

Review

# A Review of Different Aspects of Off-Earth Drilling

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**Abstract:** Off-Earth drilling may be assumed as the second phase of space exploration to discover the unrevealed subsurface on the planetary bodies. It accelerates future space objectives such as in-situ propellant production, mineral exploitation, and space tourism. Owing to the rampant progress in modern technology, the new drill tools mounted on the sophisticated robots are capable to drill the planetary regolith dispersed on the celestial objects; however, formidable obstacles such as microgravity, vacuum condition, and temperature fluctuation as well as the weight limitation, lack of real-time drilling analysis, and remote robot-operator communication impose pressing restrictions on the quick development of space drilling tools. In this study, research on the past and present aspects of off-Earth drilling has been implemented to illuminate the horizon of this technology in the near-term future. The context encompasses a detailed description of the limitations, applications and mechanisms of the different drilling techniques adopted for planetary bodies. A particular emphasis is put on the hydraulic power systems which have not been satisfactorily deployed in off-Earth drilling yet. The research strives to glance over the pivotal aspects of off-Earth drilling to contribute to the future drilling programs planned by the national and private space agencies.

**Keywords:** space exploration; hydraulic power systems; ultrasonic drilling; water extraction; space mining; mole; NASA; Mars; Moon; rover



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## 1. Introduction

Together with the curiosity sense, scientists have always been interested in revealing the nature of the soils and rocks found on distant planets. This aids human beings to distinguish the principal differences between the Earth and other planets. Moreover, such materials will be someday utilized as aggregate to fulfill the future space targets. Furthermore, if more demanding missions such as Mars-one and Artemis programs are expected to be successful, the astronauts require to be accommodated in safely permanent outposts on Mars and Moon, respectively. To provide such circumstances, the need to utilize space drilling techniques is inevitably vital. The current major applications of space drilling can be divided into subsurface drilling, sampling, water mining, anchoring and building of surface and underground habitats.

In 1970, the first off-Earth drilling program was accomplished by the Luna 16 robotic lander that drilled the lunar regolith to the depth of 35 cm and returned 101 g of dark basaltic soil to the Earth. This mission was the first successfully unscrewed drilling program carried out by the Soviet Union [1,2]. On the other side, during 1971–1972, the American space missions including Apollo 15, 16 and 17 deployed manual drilling procedures through the Apollo Lunar Surface Drill to collect subsurface samples on the Moon.

In 2001, European Space Agency (ESA) developed the SD2 sampler, driller and distribution system to conduct drilling together with in-situ tests on the comet P67/Churyumov-Gerasimenko in the Rosetta mission. In 2014, the SD2 sampler, mounted on the Philae lander, performed the first drilling operation on a remote comet [3–7]. The target of the

mission was to investigate the physical, mechanical and chemical features of the comet to extend the knowledge about the solar system, and the life evolution on the Earth.

Recently, the planet of Mars has attracted scientists' perspectives as a secondary habitable place for mankind. In 2012, the American Curiosity rover drilled a number of shallow boreholes (with the depth from 5 cm to 10 cm) in the Martian regolith and collected the powder of the drilled soil [8–10]. The objective of the Curiosity rover was to seek vital elements called CHNOPS, including carbon, hydrogen, nitrogen, oxygen, phosphorus and sulfur. The Curiosity rover found the CHNOPS elements and inspired a thriving perspective for the life feasibility on the planet. Moreover, it paved the way for the Perseverance rover deployed in the Mars 2020 mission. Launched on 30th July 2020, the Perseverance rover landed on the Martian crater Jezero on 30 February 2021. The main objective of the mission was to detect the potential signs of any previous life beneath the Mars surface. During the mission, the Perseverance will drill the regolith, and accumulate the samples within its special container to revert to the Earth in the future [11–13]. ESA's ExoMars Mission is another approaching program for finding the subsurface life signs on Mars. In 2022, as a supplementary part of this program, a rover called Rosalind Franklin will carry a driller to dig the Martian regolith to the depth of 2 m. The sample is captured, and then, the mineralogy of the borehole wall is characterized by an infrared spectrometer. After the sample delivery to the on-board laboratory, it is crashed to be prepared for the special chemical, physical and mineralogical experiments [14–16].

Besides the U.S., the EU and Russia, other countries also have launched their drill-mounted robots to discover the subsurface of the celestial bodies. For instance, China scientists have worked on the development of drill tools to capture specimens from the depth up to 2 m during the China Chang'e missions on the Moon [17–19]. In June 2010, the Japanese spacecraft of Hayabusa managed to forward some samples from the asteroid 25,143 Itokawa to the Earth. During this mission, the Hayabusa deployed a novel technique of projection sampling on the asteroid [20,21]. It is worth mentioning that the sampling process on the asteroids is much more complicated than the Moon and Mars. The reason is that the gravitational force on the asteroids is markedly less than such large planets [22].

So far, an ample range of drilling machines with different mechanisms have been examined through their rate of penetration, depth of penetration, and specific energy. Such drilling machines supply their electricity power from on-board batteries or solar batteries to generate the electricity for conduction of their tasks. The main restraint of the conventional drilling machines on space is the requirement for a high axial force due to the lack of gravity on the planetary bodies. This is why some innovative drilling procedures such as ultrasonic/sonic drilling have been introduced [23].

On Earth, hydraulics-based drilling machines were introduced in the 1970s as a potent alternative for conventional pneumatic drill rigs. Nevertheless, in case of the extraterrestrial drilling, hydraulics power systems seem to be dreadfully neglected. Currently, the hydraulics systems are fundamentally employed in the common space shuttles and space stations. Without hydraulic power systems, providing highly substantial forces for launching, moving and stopping gigantic spaceflights appears to be impossible. For instance, a hydraulics power system was utilized in Apollo 15 rover which carried the astronauts to the Moon. A hydraulic force (derived from the pressure on the water) was transferred into the brakes to stop the rover by creating friction between the tires and the lunar surface [24]. Nowadays, hydraulic systems are still much needed in common aircraft for controlling the brakes, landing gears, rudders, etc. The hydraulic systems possess two major advantages: firstly, they prepare a high force with adequate control, and secondly, they generate the maximum power with a small size [25]. On the other planets, the main challenge of the hydraulics power system is the change of fluid properties, e.g., viscosity, with the variation in the ambient temperature. Basic concepts of a hydraulic power system have been sufficiently described in [26].

Both national and private space agencies are currently seeking innovative drilling techniques which require minimum mass, volume, and power. Hence, in the future, drill

tools are designed to be further intelligent and reliable for successful penetration into the planetary subsurface. This research aims to cover the former and recent advancements in space drilling technology along with a whole description of its limitations, applications, and procedures. The article has been structured as follows: firstly, the challenges related to the off-Earth drilling are described. Secondly, the applications of space drilling for subsurface sampling, water extraction, and outpost construction are explained. Afterwards, the usage of hydraulics power systems together with their constraints are explained. And eventually, the last part of the paper is concerned with the most outstanding drilling machines that have been conceptualized or assembled so far by the various designers.

## 2. Materials and Methods

In the section Materials and Methods, the different challenges, applications and mechanisms of space drilling are described. Moreover, the applicability of hydraulics power systems as well as other innovative drilling tools are recounted. The process of drafting and writing this article was implemented through the four following stages:

- **Collation:** in this stage, a comprehensive investigation was performed to realize the past and present advancements in the area of space drilling. To this end, a large number of previous and recent documents related to space drilling were collected to build the preliminary information. Such sources of information might be in the form of journal papers, conference papers, scientific reports, online videos, websites of different space agencies, catalogs of companies manufacturing space equipment, universities offering space drilling programs, etc.
- **Classification:** once adequate, preliminary information was collected, it was found that the documents can be sorted into four principal categories: drilling challenges, drilling applications, drilling mechanisms, and drilling tools. For instance, if a document, e.g., a journal paper, described the technical challenges of the drilling operations on the planetary bodies, it was classified in the “drilling challenges” category. Or, if a video on NASA’s website presented the versatility of a special rover, e.g., Perseverance, it was inserted in the “drilling applications” category.
- **Expansion:** after classification of each document in the four aforesaid categories, it was carefully studied to trace the history, background, previous applications, similar documents, citations, references, etc. In this way, a number of secondary, complementary documents (or publications) were gathered again to enlarge the initial extent of the preliminary information. The new documents were then studied, and similarly, if they were recognized useful, their background, references, and similar topics were traced to expand the number and domain of the related literature. This process was pursued until inclusive information related to each document was recorded.
- **Concentration:** once the four different categories were supported by sufficient documents and information, the key findings of each document were extracted, and mentioned in the paper. Consequently, the main body of this paper was written during this stage. From the acquired information, it was deduced that some research areas have been neglected or underestimated in the area of space drilling. An example was the hydraulic power systems which were not adopted for drilling purposes on the planetary bodies. Therefore, the utilization of drilling tools based on the hydraulic power systems was assessed and elaborated in this article. Development of the hydraulic power systems absolutely creates a paradigm shift in the off-Earth drilling operations.

### 2.1. Space Drilling Challenges

Challenges of space drilling can be divided into two groups: environmental and technological. The first category largely relies on the drilling environment while the second one is strongly dependent on the progression of current technology. Both categories are elaborated through the following sections:

### 2.1.1. Environmental Challenges

- **Atmosphere:** due to the lack of atmosphere on the Moon, no fluid is applicable for cooling the bit, or providing the borehole stability during the drilling process. This is why that the bit hydraulics (bottom-hole cleaning) is not easy to implement on the lunar surface. Although the Martian atmosphere is slightly accessible, it is not adequate to positively address such issues related to the application of fluids.
- **Gravity:** the very low gravity on the Moon leads to the complexity of the drilling-related evaluations both on the surface and down-hole. On the Earth, such evaluations have been consolidated through decades of observations and investigations. More than this, the lack of gravity even exacerbates the situations on asteroids and comets.
- **Temperature:** surface temperature on the Moon can vary considerably during the nights and days. Such temperature shifts may intensely impair the key parts of the drilling tools. This is more problematic in the case of liquids or fluids.
- **Magnetic field:** to control the direction of drilling, only the gravitational measurements can be applied. The reason is that the magnetic field on the Moon is remarkably weaker compared to the Earth. Any change in the direction of drilling can affect the drilling, and the borehole stability [27].
- **Borehole instability:** on the Moon and Mars, the intensely fractured layers were formed as an outcome of the early meteorite impacts. This pattern continues probably below the target depth of 100 m [28–30], thereby leading to the challenges for exploratory missions in which the seismic waves and ground-penetrating radar signals are incorporated [31]. Another problem that arises from the extensive fracturing of the layers is uneven cooling of the lunar particles that may have influence on the internal stresses within the rock. As a result, this can impact all stages of the drilling process [32–34].
- **Regolith abrasiveness:** the lunar regolith particles are considerably sharper and more abrasive than their terrestrial counterparts. Thus, they can impose serious impacts, e.g., premature bit wear, on the drilling equipment.
- **Regolith variable drill-ability:** during drilling, the density of the lunar or Martian regolith increases gradually with the depth; in this condition, the drilling operation becomes more problematic as it encounters potential issues such as interlocking particles and cohesion build-up.
- **Boulders:** drilling bits are designed to drill a borehole with a distinctively small, limited diameter. However, during the drilling, the bit may encounter a piece of large rock (or boulder), leading to the failure of drilling equipment, or even, deviation from the preplanned trajectory. It is also worth mentioning that any deviation in the borehole path affects the borehole stability [35].

### 2.1.2. Technological Challenges

- **Transportation:** the drill design should satisfy the mass and volume restrictions which are intensely prohibitive. As a consequence, some applications cannot be deployed on planetary bodies. For instance, the chance of utilization of any drilling fluid for the seminal tasks such as bit cooling and cuttings removal dramatically reduces.
- **Casing:** common steel casings used in the oil and gas industry are not feasible to be transported to the planetary bodies since they are very heavy and bulky [36]. Thus, the type of material for any future casings should be considered as a crucial issue.
- **Drilling power:** as the fluid utilization is deadly limited on the space, the rover should supply its power from the solar resource; this puts a formidable constraint on the power budget of space drilling tools. To solve this issue, nuclear power sources are suggested to be applied. The reason is that they offer longer life and can be operated in harsh environments as well as their independence from location.
- **Weight on the bit (WOB):** the maximum force transmitted to the bit cannot exceed the weight of the whole drilling system. To maximize this force, the drill should be emplaced directly under the center of the rover; however, the drill is typically inserted on the side of the lander, hereby causing reduction of weight on the bit.

- Rotational speed: the optimum rotational speed should be evaluated with regard to the rock type and the bit material. The higher values of drilling speed increase the heat and bit wear while the lower ones bring about the bit fracture (because of the excessive vibration) [37].

## 2.2. Space Drilling Applications

The current applications of space drilling can be classified into subsurface sampling, water mining, and building of underground and surface habitats. Although there may be other methods to accomplish some such objectives, space drilling technology seems to be an inevitable option due to the wide versatility which it offers.

### 2.2.1. Subsurface Sampling

Similar to the weathered terrestrial rocks on the Earth, the lunar and Martian surfaces are continually being affected by wind erosion, harsh temperature, micro-meteorite impacts, intense radiation, etc. The larger proportion of the Moon is covered by the craters which have been previously formed during the meteorite collisions. Hence, the regolith near the craters shows a totally different behavior from their intact structure. On the other hand, although the Moon and Mars were formed around 4 million years ago, yet thermal activities are present in their inner parts.

At the moment, the only investigation on physical, chemical, and mechanical properties of the surface regolith is no longer adequate; many current missions aim to acquire knowledge about the formations beneath the planetary surface. Subsurface sampling provides scientists to track the origin of the Moon and Mars; additionally, the initial processes that occurred during the planetary evolution can be more identified. A conspicuous application of subsurface sampling is searching the past or present life on the extraterrestrial planets. During the recent decades, drilling techniques have been considered as the direct approaches to probe the presence of biomarkers under the lunar and Martian surface [38]. Furthermore, to perform the geotechnical applications such as foundations for surface outposts, the first essential data, that are significantly needed, include the mechanical properties of the subsurface layers. Thus, subsurface sampling is considered one of the most fundamental applications of space drilling.

On the lunar and Martian surfaces, application of common soil/rock tests are restricted by their large weight (expensive transportation), and instability due to microgravity [39]. Different space missions have managed to return distinct extraterrestrial samples to the Earth. Such specimens might be captured in the form of a collective material from the dispersed regolith (without any drilling assistance). Moreover, the specimens can be taken by robots which use drilling techniques to collect the deeper soils and rocks.

A brief history of the sample-returning missions is described here. Thus, major missions were conducted before the 2000s by the American and Soviet space missions. During 1968–1972, the Apollo space program could return more than 380 kg of lunar soils to the Earth. The first mission was Apollo 11 in which astronauts manually collected 22 kg of regolith on the Moon surface. Apollo 12 and Apollo 13 brought back 34 kg and 42.8 kg of lunar regolith, respectively. These activities were followed by some manual drilling operations through the Apollo 15, Apollo 16 and Apollo 17 missions in which lunar samples with the mass of 76.7 kg, 94.3 kg and 110.4 kg were captured, respectively. The Luna program was another space mission that included marked sample-return activities. During this program, more than 10 missions were taken to collect samples from the lunar surface. However, only three of them managed to successfully take some lunar samples in a fully automatic manner. Luna 16, Luna 20 and Luna 24 brought back 101 g, 55 g and 170 g lunar soil to the Earth. In Tables 1 and 2, the geotechnical characteristics including the cohesion force ( $C$ ) and internal friction angle ( $\varphi$ ) of the lunar and Martian soils taken through the aforementioned space missions, have been tabulated.

**Table 1.** Various sample-return missions and geotechnical characteristics of the lunar soils.

Year	Mission	C (Pa)	$\phi$ (°)	Reference
1966	Surveyor 1	150–15,000	55	[40]
1966	Lunar Orbiter	350	33	[41]
1966	Lunar Orbiter	100	10–30	[42]
1967	Surveyor 3 and 6	350–700	35–37	[43]
1969	Apollo 11	800–2100	37–45	[44]
1969	Apollo 11	300–1400	35–45	[45]
1969	Apollo 12	600–800	38–44	[44]
1970	Luna 16	5100	25	[46]
1971	Apollo 14	Less than 30–300	35–45	[47]
1971	Apollo 15	-	49	[48]

**Table 2.** Various sample-return missions and geotechnical characteristics of the Martian soils.

Year	Mission	C (Pa)	$\phi$ (°)	Reference
1975	Viking 1	1600 ± 1200 0–3700	18 ± 2.4	[49,50]
1975	Viking 1	5100 ± 2700 2200–10,600	30.8 ± 2.4	[49,50]
1975	Viking 1 and 2	1000–10,000	40–60	[49,50]
1975	Viking 2	1100 ± 800 0–3200	34.5 ± 4.7	[49,50]
1997	Mars Pathfinder	3400–5700 1800–5300	31.4–42.2 15.1–33.1	[51]

### 2.2.2. Water Extraction

As water is becoming more valuable on the Earth [52], huge investments have been put on the next-generation technologies to extract water from the icy regolith, particularly in the areas adjacent to the lunar poles. The existence of water in the lunar poles has been confirmed by some space missions [53,54]. On the Moon, areas called permanently shadowed regions, are always in shadow, thereby permitting the ice to remain in its solid form; nevertheless, the physical structure of the water is yet not straightforward meaning that the water can be in the form of icy adsorbed water, hydrated compounds or blocky icy rocks [55].

Water extraction from icy lunar soils benefits space technology through a broad multitude of possible utilizations. Firstly, the water can be used for drinking or individual consumption in satellites. Secondly, it can be decomposed to O<sub>2</sub> and H<sub>2</sub> which are key compounds in both terrestrial and extraterrestrial lives. O<sub>2</sub> can be used for breathing supply, or it can be fused with H<sub>2</sub> to provide the spaceflights with extraterrestrial fuel. Fuel production in space will be a revolutionary breakthrough in the space exploration era [56]. Moreover, water barrels also can be used for radiation shielding [57].

Evidence of the presence of water within the Martian regolith has been achieved by the Mars Odyssey mission [58]. The instrumentation of the Mars Odyssey spacecraft was equipped with a gamma ray and neutron spectrometers to evaluate the available compounds chiefly Hydrogen as an indicator of water existence beneath the Martian regolith [59]. In 2004, Spirit rover landed on the Gusev crater located on the border of high-altitude and low-altitude regions of the Mars. A few weeks later, the Opportunity rover landed on the Meridiani Planum region on the Mars. The Spirit rover could not find signatures of water beneath the Martian regolith. However, the Opportunity could record wide signatures of water existence within the altered regolith [60,61]. In 2007, the Phoenix landed on a region situated in the northern pole of the Mars. It was equipped with an on-board chemistry laboratory to examine the regolith surface for detection of icy water. It could detect some traces of water beneath the regolith [62].

### 2.3. Extraterrestrial Structures

#### 2.3.1. Surface Structures

To accommodate astronauts or other facilities, the need for construction of permanent outposts especially on the surface of Mars is continually increasing. The prospective structures can be built either on the surface or underground.

Regarding the surface outposts, the formidable challenge is microgravity. Microgravity is defined as the minor gravity so that any structure without a stiff foundation does not permanently remain on its location as it is weightless in very less gravitational acceleration conditions. Furthermore, on the lunar surface, the vacuum condition is dominant, which makes everything drop in free fall. This situation can be seen when the astronauts or other physical things float within the spaceflights. Therefore, in vacuum conditions (the Moon), the mass of the object, human, or outpost does not matter. It should be noted the in spite of the vacuum conditions on the Moon, there is a very thin atmosphere on Mars.

To overcome the effect of microgravity, an anchoring technique has been introduced as a reliable method to stick the surface outposts to the underlying ground. Many investigators probed the efficiency of this method as an attractive scenario [63]. Advantages of the anchors include their solid stability in the ground as well as prevention of the possible uplifting of the surface outpost [64]. Anchors can be very useful not only for the permanent outposts but also for the rovers. The anchor can be utilized as a base spot for the rover; if the rover is stuck in a dangerous zone, it will winch itself to rescue from the perilous situation [65]. So far, a number of exploratory rovers have been caught in the lunar and Martian craters or soft regolith. For instance, such a disappointingly catastrophic “embedding event” occurred for Mars Spirit rover on 1 May 2009. After about five years and three months of operation, the Spirit rover got stuck in the loose, soft sand. During the subsequent eight months, a great deal of theoretical and practical techniques were simulated on the Earth to figure out how the rover could be freed. However, on 26 January, NASA declared that the rover cannot rescue itself, and it will continue stationary, scientific surveys. On 22 March 2010, communication was disconnected forever, and the rover lost its applicability.

On the icy planets such as Europe, the main challenge of the rovers is the high potential of slide. Halperin and Sedwick introduced a thermal drilling technique for drilling and emplacing an anchor in Europe’s icy regolith to increase the safety and maneuver degree of the rovers [66]. The anchor helped the rover to climb over the steep grounds on Europe. Although it has been proven that mechanical drilling is more efficient in energy [67], it may break the ice structure around the anchor, hereby leading to the release of the anchor.

Performance of exploratory sampling, or even mineral mining, on asteroids is an intensely tough task owing to the lack of gravity. Williams et al. designed a technique to anchor the astronauts to the surface of asteroids so that they can collect specimens more conveniently [68]. The design of the system was based on a pneumatic drilling and auger mechanism. After drilling the regolith up to the desirable depth, the auger remained in the borehole, and the pneumatic drill was moved out.

#### 2.3.2. Subsurface Structures

The disadvantage of the surface outposts is that they are continually subjected to the outer harsh environments such as radiation, winds, fluctuating temperature and possible meteorite collisions. With the recent growth in the excavation of underground structures such as tunnels, a tendency has appeared between the space investors to probe the efficiency of underground structures as an alternative for the vulnerable surface outposts. Sheshpart et al. conducted numerical modeling to evaluate the stability of circular-profile tunnels on Mars [69]. It was concluded that performance of a tunneling technique is completely safe as the microgravity and icy rocks have a direct influence on the stability of the tunnel. They turned out that the usage of underground tunnels can be very effective as an artificial shelter for astronauts on the Mars surface. A Tunneling technique offers benefits such as insulation, and prevention of radiation or meteorite collision.

On the other hand, the effect of different parameters on the tunnel's stability must be carefully investigated. Every location on Mars has unique properties such as rock type, fractures, in-situ stress, etc. If the rock has a content of water, the effect of the temperature must be studied on the tunnel stability. Fluctuating temperature can increase or decrease the strength of the rock; Such cyclic thermal stresses change the physical and mechanical properties of the whole rock mass [70,71]. Some techniques such as Mont Carlo simulation can be adopted to investigate the influence of each parameter on the tunnel stability [72,73].

On Mars, volcanic activities have formed a wide range of Martian landforms and terrains [74]. Amongst them, there are basaltic lava channels especially in the equatorial areas which have been envisaged as potentially suitable underground bases [75]. Such channels or caves require to be more expanded by drilling machines. The Arsia Mons was proposed to be a suitable place for development of the lava tubes into underground outposts [76]. Moreover, the Arsia Mons possesses a high potential for the existence of geothermal energy [77,78]. A coincidence of such desirable conditions can pave the way for the combination of different engineering applications together. Such applications play a key role in the reduction of the total cost in every engineering project on the Earth [79,80]. A wide range of techniques for outpost construction with taking advantage of the natural landforms such as caves in steep slopes, development of lava channels, etc. have been evaluated by [81].

The concept of Rock Mass Rating (RMR) classification for underground excavations was suggested by Bieniawski in 1973 [82]. The RMR facilitates the evaluation of the geomechanical aspects of a certain site. Some researchers applied the remote sensing techniques to determine the RMR value for an outcrop in the Meridiani Planum on Mars.

Except for the development of natural caves and channels with tunnel boring machines, the technique of drill and blast was also suggested by some researchers to excavate underground structures on remote planets. The explosives must be carried from the Earth to Mars, hereby imposing a surcharge. A good alternative is using naturally available elements in the Mars atmosphere for manufacturing blasting charges. This section of space exploration needs to be more investigated [83].

#### 2.4. Hydraulic Power Systems

Every modern machine uses a distinct method to create energy and perform tasks. The majority of the on-Earth drilling rigs consume the fossil fuels such as gasoline as their main source of energy. Once the energy was generated within the engine, it is transferred to the different parts of the rig to function mechanically. There are three distinguished methods to transfer such energy to an internal unit, e.g., jacks, brakes, hammer, etc. Those methods include electric, hydraulic, and pneumatic systems. In a hydraulic system, the essential energy for substantial motions, e.g., rod rotations, is forwarded through the tubes containing hydraulic (pressurized) fluid. The hydraulic fluid transmits the energy (force or pressure) to the moving parts of the drilling rig.

Hydraulic systems function on the basis of Pascal's law. According to this law, the pressure imposed on an incompressible fluid enclosed in a vessel is transferred undiminished throughout the whole fluid [84]. On the Earth, common hydraulic jacks are a symbolic application of Pascal's law. Nevertheless, the usage of hydraulic systems on the planetary bodies is deadly complicated due to the fluctuating temperature, weak pressure, low gravity and sheer vacuum. Every hydraulic circuit contains cylinders, pistons, hydraulic pumps, reservoir, valves and hydraulic fluid. On planetary bodies, intense temperature variations induce thermal stresses within the materials. It also quickly changes the rheological properties of the hydraulic fluid. Furthermore, the low ambient pressure causes improper lubrication of the units since the hydraulic fluid evaporates in the vacuum condition. This problem endangers the working units and probably leads to failure or inefficient function of the whole hydraulic system.

The utilization of hydraulic fluids in extraterrestrial drilling machines is completely scarce although they are extensively used in shuttles, spaceflights and space stations. The



Saturn 5 launch vehicle was designed to carry approximately 140 tons shipment during the Apollo space missions. During the design phase, there were a lot of controversial arguments about the selection of the appropriate hydraulic fluid for gimbal (steering) actuation system [85]. The initial proposal was a conventional hydraulic system that utilized the MIL-H-5606 oil as the hydraulic fluid. On the opposite side, a new “fuel-hydraulic” system that used kerosene, was also suggested. Eventually, although the hydraulic system was more efficient in contamination control and chemical adaptability with the hydraulic circuit, the “fuel-hydraulic” system was chosen. The main advantage of the “fuel-hydraulic” system was in the deploying of fewer numbers of components in its structure. This advantage would cause less potential leakage because of it is less complex. Using kerosene, Saturn 5 turned to the largest launch vehicle that has been successfully used so far. This example clarifies that for any space drilling program, a suitable hydraulic fluid must be selected to satisfy the drilling requirements.

The incompressibility of hydraulic fluid is the most fundamental factor in Pascal’s law. In other words, the fluid density must be remained unchangeable to transfer the energy without any pressure loss. The most common hydraulic fluids are classified into two groups: oil-based and fire-resistance fluids. The selection of the proper hydraulic fluid enhances the efficiency of the machine while an inappropriate hydraulic fluid may lead to a whole failure of the space mission.

Application of hydraulic power systems in space drilling machines encounters a wide variety of diverse obstacles. The first is the change in the fluid properties under the intense ranges of temperature. For instance, the average temperature on the Venusian surface is around +480 °C [38]. Nevertheless, in the lunar and Martian polar regions, the temperature can be as low as −230 °C and −140 °C, respectively [38]. Consequently, on Venus, the very high temperature leads to evaporation of the fluid while on the Moon and Mars, the very low temperature makes the fluid frozen. Such problems can totally demolish the versatility of the hydraulic system.

The second issue is the leak potential of the fluid from the hydraulic circuits; such leaked fluid can cover the lenses of cameras or impair sensitive instruments such as sensors. To prevent the hydraulic fluid from leaking, sealing is unavoidable in any hydraulic system to consistently transfer the hydraulic pressure to the different units; choosing the suitable sealing is executed regarding the fluid characteristics. During their operations, the seals experience numerous cycles of repetitive movements which necessitate accurate, consistent positioning. Furthermore, stringent standards of endurance must be applied in the design phase of their components [86]. The seals must properly balance the friction and sealing effectiveness to inhibit the leakage onset. Another seminal criterion is the resistance of the seal against the wear in the presence of abrasive dust and harsh temperature [86]. Some companies such as Bal Seal<sup>®</sup> have provided space agencies with hard-wearing, resistant mechanical seals for utilization in rover mobility controls and rocket engines [87]. During the design phase, for measurement of the endurance and wear rate, the seals are examined through practical tests in the presence of the terrestrial simulants. The seal wear was found to be proportional to the diameter of the seal, and the number of operational cycles [87].

The third challenge of hydraulic systems is their high potential for fluid contamination. On the lunar and Martian surfaces, micro-size dust storms can easily penetrate into the moving parts and enter the hydraulic fluid [88]. The dust is intensely abrasive and can chiefly result in premature failure of the seals as well as wear problems. To deal with this challenge, appropriate filtrations must be deployed to keep the hydraulic system away from contamination.

The fourth problem is the complexity of the hydraulic circuits containing a large number of connecting parts. This matter also necessitates more supportive maintenance. Any failure in providing sufficient maintenance may lead to an irreparable breakdown of the operational units.

The fifth issue is the difficulty of injection of fresh fluid into the hydraulic fluid reservoir (tank). This calls for stringent insulation of the tank, supplementary tubes, and nozzles; the potential of contamination is very high in this situation.

In an off-Earth drilling machine, the main roles of the hydraulic fluid consist of the transfer of energy, circulation of heat, and lubrication of the connecting units. Hydraulic pump is an integral part of the process of transfer of energy; it must be designed with strict standards to perform successfully in difficult space conditions [89]. Within the drilling machine, the motions of the different drilling parts generate heat which is absorbed by the circulating hydraulic fluid. Moreover, the friction between the moving surfaces of the connecting units creates continuous wear which is effectively reduced by the hydraulic fluid. The most important features of hydraulic fluids used in space drilling include viscosity, lubrication characteristics, and minimal compressibility.

Zacny et al. introduced a new planetary drilling technique that was based on the usage of both pneumatic and percussive mechanisms [90]. The main advantage of the pneumatic system was the efficiency in cuttings removal (for instance, 1 g of gas at 3 Psia could lift 6 kg of the regolith). On the second hand, the essential forces for drilling operation decreased by the percussive system up to 40×. Additionally, in the percussive system, some hydraulic jacks were deployed to move the scoops mounted on the drilling tool. Narasimha Rao et al. introduced a rover that utilized legs instead of wheels for its mobility [91]. The essential power was supplied from a hydraulic system as well. A wide detail of the hydraulic parts of the rover was also elaborated in the publication.

Hydraulic power relies on the pressure and flow rate [92]. The essential hydraulic pressure for pushing a piston varies proportionally to the gravitational acceleration of the planetary body [91]. The gravitational acceleration on the lunar and Martian surface is respectively equal to 1.62 m/s<sup>2</sup> and 3.71 m/s<sup>2</sup> compared to the value of 9.81 m/s<sup>2</sup> on the Earth [91]. The flow rate depends on the time of the strokes (or rover speed). For five different planets, the variation in the essential hydraulic power with flow rate is illustrated in Table 3. As the gravitational force on the Moon and Mars is much less than the Earth, the essential hydraulic pressure for pushing the piston becomes much lower.

**Table 3.** Hydraulic power versus the essential flow rate on different planets [91].

Planet	Flow Rate (m <sup>3</sup> /s) × 10 <sup>−3</sup>	Pressure (kPa)	Hydraulic Power (kW)
Earth	2.381	33.54	79.85
Moon	2.381	5.54	13.2
Mars	2.381	12.69	30.21
Venus	2.381	30.19	71.86
Jupiter	2.381	79.16	188.45

## 2.5. Drilling Machines

Depending on the final drilling depth, the drilling machines can be divided into four categories including surface drill (a few centimeters of depth), shallow-depth (hole depth ≤ 1 m), medium depth (1 m < hole depth ≤ 10 m), and large depth (hole depth > 10 m) machines [38]. A concise description of such drilling machines is depicted in this section.

### 2.5.1. Surface Drills

Surface drills can penetrate into the regolith or boulders up to a few centimeters. The following examples are such drill machines:

- **Low-Force Sample Acquisition System (LSAS):** LSAS was a percussive drill machine capable to capture integral samples. This system was applicable for a wide variety of planetary rocks and frozen soils. Its main objective was to effectively reduce the mass, volume, and power needed for the drilling operation [93]. The drilling process was driven by a hammer which let the system collect a sample with the lowest amount of force.

- Mini-Corer: Mini-Corer or MC was designed and made by Honeybee Robotics to be a part of the Athena Science Payload. The MC system was made of a set of hardware which was able to be integrated on a rover or lander. The hardware included an MC drill mechanism with a number of actuators and sensors, MC drill bits and MC drill bit storage module.
- Coring and Abrading Tool (CAT): Honeybee Robotics designed and developed the CAT. To build CAT, the technology used for Rock Abrasive Tool (RAT) and MC were applied, and consequently, the CAT became a versatile instrument capable to brush, grind, drill, and collect cores from the planetary rocks.
- SENER Touch-and-Go Sampler: this was an instrument for collecting and storing granular regolith on the Martian moons including Deimos and Phobos. In 2008, the instrument was designed by SENER engineering company in Spain. To collect a sample, the instrument carried out a touch-and-go contact with the planet surface with an average speed of 0.5 m/s. hence, the sampling process was done by kinetic energy with repeating contacts and impulsive rebounds repeated up to four times [38].
- Honeybee Robotics Touch-and-Go Sampler: this sampling machine was designed to drill and collect poorly consolidated materials or regolith. It could also provide borehole stability when the cutter was penetrating into the planetary subsurface.
- Near-Earth Asteroid Sample Return: this machine had no biological danger and could take samples in one landing during only a few minutes. This tool was designed to collect samples and return them to the near-Earth satellites.

### 2.5.2. Shallow-Depth Drills

In comparison to the surface drills, shallow-depth drills can penetrate deeper into the regolith or planetary rocks. They generally drill boreholes with a variable depth from 10 cm to 1 m. Such drill machines utilize only one drill string. The corresponding examples are:

- CNSR Sample Acquisition System: this machine was designed to manufacture a simpler and stronger drilling system. Based on the drilling tests, a coring drill bit with polycrystalline diamond cutters was selected for this instrument. The core samples were 10 cm in diameter [94].
- Sample Acquisition and Preprocessing System (EBRC): EBRC was a good example of a core drilling and sampling system capable to drill with low power, low reaction forces, and with no lubricants or flushing fluids. This system included a 1 m class dry drill, 1 m sample capture system, a sample transfer system, and also a sample crusher.
- ATKs Segmented Coring Auger Drill (SCAD): ATK Space Systems Inc. developed the SCAD to support the future space missions on Mars and potentially comets. In such a drill tool, a pure auger technique was employed for cuttings removal.
- Sample Acquisition and Transfer Mechanism (SATM) Drill: this was a drilling tool with four axes that had sample preparation and handling systems as well as sample return containers. It was assembled to take rock samples from depths limited to 1.2 m.
- Rover-Based Deep Drill MicroRoSA: MicroRoSA was a well-set and movable automated drilling device which could drill the rock and take a sample down to 2 m.
- Construction and Resource Utilization Explorer Drill: this drilling machine was designed for investigations on the penetration mechanisms, bit geometry, and control algorithms in a variety of environmental conditions. Actually, the CRUX drill was designed to let pure rotary, rotary–percussive, or percussive drilling increase the drilling efficiency in a variety of materials such as regolith, rock, and ice.
- Subsurface Corer Sampling System: SCSS was a drilling tool to take samples from different depths. It was strongly applicable in exploratory works on the planetary bodies, comets, and asteroids. This low-power, rotary coring drill was capable to penetrate and take samples from the various rocks up to a depth of 1 m at different temperatures.
- Subsurface Telescoping Sampling System: STSS was capable to stow itself into a small adequate box fitted on an MER-class rover. The major parts of the drilling tool consisted of two telescoping stages.

### 2.5.3. Medium-Depth Drills

Medium-depth drills are capable to drill boreholes with a length from 1 m to 10 m. here are some examples of such drilling tools:

- Mars Astrobiology Research and Technology Experiment (MARTE): in 2005, the MARTE drill rig was designed by a group of engineers from NASA, Honeybee Robotics and Centro de Astrobiología in Spain [95]. It was a rotary coring rig capable of autonomously capturing and delivering core samples from the depth up to 1 m. Moreover, for drilling in lower depths, it was capable to add drilling strings with a length of 1 m to reach the depth of 10 m. In other words, there was a need for nine additional drilling strings for drilling towards the depth of 10 m. The installment of additional drilling tubes was conducted automatically by the rig. There was also a special software designed to control the WOB and reduce the stalling of the drill axis [95].
- Drilling Automation for Mars Exploration (DAME): comparing to the MARTE system, the DAME machine was much more mobile, although the mechanical dimensions and the amount of needed power were similar for both systems. In DAME, a number of below- and above-ground sensors together with an intelligent control method were inserted to enable the system to find and resolve potential drilling problems.
- Subsurface Planetary Exploration Core Extracting System (SPECES) Drill: the SPECES machine was designed to provide an efficient approach providing a dry cuttings removal mechanism (without fluids), hole stabilization approach, single deeper hole method, and ongoing sample recovery. Cuttings-related issues were effectively tackled, and friction problems were reduced by applying a BHA and an independent coaxial sample container mechanism. Moreover, clogging problems at the rock-bit interface were addressed, and power consumption was also reduced via special dry drilling coring bits with thinner walls [96]. The novel system also considerably reduced the operational time and the risk of borehole instability.
- Ultrasonic/Sonic Gopher: the USDC system was applied to develop a gopher (wireline drill) that could collect coring samples using a bit whose diameter was larger than the USDC actuator [97].

### 2.5.4. Large-Depth Drills

To omit the effects of the upper surface (dead zone) and reaching the possible habitable zones, it is necessary to drill to the lower depths. Here, some examples of drills capable to reach the depth of more than 10 m are presented:

- Subsurface Explorer (SUBEX): SUBEX was a robotic mole which was able to penetrate hundreds of meters below the surface despite its small volume, mass, and low power consumption. The first SUBEX prototype which was named a Ground Mole Demonstrator (GMD) could drill a hole up to a depth of 100 m [98,99].
- Deep Drill of Mars/Arctic: this was a low-mass and low-power planetary drilling system based on the dry rotary coring wireline. It was capable to successfully penetrate into the formations with low power, mass and volume.
- Autonomous Tethered Corer: The Autonomous Tethered Corer (ATC) was a drilling system to collect different samples from depths below 200 m [100]. ATC operated via an inch-worm type of motion in which the anchoring module extended to clamp against the borehole wall.
- Inchworm Deep Drilling System (IDDS): the IDDS enjoyed the novel technology to access the subsurface layers deeper than 100 m on the various planetary bodies. It was a low-mass, compact system to perform cuttings removal and in-situ analysis.
- Modular Planetary Drill System (MPDS): the MPDS project was designed to develop a dry drilling system with the capability to reach a depth of at least 20 m. MPDS used an advanced BHA, sample capture system, and rotational and vertical drive mechanisms that are able to operate in tough planetary situations. This BHA was able to drill ice, frozen soil, and basalt with a minor degree of wear.

### 3. Discussion

The nature of drilling activities on extraterrestrial planets is entirely different from the Earth. The unfavorable conditions on the far planets dictate a vast number of limitations in such drilling programs. Designers are restricted by a wide range of constraints from the mass budget to the need for resistant materials against the high thermal stresses originated from the celestial temperature variations.

Some points should be noted in the design and development of space drilling tools. Ultrasonic drilling reduces the essential energy and force for cutting a unit volume of the extraterrestrial regolith. This technique also deploys the mini-size tools in the drilling process, hereby reducing the mass and volume of the system. Combination of this technique together with a compressed gas as the drilling fluid should be more extended and investigated in the future. Another point is that the drilling systems have to be designed as simple as possible. The complexity of the drilling system is decreased by using fewer numbers of instruments as well as simple drilling strategies such as the ultrasonic method.

The manufacturing cost of drills is extremely exorbitant. Adequate tests are required to examine the drill function in different situations. On the planets, the drilling operation is done automatically, and there is no human to tackle the potential issues. Therefore, simulated problems are very efficient in enhancing the abilities of drill tools. Such problems include the initial error in positioning of the bit, cuttings problems, borehole instability, etc.

Cuttings removal seems to be one of the most serious challenges in off-Earth drilling. For cuttings removal, additional mechanisms necessitate more energy to transfer the debris towards the surface. The deeper the hole, the more energy is required. Hydraulic power systems represent the best choice for providing and transmitting the essential energy for the different drilling units. The limitations related to the fluid utilization in the harsh temperature conditions have halted such systems to be more widespread in space drilling technology. As the hydraulic power systems are used in the space shuttles, more studies are required to incorporate such vigorous systems in future drilling machines. The hydraulic pump along with the hydraulic fluid are the heart and blood of the hydraulic circuit. The functions of those two components must be more promoted via various tests in vacuum, harsh temperature, and low-pressure conditions. In addition, the designers must note that because of the microgravity, an outer gaseous pressure is necessary to be connected to the fluid reservoir to prevent the creation of a vacuum condition during the pump suction. Using a hydraulic system together with ultrasonic drilling doubly reduces the energy required for drilling operations.

The production of hydraulic fluid can be considered with regard to the in-situ resource utilization. The thin atmosphere on Mars prepares an exceptional chance for providing fluids needed in drilling operations. Moreover, on Mars, only a small amount of gas is essential for removal of a large volume of the drilling cuttings. Since the basic hydrocarbon elements including hydrogen, oxygen and carbon are found on the Martian surface, the possibility of utilization of different gases (for production of drilling fluid) needs to be more assessed. Special equipment is essential for creation of liquids from the gaseous elements. Moreover, a combination of the different drilling techniques in a united manner enables mankind to discover deeper layers on the planetary bodies. This requires an appropriate roadmap for development of the contemporary drilling mechanisms so that the new innovations and applications such as a hydraulic power system will aid mankind to make a second remote civilization, e.g., on Mars.

### 4. Conclusions

In this research, the most applicable aspects of space drilling technology have been reviewed. Collectively, it can be claimed that although there have been attempts in the development of practicable drilling tools, the achievements appear to be restricted and insufficient. The main reason is the lack of adequate human experience in the complicated conditions of the celestial environments. A drastic redesign is needed in the current drilling systems so that they can provide future space missions with the most benefits and

advantages. Hydraulic power systems are envisaged as strong drilling strategies that offer a high rate of penetration and low energy consumption. Further attention must be paid to the utilization of such beneficial systems in future drilling programs. The use of such powerful systems allows designers to assemble more necessary equipment on the rovers for different drilling objectives. The methods of the provision of adaptable hydraulic fluids with the planetary bodies need to be studied more closely.

The transportation cost is the main obstacle in the way of giant drilling machines on the celestial objects. New technologies have enabled energy-efficient spaceflights to transport much heavier shipments into space. This promises that someday large-scale drill machines whose weight exceeds a few hundred kilograms will be taken to habitable planets such as the Mars. A development in the type of materials, e.g., the lightness and the resistance against the tough space environments, is extremely demanding.

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