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Towards a 3U CubeSat-Payload for *In-Situ* Resource Utilisation Demonstration at C-type Near Earth Asteroids

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Abstract

The idea of *In-Situ* Resource Utilisation (ISRU) has been around since the 1960's and comprises the utilisation of space resources to produce beneficial materials outside the Earth's gravity well, *e.g.* propellants, life support, consumables, and construction materials. ISRU appears repeatedly in recent national and international roadmaps for long duration deep space human exploration as well as in future space economies. Most of the studies of ISRU are examining production of space resources at an industrial scale. However, to have demonstrator missions in advance would help mature the technologies and understand their *in situ* behaviour. The first such technology demonstration is currently planned, the MOXIE instrument is included in the NASA 2020 rover payload and is designed to demonstrate the production of dioxygen from Martian atmospheric carbon dioxide. Elsewhere in the planetary exploration community, CubeSat hosted payloads are seen as increasingly cost effective and technologically and scientifically capable approach for planetary exploration. Furthermore, Near Earth Asteroids (NEAs) are seen as important locations for ISRU. Therefore Cranfield University's Space Group has instigated a program of research to develop various aspects of CubeSat-based exploration of NEAs and in particular CubeSat compatible payloads capable of performing cost effective early stage *in-situ* demonstration of key steps for various types of ISRU. Such demonstrations would be proof-of-concept and de-risking exercises that would justify future pilot scale and eventually full-scaled implementations. This paper will focus on a systems design for a 3U payload that demonstrates low temperature extraction of water and the subsequent electrolysis of extracted water to dioxygen and dihydrogen at a C-type NEA. The system has the following features: sample acquisition via counter rotating brush-Archimedes screws, extraction of volatile components via ovens with electrical resistive heating, trapping of condensable volatiles – primarily water, electrolysis of the trapped water into dioxygen and dihydrogen gas, and analysis of volatiles at various stage of the process with a miniaturised ion-trap mass spectrometer. The baseline design allows for collection and processing of 4 discrete samples using a carousel with 4 single use ovens. Each oven has a nominal internal volume of 16 cm^3. The design is intended to be compatible with use as part of a free-flying interplanetary 8U CubeSat, a 6U CubeSat hosted by and released by a larger parent spacecraft local to a NEA, or permanently hosted on a larger NEA surface rendezvous spacecraft. This paper presents the initial concept and early stage development of each subsystem design.

Keywords: *In-Situ* Resource Utilisation (ISRU), CubeSat, Near Earth Asteroid, oxygen production, sample acquisition

Nomenclature

U: Unit of 10 cm x 10 cm x 10 cm
wt%: Weight percentage

Acronyms/Abbreviations

Carbothermal Reduction (CR)
Degree of Freedom (DOF)
Entry, Descent, and Landing (EDL)
European Space Agency (ESA)
Hydrogen Reduction (HR)
In-Situ Resource Utilisation (ISRU)
International Space Station (ISS)
Japan Aerospace Exploration Agency (JAXA)
Mars OXgyen *In-Situ* Resource Utilization Experiment (MOXIE)
Molten Silicate/Oxide Electrolysis (MOE)
Near Earth Asteroid (NEA)
Near Earth Object (NEO)
Polymer Electrolyte Membrane (PEM)

1. Introduction

Studies of utilising space resources have been on-going for around 50 years. The ability to produce beneficial material *in situ* would expand the capability of space exploration and also reduce the launch cost of many spacecraft missions. There are several models for ISRU, for example to produce precious materials (*i.e.* platinum group metals) to be brought back to Earth; and to produce materials *in situ* instead of bringing them from Earth for future manned or robotic space missions.

The pace of development of ISRU has been increasing since the early 2000's, however there is only one existing implementation scheduled for launch, the Mars OXgyen *In-Situ* Resource Utilization Experiment (MOXIE); a small (23.9 cm x 23.9 cm x 23.9 cm) payload on the NASA Mars 2020 rover that will demonstrate dioxygen extraction from Martian atmosphere via a solid oxide electrolysis method [1].

Whilst many of the studies in this area investigates ISRU for industrial/large scale implementation, MOXIE has been selected to be the first ISRU demonstration mission. MOXIE shows that a smaller technology demonstration payload can be justified as a proof-of-concept and for de-risking future pilot scale and eventually full-scale ISRU implementations.

Since MOXIE is already representing utilisation of Martian atmosphere, there is an absence of a realistic early stage ISRU demonstration that could utilise regolith at the surface of a variety of Solar System bodies. This project aims to fill this gap by proposing a miniaturised ISRU demonstration that would utilise this resource.

This project aims to extract the most desired material at this stage of space resource utilisation, namely water and dioxygen. These products can be used as oxidiser fuel for propulsion and also consumed by humans in future human space missions. In this project, dioxygen is preferred as the target material together with the co-production of dihydrogen gas.

Furthermore, we place a constraint for any developed payload to be compatible with use in a CubeSat spacecraft. This constraint enables a realistic short-term and cost effective approach for implementing an *in-situ* demonstration of ISRU both as a free-flying CubeSat or as a payload hosted on a larger spacecraft / lander / rover.

The remainder of this paper is structured as follows: Section 2 introduces the baseline target body and its expected chemical and mechanical properties; Section 3 provides the general top level requirements and constraints of the payload; Section 4 introduces the systems overview of the payload; Section 5 describes the initial design solution for the payload and the current state of subsystem design; Section 6 provides potential configuration of the payload; Section 7 outlines future work; and finally Section 8 provides a summary of the current work.

2 Target body

There are many potential locations in the Solar System that provide beneficial materials. There are three locations which appeared to be the most appropriate to perform early demonstrations of ISRU, these being the surface of the Moon, Mars, and NEAs. In the future, icy moons and comets could be additional locations.

A simple trade study was performed to select the most suitable location for a baseline demonstration mission and resulted in NEAs, specifically C-type, being chosen. Several factors drove this choice including the following: (a) There are several scenarios to get an ISRU demonstration payload to the surface of a NEA. Firstly, via a free-flying interplanetary CubeSat, secondly acting as a payload of a hosted CubeSat on a parent spacecraft which would be released near the target, and thirdly as a hosted payload on a future surface rendezvous large spacecraft. (b) The gravitational context of NEAs means a standalone CubeSat mission is realistic and for future use would allow ISRU produced resources to be transported to other locations in the Solar System. (c) Cranfield University's Space Group is actively researching other aspects of CubeSat missions to NEAs.

The understanding of the mineralogy of asteroids is limited. Based on to spectroscopic surveys, C-type asteroids are expected to have higher volatiles content, including water when compared to other types of asteroids. The expectation that C-type asteroids are the parents of carbonaceous chondrite meteorite types CI and CM means they should have very similar chemical composition. Based on the analyses of Murchison meteorite, a matrix-rich carbonaceous chondrite (CM-type); the water content could reach up to a 12wt% [2][3]. The mineralogical composition of Murchison meteorite is shown in Figure 1. This project will use these values as its upper limit of the water content of regolith feedstock material.

The understanding of mechanical and physical properties at the surface of the C-type asteroids are also limited. This project will assume values as follows: The bulk densities of C-type asteroids range between approximately 2.0 – 4.0 g/cm^3 with porosity between 30-55% [4]. The major grain size of an asteroid is potentially depended of the size of the asteroid. Smaller asteroids (<100 km in diameter) tend to be covered by larger grain size in millimetre to centimetre regime, however larger asteroids possess very fine particles between 10 μm to 100 μm [5, 6]. We assume an upper limit of 10 mm diameter grain size.

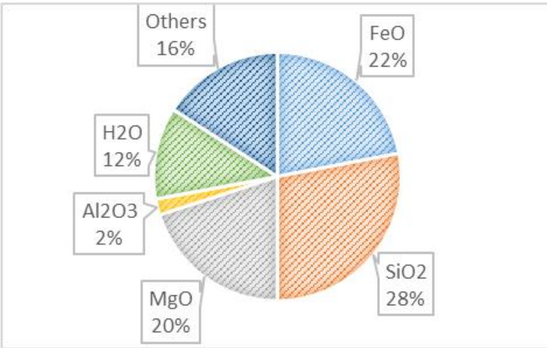

Figure 1 Mineralogical composition of Murchison meteorite, expected as the composition of C-type asteroid [2]

3 Initial payload requirements and constraints

This work will focus on investigating and designing a payload which is compatible with CubeSat integration. This paper will not discuss in detail the avionics, propulsion, and power system of a CubeSat bus that could house the payload. A current assumption is to have a CubeSat spacecraft anchored in an appropriate orientation and at a desired location on the asteroid surface so that the payload can access the surface regolith and be provided with sufficient electrical power via an assumed photovoltaic based power system.

Science requirements: To perform at the surface of a C-type NEA key steps of ISRU processes with a minimum of three replicate demonstrations to produce a statistically appropriate result.

*Functional requirement*s: Payload shall be able to demonstrate a well-established dioxygen production method, payload should be able to work in microgravity and vacuum environments.

Performance requirements: Sampling mechanism should be able to collect samples of minimum 15 g of regolith with a largest grain size allowed of 10 mm in diameter for each demonstration. Due to the uncertainty of water content in the regolith and the efficiency of the system, 15 g of sample is expected to produce at least 0.1 g of dioxygen based upon a water content of 4wt% and 50% efficiency of extraction, trapping, and conversion to dioxygen and dihydrogen. The collected sample mass requirement is relatively greater than any other previous space ovens. Larger grain sizes tend to be found in smaller asteroids, for instance, 1993 JU3, a 0.92 km diameter C-type asteroid is estimated to have grain sizes between 8 – 82 mm in diameter [5]. However, this payload will limit the allowed sampling size to 10 mm to be able to fit inside an oven/reaction chamber in the payload. The payload should be able to analyse the extracted volatiles and also estimate the amount of regolith sample collected in each oven.

Design requirements, the whole payload should fit inside a 3U CubeSat volume (300 cm^3) with a maximum mass of 4 kg. A 6U CubeSat is expected to perform this mission with assuming 2U allocated to other general spacecraft sub-systems and 1U to an anchoring mechanism. The power usage should be compatible to current available CubeSat power systems. Note that the 6U CubeSat may only be compatible with local delivery to a NEA by a larger parent spacecraft and an 8U CubeSat format may be needed for an independent interplanetary CubeSat based upon current propulsion, attitude control, power and communication technologies.

4 Systems overview

The payload requires at least three systems to be able to acquire and extract a sample and analyse the products; therefore a sampling mechanism, complete ISRU process implementation, and volatile products analyser. These systems will occupy a 3U volume of a CubeSat.

4.1 ISRU method

Dioxygen generation methods for asteroid regolith can be adopted from well researched lunar ISRU methods since there is some overlap in lunar mineralogies and those on C-type asteroids. This project selected the most suitable ISRU method for a CubeSat mission demonstration scenario by performing a trade study between relatively mature processes, such as Hydrogen Reduction (HR), Carbothermal Reduction (CR), Molten Silicate/Oxide Electrolysis (MOE), Pyrolysis, Microwave heating, and low temperature heating coupled with electrolysis. Trade parameters were defined from the thermal energy, thermal management, peak power requirement, nature of regolith feedstock material available, usefulness of secondary product, number of steps of core processing reaction, complexity of beneficiation, steps of material handling, monitoring requirement, operating temperature tolerance, maturity of the method, efficiency, lack of carrying consumable-reaction materials from Earth, and the ease of early stage laboratory research.

Although HR, CR, MOE, and Pyrolysis methods are the most popular and advanced in terms of research among other ISRU methods, the trade study showed that low temperature heating coupled with electrolysis is the most suitable method to extract dioxygen at NEAs in a CubeSat mission scenario where a significant fraction of water was present in the regolith. This in mainly due to the high energy requirement, complexity of thermal management (e.g. other methods requires heating up to 800°C and beyond), and steps required to finish the reaction [6, 7, 8, 9, 10].

The selected method is in effect a lower operational temperature version of Pyrolysis, then combined with electrolysis. Pyrolysis is the most straightforward method, a one-step reaction to extract dioxygen in high temperature (~ 2000°C) [9]. Although it is a relatively straight forward process, to have such a high heating requirement in a CubeSat would be problematic. The selected method will be less efficient compared to Pyrolysis since it only targets the extractable water content, while Pyrolysis targets most of the oxygen within a sample. However, the chosen method offsets this with reduced engineering challenges and lower power demands though with the need to process a greater mass of regolith for a given level of product.

Simplistically the selected method comprises a low/medium temperature oven, volatile trap and electrolysis module. The space application of such ovens is a well-known technology in sample analysis cases. Previous mini space ovens have already been flown in several mission, such as the Viking program that had ovens operating at 50°, 200°, 350°, and 500°C [12]; TEGA (Thermal and Evolved Gas Analyzer) on Phoenix Mars Lander operating up to 950°C [13]; COSAC (COmetary SAmpling and Composition) and Ptolemy from Philae spacecraft operating at 600°C and 800°C [13, 14]; SAM (Sample Analysis at Mars) from the NASA Curiosity Rover operating up to 1000°C [16].

The low temperature heating coupled with electrolysis process requires to heat the sample from the surrounding temperature of the target (~ -100°C) to >>0°C in a constrained environment, thus water ice in the regolith will be rapidly vaporised, will migrate to a cold trap to condense into water ice before at the end of the extraction process, being sealed, melted and transported to an electrolysis module.

4.2 Sampling mechanism

The aim of the sampling mechanism is to acquire the required samples and deliver into ovens. Each of demonstrations should have a minimum of a 15 g sample.

There are at least eleven concepts to acquire samples from asteroids [17]. NASA OSIRIS-REx, a sample return mission to asteroid Bennu, will use a pressurised gas concepts for its touch and go mission. A projectile concept is currently on board at the JAXA Hayabusa-2 mission. Airbus Defence and Space performed trade studies of potential sampling mechanisms at Near Earth Object (NEO). The top five concepts from the study were rotary bristles (brushes), pressurised gas, spherical bucket, projectile, and sticky pad method [18].

This project selects rotary brushes as a suitable method for a CubeSat mission scenario. The main idea of this concept is to have two counter rotating brushes side by side and when activated, the brushes will rotate and collect samples from beneath the brushes and through momentum transfer transport the sample particles, in a low gravity environment, into sample containers / ovens. This approach is the current baseline sampling mechanisms for ESA – Phobos sample return study. This approach has relatively fast sampling with low contact force required and compatible with loose or soft surface material [19].

4.3 Volatiles analyser

The main feature of this system is to determine and amount composition of any volatiles extracted from regolith samples and also the amount and purity of the extracted dioxygen and dihydrogen gas. This feature is expected to be of a size that will fit inside a 3U volume with other systems included. Recent developments in other research groups of miniaturised, and potentially CubeSat compatible, ion-trap mass spectrometers offers a potential technical solution for a volatile analyser sub-system.

5 Design solution

The initial design solutions to meet the requirements are presented in this section. The overall payload system description can be seen in Figure 2.

The system starts from sampling granular regolith material using a counter rotating brush-Archimedes sample acquisition system, this subsystem should deliver at least 15 g of sample into an oven. Then, the sample will be heated >> 0°C to ensure sample water ice is vaporised. The extracted volatiles are then analysed by the miniaturised ion-mass spectrometer and migrate to a cold trap, where condensable volatiles (water vapour) is trapped and non-condensable volatiles exit the system to the external vacuum environment. After sealing, the temperature in the cold trap is raised to liquefy the condensed water ice. Through capillary action and a suitable porous wicking track, liquid water is transported to the water electrolysis module. During electrolysis, the dioxygen and dihydrogen produced is analysed via the mass spectrometer to verify the amount produced and purity before venting to the external environment.

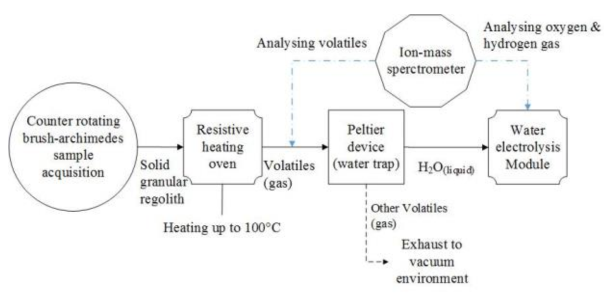

Figure 2 Description of the overall miniaturised ISRU payload

5.1 ISRU processes

The system aims to extract the water content in the regolith and convert this to dioxygen and dihydrogen. There are two major reactions to complete the process, extracting and collecting condensable volatiles from the sample via low temperature heating and a cold trap, and extracting the dioxygen and dihydrogen via a water electrolysis module.

5.1.1 Electric resistive heating ovens

The ISRU process requires the sample to be heated to >> 0°C (at present we intend a range up to +160°C). This extraction process is achieved by using electric resistive heater tape. The tape will be placed surrounding the body of the oven, the heat will be transferred directly to the oven wall.

Two options were initially considered in this study, to have one multiple-use oven or several single-use ovens. Multiple single-use ovens option is preferred in this CubeSat scenario. Compared to use of a multiple-use oven, this option will not require additional mechanisms to empty and clean the ovens and will avoid the cleaning / cross-contamination issue.

The current design has five open ended cylindrical ovens with 18 mm internal diameter and 50 mm height, and mounted in a rotatable carousel, see Figure 3. Each oven can contain 25 g of sample given an assumed sample density and particle size and void volume. This configuration will allow a minimum of three demonstrations with two back up ovens. However, in the current design, only one back up oven will be used, the other is internally exposed to the external environment during ground handling, flight and pre-deployment on the asteroid and therefore would be expected to be contaminated (note it will still have the capability to perform an extraction if required). In Figure 3, usable ovens are represented in green and the initially open and therefore potentially contaminated oven in red. Elastomer O-rings are placed on top and bottom ends of the ovens and seal the ovens by compression against the top and bottom oven plates shown in grey in Figure 4(a). Sample insertion from the sampling mechanism into an oven occurs through the hole in the lower plate in Figure 4(a). After filling, the oven carousel rotates, with the compressed O-rings sliding on the oven end plates and sealing a sample in an oven prior to heating. A port in the top oven plate (Figure 4b) allows the thermally extracted volatiles to migrate out of the oven towards the cold trap subsystem (connector not shown in figure). A particle filter is included in the port (not shown in figure) to minimise solid sample exit from the oven and into subsequent steps of the process.

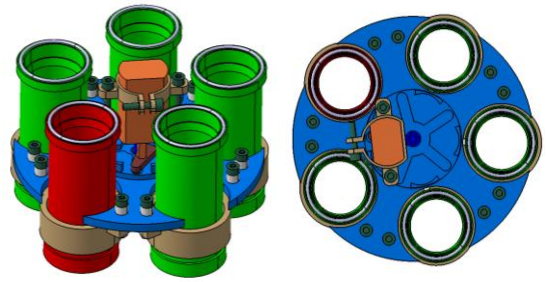

Figure 3 Oven assemblies 3D (a -left) and top view without upper and lower plates (b-right),

The overall oven carousel is rotated by a small electric motor using an internal Geneva drive mechanism. Figure 3(a) shows the Geneva drive represented in blue and the motor represented in orange and which will be clamped into the top oven plate (Figure 4b).

At any point in the operation, heating is applied to only one oven and only when this oven is positioned under the top plate port to allow volatile escape. Electric connection to the oven to be heated is via slip connections onto electric contact points on the end plates (not shown in figures). The ovens are clamped into the carousel with clamps that include thermal breaks to minimise heat soak into other parts of the structure (thermal break clamps coloured brown in Figure 3).

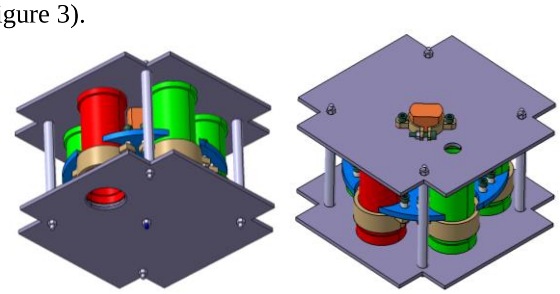

Figure 4 Oven assemblies 3D top (a-left) and bottom (b-right) view with upper and lower plates

To prevent excessive pressure rise in the oven due to release of volatiles into the vapour phase while heating is applied, the downstream subsystems will ultimately be vented to the external vacuum environment. Thus as released volatiles migrate downstream of the oven, condensable volatiles, *e.g.* water, will be trapped on the cold finger water trap and non-condensable vapours allowed to vent to the external environment.

5.1.2 Cold finger water trap

After migrating from the oven, the volatiles will pass through a high surface area metal mesh in thermal contact with a cold surface comprising a Peltier device. Condensable volatiles, primarily water vapour, will condense as water ice on the mesh and non-condensable volatile will be exhausted. This approach constitutes the cold finger trap. To remove the water for electrolysis, valving will isolate and seal and enable pressurisation of the cold finger trap. The Peltier device will be used to warm the ice, pressurise the sealed volume with water vapour and enable liquid water to form. A capillary wicking track will allow liquid water to migrate to the electrolysis subsystem.

5.1.3 Water electrolysis module

A water electrolysis module is required to extract the dioxygen and dihydrogen from liquid water. Water electrolysis is a well establish technology applied in microgravity in environments such as the International Space Station (ISS). At present, a detailed design for an electrolysis subsystem compatible with the current CubeSat payload concept has not been produced. For the planned build of laboratory breadboard versions of all the payload subsystems, an off-the-shelf solution has been identified. Horizon Fuel Cell Europe (Czech Republic) produces a miniaturised Polymer Electrolyte Membrane (PEM) electrolyser with dimensions of 54 mm x 54 mm x 17 mm with a total mass of 69.7 g. This will be used in laboratory testing prior to the detailed design of a microgravity compatible flight model representative version which will include a capillary wicking fluidic interface to the cold trap to transport liquid water to the electrolysis subsystem.

5.2 Counter rotating brush-Archimedes screw sampling subsystem

The main requirement for the sampling subsystem is to obtain samples and deliver these into the ovens. The total sample mass required for the four ovens is 60 g.

The chosen sample acquisition approach is counter rotating brushes but modified to enable sampling of the majority of the area beneath the payload and with a mechanism having only one DOF to move the sampling mechanism to access the sample. This design is driven by the significant volume constraints imposed by the CubeSat format. The modification is the addition of a pair of Archimedes screws on the same rotation axis as the counter rotating brushes and which will allow the collection and lateral transport of regolith to the brushes that are mounted underneath the oven opening. The brushes have a diameter of 44 mm and axial length of 24 mm; the Archimedes screws have a diameter of 44 mm and axial length of 60 mm (see figure 5). The rotation of each brush (blue in figure 5) will sweep via momentum transfer the regolith upward through a hole in the guide shroud (grey in figure 5) and eventually into an open oven; *i.e.* into the port in the bottom plate of the oven carousel assembly.

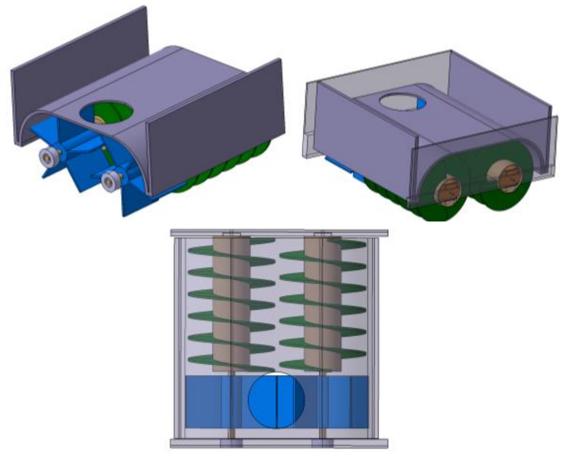

Figure 5 Sampling device 3D front view (a – top left), 3D back view (b – top right) and top view (c-bottom)

Figure 5(c) shows the Archimedes screw in green which transport the regolith from the far side to the brushes. The gap between the blades is 10 mm, this configuration is expected to exclude regolith particles of >10 mm grain size.

The rotation will be powered by two mini electric hub motors and represented in orange in Figure 5(b). The motors will be attached to structure (not shown) associated with the shroud and with appropriate bearings.

5.3 Ion trap mass spectrometer

An analysis subsystem comprising an ion-trap mass spectrometer is required to verify the products at various stages of the ISRU process. A 1U CubeSat compatible ion-trap mass spectrometer is being developed by colleagues at The Open University (United Kingdom). It is anticipated that this on-going development will provide the required subsystem to be integrated later.

6 Configuration

The configuration of the two subsystems, ovens and sampling mechanism, are critical given the significant volume constraints imposed by the CubeSat format and their respective designs reflect this need. During pre-flight and the flight to the target body, it is required to have all the payload subsystems inside the external envelope of the CubeSat bus, *i.e.* stowed, as shown in Figure 6 and 8. While stowed, the two subsystems occupy a 1.5U volume However, during surface operations, the sampling device must be in contact with the surface and extend into the subsurface as sample is removed. It is assumed the spacecraft cannot move laterally on the surface of the target body. Therefore, an additional mechanism is required to be able to extend the sampling mechanism beyond the spacecraft external envelope and into the regolith. To achieve this a scissor mechanism as shown in Figure 7 is used. This concept can extend to 40 mm beyond the base of the CubeSat, therefore will allow access to a suitable volume of regolith for collection. To guide the momentum driven transport of the regolith sample into an oven as the extension increases, the gap between the sampling device and the oven opening is constrained by the use of a telescopic tunnel creating a guide path and actuated/opened by the scissor mechanism.

The expected final subsystems configuration is shown in Figure 8. The two ½U yellow volumes represent an expected anchoring mechanism located at each side of the lower part of the 6U CubeSat. The ½U red, blue and brown volumes (1½U in total) represent the volume to house the ion trap mass spectrometer, cold finger water trap and water electrolysis subsystems. The 2U green volume represent the general spacecraft subsystems although for a realistic interplanetary CubeSat this would be expect to require a greater volume, for example a further 2U giving an overall 8U CubeSat.

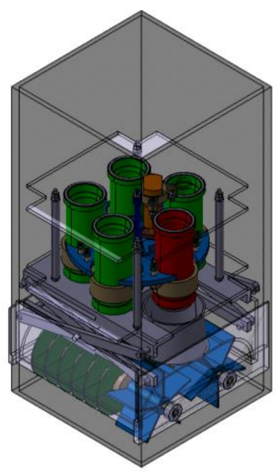

Figure 6 Representative of Ovens assemblies and Sampling devices in a 2U CubeSat volume

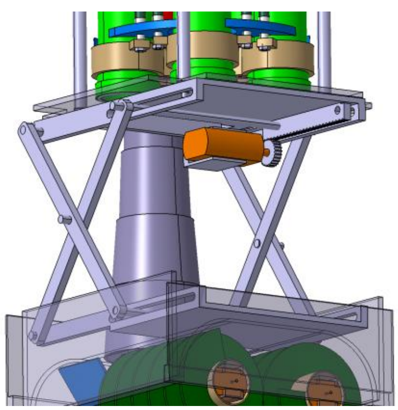

Figure 7 Extended scissors mechanism

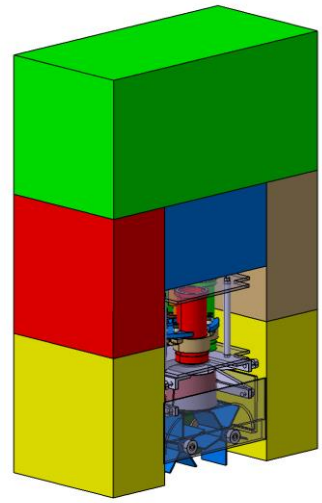

Figure 8 Expected subsystems configuration in 6U CubeSat.

7 Future work

This paper describes the current state of design for a 3U CubeSat compatible ISRU demonstration payload. The oven subsystem and the sampling subsystem are the most advanced in terms of design. Current work is focused on building laboratory breadboard versions of all the various subsystems (excluding the analysis subsystem) to allow expected performance characteristics to be confirmed and to refine the design of flight model representative subsystems. Interfaces between the subsystems and end-to-end performance will also be tested. Additionally, suitably developed breadboards are expected to be used to test critical performance features in appropriate environments such as sample acquisition and oven filling under microgravity conditions via parabolic flight and volatile extraction and trapping under external vacuum conditions.

8 Summary

This paper introduces, and reports the current development towards, a 3U ISRU CubeSat-compatible payload for early *in situ* demonstration and de-risking of ISRU processes at NEAs and other bodies. This project implements mature ISRU technologies comprising extraction of water via electric resistive heating and splitting dioxygen and dihydrogen from water via electrolysis. Concepts and designs for sampling via counter rotating brush-Archimedes screws and a scissor extension mechanism and volatile extraction via an oven carousel system are introduced. Other required subsystems for trapping condensable volatiles, for subsequent electrolysis of condensed water to dioxygen and dihydrogen, and an analysis subsystem are outlined.

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