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The Phobos-Grunt Microgravity Soil Preparation System

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Abstract
To understand the composition of regolith on distant bodies it is important to make quantitative measurement of its composition. However, many instruments on board space missions can only make qualitative measurements. The SOil Preparation SYStem (SOPSYS) designed for the Phobos-grunt mission in 2011 was a unique spacecraft subsystem that can grind, sieve, transport and measure samples of regolith in the absence of gravity. Its mission was to produce a compact plug of regolith sample composed of particles no larger than 1 mm for a gas analytic package. It delivers a sample with specified volume enabling a quantitative analysis of the volatiles produced at different temperatures through heating. To minimize cross contamination, SOPSYS self-cleans after each sample is delivered. The apparatus was a cooperative development between China and Russia for the Phobos-Grunt mission to the Martian moon Phobos and will be reused on the upcoming reattempt of that mission and other similar missions. The paper presents an overview of the subsystem and the results of qualification model testing. The flight unit of SOPSYS has a low mass of 622 g including control electronics and compact dimensions of 247 mm by 102 mm by 45 mm.

Keywords
Phobos; Phobos-Grunt; SOPSYS; sample; preparation; sample return

1 Introduction
The Russian mission “Phobos-Grunt” was planned to land on the Martian moon Phobos, where its mission was to analyze the geochemistry and return samples to Earth [1]. After a ten month cruise to Mars, the mission was intended to spend several months in Martian orbit before landing on Phobos to experiment on the surface regolith. Phobos is a small celestial body that fits into an ellipsoid of 13.05 km by 11.1 km by 9.3 km (± 0.3 km) and has an estimated mean density of 1887 kg/m3 [2]. It thus has a low surface gravity of between 0.002 and 0.008 m/s2, making it a challenging landing target. A successful mission would have served as a technology demonstrator for future missions towards Near-Earth Asteroids, comets or the moons of the outer solar system [3]. Surface sample analysis would have provided evidence of the moon’s origins and surface composition. The presence of olivine and serpentine would have indicated that the moon was a captured carbonaceous chondrite whereas a composition similar to that found on the Martian surface would indicate the moon formed from debris from an impact [4]. There was the further potential for the detection of impact ejecta originating from Mars [5]. As Phobos is in a low orbit only 6000 km above Mars, this ejecta could have been preserved on Phobos and would have given a glimpse of older Martian geology. Once a sufficient number of regolith samples were gathered, a return stage was to be ejected by springs from the lander to bring these samples to Earth. The rest of the lander would remain on Phobos to conduct further experiments. Unfortunately, the mission suffered a propulsion failure and could not leave Earth’s orbit [6], though there are plans to refly the mission in 2025 with only minor modifications.

The targets of the Phobos-Grunt regolith analysis experiments ranged from sand to solid rock. A SOil Preparation SYStem (SOPSYS) was required to grind, sieve, press and measure the samples before experimentation by a gas analytic package, shown on the spacecraft in Fig. 1. This sample preparation allowed for an exact specification of particle mass and fineness. Such consistency makes analysis of the volatiles produced during heating more accurate in absolute terms. Furthermore, SOPSYS included a self-cleaning capability to limit cross contamination between samples.

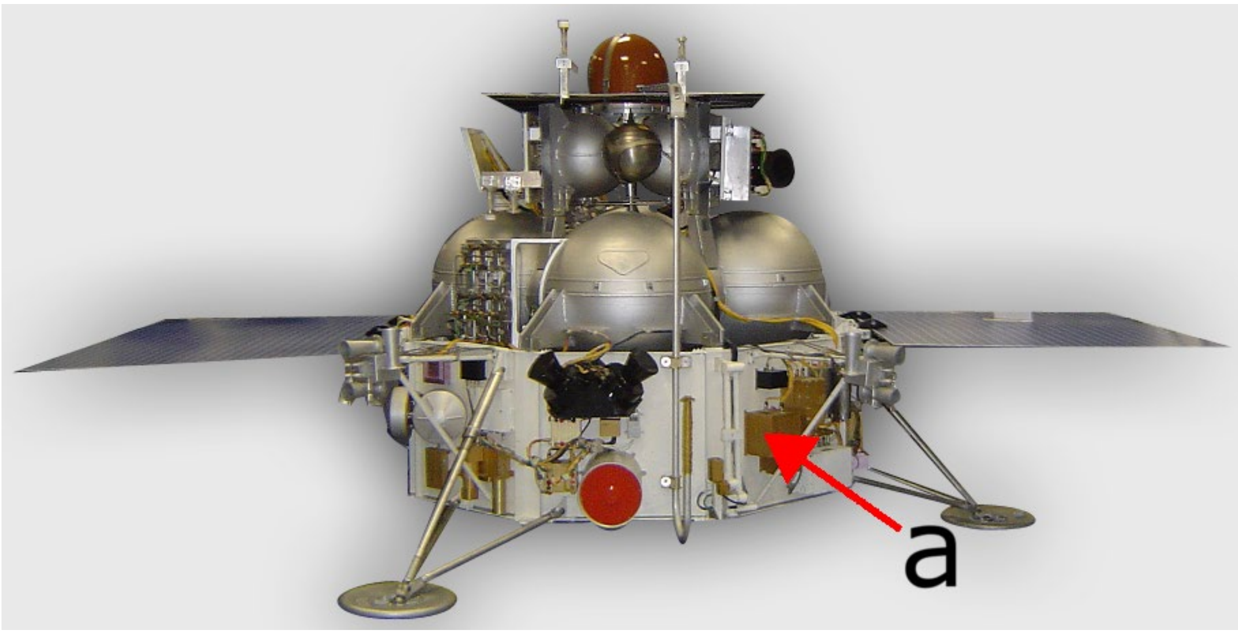

Fig. 1 – SOPSYS as located on board Phobos-Grunt, marker a.

Several regolith analysis missions have explored extra-terrestrial surfaces. Many of them have performed experiments directly to the regolith via contact experiments, such as the Surveyor spacecraft which were equipped with an Alpha-Scattering Surface Analyzer to measure the abundance of major elements on the lunar surface [7]. This approach has been taken further by the Mars Exploration Rovers which included a rock abrasion tool for cleaning and exposing new surfaces for an advanced suite of sensors to take measurements [8]. Venera 14 [9], Viking [10], Phoenix [11], Beagle 2 [12] and Philae [13] all took or intended to take samples into the main body of the spacecraft but did not carry out any further processing after acquisition. The Mars Science Laboratory [14] has a subsystem for filtering and batching the acquired regolith but performs no internal operations to further process the sample. A proposed ExoMars sample preparation subsystem uses a gravity fed crusher to process the sample into a fine powder [15]. With the exception of Philae, all the spacecraft carried out their missions in at least 0.16 g of gravity.

SOPSYS was thus the first subsystem flown with such a wide range of sample processing capabilities in a single unit and the first subsystem to attempt such processing in the microgravity.

2 Challenges and Processes

SOPSYS' task was the preparation of a sample of regolith recovered by a robotic manipulator from the surface of Phobos. The intent was to heat the samples and then measure the volatile gases released to determine the sample's composition. The requirement from Phobos-Grunt was for SOPSYS to grind, sieve and press the regolith into a plug of defined volume and that the sample composition is of particles less than 1 mm. The majority of the unit is made from space qualified austenitic stainless steel and aluminum alloy. Fig. 2 shows the subsystem architecture.

The unit has five actuators and two chambers, as labelled. Summarizing the main sequence process; firstly the sample is off loaded into chamber 1 for grinding. As the sample is ground, it is filtered through the sieve that forms the boundary between chambers 1 and 2. Once grinding is complete and the sample fully moved into chamber 2, actuator B compacts the sample and then transfers it to actuator E for delivery to the gas analytic package. Actuator C rotates chamber 2 so that the sieve is in front of actuator D. Whilst actuator D clears the sieve of debris, actuator A does the same for chamber 1. Actuator B then pushes all the debris next to actuator E which deposits the debris out of the spacecraft.

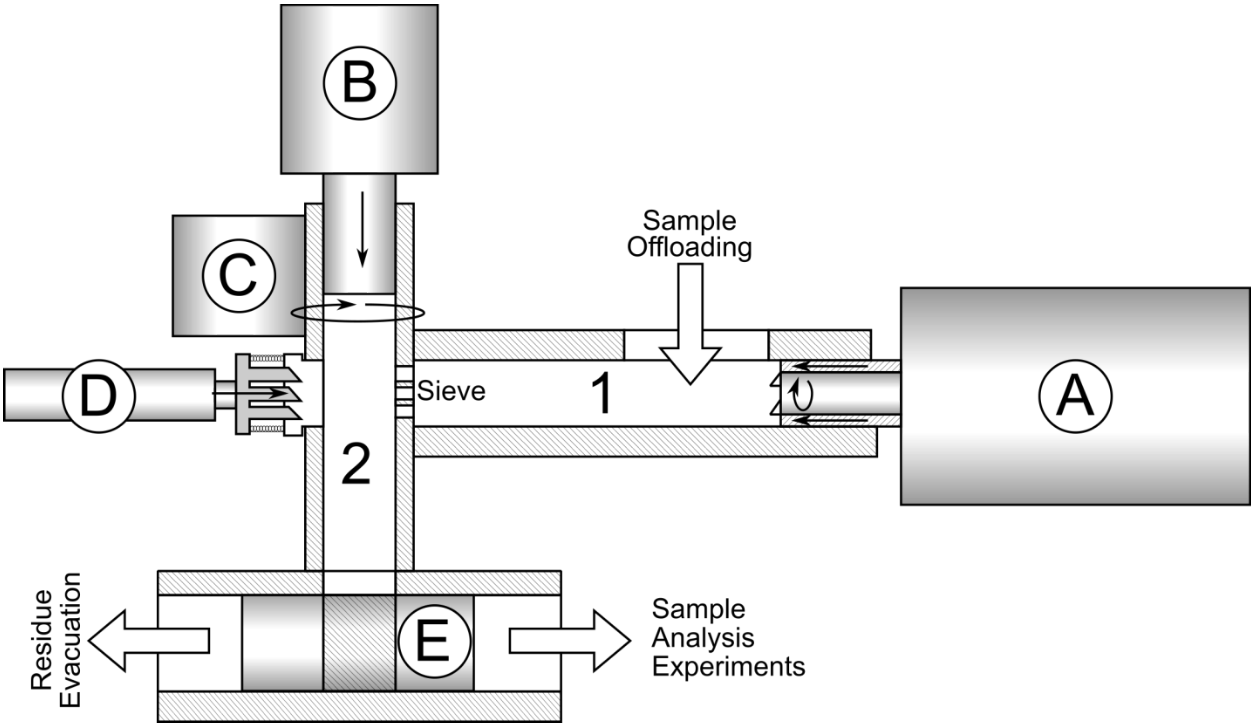

Fig. 2 - Simplified Architecture of SOPSYS

2.1 Grinding

The processed regolith samples are to be delivered to a gas analytic package that contains a gas chromatograph, a mass spectrometer and a thermal differential analyzer [1, 16]. Grinding the sample into particles no larger than 1 mm maximizes the surface area of the particles for volatile emission and minimizes the potential for volatiles to be trapped within particles. Pre-launch experiments were carried out by the mission principal investigator on a qualification model using a selection of igneous Earth rocks. These calibration experiments can be used to estimate the amount of gas released by a given volume/mass of sample through correlation of the results to the calibration minerals.. The gas analytic package is thus able to report not only the ratio of gases present but also their quantity, a significant scientific advantage.

The challenge for SOPSYS was to achieve the wanted reliable and consistent grind for the minimum amount of mechanism mass and energy expenditure. Additionally, microgravity provides no assistance in holding the sample in place. Optimization of the design for these goals starts with the grinding chamber itself, which is sized so that when full it does not contain more than 0.23 cm^3 of material. This minimizes structural mass and prevents the grinding of an excessive amount of sample. Additionally, to prevent the unit from accepting a piece of material too large for the grinding head, a wire grill covers the entranceway to chamber 1 which limits the maximum particle size to 3 mm. Once the robot arm delivers a sample of Phobian regolith into chamber 1, a transmission of planetary gears drives actuator A forward. A spring provides an additional compressive force to hold the sample against the grinding head in the absence of any gravity to help keep the sample in position. Grinding begins once the sample is pushed against the sieve. The grinding time is limited to 90 seconds to prevent the unit wasting energy attempting to grind too hard a sample. Should a sample be too hard to grind, it is ejected from SOPSYS during the cleaning operation.

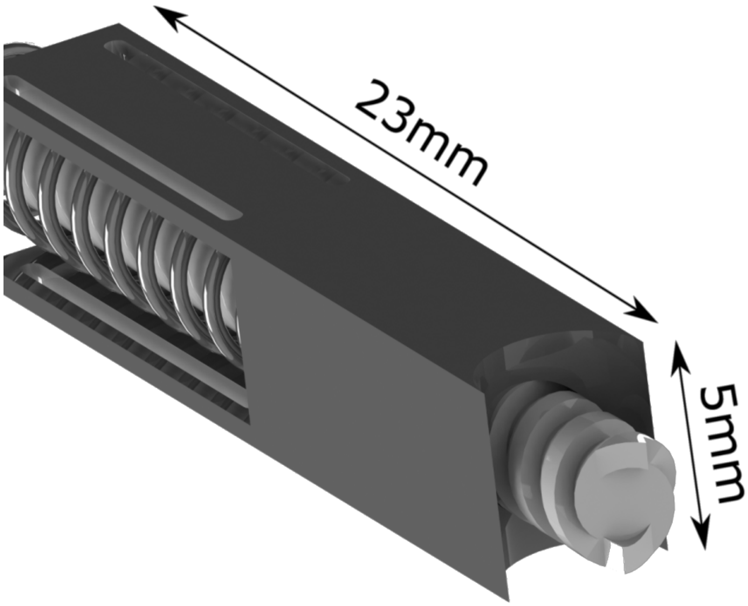

Fig. 3 - Grinding head with spring loaded shroud

The grinding head and shaft have been designed for minimum mass, allowing for a low power motor to still be able to achieve high rotation speeds. The grinding head shown in Fig. 3 is a flat surface surmounted by two small teeth coated with tungsten carbide to increase hardness. By limiting the size and number of the grinding teeth, the kinetic energy available is better concentrated. At 4000 rpm there is 40 mJ of kinetic energy available for transfer to the sample across a grinding tooth area of 0.128 mm2 and a momentum of 0.185 mJs. The small tooth size converts the low motor torque into an applied shear pressure of 63.7 MPa. In addition to the rotational grinding, frequent percussive impacts are applied. The grinding shaft includes a ratchet that moves the actuator backwards 2 mm before a spring snaps the grinding head forward against the sample with a pressure of at least 6 MPa at the teeth once every 0.015 seconds. The mechanism is shown in Fig. 4. The mechanism includes a linkage that transmits only the rotation of the front drive shaft from the motor and thus prevents the translation of the grinding shaft from damaging the motor. No other transmission exists between the motor and the grinding shaft due to mass and volume constraints. Whilst such a gear box could improve the torque available, the unit is instead focused on maximum kinetic energy and thus no transmission is wanted.

By exploiting the rotational motion of the grinding head, the ratchet allows the unit to convert rotational energy supplied by the motor into a compressive impact. This allows for the application of two different types of stress to the sample for very little increase in mechanical mass or complexity, particularly as the only additional component required is the ratchet. The grinding shaft and head are made from high speed steel to minimize flexure during grinding.

A spring loaded shroud around the grinding shaft covers the entrance to chamber 1 and supports the grinding shaft. The front of the shroud is shaped to fit seamlessly against the sieve and to funnel particles towards the grinding head. To reduce the risk of particles moving into Actuator A’s mechanisms, there is no nominal gap between grinding head and the shroud. The shroud is made from nitrogen implanted titanium alloy, chosen for its greater hardness and its low friction coefficient with high speed steel. The grinding shaft is not an enclosed unit, so even if a space qualified lubricant were to be used it would quickly become polluted with sample and the sample would become polluted with lubricant. The shroud is shown partially retracted in Fig. 3 to better reveal the grinding head.

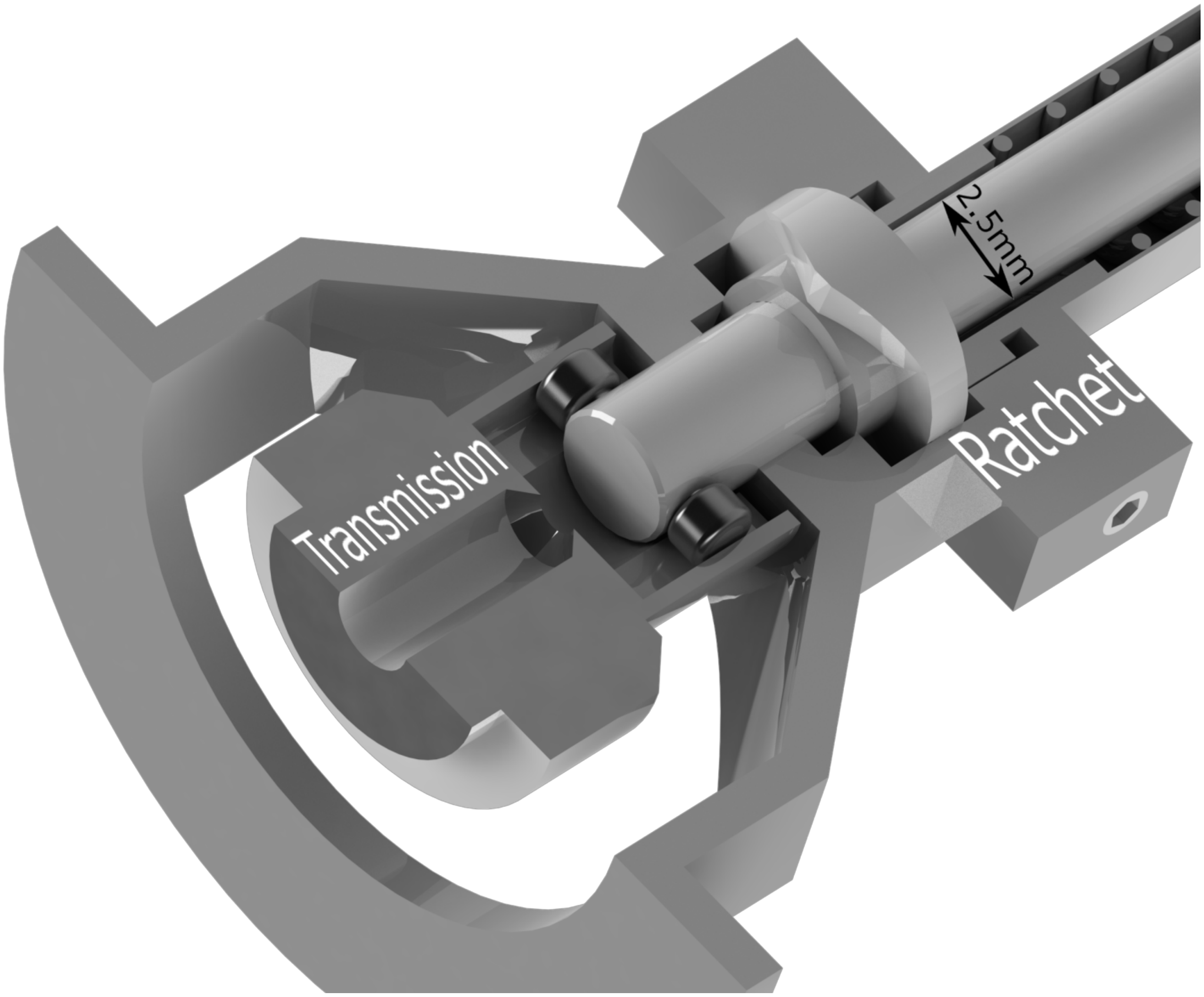

Fig. 4 - Ratchet and transmission system of the grinding shaft for actuator A.

2.2 Sieving

The surfaces of the sieve are coated in tungsten carbide to reduce wear from passing particles and from the grinding head. The microgravity present is not aligned with the orientation of the sieve, which consists of twelve 1 mm wide holes in the structure of chamber 2. Thus there is no free source of energy to move particles of suitable size through the sieve. The pressure applied by the grinding head is not suitable as larger particles will simply be jammed into the holes and prevent smaller particles from passing. To resolve this issue the teeth of the grinding head are used to agitate the particles. By transferring kinetic energy to the particles, a fluid like movement state is induced. This turbulent flow moves particles across the face of the sieve in a recirculating pattern, illustrated in Fig. 5. Particles that are small enough pass through the sieve and particles that are too large move back towards the grinding head for breaking. The grinding head can excite the particles to an expected average velocity during grinding of 2 m/s for 20 g of regolith. The grinding head thus becomes a multifunctional mechanism.

The shape of the teeth on the grinding head are a compromise design. For grinding it is preferred to have as small a tooth leading edge as possible to maximize the pressure applied. This contrasts with a desire to use the teeth to agitate the sample for passage through the cylinder, a function for which a larger tooth is preferred to maximize the likelihood of kinetic energy transfer. The design selected is focused primarily on grinding efficacy as this is the more energy intensive of the two functions. Thus the grinding head provides a method to move particles through the sieve for no additional mechanical mass and only a small increase in grinding time as a small amount of energy from the motor is used to agitate particles rather than fracture them.

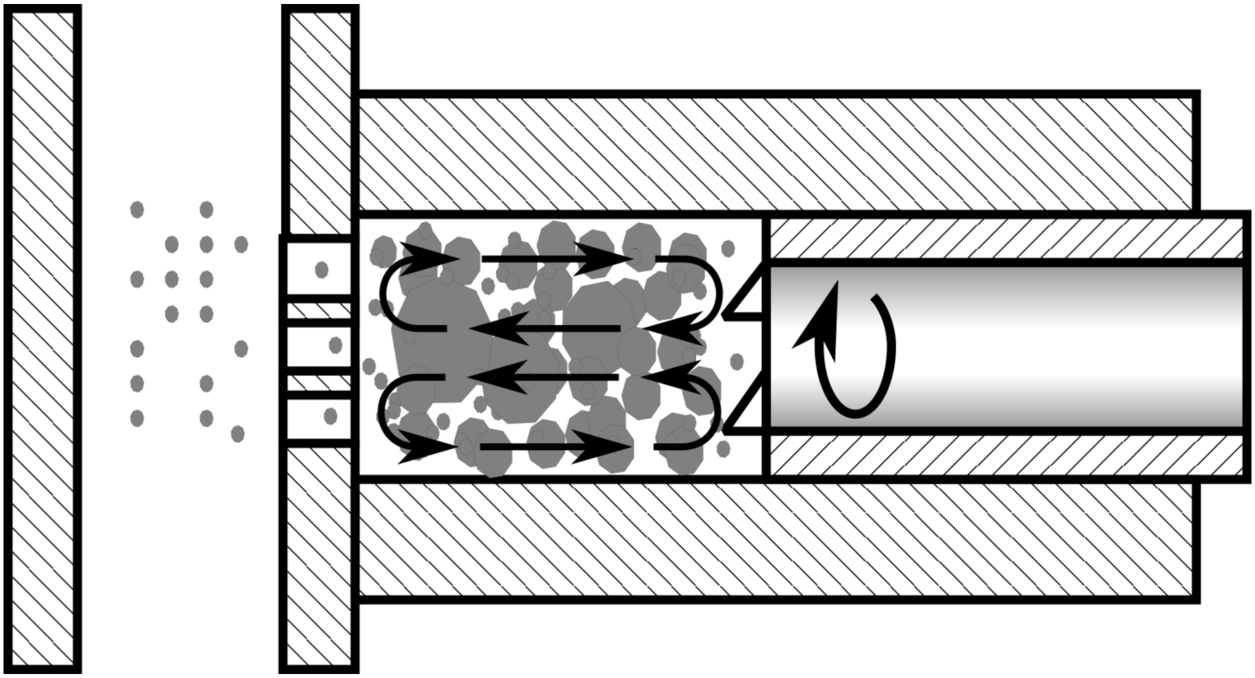

Fig. 5 - Illustration of the recirculation and flow of the particles during grinding.

2.3 Material Transfer

Chamber 2 now contains the sample reduced to particles no greater than 1 mm in size. This needs to be transferred to the experiments, but as with the sieving, there is no gravity to provide resource free movement. SOPSYS uses actuators B and E to move the sample to the waiting experiments; the process is illustrated in Fig. 6. Actuator E consists on a sliding square bar with a cylindrical chamber of 0.16 cm^3 at its center. Initially, this chamber is not open to chamber 2. Actuator B processes the loose ground particles by compacting them into a plug by pressing them against actuator E. Actuator B can apply a maximum pressure of 2.94 MPa. Actuator E then moves so that actuator B can push the plug into actuator E's chamber for delivery to the experiments via a carousel. Though this solution does require both mechanical mass and uses energy, it provides sample movement no matter the orientation of the spacecraft.

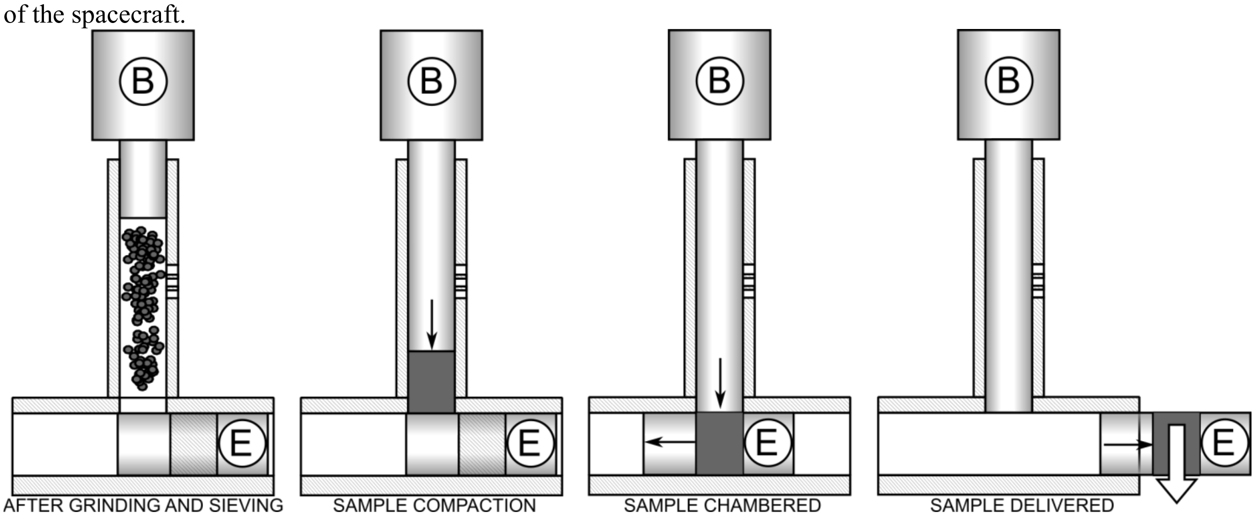

Fig. 6 - Movement of sample to experiments.

2.4 Measurement

The gas analytic package heats samples and then measures the volatile gases released to determine the sample's composition. The equipment is only capable of identifying the element ratios, so quantitation is only possible if the amount of gas released is known. In microgravity, a simple mass balance cannot be used to measure the change in mass of the sample during heating. Instead, the mass can be estimated from the volume, density and total surface area of the sample. Actuator A's displacement is used to measure the sample before grinding and actuator B's displacement when compacting the plug is used to measure the sample after grinding to obtain the sample volume. Should there not be enough material at either stage, the subsystem requests more material from the robot arm. Calibration experiments were performed before launch on a qualification model of SOPSYS to provide data on the displacement of actuator B for a selection of rock types with varied density and hardness. The results of the gas analytic package would indicate the species of rock allowing an estimation of the rock's density. These data points allow for a reasonable approximation (within 10%) of the plug mass for the cost of only several small micro sensors. As previously mentioned, this now known sample mass can be used to accurately estimate the quantities of released gas.

2.5 Cross Contamination

After delivery of the sample to the experiments, SOPSYS needs to be ready for the next sample. Having taken such steps to ensure that the sample is ideally prepared for analysis, it is thus important that the sample be as pure as possible. It is highly likely that there will be debris left in the chambers or attached to the sieve. In microgravity, debris will float freely and contaminate the next sample. Additionally, leaving material in chamber 1 could increase the likelihood of jamming through particle movement into actuator A. Brushing the chambers clean would require too many additional mechanisms and fluid cleaning solutions are not available in vacuum, even if they could be easily accommodated. Instead, SOPSYS uses a combination of existing and new mechanisms to self-clean. The process is illustrated in Fig. 7. Once actuator B is retracted, actuators A and D also retract, with Actuator D removing a plug in the wall of chamber 2 opposite the sieve. Actuator C then rotates chamber 2 by 180 degrees. Actuator D next moves forward, pushing 1 mm diameter spikes through the sieve. Actuator A also moves forward to push clear chamber 1. Both actuators finish flat or near flat with the interior surface of chamber 2.The only gap is around the grinding head, a volume of 3 mm^3, which is only 1.9 % of the sample volume and 0.3 % of the total volume to be cleaned.. Actuator E is positioned towards the interior of the spacecraft so that the sample chamber is not exposed. With all debris now in chamber 2, actuator B pushes the debris into the run of actuator E so that actuator E can eject the debris from the spacecraft. The unit then retracts all actuators and resets chamber 2 in anticipation of the next sample.

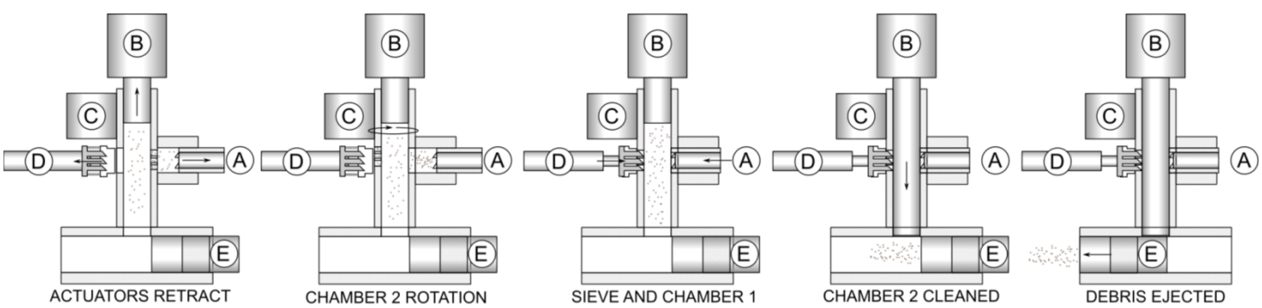

Fig. 7 - Self-cleaning process

2.6 Reliability

SOPSYS needs to perform reliably. Whilst it may only be used less than two dozen times, should it fail there is no recourse for repair on the surface of Phobos. The most likely point of failure is a possible jam of the grinding head; actuator A. A particle of regolith becoming stuck in the mechanisms of actuator A would prevent the actuator from moving or cause the motor to burn out. To minimize this risk, a reverse thread has been cut into the side of the grinding shaft, as seen in Fig. 3. Should any particles end up between the grinding shaft and its shroud, they will be pushed by the thread back toward the grinding head. The thread also provides any particles that do intrude with somewhere to go rather than become stuck, as they will likely be rapidly collected due to the high rotation speed. This anti-jam solution requires no net additional mass.

2.7 Control

Phobos-Grunt required that SOPSYS needs a minimal amount of control oversight from the primary spacecraft computer. To comply with this SOPSYS has only two binary inputs. Channel A is a communication line where 0 is a null waiting command and 1 commands SOPSYS to move onto the next state in the sequence. Channel B is the power supply which is used to turn SOPSYS on and off. This very limited control input is possible because SOPSYS' functions are a set of simple sequential states, as shown in Fig. 8. Between each state SOPSYS waits for the continue command from Phobos-Grunt. In 88 % of cases this pause is only for consideration of any reported errors. The other cases are when Phobos-Grunt needs to make a decision on if the amount of sample reported is sufficient.
If the unit encounters any problems, it can be reset by turning it off and on again. When power is supplied to SOPSYS it performs a set of actions to rest the range and freedom of each actuator. If this reports no errors then the actuators are positioned so that SOPSYS is ready to receive sample material. Should it be decided that more sample is required, the start-up process has been designed so that any material already within SOPSYS is left in its current chamber. Though SOPSYS will report that either actuator A or actuator B was not able to fully traverse, these errors can be ignored in this situation. The use of an automated start up and test routine that puts SOPSYS in a state ideal for additional external actions removes the need for a set of extra control channels, making a small contribution to the unit's efficiency.

The control output of SOPSYS is seven bits, labelled C6 to C0. C6 is the ready signal where 1 indicates SOPSYS is busy and 0 means SOPSYS is waiting for the command to continue. Bit C5 is a flag that indicates if the remaining bits are reporting SOPSYS' state or a data transmission. If C5 is 1 then C4 indicates which actuator displacement is being reported (1 for actuator B, 0 for actuator A) with C3, C2, C1 and C0 comprising a 4 bit number. If C5 is 0, the C4, C3 and C2 are a 3 bit number indicating which state the unit is currently waiting to move into. C1 and C0 in this instance are a two bit number used to report any errors from the previous state.

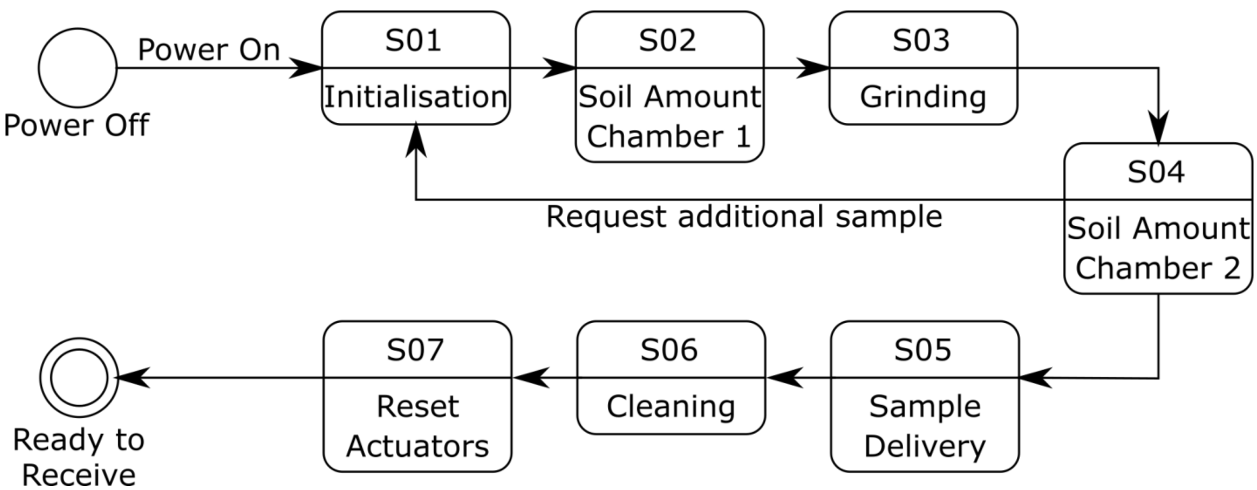

Fig. 8– SOPSYS control state flow diagram

Control of each state and the transition between them is handled by a field-programmable gate array (FPGA). Whilst FPGAs can be vulnerable to radiation induced single event upsets [17], their reduced mass, volume and power requirements make them the preferable solution to a less flexible application-specific integrated circuit design. The mechanical design of SOPSYS means that it can be adequate controlled with a system of logic gates as the need for decision making within the unit has been eliminated. In total, SOPSYS has seven electronic sensors; linear encoders on actuators A and B, a rotary encoder on actuator C, overcurrent detection on actuators A, B and C and a micro-switch to indicate when actuator C is in the home position during start-up.

On large units, the mass, volume and power costs of control hardware and the associated sensors are a very small percentage of the unit totals. SOPSYS is so small and compact that there is little room for the addition of sensors, even if the mass budget could accommodate them and the parasitic structure required to support them. Additional sensors also lead to an increase in the amount of control hardware. With a current budget of only 2 amps, for SOPSYS to maximize the energy available for grinding it must minimize power usage elsewhere. The most complex operation SOPSYS undertakes is management of the risk of jamming during grinding. Rather than electronically monitor and control the response of actuator, a mechatronic system is used instead.

Actuator A's transmission consists of two sets of a planetary gears, one for forward movement during grinding and one for reverse, that connect to a thread on the inside of the actuator housing. Between these is a magnetic clutch. A simplified schematic of the intricate gearing and mechanism is shown in Fig. 9 to illustrate the principle. During normal forward grinding, the kinetic forces on the clutch are insufficient to overcome the magnetic forces holding it in contact with the forward movement planetary gears. The pushing spring and magnets have been tuned so that if resistance to grinding head translation exceeds a value of 2 N, the motor and grinding shaft are pushed back against the planetary gears, disengaging the clutch from the forward gears and engaging it with the reverse gear set. Actuator A then reverses until the resistance to the motion of the grinding shaft ceases which leads to the clutch disengaging from the reverse gear set and reengaging with the forward grinding gear set. The transmission uses only the rear shaft of the motor and does not require the motor to change rotation direction. As such, the front shaft of the motor is free to spin up the grinding shaft so that when it reengages the sample it does so with the maximum amount of kinetic energy.

The mechanical transmission removes a need for electronic sensors, decision making hardware and motor reverse control and has a mass of only 20 g, 3 % of the total mass of SOPSYS. An equivalent unit that used sensors and a decision making control system would at the minimum include a torque sensor. The addition of a space qualified torque sensor of a suitable scale to accurately measure the torques produce could be expected to add at least 40 mm to the length of SOPSYS as it would be in addition to a reduced transmission. The additional structural mass combined with an expected 200 grams of sensor clearly indicates that the mechanical solution is more mass efficient.

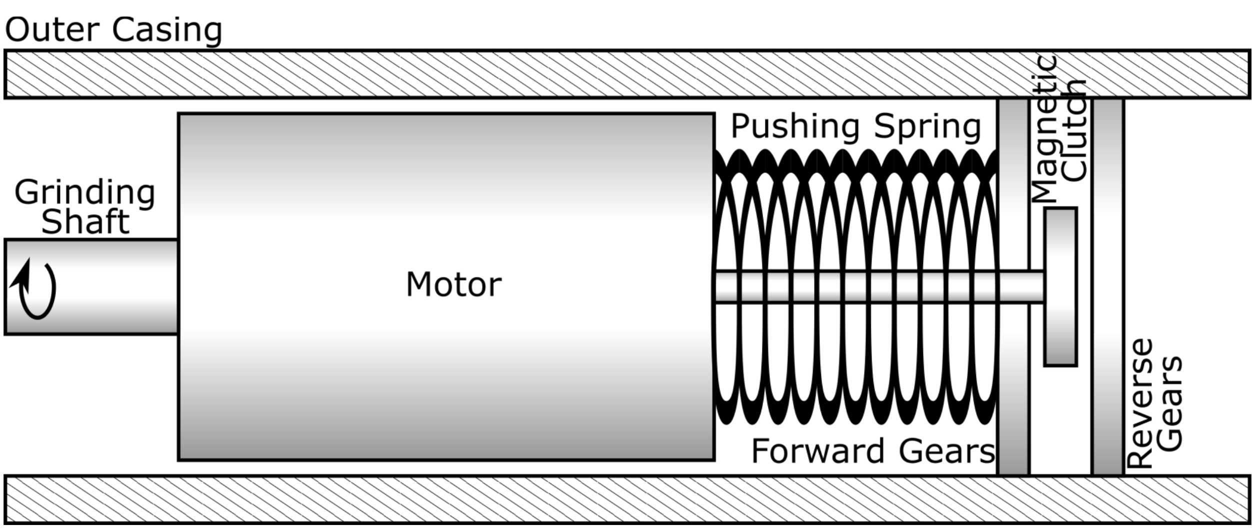

Fig. 9 – Schematic of Actuator A's transmission.

3 Performance Testing

The unit passed all qualification tests required for the Phobos-Grunt mission; such as thermo-vacuum, vibration, shock (mechanical and electrical) and radiation, Fig. 10. The thermal qualification requirement for SOPSYS was that it be able to withstand without loss of performance or dangerous thermal expansion 36 cycles of between 248 K to 348 K. The unit was qualified for launch on a Zenit-2M rocket. On the completion of development, a set of grinding performance tests were carried out on a qualification model, shown in Fig. 11. The initial performance testing was carried out at room temperature with the unit tilted through various angles to accommodate for the presence of Earth's gravity. Subsystem tests carried out by the mission principal investigator (the Russian Space Research Institute) on the qualification model were carried out in a thermal–vacuum chamber. Whilst the presence of Earth's gravity will induce a downward trend in the particles' movement, the low mass of the sample means that the force of gravity is significantly smaller than the agitation caused by the grinding head. The tests were intended to verify functionality and measure power usage and operation time. There exists competing theories on the formation and composition of Phobos, driven by a lack of information [18, 19]. There is thus a wide range of possible mineralogies, so for the testing of SOPSYS three igneous rocks with a range of hardness and brittleness were selected as a best approximation. Mass measurements were taken for three of these tests: a pyroxenite with high calcite content, a pyroxenite with low calcite content and a volcanic glass. The Moh's hardness of these samples were between 5 and 6.

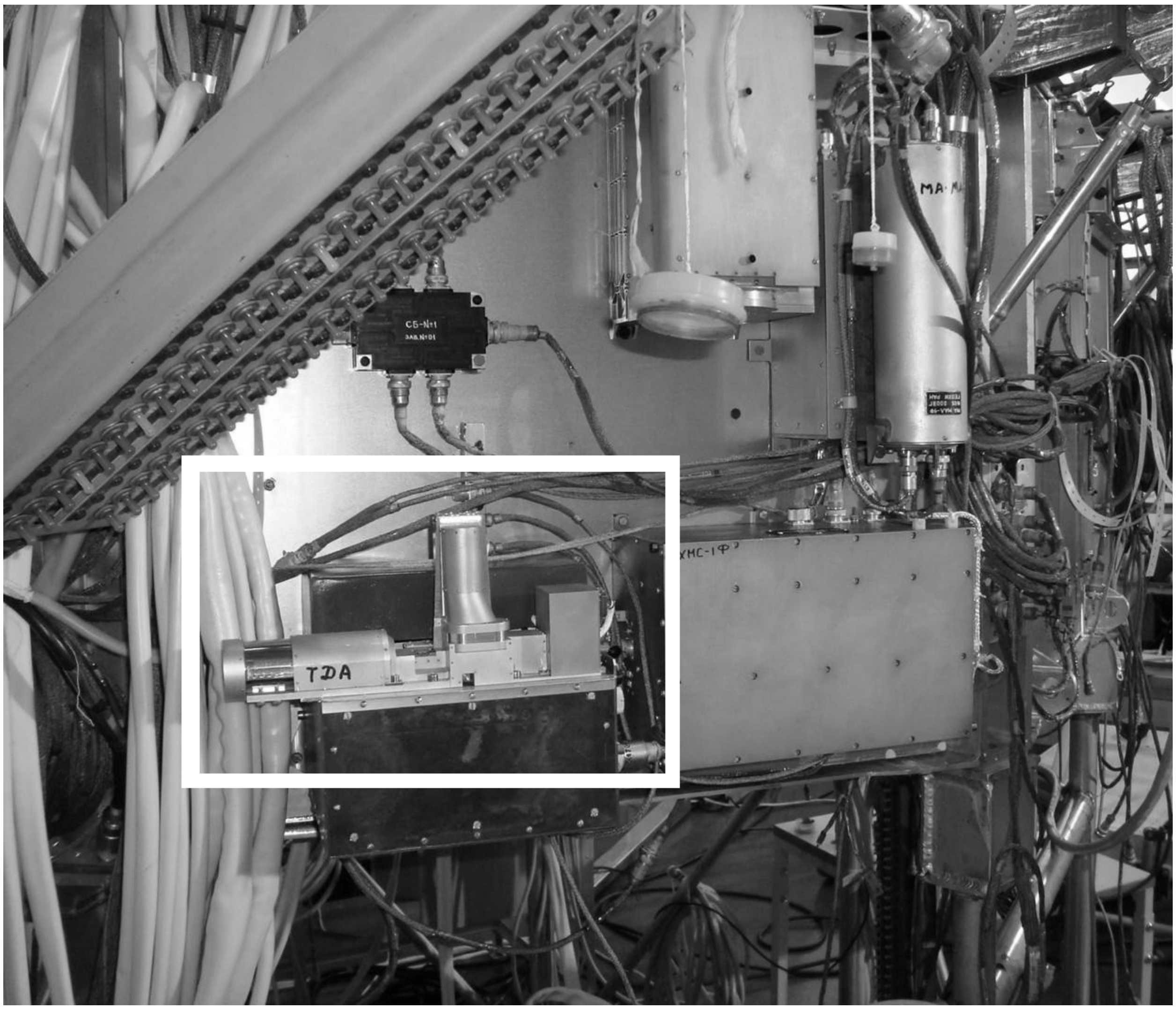

Fig. 10 - SOPSYS mounted onto the side of the Phobos-Grunt qualification model.

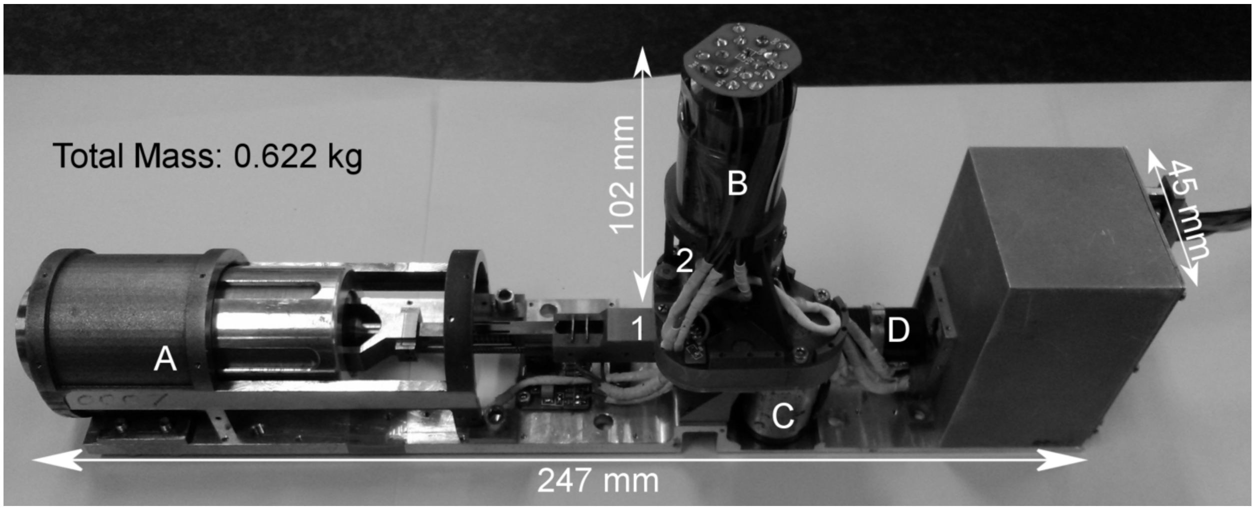

Fig. 11- Photograph of the SOPSYS qualification model (without housing) with actuators and chambers labelled. The box on the right of the unit contains the controlling electronics.

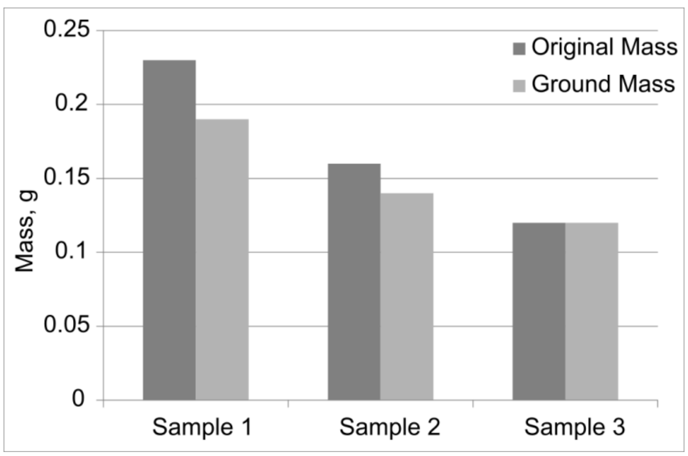

Fig. 12- Measured masses of samples before and after processing.

Sample 1 was ground in 180 seconds, requiring two complete 90 second cycles. Samples 2 and 3 did not require repeated grinding, needing only 50 seconds and 46 seconds for the process to complete respectively. The temperature of the samples before and after grinding was measured by non-contact probe and was found to have increased by at most 5 K. This low temperature increase ensures that no volatiles are prematurely produced. Fig. 12 shows the mass lost by each sample during processing. The higher calcite content of sample 1 is believed to be the reason why this sample required more processing. Though calcite has a lower Moh's hardness of 3, indicating easier grinding, it has high self-adherence. As such, when it is broken down into smaller particles, these particles adhere to other calcite particles to create lumped groups that do not fit through the sieve. Repeated processing is thus required to break up these groups. The high adherence of calcite is also the cause of the sample mass losses, with material being left behind in chamber 1 and on the sieve. Sample 3, being an easily ground brittle glass with little adherence, lost a negligible amount of material. The power usage for each of the actuators was measured to be A - 6.5 W, B - 1.2 W, C - 2 W, D - 6 W.

4 Discussion

Table 1 Summary of the SOPSYS challenges and solutions.

Function	Challenges	Solution
Grinding	Low energy usage	Low mass grinding head and ratchet based impacts
Sieving	Microgravity	Multifunctional grinding head
Material Transfer	Microgravity	Mechanical actuators
Cross Contamination	Loose particles	Self-cleaning
Reliability	Jamming	Shaped shaft
Control	Power usage	Automatic mechanical clutch

Table 2 compares SOPSYS with the sample preparation subsystems aboard MSL, EXOMARS and Philae. In addition to the sample mass, subsystem mass and maximum power usage the table uses two metrics. The ratio of subsystem mass to sample volume is a measure of how much structure and mechanism the subsystem requires to process a sample and indicates the mass efficiency of the subsystem. The ratio of maximum power usage to sample volume is a measure of the amount of power needed for each gram of sample and indicates the energy efficiency of the subsystem. As sample volume is a parameter of the subsystem it is independent of the properties of the sample, unlike sample mass which is dependent on the mineral density. It thus provides a missionless comparison between subsystems.

Table 2 - Comparison of Spacecraft Regolith Handling Systems

Name	Sample Volume	Subsystem Mass	Maximum Power Usage	Subsystem Mass / Sample Volume	Maximum Power / Sample Volume
CHIMRA	190 cm^3	8 kg	23 W	0.042 kg/cm^3	0.121 W/cm^3
SPDS	2.35 cm^3	2 kg	9 W	0.85 kg / cm^3	3.82 W/cm^3
SD2	0.03 cm^3	5 kg	18 W	166 kg / cm^3	600 W/cm^3
SOPSYS	0.16 cm^3	0.6 kg	6.5 W	3.89 kg / cm^3	40 W/cm^3

The Collection and Handling for Interior Martian Rock Analysis (CHIMRA) device on the end of the robotic arm of MSL Curiosity [20] is a system of chambers and sieves that rotates to use Martian gravity to sieve and batch the collected material. The subsystem makes use of existing actuators on the robot arm for the rotation but does have a set of dedicated actuators for thwacking the sieves to clean them and a rotating eccentric mass to vibrate material through the sieves at 80 Hz. The subsystem has a lower subsystem mass to sample volume ratio than SOPSYS but this is achieved because CHIMRA can use gravity to move its samples, reducing the number of actuators needed.The device cannot be used in microgravity. Additionally, CHIMRA performs no sample refinement, unlike SOPSYS which grinds the incoming sample to minimize the amount of rejected material. CHIMRA's power usage to sample volume ratio is superior to SOPSYS' but its sieving process takes 20 to 60 minutes, implying a greater total energy usage. The vibration technique used works well on Mars where gravity gives direction to the vibrated material to pass through the sieve. In microgravity a similar subsystem would only result in a distribution of the material throughout the compartment.

A Sample Preparation and Distribution System (SPDS) is under development as part of the EXOMars program [15]. The subsystem uses a jaw crusher to reduce samples to a size between 50 and 400 microns which are then distributed using a rotating arm. The subsystem does not sieve the sample after crushing. Whilst the crusher can achieve a maximum particle size smaller than SOPSYS, the subsystem requires both more mass and more power for a longer period of time, as crushing the sample takes between 30 and 50 minutes compared to SOPSYS' 90 second processing time. The subsystem is not suitable for use in microgravity as the crusher relies on gravity for the material feed and it would be highly complex to replace this motion with an actuator.

The Drill, Sample and Distribution System (SD2) on Philae [21] can only sample a very small amount of material. A probe extends from the drill tip to collect a sample of material after drilling is complete. A carousel moves under the drill after its retraction to accept the sample pushed into it. No action is taken to control the particle sizes in the sample and pure drilling without the assistance of impact/shock to break the material runs the risk of increased sample temperature and thus release of volatiles before delivery to an experiment. SD2 is the only other known sample preparation subsystem that operates in microgravity and for this reason it is included for comparison despite the very limited amount of sample preparation it actually performs; though the drill can be said to be a device that reduces the sample into a testable form. Because the majority of the subsystem is the high performance drilling apparatus, it is much less efficient than SOPSYS.

5 Conclusions

SOPSYS is an effective, low mass, low volume and low power sample processing unit. It provides an efficient solution to the problem of processing regolith samples in the microgravity of small solar system bodies and moons. These successes were achieved by using multipurpose and multifunctional actuators to minimize the number of mechanisms required. The process is repeatable and the unit minimizes contamination between samples.

In the in-situ analysis of small solar bodies there is the requirement to ascertain the quantitative measurement of volatile content inside the regolith in order to estimate more accurately its chemical compound constituent. Many instruments on other missions to small solar bodies such as asteroids have only been able to obtain qualitative measurement of the volatiles. Their instruments do not have a sample preparation system to ensure the sample particles expel all of the volatiles when heated up to a specific temperature. Moveover the volume and compactness were not measured to give a zero gravity estimation of the sample mass.

Therefore, SOPSYS and the gas analytic package combined are an instrument unique to enable quantitative measurement under micro or no gravity for better estimation of the chemical compounds on small solar bodies such as Phobos and asteroids. Hence SOPSYS was not only useful to the Phobos Grunt mission of 2011 but also very useful for other future missions to asteroids and the coming repeat of the Phobos Grunt mission. SOPSYS is unique in that it is the only subsystem of its kind to combine the functions of grinding, sieving, material transport, sample measurement and self-cleaning into a single unit that functions in micro or zero gravity.

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