a small body can pose significant risk to a spacecraft, especially if that body has a high spin rate or is tumbling. In these cases, the spacecraft must possess a highly capable Guidance, Navigation and Control (GNC) system to time the spacecraft's descent with the small body's rotation, while keeping the spacecraft in proper orientation. This is especially important if large solar panels or other protruding structures are present. If the spacecrafts' altitude is not maintained, the solar panels might impact the surface and be permanently damaged.

To mitigate the risk associated with landing, missions may opt for a *touch and go* concept of operations instead. For example Hayabusa, Hayabusa 2, and OSIRIS-REx all include *touch and go* operations. Hayabusa, Hayabusa 2, and Rosetta all delegate landing attempts to a daughter craft – MINERVA, the MINERVA derivatives, MASCOT, and Philae. Hayabusa's loss of MINERVA during the probe's deployment on 12 November 2005 illustrates the risk of landing. The Hayabusa spacecraft was ascending and at a higher altitude than intended when releasing MINERVA. As mentioned earlier, MINERVA escaped Itokawa's gravitational pull and missed the surface.

The only successful demonstration to date of a spacecraft landing on a small body is NEAR Shoemaker's landing on *433 Eros*. However, it is worth noting that the mission team had gained tremendous risk tolerance by virtue of already completing their baseline mission goals. For all practical purposes, the risk associated with losing the spacecraft was minimal and the team had nothing to lose! Their gamble paid off; the spacecraft successfully landed on *433 Eros,* demonstrating a soft landing on an asteroid and providing valuable information about the surface. While none have been demonstrated through successful landing on a small body, a number of different anchoring concepts have been proposed over the years, and/or developed to various technology readiness levels or TRLs (Mankins 2005).

Table 12.2 summarizes some of these anchoring concepts. One of the primary requirements for any spacecraft anchoring system is the capability to engage a wide range of surfaces, unless two or three different anchoring concepts are employed, each designed to address a specific set of surface conditions. This multi-surface requirement is quite challenging. The vast majority of universal anchor systems rely heavily on spacecraft resources such as fuel for thrusters or momentum from control moment gyroscopes or CMGs. However, these approaches could be ideal as a temporary solution within a sequential stepwise approach, allowing time for the deployment of more permanent anchors.

Table 12.2 Comparative assessment of anchoring methods

Method	Description	Advantages	Disadvantages	Applicable Surfaces
Thrusters	Fire thrusters to push the spacecraft to the surface	Uses existing spacecraft technology. Good as a backup option or to enable deployment of permanent anchor	Requires extra fuel and hence might be good for short stays or during sample acquisition only.	Any

Table 12.2 (*continued*)

Method	Description	Advantages	Disadvantages	Applicable Surfaces
Reaction Wheels	Spin up reaction wheels to counteract reaction forces from sampling systems (e.g. drill) or deploying robotic arm.	Uses existing spacecraft technology. Reusable approach Good as a backup option or to enable deployment of permanent anchor	May require large reaction wheels to achieve proper stability.	Any
Spacecraft momentum	When a spacecraft moves towards the asteroid at certain velocity, any sampler deployed in the direction of the asteroid surface will be reacted against spacecraft forward momentum.	Uses existing spacecraft technology The approach could be used multiple times Good as a backup option or to enable deployment of permanent anchor	The operation time on the surface highly limited. The approach might be good for touch and go mission.	Any
Grippers	Anchor sharp "fingers" or microspines positioned opposite each other. System under development by NASA JPL	Offers strong anchoring forces in rocks Could be reused	Works only on solid surfaces. Will not work in pebbles or soil. Requires additional hardware (grippers) and power during deployment	Rocks

Table 12.2 (*continued*)

Method	Description	Advantages	Disadvantages	Applicable Surfaces
Harpoon/Nail Gun	Fire a harpoon into a surface and use a winch to pull a spacecraft towards the surface. Rebound taken up by spacecraft momentum energy or a free mass ejected in the opposite direction to the harpoon. System developed for Rosetta Philae lander	Could generate high anchoring forces if regolith properties allow. Rosetta Philae lander future heritage	Requires additional hardware (i.e. harpoon). May not work in harder rocks, and very loose gravel or soil. If harpoon hits a rock it may rebound towards the spacecraft. Non reusable (i.e. tether has to be cut for the spacecraft to move to another location or return to earth)	Gravel/soil
Drill/Auger	Deep fluted augers driven into the subsurface	Offers strong anchoring forces Could be reused Can use two counter-rotating drills to off-set reaction torque Can use tapered augers to assist with removal Can use deep flutes to engage large surface area	Need initial reaction compensator during deployment Requires additional hardware (drill) and power during deployment May not work in rocks if they are too hard and reaction compensator during initial deployment is not strong enough.	Rocks and more consolidated gravel/soil

Table 12.2 (*continued*)

Method	Description	Advantages	Disadvantages	Applicable Surfaces
Self-opposing Systems	Spikes or drill bits penetrate the subsurface at oblique angles providing a bracing force.	Takes advantage of rock roughness, porosities (holes) in a rock or cavities between rocks Could be used with a harpoon or auger	Needs more than one anchor to provide the bracing effect. Subject to same penetration limitations as component subsystems.	Any
Fluid System	Fluid is injected underneath the footpad onto and into the subsurface and hardness. Similar to Velcro except it engages subsurface.	Could work on any surface. One anchor is sufficient.	Non-reusable.	Any
Envelopment	The target is encircled using cables or even a complete bag.	No need to penetrate the surface.	Large relative to other anchoring concepts.	Relatively small and/or highly consolidated bodies.
Magnetic Anchoring	Magnetic pad is used to attach to ferromagnetic surface.	No need to penetrate the surface.	Not applicable to non-ferromagnetic bodies	Ferromagnetic bodies

The following sections describe some of the anchoring concepts in more details.

12.5.1 Hard Rock Drilling

Drilling is often the method of choice for penetrating hard rocks. In a vast majority of applications, drilling employs the durning of a hardened bit forced into the rock, abrading small particles. Once the drill bit becomes dull, however, the rate at which the drill bit penetrates the rock drops dramatically unless an ever-increasing downforce (in the case of vertical downward drilling) is applied, creating higher and higher frictional heat. The amount of applied downforce is referred to as "weight on bit" (WOB). In a low-gravity environment, WOB can be severly limited and must be provided either by spacecraft thrusters or an anchored "base" for the drill to push against. Rotary-percussive drilling action can be employed to circumvent the need for prohibitively high WOB. Percussive or hammer systems consume more power, but reduce the required WOB by an order of magnitude, especially in hard rocks (Zacny et al. 2013).

The feasibility of drilling into small bodies with low WOB has been tested using relevant analog rocks as stand-ins for likely asteroid surface materials as shown in Fig. 12.9 (Bar Cohen and Zacny 2009). Such testing demonstrates that the feasibility of drilling into a small body with low WOB is dependent upon the strength of the materials comprising the small body.

For example: Drilling in low-strength materials such as plaster or limestone is feasible using a commercially available drill with a 1.6 mm diameter bit and as little as 5 Newtons WOB. Plaster and limestone have an unconfined compressive strength (UCS) of 8 MPa and 40 MPa, respectively, which would be representative of a materials in a C-type asteroid. However, higher strength materials such as those that would be representative of an S-type asteroid cannot be drilled under those same conditions. For instance, 120 MPa basalt is representative of the upper range of S-type asteroid materials, and cannot be penetrated under the conditions listed above. This is not to say that it is infeasible to drill an S-type asteroid, but it does indicate that the drilling system must be designed with the target material in mind.

Fig. 12.9 Low WOB drilling tests in basalt

12.5.2 Hard Rock Hammer Nailing

Another approach to setting an anchor in consolidated or unconsolidated formations is to hammer an anchor into the surface. Launching an anchor into unconsolidated formations is relatively easy, however setting an anchor in rocks might be difficult.

As with drilling, preliminary feasibility tests yield interesting results: Testing was performed using a 3.8 mm nail and traditional hammer as well as with an off the shelf nail gun (Fig. 12.10), and the same three rock types as for drilling (8 MPa plaster, 40 MPa limestone and 120 MPa basalt). Hammering a nail worked as long as the nail was perpendicular to the surface, but any deviation from vertical resulted in side forces and moments that had a tendency to bend the nail. Stiffer nails would resist buckling, but underline the need to design for off-axis loading. The nail did not penetrate basalt or limestone, but managed to penetrate plaster. The nail gun, on the other hand, was powerful enough to drive a short nail into all three rock types. However, the nail gun also required significant preload, of the order of 10s of Newtons prior to impact. The rebound energy within the nail gun was absorbed by an internal spring.

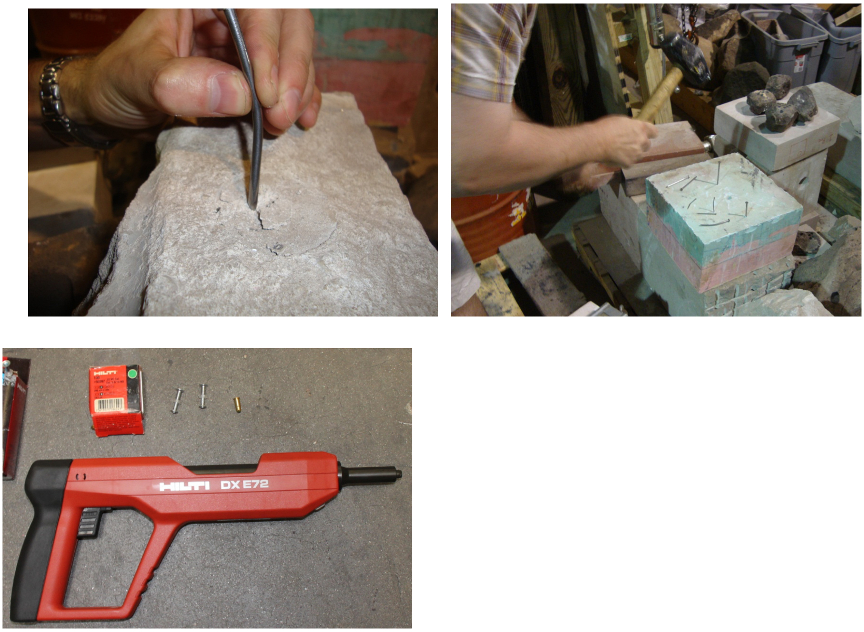


Fig. 12.10 Nailing experiments. From top (left to right) and bottom: Hammering into 120 MPa basalt, Hammering into 8 MPa plaster, Using a nail gun.

These tests have shown that as long as a nail is constrained so as to prevent buckling, it could be successfully impact driven into rocks as hard as basalt. However, during the anchor setting, the spacecraft has to use some other means of providing a reaction force, e.g. by firing of thrusters in the opposite direction.

12.5.3 Fluid Anchor

In the fluid anchor approach, a wetting fluid (e.g. foam, cement, epoxy etc.) is injected onto a surface or into the soil via a hollow spike beneath the footpad. If applied to the surface, the goal of a fluid anchor is inject an adhesive cushion between the rock surface and the spacecraft footpad, and in turn provide an anchor. If injected into the ground, the fluid would go deeper into the loose gravel or soil, allowing the anchor to engage a larger volume of asteroid material forming a composite footing (glue mixed with soil and gravel).

To free the spacecraft from such an anchor would require that either an entire footpad is detached (in this case, the spacecraft could have a set of 2 or 3 footpads per leg) or the footpad could be warmed up to 'melt' the adhesive underneath and disengage the anchor. One of the benefits of this approach currently under investigation by Honeybee Robotics is that the anchor deployment does not exert any force that requires reaction by the spacecraft. That is, upon soft touch down, the fluid can be discharged and almost instantly glue the spacecraft to the surface.

Applying epoxy-like substances in the harsh environment of space has been demonstrated. In July of 2005, astronauts applied a pre-ceramic polymer sealant impregnated with carbon-silicon carbide powder known as NOAX (Non-Oxide Adhesive eXperiment) to a number of test coupons during an Extra Vehicular Activity on board the Space Shuttle mission STS-114 (see Fig. 12.11). This material has the initial consistency of peanut butter before it is worked into potential cracks and crevices of the Shuttle's Reinforced Carbon-Carbon panels in areas such as the wing leading edge, which sees the highest temperatures during atmospheric re-entry.

Fig. 12.11 Astronaut Soichi Noguchi, STS-114 applies a sealant to a number of test coupons during an Extra Vehicular Activity. Photo courtesy NASA.

12.5.4 Self-opposing Systems

Several concepts developed to date employ a common strategy of using multiple instances of an anchoring mechanism to simplify the reaction loads required of the spacecraft. Somewhat like the guide lines on a tent, these multiple anchors pull against each other, providing a balanced net anchoring force. The independently developed examples presented here all employ this general strategy, but use somewhat different means to engage the target surface.

12.5.5 Self-opposing Drills (Cadtrak Engineering's Low Gravity Anchoring System)

Cadtrak Engineering developed a novel low-gravity anchoring system which could anchor a sampling tool as shown in Fig. 12.12, or an entire spacecraft as shown in Fig. 12.13. This device would decrease the preload requirement, peak reaction forces and vibration levels on a deployment device, and would significantly reduce the mass and complexity of the spacecraft propulsion system. It employs multiple inclined anchors to generate a net anchoring force perpendicular to the surface while at the same time balancing out any forces transverse to the surface.

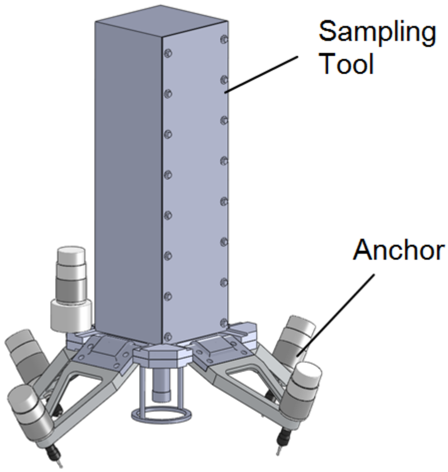


Fig. 12.12 Cadtrak Engineering anchor integrated with a sampling drill

In the absence of an anchor on an asteroid or comet mission the preload on a sampling tool must come from the propulsion system. For example, a sampling mission that requires a 100 N preload for 15 minutes from a spacecraft whose propulsion system has a specific impulse (I_{sp}) of 350 s, the mass of propellant alone would be 26.2 kg. As an alternative, this particular anchoring system can be set in less than 30 seconds and require 20 Newtons of preload. The propellant mass used to set the anchor would equate to 0.2 kg. If the anchoring system weights 5 kg, the net mass savings would be 21 kg.

The anchor uses multiple anchor arms acting in a coordinated manner as to keep the forces in equilibrium horizontally, thus keeping the system in place. The base of each arm is hinged on the tool body or spacecraft, and the far end of each arm contains a small pilot drill. The anchor is deployed by rotating the arms toward the subject rock and drilling into the rock a short distance. The arms are connected through a novel gearing arrangement which allows them to be driven by a single actuator and still conform to any surface profile. Each anchor drill can be engaged with as little as 10 Newton of Weight-on-Bit (WOB). When any two opposing anchor drills have penetrated the rock, the anchor is set, creating a stable platform for sampling or other *in situ* science operations (e.g. deploying an instrument using a robotic arm). The anchor system is compliant to large surface variations and placement can be accomplished with less precision and less preload than that of a sampling tool. The anchor hold down strength could be verified prior to commencement of *in situ* operations. The anchor also allows multiple uses

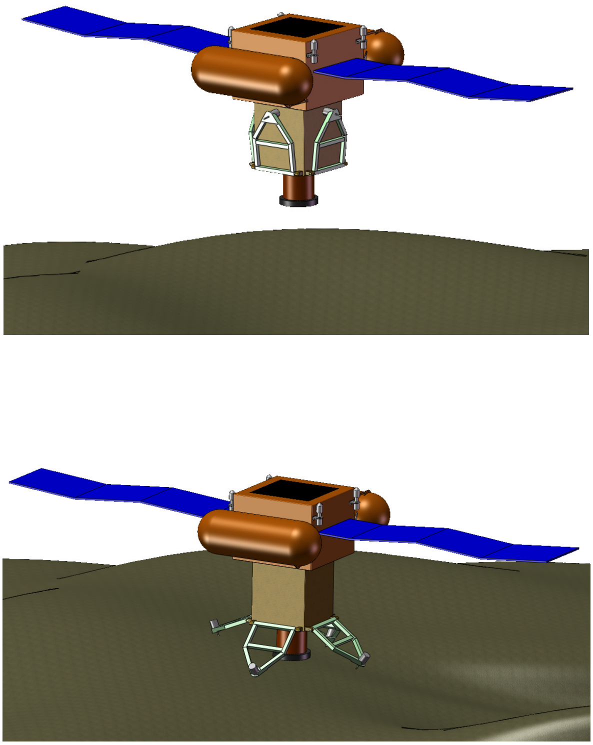


Fig. 12.13 Cadtrak anchor stowed and deployed during a spacecraft landing on an asteroid or comet

and could therefore be used as temporary system for a spacecraft making multiple landings on an asteroid.

Cadtrak developed a bench top anchor testbed which incorporated an anchor platform and simulated sampling system attached to a vertical slide. The setup included several anchor arms with a drill motor and ball-end diamond burr. The 2 mm diameter drill bits ended with a spherical ball with integrated diamonds. The anchoring was accomplished by simultaneously driving the anchor drill motors and the arm actuator until the anchor drills penetrated the rock to a set depth. The individual drill bits would generally encounter the rock surface one at time and hover at the rock surface until all of the bits have engaged the rock. The differential gearing system of the arms ensures that power is always transferred to the free arm or all the arms as shown in Fig. 12.14. This enables the mechanism to accommodate varying surface topography. For a flight system, the anchors might include proximity sensors or contact switches to indicate when the target depth has been reached.

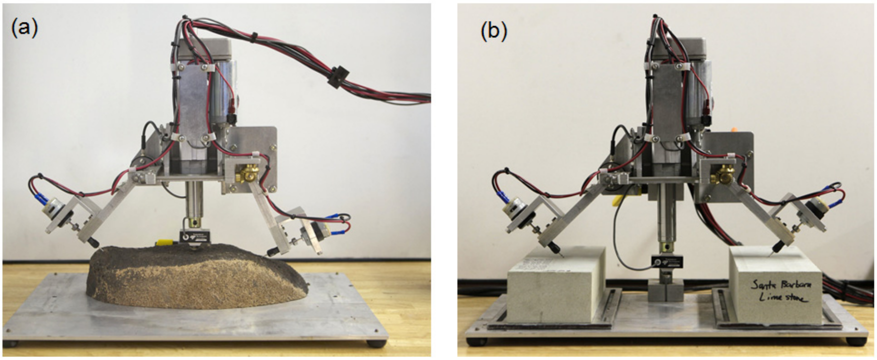


Fig. 12.14 (a) Anchor testbed shown conforming to arbitrary rock surface. (b) Anchor testbed shown with standardized rock samples for weight-on-bit and pull-out tests.

Data from a number of tests in limestone, basalt, sandstone, and kaolinite is shown in Fig. 12.15. It was determined that at a depth of approximately 3 mm, the pullout force for a single anchor arm reached 200 N in basalt and around 100 N in kaolinite rock. When pullout occurred the rock fractured along shear planes forming small craters (Fig. 12.16). In general the pull-out strengths were at least 10 times higher than the WOB requirement to drill the anchor holes.

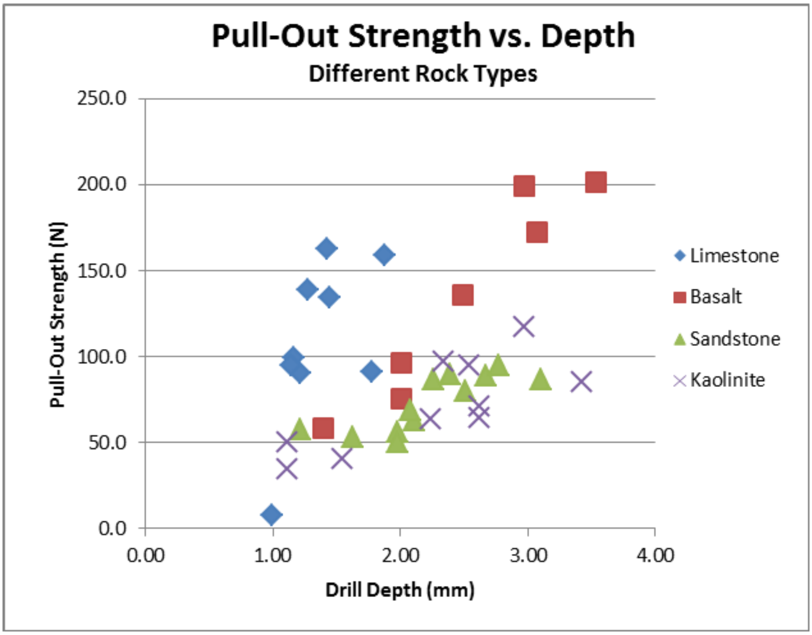


Fig. 12.15 Pull-out strength vs. drill hole depth for different rock types

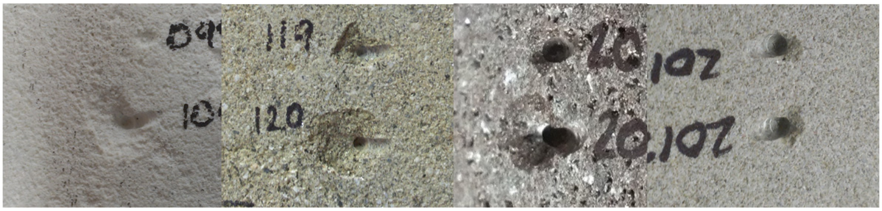


Fig. 12.16 Pull-out craters for various rock samples. (a) Kaolinite (b) Sandstone (c) Saddleback Basalt and (d) Santa Barbara Limestone rocks.

12.5.6 Self-opposing Multi-mode Anchor (Honeybee Robotics' Bracing Anchor)

The bracing system uses two or more multi-mode rock and soil anchors positioned at an oblique angle to the surface as shown in Fig. 12.17, resulting in a net force component along the asteroid surface. This resultant force braces the spacecraft to the surface. The advantage of this approach is that during the anchors' deployment only the force componenet in a vertical direction has to be overcome by, for example, firing rocket thrusters in the opposite direction.

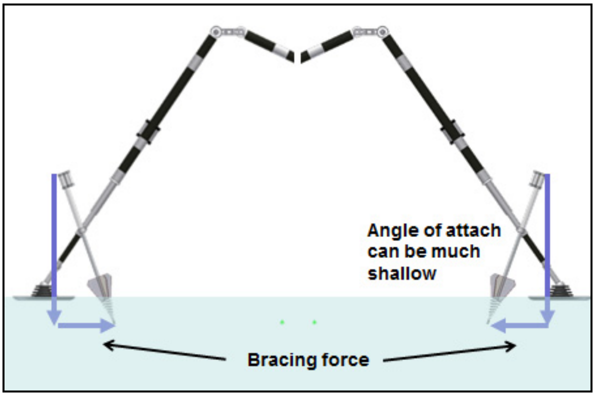


Fig. 12.17 The bracing anchor engages the surface at an oblique angle

Honeybee Robotics' bracing approach uses a long "drill" with a three tier system – each designed for a different surface condition (Fig. 12.18).

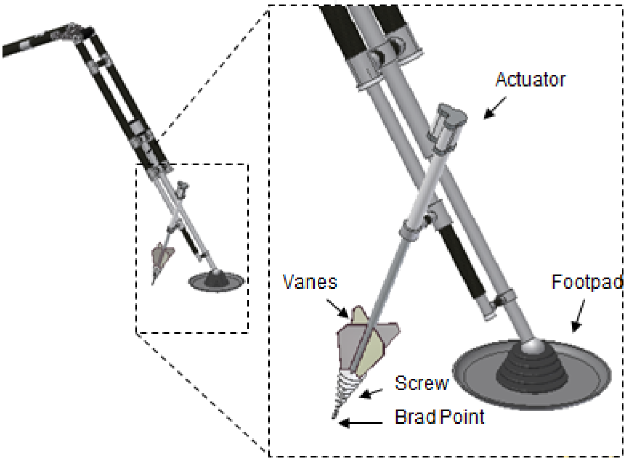


Fig. 12.18 A concept of a bracing anchor with a 3-tier system for 3 different surface conditions

First, the tip of the drill has a sharp Brad point whose purpose is to exert maximum pressure on the surface and ultimately find purchase in small-scale surface features like cracks, crevices, or valleys (if large rocks are present). This is similar to the approached used by microspine anchors. Further up is a self-tapping auger thread form (tapered screw auger) that will draw the anchor into rubble or gravel piles, if present. Lastly, in the weakest of materials such as powder, the bit's non-rotating vanes at the end will distribute lateral forces attempting to take advantage of the material's shear strength. Because the anchor's bit is designed to engage in all possible surface materials: rocks, gravel piles, and loose soil, it considerably reduces risk related to lack of knowledge of asteroid surface conditions.

Upon landing and when commanded, the anchor would be driven into the surface by simultaneously rotating the anchor's "bit" and moving in a linear fashion toward the surface. Bit rotation and translation would be provided by a single reversible actuator. Following surface operations and prior to spacecraft take-off, the anchoring system would disengage as each actuator would retract the bit to a safe position. The anchors should be deployed very slowly because the strength increases with strain-rate resulting in values about an order of magnitude higher (or even more) than the quasi-static strength for the same material (Biele et al. 2009).

This particular anchoring concept has been applied to a NASA Discovery-class mission concept called Amor shown in Fig. 12.19. The goal of the mission was to rendezvous, land, and explore the C-type triple near-Earth asteroid (NEA) system 2001 SN263 (Jones et al. 2011).

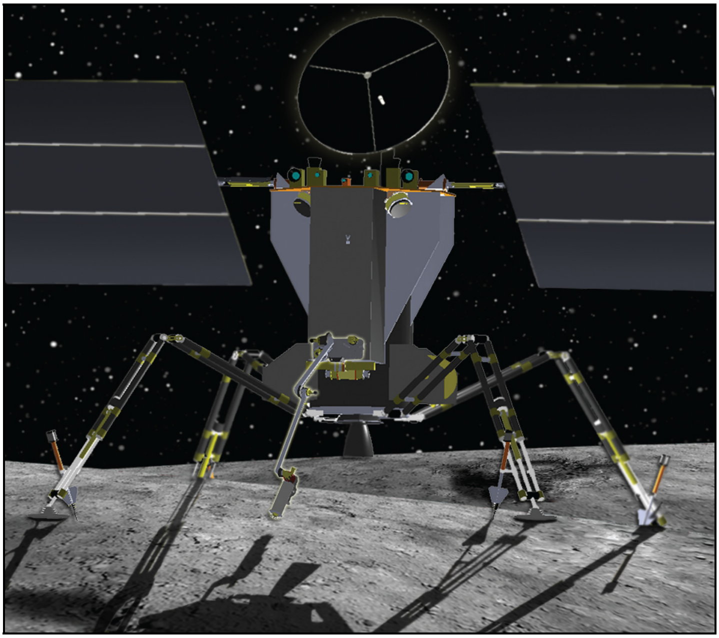


Fig. 12.19 Universal Hybrid Anchor for a lander mission to explore the C-type triple Near-Earth Asteroid System 2001 SN263 (Jones et al. 2011)

12.5.7 Self-opposing Tines (JPL's Microspine Anchors)

The NASA Jet Propulsion Laboratory (JPL) has developed a self-opposing anchoring system based on small tines called microspine anchors (Parness et al. 2012a). Microspine toes were initially invented at Stanford University for the RiSE climbing robot, which could scale the exteriors of buildings that used rough materials like brick, stucco, cinder block, and adobe (Asbeck et al. 2006; Spenko et al. 2008). NASA JPL has extended this technology for use on natural rock surfaces by first, using new configurations of opposing microspines that can resist forces in any direction, second, using a hierarchical design that complies to the rock at multiple length scales, and third, substituting materials and mechanisms that are appropriate for the extreme environment of space.

A microspine toe consists of one or more steel hooks embedded in a rigid frame with a compliant suspension system made of elastic flexures or spring elements (Figs. 12.20 and 12.21). By arraying tens or hundreds of microspine toes, large loads can be supported and shared between many attachment points. Since each toe has its own suspension structure, it can stretch and drag relative to its neighbors to find a suitable asperity to grip. The suspension system also works to passively distribute the overall load across an array of toes.

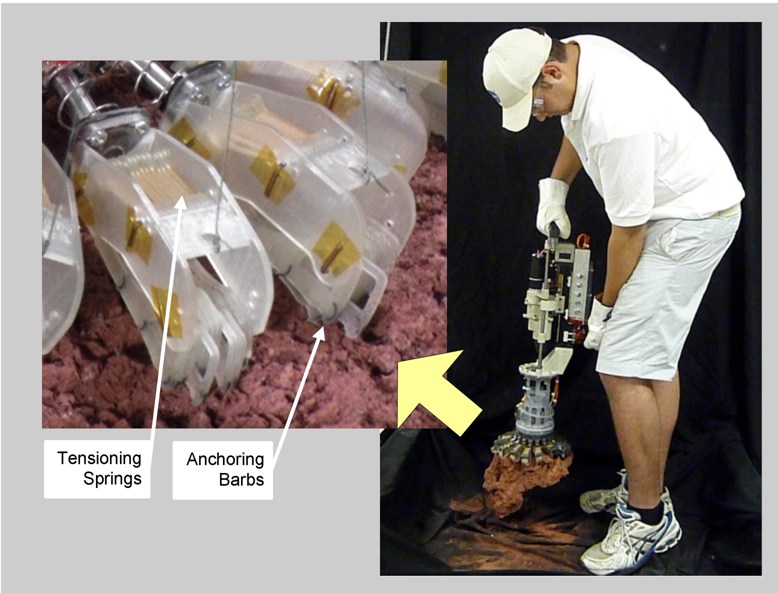


Fig. 12.20 A microspine anchor integrated with a rotary percussive coring drill to produce a sample acquisition instrument that can obtain a subsurface core from consolidated rock without requiring any externally applied forces

For gravity independent rock-climbing and drilling, the omnidirectional anchors use a radial arrangement of microspines with a centrally tensioning degree of freedom. The hierarchical compliance system contains 16 carriages that conform to cm-scale roughness. Each carriage contains 16 microspines, which conform to mm-scale roughness and below. A torsion spring biases each of these carriages into the rock face regardless of gravitational orientation so that the toes will drag across the rock surface and establish a grip, even in an inverted configuration. The radial symmetry creates a secure anchor that can resist forces in any direction away from the surface. Figure 12.21 shows many of the important components of the gripper with an explanation of the function of each.

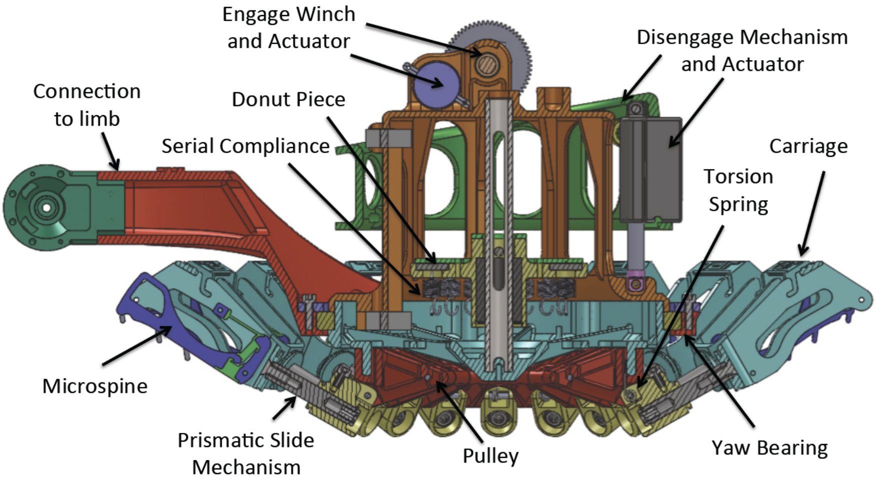


Fig. 12.21 Details of microspine-based anchor system

These anchors support loads in excess of 180 Newtons both tangent and perpendicular to the surface when used on rough, consolidated rocks like vesicular basalt and a'a lava rock. Anchor strength falls off as the roughness of the rock decreases due to the decreased number of potential asperities to grip. Anchor strength values in excess of 100 N were common on Bishop Tuff, and values of 50 N were consistently achieved on a smoother saddleback basalt sample. For unconsolidated materials like pebbles and sand, negligible (<10 N) anchoring forces were measured (Parness et al. 2012c).

A microspine anchor was integrated with a rotary percussive coring drill to produce a sample acquisition instrument that can obtain a subsurface core from consolidated rock without requiring any externally applied forces (see Fig. 12.20). The instrument is self-contained; redirecting the load path back into the rock, with forces reacted by the microspine gripper. The drill uses an additional two actuators, one to activate the rotary-percussive motion, and a second to feed the drill into the rock. Compression springs are used in series with the feed actuator to preload the drill bit into the rock with approximately 50-100 N of WOB (Parness et al. 2012b).

The microspine-based drills successfully cored in multiple configurations including drilling into the ceiling, into a vertical wall, and, using the Astronaut microspine drill, lifting a rock using the anchor and then drilling into it while the rock is lifted. These tests were performed on multiple rock types including vesicular basalt and a'a. Bore speed was dependent on the WOB, drill speed, and material properties of the rock, but nominally ranged from 15-45 mm/min. A carbide-tipped coring bit created a 20 mm diameter borehole to depths ranging from 25-82 mm for the inverted drill test, and 15 mm for the vertical and horizontal drill tests. The retained core samples measured 12 mm in diameter and usually were extracted in several broken pieces, but with stratigraphy maintained. While a broken core may not always be desirable, it does eliminate the need to perform a core breakoff.

During the drilling process, failure most often occurred during hole-start. The bit would sometimes wander before achieving a good hole-start. Occasionally, this caused the microspine anchor to lose grip. This was accentuated by the built-in compliance in the microspine anchor, which must resist the wander. However, this compliance also acts to dampen the vibrational forces, and is essential to the load sharing within the gripper.

12.5.8 Magnetic Anchoring

If an asteroid is metal-rich, highly consolidated, and magnetized, a magnetic anchor could be effective. The asteroid Gaspra, discovered by Galileo mission, is an example of such an asteroid (Kerr 1993).

12.5.9 Envelopment

Envelopment blurs the distinction between anchoring to an asteroid and grabbing a sample from it. In an envelopment -based mission's architecture, the spacecraft grabs the whole asteroid! In general, the suitability of the envelopment concept depends upon the size and makeup of the asteroid, and the ability of the spacecraft to control it once enveloped. An envelopment system might use cables that span around the small body (see Fig. 12.22) or long and skinny legs to embrace the small body in the same way a spider captures its prey. If an asteroid is relatively small, an entire body could then be captured inside a bag as shown in Fig. 12.23.

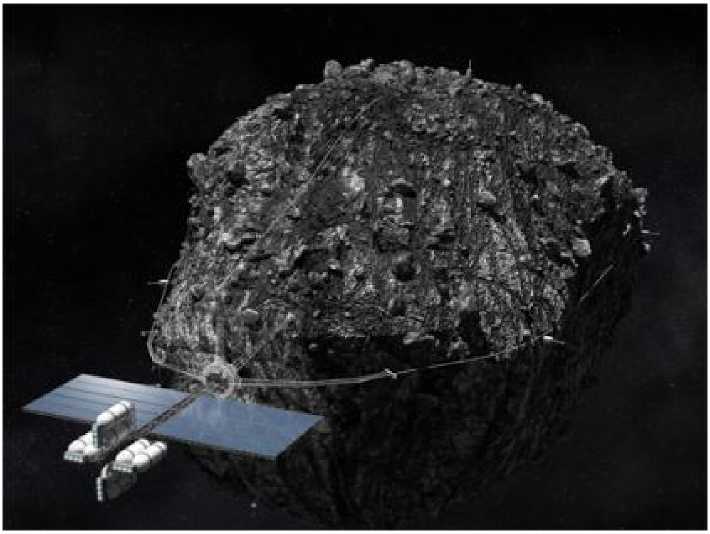


Fig. 12.22 Deep Space Industries (DSI) concept of a Harvestor™-class asteroid collection mission. (Image Credit: DSI).

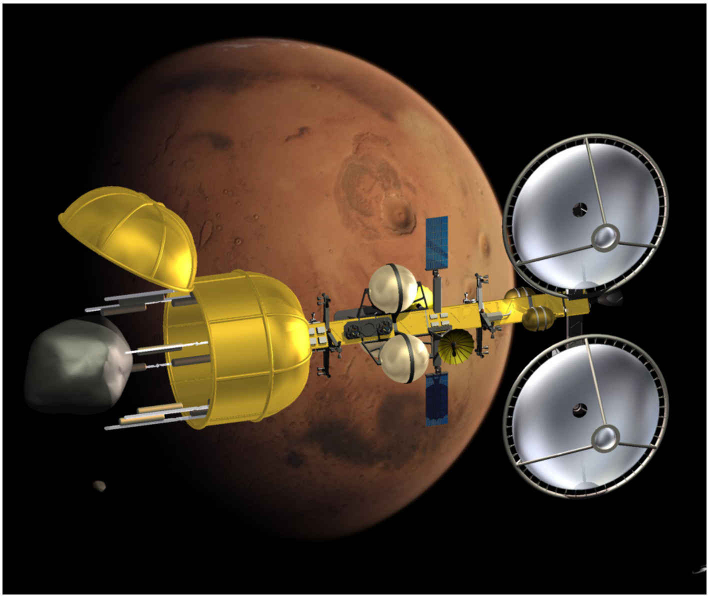


Fig. 12.23 Illustration of an asteroid retrieval spacecraft in the process of capturing an asteroid (Courtesy Honeybee Robotics and V Infinity Research)

12.6 Small Bodies Sampling and Excavation Approaches

There are two main reasons to acquire material from an asteroid or a comet: for science investigations, and for extracting resources. The two different motivations impose different performance requirements on the system acquiring the material.

For the purposes of science investigations, comets and asteroids are remnants from the solar system formation and can offer clues to the chemical mixture from which the planets formed. Science investigations normally require relatively small (on the order of grams) but pristine samples with no forward contamination. Hence sampling systems have to be designed to withstand various sterilization techniques, such as Dry Heat Microbial Reduction. For a sample return mission, the sample (in most cases) must be placed in a hermetically sealed container and kept within a specified temperature range at all times. The thermal requirement is of particular importance to prevent the loss of volatiles and/or possible chemical reactions.

For the purposes of resource mining and extraction, the amount of material to be retrieved and processed is much larger. In general, there are two options for resource extraction: transport the raw material to a processor, or transport the processor to the raw material. In the first case either a fraction or an entire asteroid could be brought back to cislunar space such as the Earth Moon Lagrange Point 1 (EML1). In the second option, the asteroid material could be processed *in situ* and only the useful material brought back. There are advantages and disadvantages to both approaches. It should be noted that for the purpose of commercial ISRU, only NEA's are considered, because of their proximity to Earth.

Processing material *in situ* and returning the final product means substantial savings in rocket fuel. This approach would also be desirable if the resource would be required for a mission to continue exploration of other planets rather than return to Earth. However, in this case, the mining and material processing systems must be very robust and fully autonomous.

Bringing an entire asteroid, some fraction of it, or even an ore concentrate to cislunar space would require more fuel and would take more time. However, it would also allow for teleoperation or human operation and the testing and verification of a number of extractions and processing technologies. The latter would be particularly advantageous since systems could be easily fixed if broken. In 2011 the Keck Institute for Space Studies (KISS) sponsored a study to investigate the feasibility of returning an entire 7 m asteroid weighing approximately 500 tons to the vicinity of the Earth. A 500 ton, C-type asteroid may contain up to 200 tons of volatiles such as water and carbon-rich compounds (100 tons of each), 90 tons of metals (83 tons iron, 6 tons nickel, and 1 ton cobalt), and 200 tons of silicate residue which is similar to the lunar surface material. The study found that it is feasible to capture and retrieve such an asteroid at a cost of approximately $2.6B (Brophy et al. 2012).

Capturing a small asteroid and bringing it back to Earth's vicinity might be the best first step in mining asteroids. Mining and processing technologies, as well as concepts of operation, could be tested and further developed within reasonable reach of Earth. Once robust technologies for mining asteroids are validated, it might be more cost effective to process all the materials *in situ*. The decision on whether to bring material (e.g. metal or water) back to Earth's vicinity or use it *in situ* for developing new spacecraft components ultimately depends on the cost of each approach. Furthermore, the current lack of pertinent data and information makes modeling these approaches particularly challenging. It is, however, safe to assume that bringing material to Earth will never be as cost effective as mining it even from great depths on Earth. Currently several South African gold mines are 4 km deep and heading to 5 km to tap into new gold reserves. Mining gold from these depths, even at grades as low as a few grams per ton, is still highly profitable. Commodities mined in space will have to compete economically against commodities mined on Earth. The intended location of end use becomes important to the relative economic appeal of resources mined in space. If the resources are to be used in space, then space-based sources become more attractive. Technologies to extract and process materials that will be widely useful in space (e.g. aluminum or titanium to create space structures) would be more valuable than technologies to extract materials that may command a high price on Earth, but are less useful in space. By way of analogy, 1 kg of water in a desert could be more valuable than 1 kg of gold.

Over the past few decades a number mining and sampling technologies have been developed (Bar-Cohen and Zacny 2009; Zacny et al. 2008; Ball et al. 2007). A vast majority of the exploration technologies focused on asteroids are in conceptual stages and only a limited number of them have been breadboarded, tested, and validated even under terrestrial conditions. Some sampling approaches have been tested on past missions or will be tested on future missions (Marchesi et al. 2001; Yano et al. 2002; Fujiwara and Yano 2005). In general, the progress has been slow because of the difficulty and costs associated with testing in reduced gravity and vacuum. The following sections describe a range of promising sampling, mining, and processing technologies. It should be noted that the list of presented methods is not all inclusive, but rather aims to give the reader an idea of the range of approaches.

12.6.1 Hayabusa

Hayabusa was the first mission to return sample material from another celestial body surface other than the Moon. Due to multiple malfunctions of the attitude control devices, the sampler did not work as designed. However, the mission did ultimately succeed in retrieving sample material from the Near Earth Asteroid (25143) Itokawa (Fig. 12.24).

The Hayabusa spacecraft used a small 5 gram tantalum pellet fired at 300 m/s into the surface to acquire a few grains of samples as shown in Fig. 12.25 (Barnouin-Jha et al. 2004). The material ejected by the pellet's impact was collected using a bi-impact sampler designed as a single collection system suitable for a range of target materials: metal-silicate hard bedrock, regolith layers with gravel, and micro-particles. The sampler consisted of a 1 meter long horn made of aluminum. The horn diameter at the tip was 15 cm. The goal of the horn was to direct sample into a sample chamber.

Fig. 12.24 A graphic of Hayabusa spacecraft acquring a sample from the Itokawa S-type asteroid. Courtesy JAXA

This approach was chosen because the mission planners could not know *a priori* what the surface properties would be – hard and consolidated or soft and powdery? This is unlike the Moon, Mars, or Venus, for example, which have been visited many times, within a relatively short period. In addition, information about the asteroid target is very limited even with a substantial ground observation campaign effort. This means that only once the spacecraft arrives at the target, will it be possible to perform detailed examination.

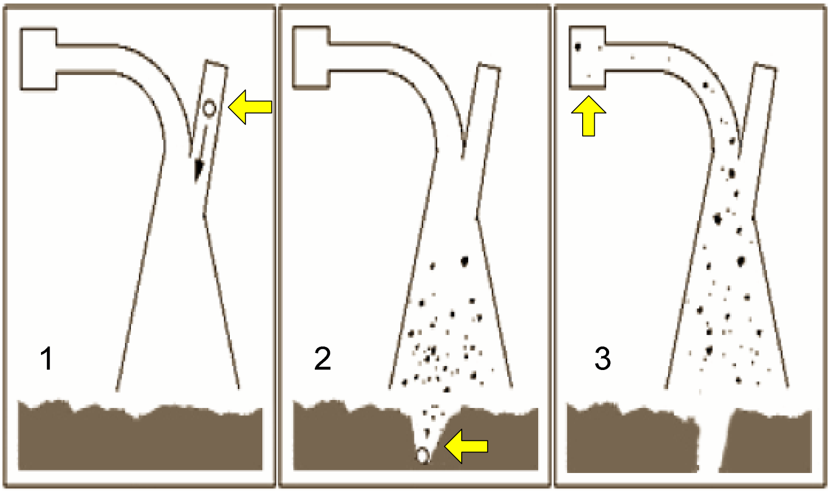


Fig. 12.25 Hayabusa sample acquisition sequence. (1) Pellet is launched at the asteroid surface. (2) Pellet strikes surface, scattering material. (3) Some of that material is captured for return. (Barnouin-Jha et al. 2004).

To determine the characteristics of a sample for planning the sampling operation, a number of impact experiments were performed during the development stage in various analog materials such as heat-resistant bricks, 200-mm glass beads, and lunar regolith simulant. Tests were performed at a normal and oblique impact angles as well as at 1g and in micro gravity by using a 140 m tall vacuum drop tower. Results indicated that sampler could acquire several hundred milligrams to several grams per shot. For oblique impacts at 45° or greater, however, the collection mass was less than 100 mg per shot.

For the nominal sampling procedure at the asteroid, once the tip of the sampler horn touched the surface, a pair of 5 gram tantalum pellets were fired at a surface at 300 m/s. These pellets would impact the surface, throwing ejecta into conical horn. On the actual mission, anomalies that occurred during the sampling operation prevented the spacecraft from firing the projectiles and capturing regolith material (Yano et al. 2006). However, during the first of the two attempts, some surface particles made their way up the horn and into a sample chamber when the horn touched the surface.

12.6.2 Rosetta

The goal of the European Space Agency's Rosetta mission is to study the comet 67P/Churyumov–Gerasimenko. The Rosetta mission consists of two spacecraft: the Rosetta orbiter and the Philae lander. The mission was launched on 2 March 2004 and will reach the comet by mid-2014. In November of 2014, the Philae lander is scheduled to land on the comet and perform investigations of its surface. To enable investigations of the comet, the lander is equipped with a sampling drill, named the sampling, drilling, and distribution (SD2) subsystem. The SD2 weighs 5 kg and can penetrate up to 250 mm below the surface and capture samples at predetermined depths. The samples, up to tens of mm^3, then can be transported to a carousel which distributes them into various onboard instruments (Finzi et al. 2007).

SD2 was designed and built by Galileo Avionica and consist of three subsystems: a tool box, a carousel, and a local control unit (Fig. 12.26).

Fig. 12.26 Rosetta Drill, Sample & Distribution, called SD2 (SD2, 2012). Courtesy ESA

The tool box contains the actual drill and the sampler and can rotate about its vertical axis. The drill has two degrees of freedom: the Z-axis and rotation. To enable autonomous operation, the drill head is fitted with a compact force and torque sensor. The drill has been designed to penetrate material with strength ranging from fluffy snow to materials with a strength approaching a few MPa. The average drilling power is in the range of 10 Watts. The drill can also withstand storage temperatures to -160°C and can operate at temperatures down to -140°C.

Upon reaching the target depth, a sample is captured inside a drill bit, the drill is removed from the borehole, and the sample is delivered into a carousel. The carousel consists of 26 ovens and mates with scientific instruments (Finzi et al. 2007).

12.6.3 The Sample Acquisition and Transfer Mechanism (SATM) Drill

The Sample Acquisition and Transfer Mechanism (SATM) is a four-axis, highly instrumented drilling system that features sample preparation and handling system and also sample return containers. A prototype was developed and tested by Honeybee Robotics to validate the performance requirements for the NASA ST/4 Champollion mission (Fig. 12.27).

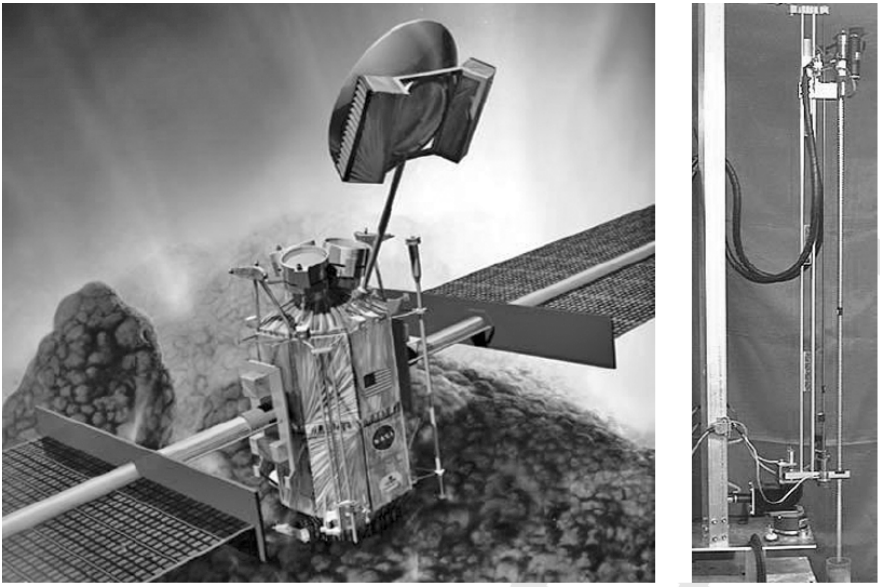


Fig. 12.27 SATM system. (a) Artistic impression of SATM on Champollion spacecraft. Image: NASA. (b) Prototype system developed and tested by Honeybee Robotics.

The drill was designed to acquire subsurface samples from a comet at selectable depths up to 1.2 m with little cross-contamination. The sample size is continuously adjustable between 0.1 and 1.0 cm^3 to cater for a variety of analytical instruments' requirements. The SATM creates a 13 mm diameter borehole. The mass of the prototype shown in Fig. 12.28 is 9 kg and its volume envelope is 60 x 60 x 138 cm.

The SATM sample is always delivered as fine powder regardless of the material type sampled (i.e., consolidated or unconsolidated). Powder samples can be transported and transferred to instruments or vessels such as chemical analysis ovens, a microscope/IR spectrometer, and a sample return container located at the base. To maintain the sample temperature to within 5 °C of its natural environment, the SATM drills at low speeds.

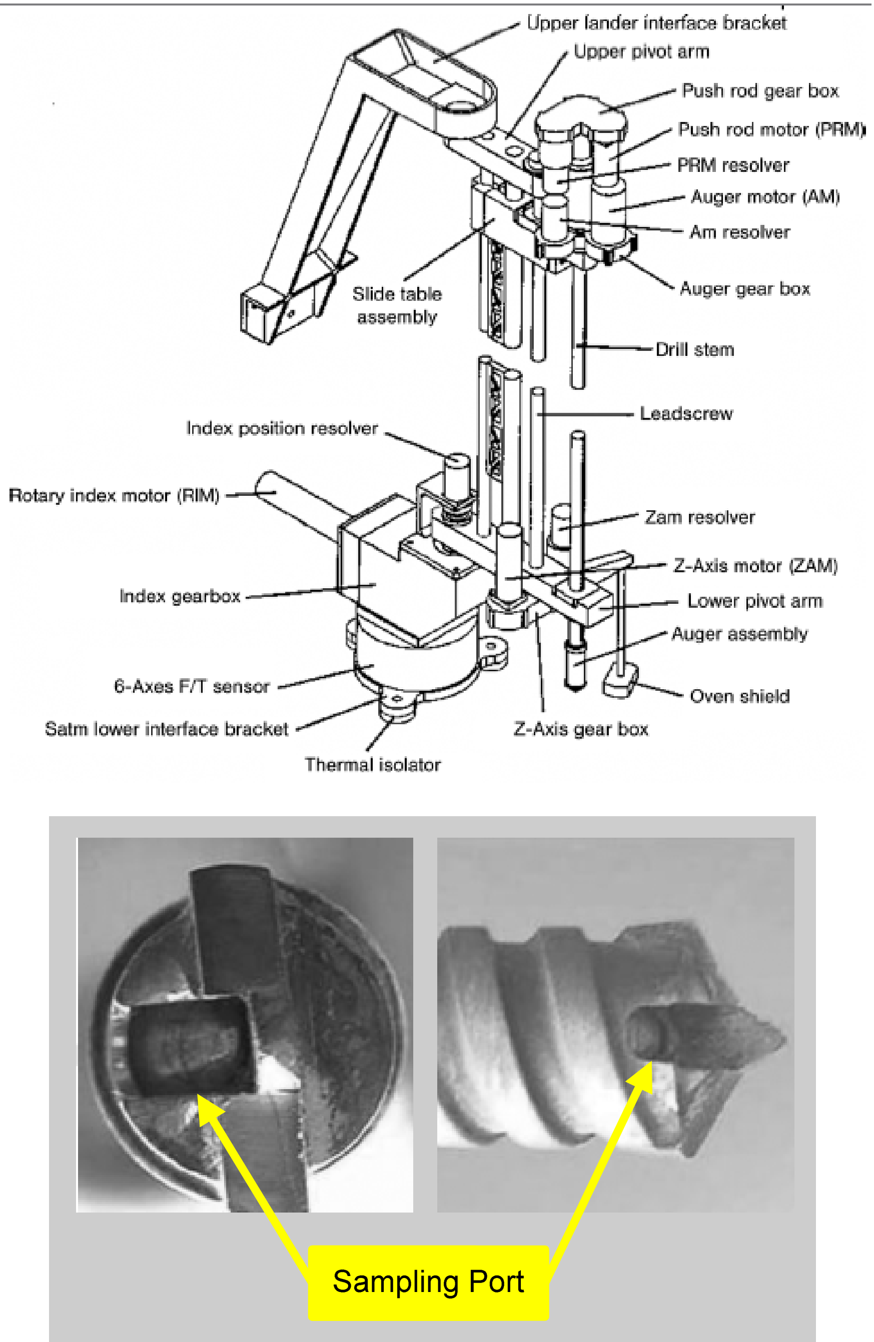


Fig. 12.28 SATM system. Top: System components. Bottom: Sample inlet feature.

Major components of the SATM design are shown in Fig. 12.28. The images on the right show the sample inlet feature of the drill tip. This door can be open at a desired depth to allow powder cuttings to flow into the sample chamber. The system also features a positive sample-eject mechanism within its sample chamber to ensure that samples are delivered to the *in situ* instruments. Samples can also be presented for analysis via a sapphire window located on the side of the drill stem. SATM can accommodate the bonding of a small cesium-137 source at the drill tip to permit density measurements. The drill tip can also be used as a tool to open and close the sample return container; eliminating the need for a separate actuator.

Fig. 12.29 Prototype testing in laboratory with (a) limestone and (b) cryogenic regolith stimulant

Specialized control algorithms were developed to allow autonomous adaptive operation in a low-gravity environment. The algorithms could also be adjusted for off-normal drill approach angles to minimize bit wandering. Laboratory tests conducted in limestone, basalt, and a cryogenic regolith simulant (see Fig. 12.29 have shown that a total energy of 25 W-hr is required to sample limestone (40 MPa UCS) at a rate of 0.88 cm/min with an auger speed of 194 rpm, a WOB of 55.6 N, and a drilling torque of 325 mNm. Limestone is an adequate ice simulant since the strength of ice at cryogenic temperature is similar to that of limestone.

12.6.4 Touch and Go Surface Sampler

The "Touch and Go Surface Sampler" (TGSS) developed by Honeybee Robotics, can drill and acquire a sample of regolith (up to 50 cc) or weak consolidated materials (UCS < 10 MPa) while the cutters penetrate to a depth of 1 to 4 cm. The system is reusable, and can store samples inside individual containers for *in situ* analysis or sample return. The TGSS consists of a high-speed sampling head attached to the end of a flexible shaft (Figs. 12.30 and 12.31). The sampling head rotates its counter rotating cutters at speeds of 5000 to 8000 rpm and consumes 20 W to 30 W of power. The mass of the current prototype is 450 grams, with a volumetric envelope of 50 mm x 75 mm x 150 mm (excluding the center drill bit).

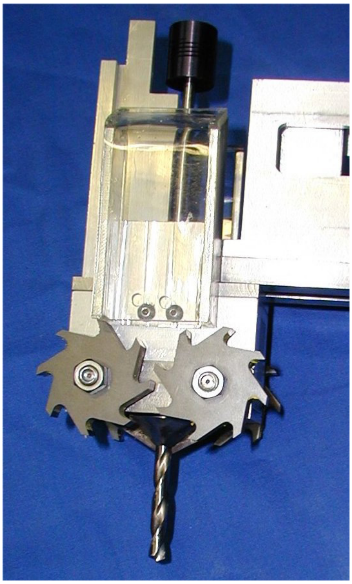


Fig. 12.30 Touch and Go Surface Sampler (TGSS) developed by Honeybee Robotics

The TGSS consists of three subsystems: a deployment mechanism, a sampling head, and a sample containment subsystem. The deployment mechanism deploys the sampling head by extending a boom to the surface. The sampling head contains 5 high-speed cutters (center drill side mounted toothed wheels) driven by a single motor. These high-speed cutters throw up surface material on contact and two guides mounted above the cutters direct sample debris/chips into a removable sample chamber. The sample containment subsystem transfers and seals multiple samples. The sampling head has a removable sample chamber on top of the cutters.

A prototype was developed and tested in a laboratory ambient environment on various target materials. The TGSS was demonstrated to sample regolith at a rate of 30 cc/sec and consolidated chalk with strength of 10 MPa at a rate of 0.5 cc/sec. A number of microgravity tests have shown that the TGSS can sample both consolidated and unconsolidated material, and includes a sample canister changeout system that allows sampling of multiple sites with minimal cross contamination.

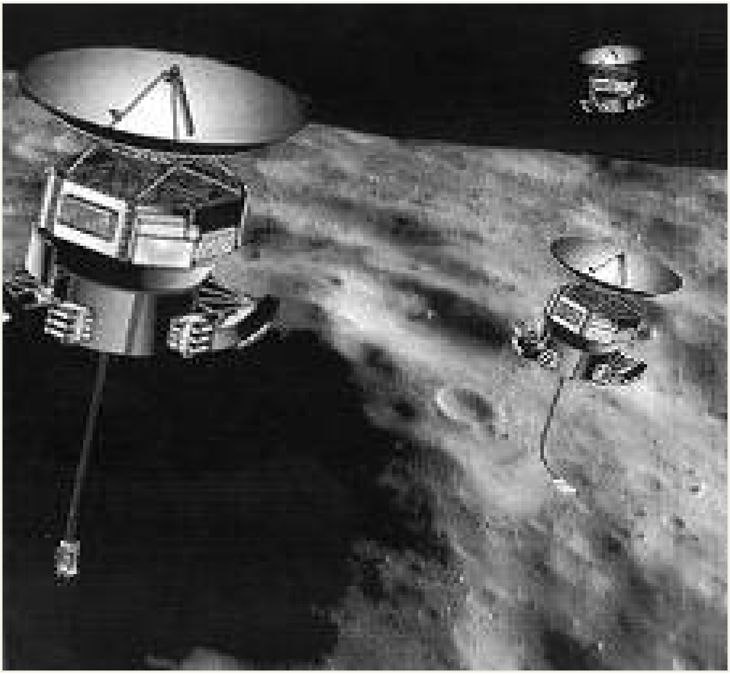


Fig. 12.31 A concept of a Touch and Go Surface Sampler (TGSS)

12.6.5 Brush Wheel Sampler

Another Touch and Go concept with brush-wheel mechanisms as shown in Fig. 12.32 rather than cutters has been developed at NASA Jet Propulsion Laboratory (Bonitz 2012). The main advantage of using brush wheels (as opposed to cutting wheels or other, more complex mechanisms) is that upon encountering soil harder than expected, the brushes could simply deflect and the motor(s) could continue to turn. That is, sufficiently flexible brushes would afford resistance to jamming and to overloading of the motors used to rotate the brushes, and so the motors could be made correspondingly lighter and less power hungry. Of course, one could select the brush stiffness and motor torques and speeds for greatest effectiveness in sampling soil of a specific anticipated degree of hardness. In simplest terms, such a mechanism would contain brush wheels that would be counter-rotated at relatively high speed. The mechanism would be lowered to the ground from a spacecraft or other exploratory vehicle. Upon contact with the ground, the counter rotating brush wheels would kick soil up into a collection chamber. Thus, in form and function, the mechanism would partly resemble traditional street and carpet sweepers.

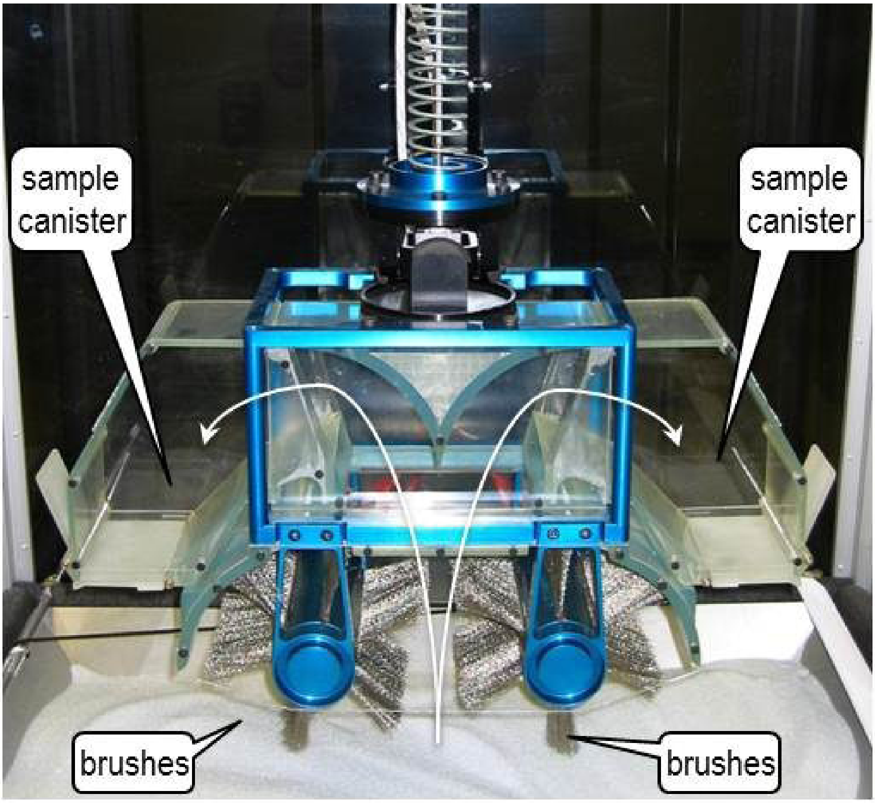


Fig. 12.32 2nd generation prototype of Brush Wheel Sampler (BWS) used for testing in micro-gravity environment aboard NASA's micro-gravity aircraft in 2004 and in vacuum on earth in 2009 (Bonitz 2012)

12.6.6 Sample Return Probe

A slightly different approach for small body sampling includes a standalone small spacecraft with a sample acquisition system. The concept includes several sampling probes that travel to a small body onboard a parent spacecraft. After arriving at the small body of interest, establishing an orbit, and selecting a site of interest, one of a probes will detach from the parent spacecraft, spin stabilize using an attitude control system, and propel itself towards the surface. Upon impact, the probe will collect a sample and transport the sample into its upper stage where it will later be hermetically sealed. The upper stage of the probe with the collected sample will then detach from the rest of the probe body and take off from the surface using the same attitude control system used to guide it to the surface. The probe with a sample inside it will then dock with the mother spacecraft and hand-off the hermetically sealed sample (Fig. 12.33). Multiple probes could be used in this way to insure mission success or to sample multiple locations.

The main advantage of this approach is that the sampling system is completely independent of the spacecraft. As such, the dangers associated with proximity operations in more conventional approaches, are eliminated. Developing tiny spacecraft is quite feasible. For example the Hayabusa mission carried the 591 gram and approximately 10 cm tall by 12 cm in diameter MINERVA lander. Hayabusa 2, on the other, hand will carry at least one MINERVA type lander as well as another small lander named MASCOT (Mobile Asteroid Surface Scout) from the German Aerospace Center. Given the small size of sample return probes, technologies developed for nano-satellites could be directly applicable.

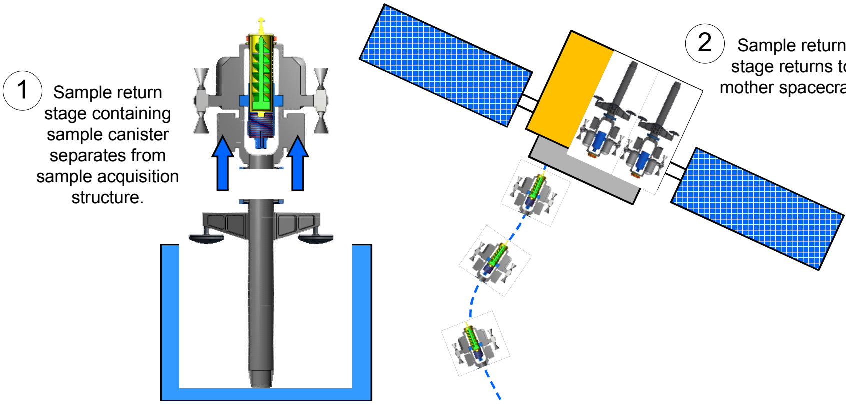


Fig. 12.33 A standalone sample return probe. Upon sample acquisition the upper stage releases and rendezvous with the mother spacecraft.

12.6.7 Harpoon Samplers

A harpoon sampler provides a means to rapidly collect samples from microgravity bodies at distances defined only by the length of the tether system. Such systems do not require landing on the target or a means to hold the spacecraft to the surface. The time to acquire a sample using a projectile could range from seconds to minutes, and is therefore compatible with a slowly moving science platform. This allows samples to be collected from specific interesting regions, such as inside a crevasse or vents of an active comet. Harpoon samplers can be fired into the surface of a small body, capture a sample during the course of penetration into the subsurface, and reeled back into the spacecraft using a tether. All these operations could be accomplished at a relatively safe distance from the asteroid.

A number of potential concepts for capturing and retrieving a sample exist (Bar-Cohen and Zacny 2009; Nuth 2011). These vary from a harpoon dropped from the spacecraft to lowering a mechanism that could fire a sampling tip into the surface using compressed air or stored mechanical or chemical energy. A number of harpoon acceleration concepts could impart enough energy on the sampling tip to accomplish sampling in relatively consolidated formations. Of course a drawback to any high powered harpoon is that if the formation is very soft, the harpoon will penetrate much deeper than expected, making it more challenging to retrieve the sample.

Fig. 12.34 Honeybee Robotics Harpoon Breadboards

Honeybee Robotics developed a number of harpoon concepts that could be deployed in a variety of formations (see Fig. 12.34). The final harpoon breadboard was tested with cryogenic ice at approximately -150° C. The tests were conducted in order to determine the ability of the tip to sample ice when impacted at a 45° and at a 0° angles. During these tests, the harpoon tip successfully captured samples of cryogenic ice when impacted at up to 45° off vertical.

NASA Goddard Space Flight Center has also developed a projectile-based sample acquisition system (SAS) for comet sampling. The system consists of a launcher, a tether payout and retrieval system, and a Sample Retrieving Projectile (SaRP). Goddard's 3rd generation sample retrieving projectile (SaRP) prototype shown in Fig. 12.35 consists of an outer sheath and an inner sample collecting cartridge. The sample cartridge uses a spring loaded rotating knife-edged seal to contain the collected sample. This prototype has been tested and consistently collects and retrieves several hundred grams of sample (Wegel and Nuth 2013).

Fig. 12.35 NASA GSFC Sample Retrieving Projectile (SaRP). The photo shows a prototype sampler tip (right) and the sample collection cartridge (left).

12.6.8 Pneumatic Approaches

Many terrestrial applications use vacuum cleaners for picking up dirt. The principle lies in creating a lower pressure at the back end of a pick-up hose than at the front, and thereby forcing the outside air to flow in and loft particles along the way. Such a system will not work in the vacuum of space. However, one can create a differential pressure by injecting gas into the regolith and then guide this gas, as it escapes from the regolith, into appropriate pick up tubes (Zacny et al. 2004, 2008, 2010). Figure 12.36 shows two potential approaches. The first one relies on injecting pressurized gas into the top few centimeters of regolith and then capturing the regolith propelled upwards by the escaping gas into a transfer tube. The second approach entails a self-enclosed tube with injector holes. Once the regolith is acquired into the tube, gas is injected into a tube and lofts the captured regolith above the gas injector holes up the tube. Some of this gas will escape into the surrounding vacuum, reducing the excavation efficiency. The exact volume of gas lost will be a function of the permeability of regolith, the depth of the external tube buried inside the regolith and the depth of an injector nozzle inside the regolith.

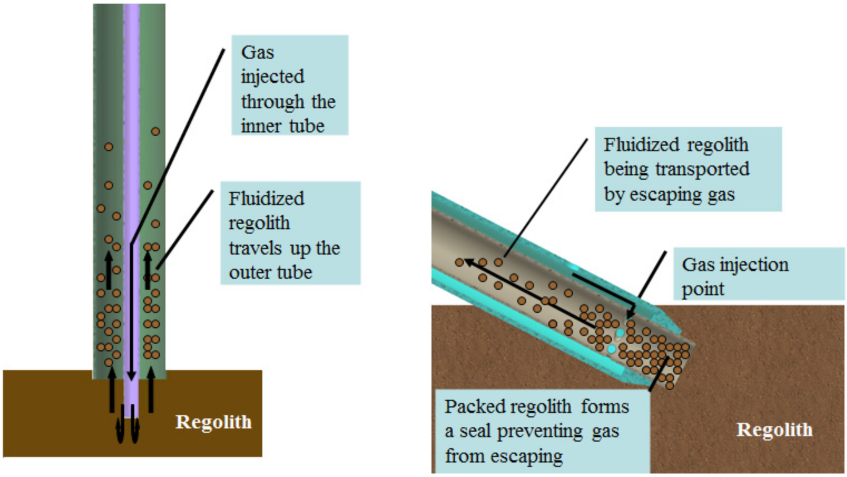


Fig. 12.36 Left: Plunge method of pneumatic lift/excavation. Right: Traverse method of pneumatic lift/excavation.

The pneumatic approach can be ideally suited for obtaining both small samples for scientific analysis, as well as a bulk sample for mining and processing of resources. The working gas could be supplied by electrolyzing water into its constitutive elements: Hydrogen and Oxygen. Since the pneumatic system consist of fixed nozzles and a series of tubes for providing of gas for mining and guiding of excavated regolith to a storage container or storage area potentially hundreds of meters away it has no moving parts such as motors, bearings and so forth, and hence is well suited for the dusty environment. By adjusting the pressure and flow rates, it is possible to differentiate smaller and larger particles, allowing optimization tailored for specific ISRU processing systems (Zacny et al. 2008). If only smaller particles are removed from the surface, it may remove the need for communition of the regolith, and thus reduce the energy consumed in the regolith processing stage. In addition, since smaller particles have larger surface area to volume ratios, the extraction efficiency will naturally increase.

Pneumatic excavation in the context of space applications is not a new concept. David McKay at NASA Johnson Space Center has proposed pneumatic excavation for lunar mining (as shown in Fig. 12.37) and evaluated the feasibility of pneumatic transfer for the movement of lunar regolith at lunar gravity conditions (and atmospheric pressure) on NASA's KC-135 reduced gravity aircraft (Sullivan et al. 1994). They found that the choking velocity (in the vertical transfer) and the saltation velocity (in the horizontal transfer) at lunar gravity were reduced to 1/2–1/3 of the velocity required at 1 g (choking and saltation velocities are the minimum gas velocities required to keep particles aloft).

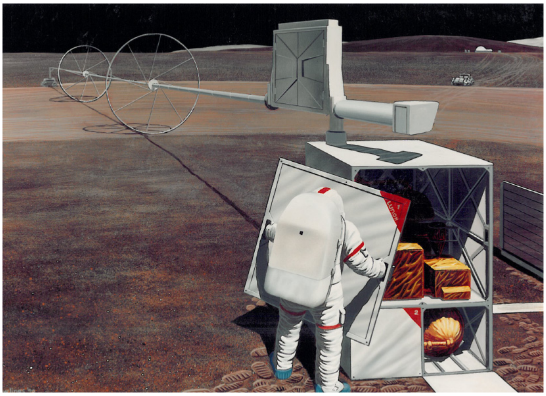


Fig. 12.37 Lunar pneumatic mining with a production-scale system: LUNOX Pilot Plant. NASA image: S91-25382 created by Pat Rawlings.

Additional tests in vacuum conditions have shown that 1 g of gas (air) at 101 kPa absolute (i.e. at atmospheric pressure) can successfully lift 6000 g of soil particles at high velocity at 1g gravity (Zacny et al. 2008, 2010). Tests conducted at various pressures suggested that gas lofting efficiencies increase as the ambient pressure drops, reaching a maximum value at approximately 1 mTorr.

For bulk regolith mining, a potential approach might use a system that has been initially developed for lunar regolith mining (Zacny et al. 2010). The pneumatic regolith miner is similar to a conventional vacuum cleaner; however instead of creating suction at the nozzle mouth, a compressed gas is injected, moving the captured soil within the nozzle up the tube and through the cyclone separator into a soil bin. Figure 12.38 shows a pneumatic excavator integrated onto the NASA Ames research Center K10-mini platform. The system has been successfully tested in a 3 meter long bed filled with GRC-1 soil simulant within a 3.5 long vacuum chamber (Zacny et al. 2008).

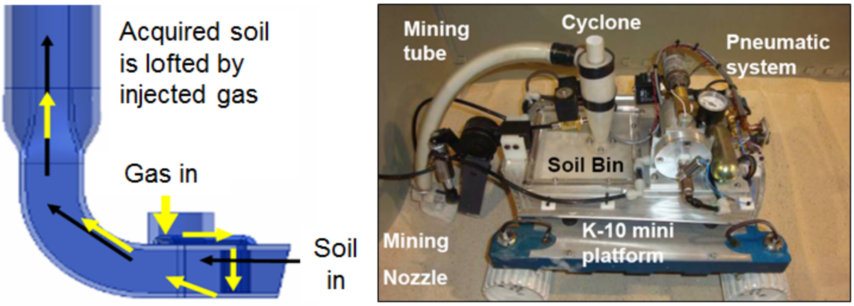


Fig. 12.38 Components of the pneumatic mining rover

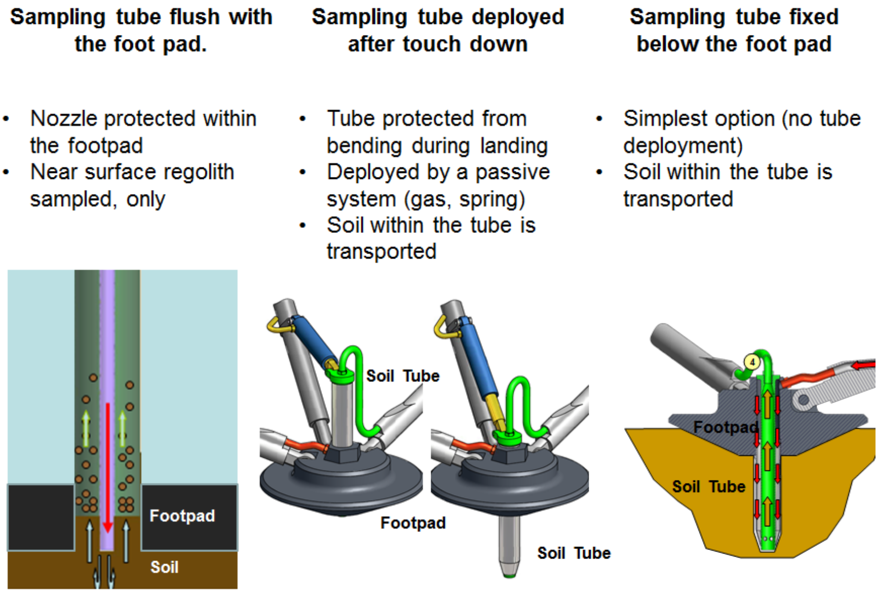


Fig. 12.39 Various approaches to sample acquisition using pneumatic systems embedded inside a lander footpad

For acquisition of small samples for scientific analysis, the pneumatic system could be integrated, for example, within each of the footpads of a lander. Sampling tubes could either be fixed or deployable, flush with the footpad or sticking beneath the footpads (Fig. 12.39). One would use deployable tubes if there is some risk that the lander will not contact the surface perfectly vertically. If only near surface regolith is of interest, a tube that is flush with the footpad would be the method of choice (Zacny et al. 2008, 2012).

With this type of deployment a level of redundancy is built into the system. For example, in case one of the legs lands on a rock the other two or three pneumatic tubes (if the lander has 4 and not 3 legs) will still be functional. Upon landing, the tubes within each of the legs will fill up with regolith. With one puff of gas, the captured soil can be lofted to a sampling chamber onboard of the spacecraft. Hence, this sampling system requires just one valve to open and close the gas cylinder and one actuator to open/close a sampling chamber.

Pneumatic sample acquisition will be demonstrated for the first time on the OSIRIS-RE-x asteroid sample return mission (Fig. 12.40). Just recently, NASA has selected the OSIRIS-REx mission to travel to a near-Earth carbonaceous asteroid (101955) 1999 RQ36, study it in detail, and bring at least 60 grams of sample material back to Earth (OSIRIS-Rex, 2012). The sampling operation will be conducted using a Touch-And-Go Sample Acquisition Mechanism (TAGSAM) system. Upon contacting the surface, an annular jet of nitrogen pointed at a surface fluidizes the regolith. This dusty gas escapes through a filter element within the round sampler. The filter then captures regolith and lets the nitrogen escape into space. During this time, the surface contact pads also collect fine-grained material. After sample acquisition, the sampler is placed inside a Sample Return Capsule for return to Earth.

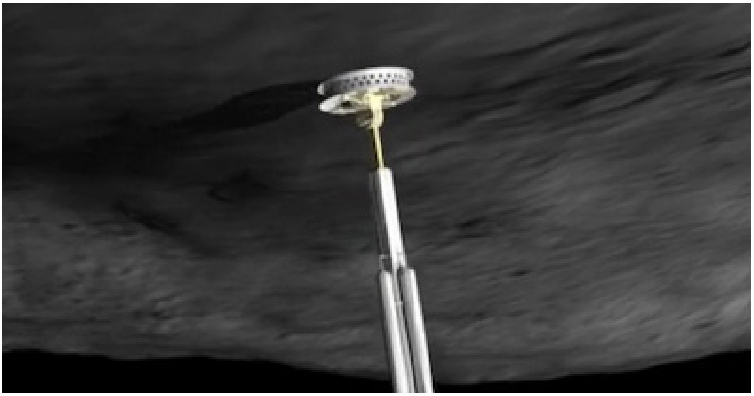


Fig. 12.40 OSIRIS-Rex asteroid sample return mission will use pneumatics to capture at least 60 grams of asteroid material. Credit: NASA/Goddard/University of Arizona.

12.6.9 Mobile In situ Water Extractor System

Many approaches to extracting water from frozen soil follow a 'terrestrial' mining approach; they consist of mining ice or ice-bearing soil, transferring the feedstock to a water recovery plant, and then extracting and storing of the water. The Mobile *In situ* Water Extractor (MISWE) eliminates the transfer or processing of feedstock steps and in turn simplifies the water extraction process. The MISWE approach is to integrate both the mining and the water extraction systems into a single unit, integrated with the drill. The water extraction process follows three steps: 1) mining the soil using deep fluted auger, 2) extracting the water from soil within the flutes, and 3) discarding the soil. Hence only the water is transported back, while dry soil is left behind.

A single MISWE reactor consists of the Icy-Soil Acquisition and Delivery System (ISADS), and the Volatiles Extraction and Capture System (VECS). The ISADS is a deep fluted auger that drills into the ice or icy-soils and retains material on its flutes. Upon material acquisition, the ISADS is retracted into VECS and sealed. The VECS consists of a cylindrical heat exchanger and volatiles transfer system (a reactor). The material on the deep flutes is initially heated and resultant water vapor is bled into a water collection canister by a one way valve where it condenses. The heat from the water collection canister can be circulated back into the reactor via a heat exchanger. After water extraction is complete the ISADS is lowered towards the ground and spun at high speed ejecting the dry soil via centrifugal action. At the same time, the collected water is pumped from the canister into a holding tank. The MISWE then moves to the next location and the operation is repeated. Once the water tanks are full, the spacecraft is launched back towards Earth or other destination.

Since the regolith is not actually transferred, there is no need for a transfer system and associated mechanisms. Also, if a spacecraft is powered using Radioisotope Thermal Generators (RTG) or more efficient the Advanced Stirling Radioisotope Generator (ASRG), the heat generated by the unit can be transferred to the reactor. For example, the RTG on the 2011 MSL Curiosity rover generates ~120 Watts electrical power and > 1 kW heat.

Figure 12.41 shows a concept of the Asteroid MISWE with 8 water reactors attached to each leg of the lander. The reactors are placed at oblique angle to provide anchoring. Hence, reactors have dual use: anchor and water extraction.

To determine feasibility of this water extraction approach, approximately 50 tests were completed in vacuum chamber as shown in Fig. 12.42 (Zacny et al. 2012). The MISWE breadboard, in the optimum configuration, has been demonstrated to extract 19 grams of water from icy soil. The water extraction efficiency was 92% and the remaining 8% of water was lost and never captured. The power usage during the 30 minute process was 34 Watts. This translates to the energy usage of 17 Wh or 0.9 Wh/gram of water, or ~80% energy efficiency.

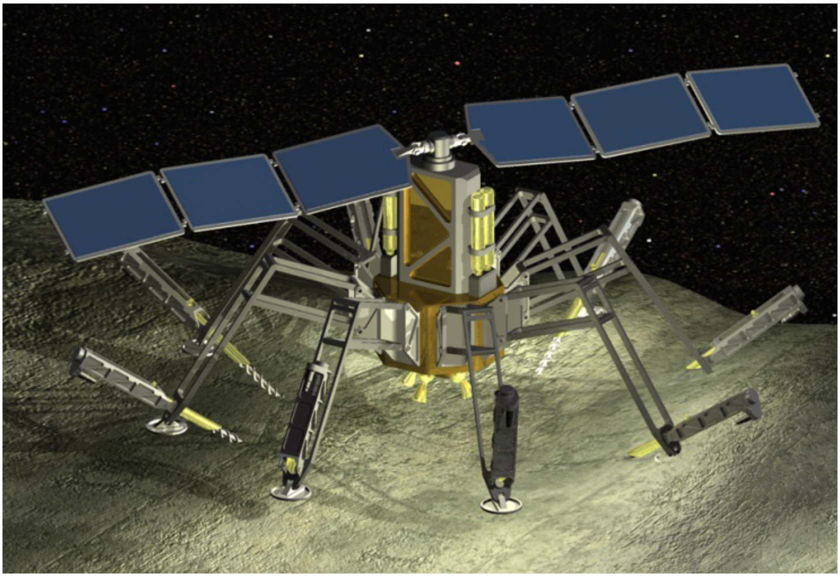


Fig. 12.41 A concept of the Asteroid water extraction system called Mobile *In situ* Water Extractor (MISWE) with 8 water reactors attached to each leg of the lander. The reactors are placed at oblique angle to provide anchoring. Hence, reactors have dual use: anchor and water extraction.

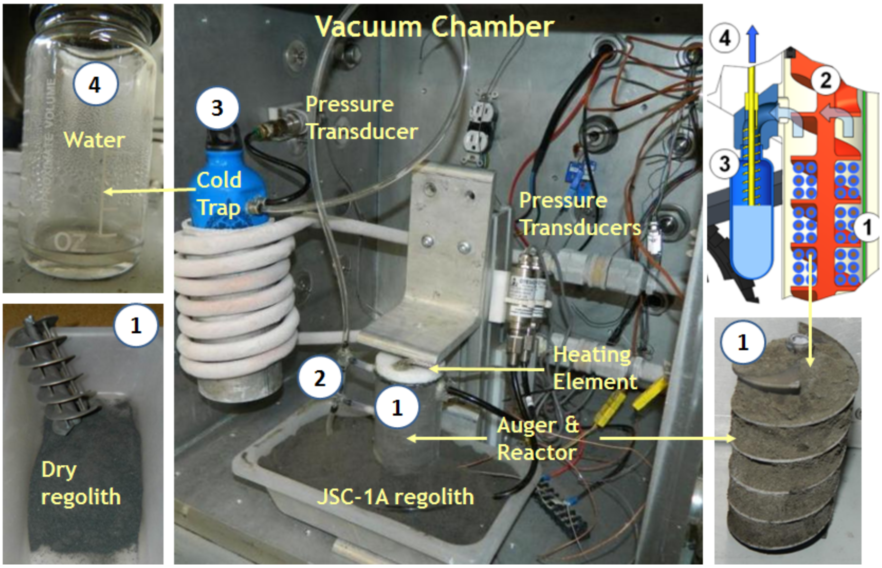


Fig. 12.42 MISWE water extraction system being tested in vacuum chamber: 1. Icy soil is collected between auger flutes. 2. Auger is heated, releasing water vapor from soil. 3. Water vapor condenses on cold finger and collects inside a canister. 4. Liquid water is pumped out of the canister to holding tank.

During the tests it was observed that a soil's temperature can be used to monitor the drying cycle. Once the temperature starts increasing it indicates that the soil is dry and the heat is no longer absorbed by the water sublimation process. Hence the heating process can be terminated making the extraction system more efficient. To make the process even more efficient, the power and duration of the applied heat and dwell time after the heating cycle could also be varied.

A MISWE reactor with a 1 meter long and 20 cm diameter auger will be able to recover ~3 kg of water every 40 minutes from regolith with ~10 wt% water. Assuming that it takes another 20 minutes for the remaining tasks (drilling to 1 meter depth, discarding of dry soil), a total of 3 kg of water can be recovered every hour. Thus the mass of water that the Asteroid MISWE system with 8 reactors can recover per hours is 8 x 3 kg per hour = 24 kg per hour or 16 tons per month. At a very conservative cost of water at EML1 of $10K/kg, this translated to a value of extracted water of $160M.

12.6.10 Percussive and Vibratory Systems

Percussive and vibratory systems are employed in circumstances where reduction in excavation forces is of primary importance (Craft et al. 2009; Zacny et al. 2009, 2012; Green et al. 2013). They are ideally suited to applications where the excavator is very light, e.g. small robots and/or low gravity environments. The main drawback to these systems is that percussive or vibratory mechanism requires additional power and in turn energy, which of course taxes the spacecraft energy supply.

The difference between percussive and vibratory operation is that the former uses hammer blows (i.e. a scoop or other digging end effector is periodically impacted by some kind of a hammer), while the latter uses for example off-centered spinning masses to induce vibrations along various planes. It should be noted that percussive systems also vibrate, but vibrations lies along the direction of the hammer blow. There are numerous ways of producing vibrations and hammering such as cam-spring, voice coil, magnetic and so on. Figure 12.43 shows an example of vibratory scoop developed by Honeybee Robotics, at the end of a robotic arm.

The reduction in digging forces in soils is attributed to reduction in friction angle because of soil dilation (increase in volume). That is vibrating or percussive scoops fluidize soil, which are therefore easier to penetrate. If soils have substantial cohesion, percussive systems are probably better suited since these tend to impart various energy impacts to crusty soils. Note that in icy soils, where ice is firmly bonded to soil particles, neither of the systems will be able to succeed due to the high strength of ice-bound soil.

Fig. 12.43 Vibratory scoop can substantially reduce excavation forces

12.6.11 The Regolith Advanced Surface Systems Operations Robot (RASSOR)

The Regolith Advanced Surface Systems Operations Robot (RASSOR) excavator robot developed at NASA Kennedy Space Center and shown in Fig. 12.44 is a teleoperated mobility platform with a space regolith excavation capability. This more compact, lightweight design (<50 kg) has counter rotating bucket drums, which results in a net-zero reaction horizontal force due to the self-cancelation of the symmetrical, equal but opposing, digging forces.

This robot can operate in extremely low-gravity conditions, such as on the Moon, Mars, an asteroid, or a comet. In addition, the RASSOR system is designed to be easily transported to a space destination on a robotic precursor landing mission. The robot is capable of traversing over steep slopes and difficult regolith terrain, and has a reversible operation mode so that it can tolerate an over-turning incident with a graceful recovery, allowing regolith excavation operations to continue.

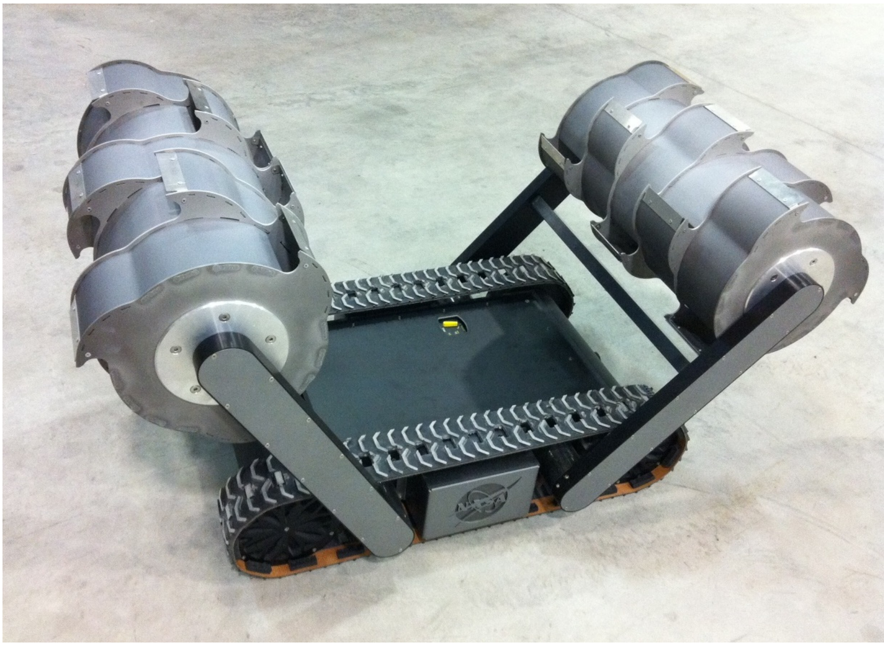


Fig. 12.44 The Regolith Advanced Surface Systems Operations Robot (RASSOR)

The RASSOR excavator consists of a mobility platform with tread belts on the port and starboard sides that are each driven by electrical motors, but it could also operate with a wheel system to further reduce mass. Two batteries are mounted in a "saddlebag" configuration on either side. Two counter-rotating bucket drum digging implements are held by a rotating cantilever mechanism at the fore and aft ends of the mobility platform. The cantilever arms are raised and lowered to engage the bucket drum into the soil or regolith. A variable cutting depth is possible by controlling the angles of the cantilever arms.

The unit has three modes of operation: load, haul, and dump. During loading, the bucket drums will excavate soil/regolith by using a rotational motion whereby scoops mounted on the drum's exteriors sequentially take multiple cuts of soil/regolith while rotating at approximately 20 revolutions per minute. During hauling, the bucket drums are raised by rotating the arms to provide a clearance with the surface being excavated. The mobility platform can then proceed to move while the soil/regolith remains in the raised bucket drums. Finally, when the excavator reaches the dump location, the bucket drums are commanded to reverse their direction of rotation to the opposite spin from digging, causing the gathered materials to be expelled out of each successive scoop. It can also stand up in a vertical mode to deliver regolith over the edge of a hopper container. For ore recovery from captured regolith, the buckets could be designed to form a reactor. In particular, once regolith is captured, the bucket drum can be sealed and the regolith inside it can be heated to recover valuable volatiles, such as water-ice.

The RASSOR can operate with either side up in a reversible mode and it can flip itself over. This means the unit can drive directly off of the deck of a lander to deploy in low gravity, eliminating a deployment mechanism, which saves mass and increases reliability due to decreased complexity. The RASSOR system is scalable and may be mounted on mobility platforms of various sizes.

12.7 Conclusions

For decades, asteroid mining has been a very popular subject of study (Ross 2001; Sonter 1998; Lewis 1996). However, only recently a number of studies demonstrated that capturing a small asteroid and bringing it back to cislunar space is feasible with a current state of technology (Brophy at al. 2011, 2012).

In addition, the *In situ* Resource Utilization (ISRU) community has been very active in developing various planetary mining and processing technologies. The community published their research at various meetings and hence there exists a wealth of information on the subject. More information could be gained, for example, by tapping into proceedings from the following meetings: Space Resource Roundtable, Planetary and Terrestrial Mining Sciences Symposium, the AIAA Space Conference and Exposition, and the ASCE Earth and Space Conference.

However, when examining available literature, it becomes clear that there has been an extensive technology development for the Moon and Mars, but very little for asteroids. Some of the Moon-focused technologies could also be applied to a microgravity environment (i.e. asteroids), but each technology has to be treated on a case by case basis.

This chapter attempted to consolidate asteroid focus technologies related to anchoring, mining, and excavation. One notable commonality among these technologies is the low level of maturity. Only a few have even been tested in a relevant environment. If NASA or a commercial sector is planning to explore these bodies, the excavation and processing technologies would have to be developed and tested from scratch. In technology development, all potential investors are of course concerned about the associated cost to increase the maturity of the technology. However, it takes many years to develop and mature a space-rated technology so it can be robust for commercial applications (i.e. multiple rather than a single operation). This timeline cannot be shortened by simply investing more money. Hence, it would be more cost effective in a long run to have a steady research and development effort even at a modest level of funding, rather than nothing for many years followed by a massive cash investment to meet a deadline.

Useful Websites

NASA Asteroid and Comet Watch http://www.nasa.gov/mission_pages/asteroids/main/index.html

JPL Near Earth Object Program; http://neo.jpl.nasa.gov/

NASA National Space Science Data Center Asteroid Photo Gallery; http://nssdc.gsfc.nasa.gov/photo_gallery/photogallery-asteroids.html

National Space Society's Asteroid Page; http://www.nss.org/settlement/asteroids/

Planetary Resources; www.planetaryresources.com

Deep Space Industries; http://deepspaceindustries.com/

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