Prototyping of Lunar surface geological sampling tools for Moon spacewalk simulations by ESA

Conference Paper · October 2018

5 authors, including:

Dorota Budzyn
University of Glasgow
11 PUBLICATIONS 13 CITATIONS
SEE PROFILE

Matthias Maurer
European Space Agency
20 PUBLICATIONS 249 CITATIONS
SEE PROFILE

Francesco Sauro
Miles Beyond for ESA
138 PUBLICATIONS 1,082 CITATIONS
SEE PROFILE

Loredana Bessone
European Space Agency
64 PUBLICATIONS 195 CITATIONS
SEE PROFILE

IAC-18,A5,1,12,x47143

Prototyping of Lunar surface geological sampling tools for Moon spacewalk simulations by ESA

Dorota Budzyń[a]*, Hervé Stevenin[b], Matthias Maurer[c], Francesco Sauro[d], Loredana Bessone[e]

[a] Directorate of Human and Robotics Exploration, European Space Agency, ESA NBF Young Graduate Trainee, dorota.budzyn@esa.int,
[b] Directorate of Human and Robotics Exploration, European Space Agency, ESA NBF EVA Training Lead, herve.stevenin@esa.int,
[c] Directorate of Human and Robotics Exploration, European Space Agency, ESA Astronaut, matthias.maurer@esa.int
[d] Department of Biological, Geological and Environmental Sciences, Italian Institute of Speleology, Bologna University, Researcher in Speleogenesis, Planetary Geology and Geomorphology, cescosauro@gmail.com
[e] Directorate of Human and Robotics Exploration, European Space Agency, ESA Analogue Field Training and Exploration Testing Lead, loredana.bessone@esa.int,
* Corresponding Author

Abstract

Apollo Lunar missions returned to scientists on Earth the first collection of geological extra-terrestrial planetary samples, other than meteorites. Scientists around the world are still studying rocks and soil samples that were collected, by the Apollo 11 through 17 missions, using modern equipment, methods and technologies. The return of samples has allowed the field of planetary science to advance in ways unthinkable with the restrictions of in-situ analysis and remote observations.

As for every other aspect of the Apollo programme, the design and manufacturing of the tools utilized by astronauts for sample collection had to meet rigorous planetary protection requirements, whilst respecting stringent environmental and operability constraints. Many of those tools went through various redesign efforts, based on feedback from the very skillful and resourceful astronauts using them. In future planetary exploration missions, geological and geo-microbiological sampling will be a key to further development of our understanding of the evolution of the solar system, and to develop successful technologies for in-situ resource utilization and 3D printing.

Designing and manufacturing technologies and ergonomics have developed since the 1960s, and so have chemical and biological hazard containment protocols, and analytical tools. Whilst it is important to solidly build on the lessons learned in the Apollo era, there is a serious opportunity for innovative design solutions.

The European Space Agency (ESA) Neutral Buoyancy Facility (NBF) based in the European Astronaut Centre (EAC) in Cologne has a large experience in performing 0g simulations for ISS (International Space Station) Extra Vehicular Activities (EVA), and has recently engaged in simulations of Lunar surface operations, replicating reduced gravity and mobility constraints, in order to prepare future human and robotics surface operations. One of the main objectives within this area is prototyping and testing new geological sampling tools which could be used in future human surface Lunar missions. The tools are being developed in cooperation with the team of planetary geologists of the PANGAEA project (Planetary ANalogue Geological and Astrobiological Exercise for Astronauts), and field tested during the PANGAEA Space Analogue test campaigns.

This paper discusses the requirements and objectives to be met while developing such tools, the challenges related to EVA suits and Lunar environment which impact the astronauts' mobility and tools performance. It presents the status of development achieved during NBF and PANGAEA analogue field testing. The examples include a variety of sample collectors, containers, markers and the outcome of test performed in various mission scenarios.
Keywords: surface EVA, Moon, sampling tools, geological samples, underwater simulations

Acronyms/Abbreviations

ASSET Adaptive Spacewalk System & Equipment Transporter
EAC European Astronaut Centre
ESA European Space Agency
EVA Extra Vehicular Activity
ISS International Space Station
IVA Inner Vehicular Activity
LESA Lunar Evacuation System Assembly
LEVA Lunar EVA
SAVE Situational Awareness Video Equipment
NASA National Aeronautics and Space Administration
NBF Neutral Buoyancy Facility
NEEMO NASA Extreme Environment Mission Operations
NEST Nearby Equipment Support Trolley
PANGAEA Planetary ANalogue Geological and Astrobiological Exercise for Astronauts
PLSS Primary Life Support System
SAMCO Sampling Sequence with Mobility Constraints
OPSCO Operation Concepts Comparison

1. Introduction

Altogether, the six Apollo missions that landed on the Moon returned 382 kg of soil samples. Through examination of Fig. 1 and Fig. 2, which are based on data originally published by NASA [1], one can observe certain patterns. First of all, the total mass of the samples returned in each mission increased from Apollo 12 to Apollo 17. This additional material was broadly beneficial to the planetary science community. Furthermore, the average size of the samples decreased, this implies that astronauts were able to collect more varied samples including smaller rocks and fine regolith. One of the factors that contributed to these changes is that, with each mission, the teams overseeing operations and equipment became more experienced and aware of all the limitations of the lunar environment and EVA suits.

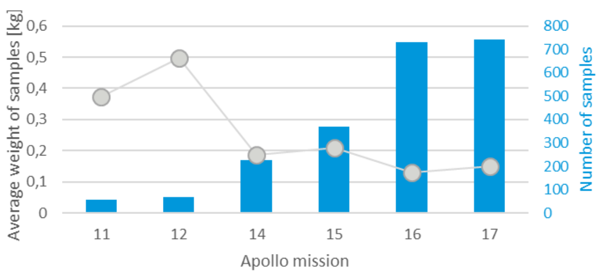

Fig. 1: Numbers of samples, average sample weight by mission, based on [1].

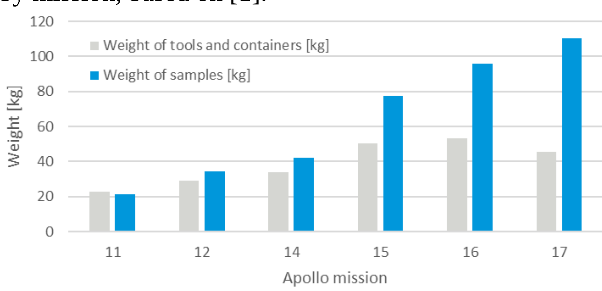

Fig. 2: Weight of samples vs weight of tools by mission, based on [1].

Fig. 2 further reinforces the existence of such development. In Fig. 2, the growth of sample mass brought to Earth is not linearly proportional to the mass of equipment used for collection. This implies that the average sample mass obtainable for a given tool's mass increased over time. This is likely the outcome of an improvement in the tools themselves as well as the training of the tool operators. Moreover, during the Apollo 17 mission the mass of the tools and equipment decreased as compared to two previous missions while the samples mass continued to increase. This further represents a marked increase in the sample collection efficiency of the tools used over the course of the Apollo program.

The overall mass of sampling equipment grew due to the fact that new tools were introduced over the course of the Apollo program. Table 1 shows the types of tools used in each mission [2]. Table 2, based on documents published by NASA [1, 2], shows the types of samples collected by particular tools. An important aspect to note is that after the Apollo 11 mission adjustable tools were introduced and then later they remained in the tools inventory of further missions until the end of program. Angle adjustment is a good approach to compensate for the fact that suit stiffness affects the sampling process making the task more difficult. Another notable aspect present in Table 1 relates to the tongs. The tongs were spring loaded and held the sample within its end effector using initial spring force. They were used in all missions without major changes which suggests their design was well suited for sample collection.

Tool	Apollo Mission					
	11	12	14	15	16	17
Contingency sampler	✓	✓	✓	✓		
Tongs	✓	✓	✓	✓	✓	✓
Large scoop	✓	✓				
Adjustable scoop		✓	✓	✓	✓	✓
Adjustable trenching tool		✓	✓	✓	✓	✓
Hammer	✓	✓	✓	✓	✓	✓
2-cm drive tubes	✓	✓	✓			
4-cm drive tubes				✓	✓	✓
Drill				✓	✓	✓
Rake				✓	✓	✓
Surface samplers					✓	

Table 1: Tools used in each Apollo surface mission.

Tool	Sample
Contingency sampler	Surface soil, small rocks
Tongs	Rocks < 6 cm
Large scoop	Surface soil, small rocks
Adjustable scoop	Surface and subsurface soil
Adjustable trenching tool	Subsurface soil
Hammer	Pieces of large rocks
2-cm drive tubes	0,5 m soil column
4-cm drive tubes	0,5 m soil column
Drill	3 m soil column
Rake	Statistical fragments >1 cm
Surface samplers	Upper 100 µm and upper 1 mm of soil

Table 2: Sample obtained by different tools.

The tools were improved over a time between the missions and it is important to note that the last mission, Apollo 17, took place in 1972. Since then, new materials, manufacturing processes and design approaches have become available and more popular. Presently, engineers and designers have several options to develop tools using different techniques and to rapidly prototype them. Rapid prototyping methods, especially 3D printing, have continued to increase in popularity and reliability since the 1980s. Despite advancements in the design and development of new technologies, it remains important to understand the present-day requirements of the science community who await lunar samples.

During future planetary missions astronauts will explore planetary geologic environments with the objective of resolving important scientific questions through sampling and documentation in the field. Compared to the Apollo missions, more complex and difficult environments, such as lava tubes, canyon rills and rough surfaces could be made accessible through new surface EVA technologies. This places astronauts as the primary actors in the effectiveness of geological tasks. The scientific objectives of future lunar missions will require the sampling of much different type of material compared to the Apollo missions, demanding the capability of extracting samples from massive boulders as well as loose materials like regolith and pyroclastic deposits. In addition, such sampling will require specific protocols and tools to preserve the volatile content and to strictly avoid cross-contamination between different samples. In this context both sampling grabbers and sample containers will need to be developed within not only ergonomic and environmental constrains but also specific non-contamination and preservation science requirements. Depending on the scientific objectives, the sampling will require different approaches and tools whose primary aim shall be the maximization of the number of samples and their original conditions.

The Neutral Buoyancy Facility in cooperation with the Pangaea team, both based at the European Astronaut Centre, are working to bridge the gap between Apollo era geological tools and the tools required for the next generation space exploration. To close this gap, data from the Apollo era and visions of future exploration challenges are combined with state-of-the-art design, prototyping and manufacturing approaches.

2. Limitations of EVA suits and Moon environment

Thus far, only pressurised spacesuits have demonstrated their capability to perform spacewalks in the vacuum of space. Even if the pressure inside the suit is reduced to the minimum amount to provide acceptable life support inside the suit, this pressure results in an increased stiffness of the suit. It imposes strong limitations to the astronaut's mobility and requires the astronaut to exert greater-than-normal forces to perform even the simplest movements.

Anyone, who has experience in wearing such a pressurised spacewalker suit, knows that it induces:

- Lack of dexterity and rapid build-up of hand and forearm fatigue (closing the hand feels like pressing a tennis ball).
- Arm movement limitations imposed by the articulation joints and bearings (at shoulder, elbow and wrist) reducing the range of the reaching capability.
- Reduced mobility of the legs preventing safe bending to reach something close to your feet (for example a tool on the Moon surface) or to kneel down.
- Reduced mobility of the waist increasing risk of high torque loads on the knees when the feet rotate
- Discomfort and bruises from repeated body contact with the inside shell of the hard torso bearing the Primary Life Support System (PLSS "backpack")
- Minimal internal volume of the helmet (including headset cap and boom microphones) limiting astronaut upward and downward visibility.

All these constraints are already very difficult to cope with for spacewalks in weightlessness on the International Space Station and require the development of a very specific set of skills through intensive and challenging training regimes. On the Moon, the partial gravity (1/6 G) plays additional tricks and adds more complexity, due to:

- The perceived weight of the spacesuit (close to 14 kg on the Moon for the Apollo suits) changing your body balance.
- The need to interact with items mostly laying on the lunar surface, which are out of reach and out of the near visual field of the astronaut (e.g. sample of Moon rocks or regolith, sample markers, fallen tools, small bags or instruments on the ground).
- The risk of falling down if you trip on an obstacle that your helmet prevents you to see or if your movements bring the centre of gravity of your spacesuit outside your base of support.

There exists extensive Apollo footage (Fig. 3) featuring EVA astronauts falling down multiple times with the risk of puncturing the suit or the helmet on an abrasive surface with sharp edges and showing how challenging it is to stand up again.

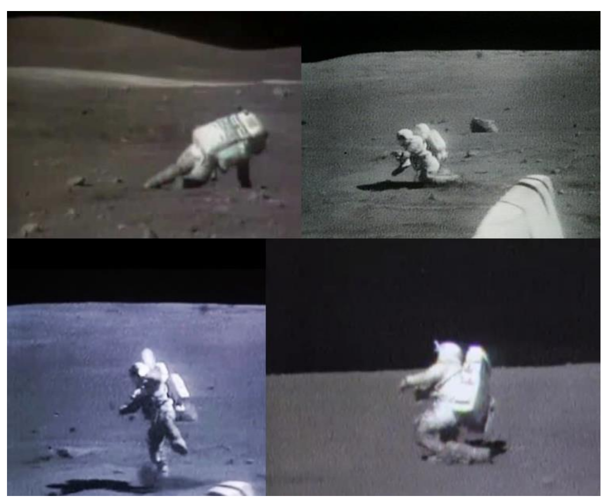

Fig. 3: Apollo astronauts falling down on the Moon surface.

Of course, the future generation of lunar EVA suits will be designed to minimise all these well-known constraints and to decrease the discomfort of the astronauts, but we are still far away from the comfortable body fitting spacesuits worn in modern sci-fi movies. The next spacewalkers on the Moon will have to cope with similar challenges to the ones experienced by the first humans on the Moon half a century ago and they will have to perform much longer EVAs filled with more complex tasks.

The Lunar environment not only affects the humans therein but also any utilized equipment. The Lunar atmosphere is effectively a vacuum which dramatically affects heat transfer by blocking convective transfer. Lunar dust is very fine, sharp and unfortunately extremely adhesive. All surface Apollo astronauts reported the dust creeping into joints and mechanisms of their suits and equipment. The lack of atmosphere also has an impact on dust dynamics, as there is minimal interfering gases to slow the ballistic trajectory of dust particles once they are ejected. Lower gravity changes the way dust behaves while falling, i.e. it stays above the surface longer. Reduced gravity also impedes the general balance and locomotion of astronauts.

3. Simulating Moon on Earth

Replicating a lunar environment on Earth is a complicated topic. At the time of writing, scientists and engineers around the world tend to focus on simulating a small subset of aspects of the lunar environment at once. For example, there are ways to simulate lower gravity: in parabolic flights or by adjusting buoyancy while diving. Simulations can also focus on the geological environment through the use of areas on Earth that can simulate lunar geology or using lunar regolith simulants. To simulate the lunar atmosphere vacuum chambers may be used. Depending on the requirements of a given experiment, suitable analogue environments must be chosen. However, choice is often limited to single aspect environments with very few analogues capable or replicating multiple aspects at once such as atmosphere and geology or gravity and geology etc.

The points mentioned below are considered to be relevant not only to the tool development mentioned in this paper but as general useful analogues for testing EVA hardware designed for the Moon.

3.1. Tests in Parabolic Flights

Parabolic flights in Europe are conducted in an Airbus A310 aircraft operated by Novespace in Bordeaux (France). During 0g flights pilots fly in long parabolic arcs and, by fine adjustment of the pitch of the plane, they are capable of simulating reduced gravity on board. Each parabola lasts for around 25 seconds. Such simulations provide unparalleled environments in which to test human movement capabilities. The primary disadvantage of this method is time, unfortunately each reduced gravity period, as mentioned, lasts for around 20 seconds. Because of this, it can be challenging to test each iteration of the prototypes mentioned in this paper during such limited time periods. On the other hand, parabolic flights could be a suitable manner to train crew on the later, more final, versions of tools.

Fig. 4: Test of an Apollo Motorbike prototype in flying the former NASA KC-135 aircraft in parabolic curves to reproduce a 1/6 gravity environment in short 20-second bursts.

3.2. Tests in the ESA LUNA

The LUNA facility of ESA is currently in the design and planning stage and will be located next to the European Astronaut Centre in Cologne, Germany. It will provide an appropriate lunar like environment which will enable the preparation of future astronaut operations on the lunar surface and to support and drive the development of the required hardware. Among other technical features, it will comprise of a significant lunar regolith simulant environment shaped into typical lunar surface profiles for extravehicular activities (EVA) and a small lunar station for inner vehicular activities (IVA) of the crew. LUNA facility will be a controlled environment for both lunar EVA and IVA operational scenarios.

LUNA will be a platform that offers a broad set of features, attractive to a large science and technical space community across Europe with the aim of spinning in new technology for lunar exploration and combining this with the operational expertise of the astronaut centre. In that sense, it is also considered as place for future tests of geological tools, where they could be exposed to lunar regolith simulant during EVA operations.

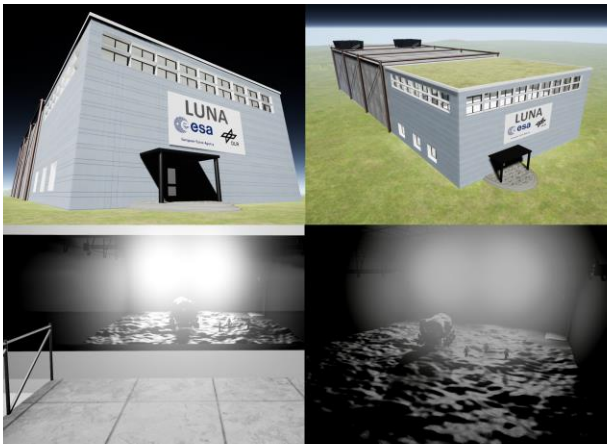

Fig. 5 The ESA LUNA buiding concept at EAC.

3.3. Tests in the Neutral Buoyancy Facility of ESA

The Neutral Buoyancy Facility of ESA is a large immersion tank (10 meters deep) located at the European Astronaut Centre and used to train in Europe the ESA astronauts on spacewalk operations for the International Space Station.

The ESA astronauts are immersed in neutral buoyancy (simulation of weightlessness) and geared with equipment and tools reproducing the working environment of ISS Extra Vehicular Activities. They learn and practice how to apply the EVA operations rules for efficient and safe spacewalks and how to increase their performance in the EVA spacesuit training which takes place in Houston (or Star City).

The immersive capability of the NBF can also allow the fine tuning to a slightly negative buoyancy of the astronaut body, spacesuit and of its tools/equipment, which offers a perfect environment for the simulation of partial gravity.

Simulations in a Moon gravity-like environment were already conducted in the NBF to:

- Test the LESA prototype (Lunar Evacuation System Assembly of ESA).
- Assess the space suit movement limitations during a lunar rock sampling operation (with a spacesuit-like exoskeleton provided by COMEX reproducing the spacesuit constraints).
- Test prototypes of Lunar Surface Geological Sampling Tools designed at EAC.

When the submerged astronaut (wearing his/her suit/gear) has an apparent weight equivalent to 1/6 of their weight, the astronaut's mobility is driven by exactly the same constraints as the ones on the Moon. For example the famous Kangaroo jumps [3] of the Apollo astronauts naturally become the most efficient way to move.

The immersion in such conditions is a perfect environment to simulate spacewalk in lunar gravity for the long duration of an EVA and for movement at low speeds (walking, transporting hardware etc.). Only for high speed movements (like golf shots) will the water drag effect on the fast moving object be significant enough to degrade the realism of the lower gravity effect on the movement.

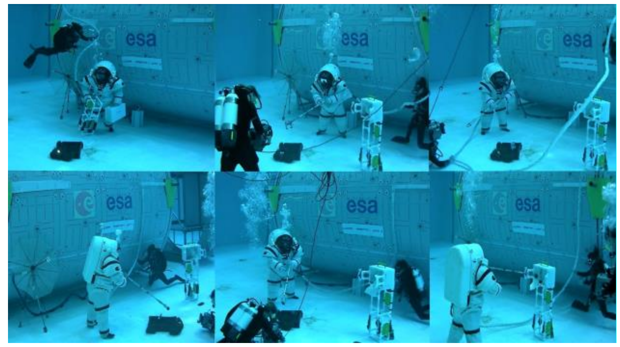

Fig. 6: Testing of Lunar Surface Sampling Operations with spacesuit constraints in the ESA NBF [4].

3.4. Tests in PANGAEA-X

The Pangaea course is designed to provide European astronauts with introductory and practical knowledge of Earth and planetary geology to prepare them to become effective partners of planetary scientists and engineers in designing the next exploration missions. The course also aims to give astronauts a solid knowledge in the geology of the Solar System from leading European scientists.

Pangaea is the first step in preparing European astronauts to become planetary explorers on missions to other planets allowing them to communicate with science advisors on Earth effectively, using common and geologically correct language to increase fast and fruitful decision-making while selecting scientifically-relevant places to take samples.

The astronaut training locations for PANGAEA are the Ries meteorite impact crater - used by the Apollo astronauts for geological field training - in south Germany, the Bletterbach Geoparc in the Italian Dolomites and the volcanic island of Lanzarote (Spanish archipelago of the Canary Islands).

An extension of ESA's Pangaea geology training, the PANGAEA-X test campaign, involves performing scientific investigations in extreme environments on Earth. The crew work with the latest technologies in instrumentation, navigation, remote sensing, 3D imaging and geoscience equipment, as well as testing operational concepts for surface missions where astronauts and robots work together.

Known as the island of a thousand volcanoes, Lanzarote was chosen by ESA to perform the PANGAEA-X test campaigns because of the island geological similarity with Mars and the Moon, such as a volcanic origin, mild sedimentary processes owing to a dry climate, hardly any vegetation and a well-preserved landscape. Such a privileged environment is ideal to perform Lunar spacewalk simulations while taking into account real science requirements and constraints.

In the first PANGAEA-X campaign in November 2017, Moon EVA geological traverses were simulated with NASA provided replica of Apollo Lunar Surface Geological Sampling tools to evaluate how the surface sampling operations can be performed in a Lunar surface analog field within the known spacewalk constraints by ESA EVA experts.

Fig. 7: Testing of Moon EVA traverse concepts in PANGAEA-X 2017 in Lanzarote.

The only drawback of the PANGAEA-X environment is that all operations can only be done in Earth gravity.

3.5. Tests in NASA-NEEMO

NEEMO (NASA Extreme Environment Mission Operations) is a NASA space analog simulation that sends crews of four “aquanauts” (astronauts, engineers and scientists) to work in Aquarius, the world's only undersea research station, for up to three weeks at a time. Aquarius is an underwater habitat located 7 kilometers offshore of Key Largo, Florida. It is deployed on the ocean floor 20 meters below the surface. The pressure inside the habitat is the ambient ocean pressure, exposing the body of the crewmembers to full nitrogen saturation. The risks raised by the living conditions of the aquanauts require the NEEMO mission to be prepared and operated with the same rigorousness as for human space flight operations. The main goal of the NEEMO missions is to test concepts, procedures, equipment, experiments and tools in an operational “space-like” mission environment, inside the crew habitat and outside during EVA simulations.

As in the ESA-NBF, the immersion conditions allow the NEEMO crewmembers to be exposed to a slight negative buoyancy simulating the Moon partial gravity during Extra Vehicular Activities from Aquarius. The NEEMO also environment adds two additional key assets:

- The uneven sandy & rocky surface of the ocean bottom on which the Aquanaut crew performs EVA
- The high fidelity space exploration mission operations featuring an IV (Intra-Vehicular) crew member coordinating the spacewalk from inside the Aquarius habitat and a remote monitoring and support from a Mission Control Center located on shore in the Florida Keys.

These two assets added to the immersion in partial gravity provide a very high realism to the Moon surface exploration simulation and a unique environment in which to test and validate innovative European spacewalk tools, equipment, procedures and operational concept for the return of mankind on the Moon surface.

Fig. 8: Testing the LESA prototype (Lunar Evacuation System Assembly of ESA) during NEEMO-22 in 2017 [5].

4. Impact of Lunar environment limitations on tool design

The limitations driving the design of lunar geological tools are not always easy to transfer to terrestrial test environments. Moreover, some tests on Earth have their own requirements. In this case, before reading the following section detailing NBF tools design, it is important to understand the following groups of factors.

When designing tools for the Moon it is important to consider all movement limitations mentioned in section 2. These limitations directly affect the shape and size of the tools. Equipment must have long bars so the astronauts would not have to kneel down or bend over to perform a task. Another significant point is the stiffness of the gloves. All handles must be quite big and easy to grab. Every pin or wing bolt, that would be easy to use with no gloves, must be notably larger for use with EVA gloves.

The next point of note is the lunar dust. The current state-of-the-art presents no ideal approach to the protection of the joints from dust, even on Earth. Best practices mostly involve minimalizing the number of dust particles getting into the joint. It is worth mentioning that in dusty environment like Moon using ball bearings would be a challenge. Recently popular plastic plane bearings, which have solid lubricants in their structure, present a better solution. Of course, one must pick the correct model that can maintain its lubrication capacity in vacuum. In general, plastic plane bearings have the ability to absorb some amount of dirt or dust within their structure with no significant change in efficiency. Nonetheless, one should try to minimalize the number of dust particles ingressing into joints. Using labyrinth structures is complicated, keeping in mind that for hand tools the joints are often small. A good approach to this issue can be observed in robotic industry – some robotic arms working in dusty environment are covered with fabric sleeve protections – a solution of this type could be used to protect some of the mechanisms on the Moon.

The heavier the tool the more expensive a launch will become. Preferably, tools would always be designed to be as light as possible while respecting robustness requirements. It should be noted that even if one of the tools would be heavy and difficult to operate on Earth it would still be only around 1/6 of its weight on the Moon, and may be considerably easier to operate. Another point to consider is that, during the Apollo program, a list of elements that should have be avoided in equipment design for lunar operations was formed. The list includes Pb, U, Th, Li, Be, B, K, Rb, Sr, noble gases and rare earths [2]. The most frequently used materials were aluminium alloys and stainless steel. Of course, it is useful to keep in mind that after Apollo flights a lot of new materials including interesting composites were designed and could be considered in the future.

As mentioned, in order to test tools in terrestrial analogue environment other limitations must be considered alongside lunar limitations. For example, when creating tools to be tested underwater in the pool or in the salty water one must design protection against corrosion. This is especially important when it comes to salty water and two different metals touching each other. Combining aluminium with stainless steel (as it was done in Apollo tools) unfortunately shows bad results for aluminium components in salty water. Also notable are the differences due to terrestrial gravity. Tools would be significantly easier to lift on the Moon, which can be simulated by buoyancy in the pool, but can not be simulated in test campaigns like Pangaea. This is why some lightweight versions of tools should be designed for field testing.

5. Tool prototyping

For the purpose of the NBF Lunar EVA tools prototyping project, the prototyping process shown in Fig. 9 was developed. It follows a path similar to any modern prototyping process. It starts with a discussion of the problem e.g. how to gather rock samples given a good understanding of all constraints. Then, some ideas are proposed and, after initial sketching, the best approach is being chosen. At this point, detailed CAD modelling starts. Once modelling is complete, the project enters the manufacturing phase.

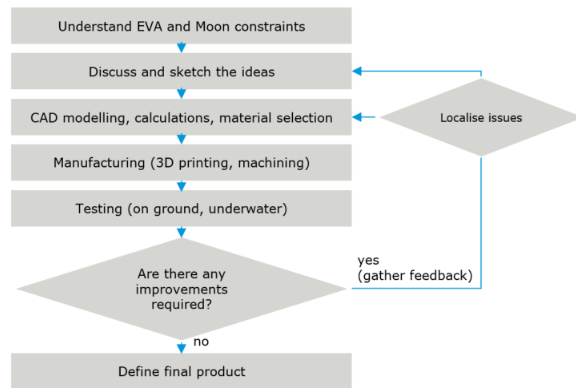

Fig. 9: Prototyping process steps followed during development at NBF.

In the early phases of prototyping, the first generation of tools are mostly 3D printed or made from easy accessible components like PVC tubes. Early prototypes undergo testing on ground or in the NBF pool. The purpose of testing is the validation of the tool as a whole piece and also the validation of its separate components and features. If there are matters that could be improved detailed feedback is collected. As Fig. 9 shows, received feedback can lead to changes at the level of underlying ideas or modelling depending on the issue. For example, if during the testing, an idea for an additional feature was proposed this has to be included in the overview ideas sketches and then must be followed by the remaining prototyping steps including a redesign of the model. However, if some parts of the equipment were problematic based on their geometry or material it would be enough to go back to the modelling phase. The loop of feedback theoretically should be iterated until there is nothing to be improved and the final product can developed. Since the project start, at the beginning of October 2018, this phase has not been met yet and most of the tools are now third generation prototypes.

The sections 6.1-6.3 discuss in more details the process of prototyping three systems

5.1. Marking system

Sampling on the Moon will consist of taking the samples and transporting them into pre-prepared containers. It will also require astronauts to photograph samples beforehand. It is important for the scientists who will analyse the samples that the area surrounding a given sample is well documented. For this purpose samples will have to be labelled on the ground prior to photographing.

Unfortunately, putting any label on the lunar ground is more complicated than it would be on Earth. First of all, flat labels laying on the ground would get covered with very adhesive lunar dust.

Another aspect is the indication direction to the sample. Most of the geological labels used on Earth have an arrow pointing towards north. A compass would not work on the Moon so this solution cannot be used. On the top of this, operating with the labels is more complex in the gloves and putting them on the ground is complicated due the restrictions of EVA suits.

To find a solution to these problems a system consisting of 3D structures for holding the labels above the soil and a tool to deploy them on the ground were introduced. The main idea behind the 3D printed structures was to make them foldable and easy to transport. While folded, their 3D shape would display a shadow on a Moon surface which, with combination of a known time and Sun position, can be used to determine the directionality. At the same time, the structure itself has an arrow-like shape pointing towards the sample and three surfaces for a label attachment so the label could be visible from different angles. The structure also includes a ferromagnetic piece that could be easily attached to a tool with a magnet. The tool has a long bar, so the astronaut would not have to lean over. It's handle also has a mobile component which is coupled to a magnet. By pulling the mobile component, one would drag the magnet away from a marker, releasing the marker. A hook at the end of a tool to can also be used in case of any problems with positioning the magnet and the ferromagnetic part on the marker.

5.1.1. Early 3d printed attempts

Prototypes of the tool generations 1 and 2 were manufactured mostly by 3D printing. The long bars were PVC industrial pipes. Those prototypes had all the features mentioned in section 6.1 and they focused on testing those features and their geometry and ergonomy. The changes between generation 1 and 2 were small, focusing mostly on the end effector. In any case, they required redesign of end effector. They included the changing of a spring loaded mechanism, magnet model and distance between magnet end the end tip of a tool. Both tools are visible on the Fig. 10.

Fig. 10: Marking Tool: generation 1 on the top, generation 2 on the bottom.

Generation 1 and 2 of structures for holding the labels were also very similar. The major change focused on the mass of structures, which were required for underwater testing. Generation 2 was heavier and had additional bolts in the lower part to make it more stable underwater.

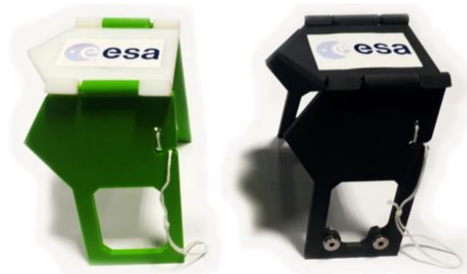

Fig. 11: Structures for labels: generation 1 on the left, generation 2 on the right.

5.1.2. Present status

Generation 3 of a Marking Tool was more robust compared to two previous ones. The main tool body was made from carbon fibre tube. Angle adjustment was added enable marking samples on a slope. All the structural parts were manufactured using stainless steel or aluminium. Some of the covers were made from PVC and parts of the handles were 3D printed using an accurate industrial printer.

The sample marker stands were heavier than the two previous generations. The very bottom parts were manufactured using stainless steel and had pointy shape to enable pushing them into the soil for additional stability. Previously 3D printed hinges were replaced with stainless still ones while the remaining structure remained printed.

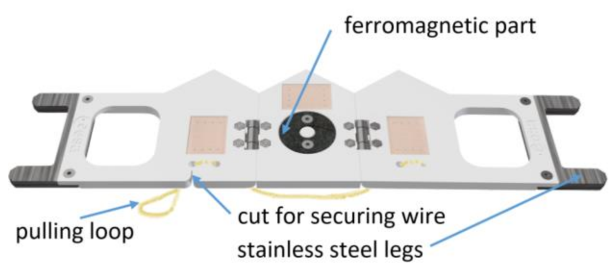

Fig. 12: Model of unfolded structure for labels.

Fig. 12 shows the model of generation 3. After initial testing the configuration changed slightly which is shown on the actual system in Fig. 14 – it created a version 3.1. The first change was the pulling loop in the marking structure which was too soft for gloves use and was replaced with stiffer wire ring. Another change related to the Marking Tool's handle which was replaced with a bigger, asymmetric model to better fit the EVA gloves – see Fig. 13.

Fig. 13: Marking Tool generation 3.1.

Fig. 14: Structures for labels: generation 3 on the left, generation 3.1 on the right.

5.2. Tongs

The tongs developed by NBF were introduced for sampling both small particles and also bigger rocks. The principle of the tool's function is simple: by pulling a handle one can open end effector to gather a sample. Releasing the handle closes end effector box. The evolution of the tool is detailed in the following sections.

5.2.1. Early 3d printed attempts

Like the Marking Tool, early Tongs were made from 3D printed PLA parts and PVC tubes. The generation 1 end effector was very instable on its mount so the redesign process was applied. This also led to an increase in the size of end effector. Generation 1 could accommodate samples up to 55 mm in diameter while generation 2 was able to grab samples up to 95 mm.

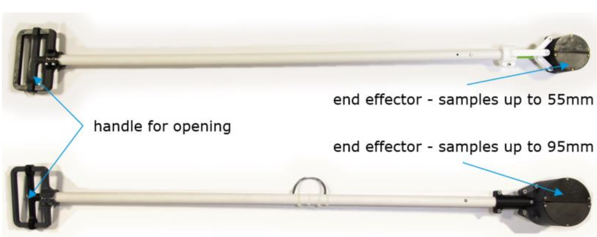

Fig. : Tongs: generation 1 on the top, generation 2 on the bottom.

5.2.2. Present status

The generation 3 Tongs had the same size and features as version 2 but were made from more robust materials including a carbon fibre tube, stainless steel end effector, few aluminium parts and partly 3D printed handle. After some tests, as with the handle of the Marking Tools, the Tongs handle was changed to a bigger asymmetric model which is more ergonomic for EVA gloves use. Also, version 3.1 focused more on implementing a stronger and more robust spring-loaded grip.

Fig. 15: Model of Tongs generation 3 with opened end effector.

Fig. 16: Tongs generation 3.1.

5.3. Scoop

The last tool that will be discussed in this paper is a Scoop with a closing mechanism. The idea for adding a closing mechanism started after testing some open scoops. During operations, one of the astronauts was sampling while the other one had to hold a bag and make sure the sample is traveling safely from scoop to bag. To avoid the need of help from a second person the closing mechanism should hold the samples inside in every orientation of the tool, so it would be easy to transport. The closing lid should also have an easy way to open it both for taking the sample and also for putting it into a sampling bag. The idea was to have an opening mechanism that gives a possibility to open a lid on the end effector from the top of a tool. This would allow the opening of the end effector 'scoop' while the end effector is on the ground. Another way to open it would be to open it with a handle of a lid (for removing the sample form interior). Another important feature was the angle adjustment feature which evolved over several prototypes. The mounting of the end effector was supposed to be easy to handle and also provide the possibility to mount it with different angles.

5.3.1. Early 3d printed attempts

The first generation of the scoop was prototyped using a universal rod replicating the one from the Apollo tools (bottom tool Fig. 17). Different ideas for opening a lid of end effector were tested. After the generation 1 prototype the team decided to change the way the angle adjustment was operated. Generation 2 was built form 3D printed parts and an aluminium rode. The tool's design allowed for the adjustment of the end effector's angle without bending over or raising the tool to reach its bottom. Also, the lid opening mechanism was changed – to open a lid one has to rotate handle 90 degrees around the tool's rode – see Fig. 18.

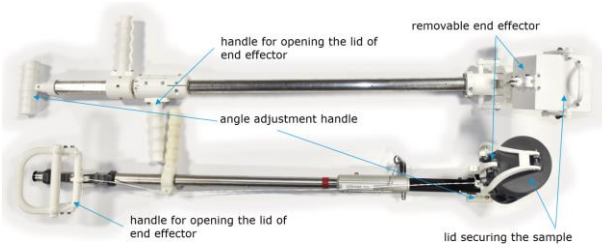

Fig. 18: Scoop: generation 1 on the top, generation 2 on the bottom.

5.3.2. Present status

Generation 3 of a Scoop is very similar to generation 2. Only small adjustments were made to the general geometry of a tool. To make it more robust it was redesigned using new materials which included carbon fibre, high quality 3D printed plastics, aluminium and stainless steel.

Fig. 19: Scoop generation 3.

6. Testing activities

As the aforementioned tools are being developed in a rapid prototyping cycles, the testing approach shall allow for rapid identification of potential issues. In this case, every change in the equipment culminated in on-ground testing in EAC laboratories and workshops. Moreover, generation 2 and generation 3 prototypes were tested underwater in NBF during test dives in simulated Moon gravity. The plan of these dives was to mark and obtain previously prepared rock samples of different sizes. Moreover, the tools were used by a diver who was equipped with EVA gloves to replicate the hand stiffness that astronauts would experience on the Moon. The primary objective of dives was to spot all the problems or malfunctions of the equipment. With each testing activity the feedback was collected and immediately applied in the form of design adjustments. If small changes result in the overall tool change the next generation prototype entered design. It is also important to mention that during previous Pangaea-X activities in 2017 (before the 1st generation of NBF tools) NASA replicas of the Apollo Lunar Surface Geological Sampling Tools were used. This helped in forming requirement lists for NBF's prototyping activities and hardware.

Section 6 discusses the development of the tools and points out the reasons for some changes. This section focuses on detailing how the testing was carried out rather than the outcome of testing which was already described. This section then will only include some general comments as a summary of lessons learned.

The figures below show in sequence NBF testing activities: marking the sample (Fig. 20 on the left), using solid tongs to obtain the sample (Fig. 20 on the right), using closable scoop to obtain the sample (Fig. 21 on the left) and transporting the sample from the closable scoop to the sampling bag (Fig. 21 on the right).

Fig. 20: Left: marking samples; right: taking samples with solid tongs.

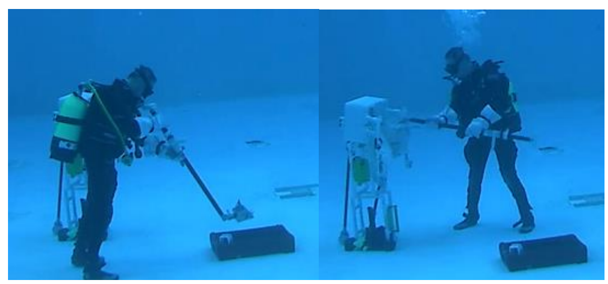

Fig. 21: Left: scooping sample; right: transporting sample from a scoop to sampling bag.

In general, a lot of changes and developments were carried out to design tools which could be operated as much as possible from their primary hand-holds i.e. the handles at the opposing end of the tool to the end effectors. All the small parts that need to be operated received a lot of attention in the design process to ensure they are easy to use with gloves (e.g. visible in Fig. 22). Some equipment which included parts that had to be pulled were considered hard to grab so all the pulling points were changed such that an EVA glove finger can be put inside of a stiffer loop to facilitate pulling.

Another aspect to consider is the usage pattern of different fingers while operating in pressurised EVA gloves. The only efficient fingers for grasping are the thumb and the index (acting like a crab claw) and this has an impact on handles shape and size. Also, an important point is that very stiff joints or even tightly fixed parts always become more loose at the depth of 10 m where the NBF operations take place. This introduces some differences which can be hard to compensate for.

Fig. 22: Removing end effector of the scoop with EVA gloves – unscrewing wing bolt.

7. Future plans

During PANGAEA-X in November 2018, ESA EVA experts from EAC team will test Lunar EVA operational concepts focussing on Lunar Surface Geological Sampling. The testing will utilize newly developed ESA prototypes of lunar EVA tools and spacewalk protocols which take into account mobility constraints imposed by pressurised spacesuits and EVA voice communications standards. The LEVA (Lunar EVA) SAMCO/OPSCO (Sampling Sequence with Mobility Constraints /Operation Concepts Comparison) tests will evaluate how the surface sampling operations can be performed in a Lunar surface analog field within the known spacewalk constraints. While OPSCO will focus on the evaluation of two different Lunar EVA strategies to complete the same tasks over two 'Work Sites'. The SAMCO test will assess the functionality and ergonomy of the tools introduced in this paper together with the ESA prototypes developed in the EAC NBF for the EVA tool transport: the Adaptive Spacewalk System & Equipment Transporter (ASSET) and the Nearby Equipment Support Trolley (NEST). The Lunar Spacewalk simulations will also test a first version of the Lunar EVA Situational Awareness Video Equipment (LEVA-SAVE) developed at EAC.

The Lunar Surface Geological Sampling Tools prototypes designed by ESA will also be further tested in the next NEEMO simulation (NEEMO-23 in June 2019) in addition to an upgraded version of LESA.

At present, a lot of focus is being driven towards study into material selection to keep the next prototypes generation lightweight. Also, further ground tests with lunar simulant are foreseen. Some joints were already equipped with industrial dirt-resistant plastic slide bearings which will be the main focus of these upcoming tests. Tools presented in this paper in the future will also be equipped with an easy way to insert the sampling bags into a tool before sampling to avoid cross contamination of samples.

Acknowledgements

We thank our EAC colleague Stephen Ennis for comments that greatly improved the manuscript and NBF diver Kathrin Nowak who supported testing of the tools underwater. We would also like to thanks HAL 3 Projects (http://www.hal3projects.com/) for their support with manufacturing parts of the equipment.

References

[1] J. H. Allton, Catalog of Apollo Lunar Surface Geological Sampling Tools and Containers, Houston, Texas, United States, March 1989.
[2] J. H. Allton, C. B. Dardano, How successful were the lunar sampling tools: Implications for sampling Mars, Lunar and Planetary Institute Workshop on Mars Sample Return Science, Houston, Texas, United States, 1 January 1988.
[3] R.C. Jr. Seamans, Project Apollo: The Tough Decisions, Washington, DC, United States, 1 January 2005
[4] How to rescue a Moonwalker in need, www.esa.int/Our_Activities/Preparing_for_the_Future/Discovery/Walking_on_the_Moon_underwater (accessed 11/09/2018)
[5] Walking on the Moon – underwater, https://www.esa.int/Our_Activities/Human_Spaceflight/Astronauts/How_to_rescue_a_Moonwalker_in_need (accessed 11/09/2018)