A Robotic Rover-Based Deep Driller for Mars Exploration

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Abstract

VTT Automation has developed an advanced rover-based mobile drilling device for planetary exploration. The mobile Robotic Sampling System has been designed to perform deep (up to 2 meters) soil sampling on the surface of Mars or other planetary objects. Due to the complexity of the task, very strict limitations as to limited mass and volume, and the need for complete automation of all its operations, the system demands a very ambitious mechatronic design. In this paper the design of the system is described as well as the first functional prototype to be manufactured and now under testing. This work is being performed under European Space Agency funding by Space Systems Finland Ltd. (SSF, Finland) as the prime contractor, together with the Technical Research Center of Finland (VTT, Finland) (the drill system) and Helsinki University of Technology (HUT, Finland) (the roving system and drill electronics).

Introduction

In the past few years the world has witnessed the discovery of life forms thriving in extreme environments such as rocks several kilometres underground or underwater thermal vents where temperatures exceed +100 degrees Celsius. These environments were previously considered to be too hostile to sustain any form of life. One of the possible implication of this unexpected proliferation and survivability of life forms, is that some sort of life could have possibly also evolved on other planets and moons like Mars or Europa. In order to develop instruments for searching any signs of such extraterrestrial life, the European Space Agency (ESA) has funded a technology research contract called “Micro Robots for Scientific Applications 2”. Under this contract a robotic sampling system (RSS) consisting of an automated drilling device and a tracked roving vehicle has been designed and constructed. The Robotic Sampling System (RSS) consists of the following components: 1) A Mobile Drilling Platform (MDP) that is basically a small (10 kg) tracked rover whose function is to house the drilling and sampling subsystem and transport it between the lander and the sample acquisition locations. 2) A Drilling and Sampling Subsystem (DSS) that is the subsystem to perform the actual drilling and sampling. 3) A Docking and Sample Delivery Port on lander where the RSS can deliver the collected samples for further processing. Figure 1. Illustrates mission scenario.

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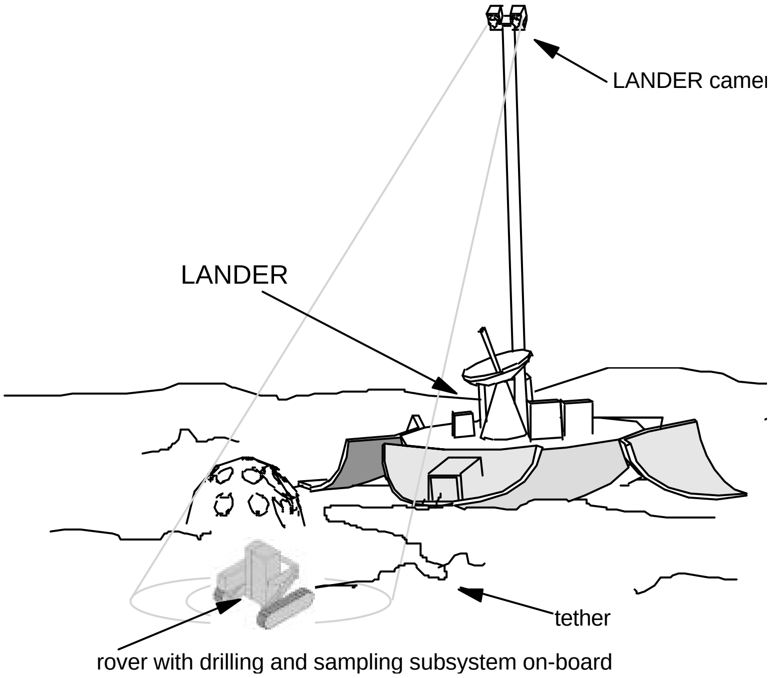

Figure 1. Robotic sampling system scenario.

Specifications

The search for possible extinct or extant life is the primary goal of the exobiology investigations during future Mars missions. As it has been learned from the NASA Viking and Pathfinder missions to the Moon and Mars, sampling of surface soil and rocks can gain only limited scientific information. Any sensible Martian exobiology investigation requires pristine samples that have never been exposed to the lethal effects of Martian surface environment. Two types of samples have this characteristic: 1) samples extracted from surface stones/rocks by coring at a depth of a few centimeters, 2) deep soil samples acquired vertically from a depth of more than 1 meter.

For extensive search for life a Robotic Sampling System to be used as part of an exobiology investigation facility has to accommodate the following list of operational requirements, as set at the beginning of the project:

1. Drill at depths ranging from 0 to 2 meters into regolith with 5 mm depth accuracy
2. Drill up to 2 centimeters into surface rocks/stones
3. Drill into non-homogeneous material of density and hardness ranging from loose sand to hard rock
4. Drill at commanded elevation angles from 0º to 90º (drill into surface rocks or directly into the ground)
5. Drill with independent rotation and thrust actions
6. Allow control of drill depth (0-2 m), rotation speed (0-30 RPM) and thrust force (0-30 N)
7. Acquire cylindrical samples (radius 5 mm and height 2 cm) of non-homogeneous material of density and hardness ranging from loose sand to hard rock
8. Ensure that the sampled material belongs to the specific depth of sampling (i.e. do not carry down material from upper layers)
9. Preserve the morphology of the sample (i.e. do not scramble, compress or stretch it)
10. Preserve the purity of the sample (i.e. do not mix it with other material)
11. Allow acquisition and storage of at least 10 samples per trip
12. Carry out 3 trips at minimum
13. Size of DSS is restricted in volume of 110 x 110 x 350 mm
14. Mass of DSS is restricted to 5 kg.

Concept

Lay-out

The robotic sampling system consists of a tracked roving vehicle (110 mm tall, 400 mm wide, 400 mm long and weighs 10 kg's) and a drilling system (110 mm x 110 mm wide, 350 mm long and weighs 4 kg's). See Figure 2.

Drilling and sampling system should reach a depth of at least 2 m. It is obvious that rover mobility would suffer greatly from any drill parts longer than 0.5 m, no matter how they are carried: vertically, horizontally, or perhaps dragged behind the rover. Therefore the drill string must be assembled on the rover from shorter sections which are stored inside the drillings system. Since a total of 30 samples are expected, several holes must be drilled. Therefore the drill string must be reused from hole to hole and the drill-string sections shall be assembled, disassembled and re-used on the rover in an automatic way. The extendable DSS drill string is assembled from up to 10 separate pipes in a similar manner that is used on terrestrial automatic rock drilling machinery.

The 10 drill pipes are stored in a rotating pipe carousel, as are also 11 drill tools stored in another carousel. Linear slides and ball-screw that give drilling thrust and guidance for a moving rotation actuator are located inside the pipe carousel, which solution saves lots of volume and gives the DSS its compact appearance. Another visible feature is a clamping system that is used for holding the drill string during addition or removing a drill pipe.

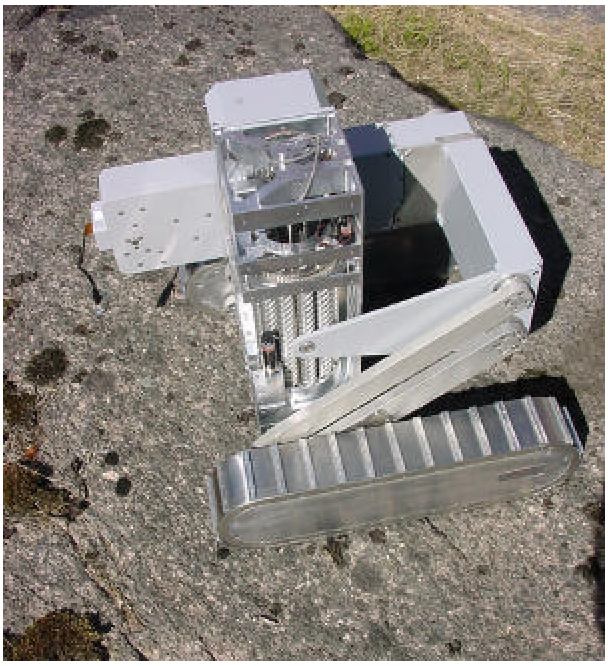

Figure 2. RSS in drilling position.

The Roving Vehicle

The roving vehicle procured by Helsinki University of Technology; Automation Technology Laboratory, is a tracked tethered vehicle, serving as a platform for the DSS. Its function is to enable the DSS to sample at desired locations and to deliver these samples back to the lander. During its mission, the rover makes multiple trips between the lander and the various sampling locations. The rover is commanded and supplied with power from the lander via a tether. Special feature of the tether system is that it can be rewound. When returning to the lander the rover follows the tether left earlier behind and winds it back to the reel, after cleaning it from excess dust. This way the length of tether stored does not limit overall travel length of the rover, and a danger of damaging the tether by over-riding it is avoided. The rotating axis of a payload cab holding the DSS allows drilling/ sampling at angles ranging from the vertical to the horizontal. Moreover the lifting bridge allows adjustment of the rover's ground clearance. This feature significantly improves the rover cross-country ability.

Operation

Drill operation is similar to that for conventional automated drilling machines using extendable drill string. Two independent actuators, one for rotation (0-30 rpm, 1 Nm) and one for thrust (0-100 N) perform the drilling. Drilling and sampling procedure consist of the following actions:

1. Selecting the drill head from storage,
2. Assembling the drill string from sections,
3. Drilling to the desired depth (in the soil, or in a surface rock),
4. Acquiring the sample inside the drill head,
5. Elevating and disassembling the drill string, and
6. Storing the drill head -with the sample- in the sample storage.

The rotation actuator -or spindle- is mounted on a sledge moving in and out along linear guides propelled by the thrust actuator and ball-nut and -screw. The spindle is equipped with a trihedron coupling, similar to ones used for industrial robots, and with necessary electrical feed-through.

First the spindle is connected to one drill pipe on the pipe carousel, after which a tool from a tool carousel is connected to the lower end of the pipe. Then drilling, which continues for the length of the pipe, is started. As the spindle reaches the lower limit of its travel, a clamping system crabs on the pipe and the spindle is separated from the drill string. As the clamping system holds the drill string steady, the spindle is elevated back to the upper end of the linear feed and a new pipe is selected from the pipe carousel. After the spindle is connected to the new pipe that is further connected to the drill string held by the clamping system, the clamp can be opened and drilling can be continued for an another length of the pipe. The procedure is repeated until the desired drilling depth is reached. Retraction of the tool and storing the pipes in the pipe carousel is a sequence opposite to the assembly and drilling.

Tool bit design is such that as the tool penetrates through terrain soil can flow through it, entering from lower end and exiting from holes in the upper end of the tool. This is how the tool always holds a sample representing the current depth in terrain. Upon retrieval of the tool internal wedges or flaps inside the tool hold the sample and prevent it from falling out of the tool.

The RSS does not contain any means for anchoring to prevent rotation or moving of the system during drilling operations. Initial requirements, and also selection of motors and hardware design, limit the drill thrust to 30 N and torque to 1 Nm. Simulated tests using off-loading methods indicate that weight of the RSS on Mars would hold it still on sandy surface during drilling, but for example on Moon surface additional holding methods would be needed.

Passive and active operations

During system design several times a trade-of between passive and active operations had to be made. Active operations are operated with actuators, like motors and solenoids, and thus provide high controllability and flexibility of these actions.

Passive operations, however, rely on geometry and movement of other parts of system to provide desired action. Passive operations do not need separate actuators or any sort of power or information transmission, and so they have less effect on volume, mass and control needs. Passive operations can not be re-programmed though, and they produce a risk in case something should go wrong, in case of jamming of movement, for example.

Since the DSS has already quite many degrees of freedom and power feed to motors and actuators appeared quite challenging already in the beginning, it was decided to utilize passive operations as much as possible. Active operations were selected where operation was required independent from current operational state of drilling system.

Active operations:	
Carousel rotation	Two independent carousels. Any of the tools or pipes can be selected.
Spindle rotation	Independent drill rotation.
Drill feed	Independent drill thrust.
Spindle locking solenoid	The spindle must be connected to and separated from the drill string in the lower end and in the upper end of travel. In case of string emergency release the spindle must be released also in the middle of travel.
Clampers	The clampers must be able to operate together with the locking solenoid, i.e. anytime in drilling phase.

Passive operations:	
Connection between the pipes and between a pipe and the spindle	Connection happens by pushing the couplings together, and is held by spring force of a locking ring. Separation force (pull) of couplings is roughly three times larger than nominal drilling thrust. It was found very difficult to use any kind of an actuator to realize an active coupling system. Also delivering external power to the coupling for active operations appeared very challenging. The passive solution selected does not appear very repeatable and requires re-work or alternative solutions.
Separation of a pipe from the spindle at the upper end.	As the spindle with a pipe (the locking solenoid opened) reaches the upper limit of travel, mechanical forks separate the pipe from the spindle and leave the pipe in the pipe carousel. Solution is simple and reliable.
Tool locking inside tool carousel	Tools are locked inside the tool carousel with a sort of bayonet. Locking in happens by rotating and pushing the tool past flexible spring blades that snap over a shoulder formed by cutting bits of the tool. The lock is released by rotating the tool so that due to geometry the blade becomes lifted above the cutting bits and the tool can be removed from the carousel. Locking system is functional but requires sophisticated control of spindle rotation and axial feed during procedure.
Core cutting and sample holding.	Although pipe connections provide a possibility to route electrical energy to tool bits, a passive operation method was selected. The core is cut from the base material by combined rotation and push/pull of the tool. Core cutter operates in a similar manner as the core cutters for conventional core drills.

Sample storage and delivery

Tool bit design is such that as the tool penetrates through terrain soil can flow through it, entering from lower end and exiting from holes in the upper end of the tool. Upon retrieval of the tool internal wedges or flaps inside the tool hold the sample and prevent it from falling out of the tool. Thus the samples are collected inside the coring tool. After a sample is captured inside the tool the string is retracted from the borehole. The coring tool where the sample is stored is transferred to the tool carousel in the end of a drill pipe.

The samples are transferred from the carousel to the lander with the aid of the drill string by connecting a pipe to the spindle, and to the tool to be transferred to the end of the pipe. The DSS is then aligned towards the sample receival port (SRP) of the lander and the string is extended to insert the tool into the

SRP. If the distance to the SRP exceeds the reach of a single pipe, connecting more pipes to it with the aid of the string holding device can extend the string further.

Mechanical design

Spindle and couplings:

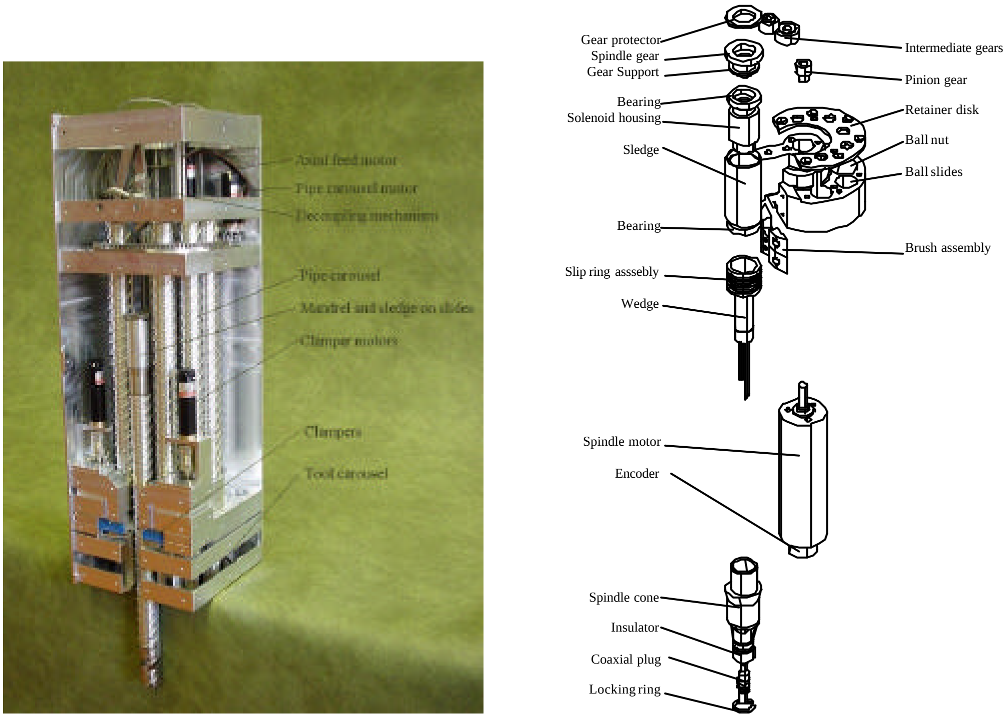

Figure 3. DSS and an exploded view of the spindle.

The spindle gives the drill string the needed drilling rotation, and provides an electrical feed-through for spindle locking system and active drill tools. Coupling of the spindle, that connects to drill pipes, is similar to robotic couplings with round-edged trihedron design. This geometry fluently allows passive coupling of mating parts and has an ability to transfer torque too. Electrical connections for active tools are located concentric in the middle of the pipe cone using a coaxial plug, see Figures 3 and 4.

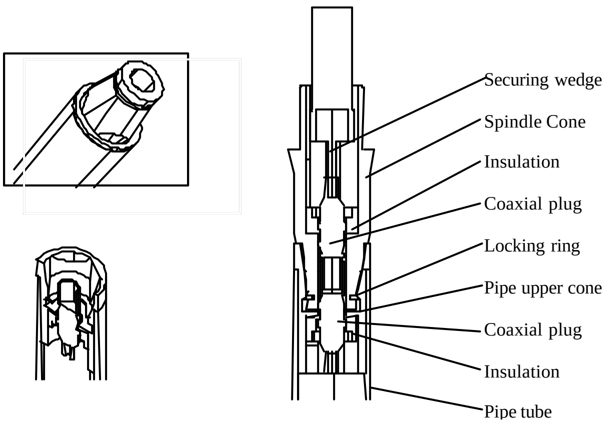

Figure 4. Design of the coupling.

Coupling is locked with a split ring, or a C-ring, on the spindle part (male), the female coupling on the pipe upper ends has a mating groove for the ring. Shape of the groove is made non-symmetric with different conical angles such that coupling by pushing happens easily, but de-coupling by pulling requires a force close to 100 N, which is close to linear drive capacity. It was soon learned that the C-rings needed to have a special design to operate with desired forces. Several different designs were incorporated and tested. Groove for the C-ring has angled surfaces so that the slightly contracted ring causes some pre-load for the coupling.

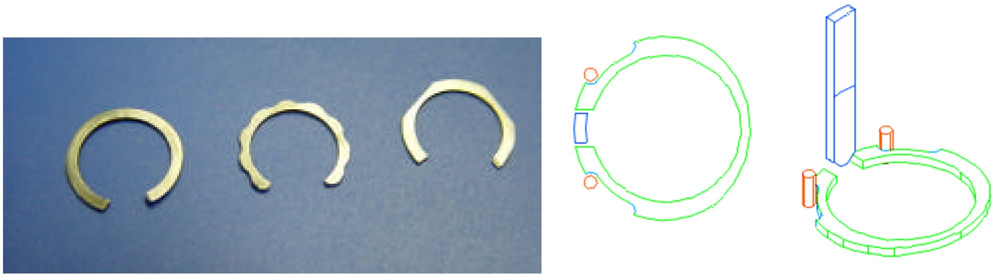

Figure 5. Prototypes and final design of the C-ring. Diameter of the ring is ~9 mm.

An in-house developed spindle solenoid (or an electromagnetic flip-flop), see Figure 6, is used to operate a wedge that can prohibit contraction of the locking ring and thus control disconnection of the spindle coupling when separating pipes from each other and from the spindle. When the wedge is located between the ends of the C-ring its contraction is prohibited and de-coupling requires very high forces. De-coupling may happen nominally when the wedge is removed from between the ends of the C-ring. The solenoid is a flip-flop-type using a permanent magnet core to maintain each of its two positions and thus does not require any springs, separate locking mechanisms or continuous power input. Power feed is realized with a capacitor that can produce a high short-term output power for solenoid, while collecting energy for the next operation with a low input power.

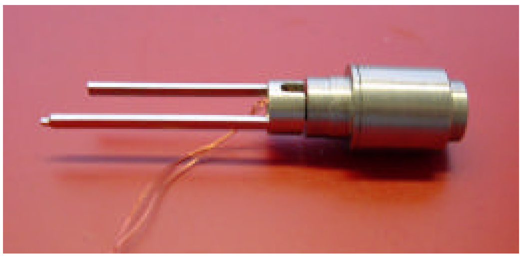

Figure 6. Electromagnetic flip-flop and a wedge.

A disadvantage with circular C-rings was also found; Prior to coupling the C-ring is in free state and can rotate freely during coupling. The ring may rotate so that it slightly touches thin end the securing wedge. After the coupling is performed, however, the ring is in slightly stressed state to provide some preload for the coupling. In the stressed state the ring can cause extra friction which prevents moving of the securing wedge and thus prevents securing action or release of the lock. A couple of designs were tested to reduce movement of the ring. First a single axial spring wire was mounted on the ring opposite to split to give some guidance. Later the ends of the ring were shaped so that two stationary pins would define position of the unstressed ring. This enhanced action of the ring slightly. A larger ring would allow larger tolerances and would make use of the moving wedge easier. It was also noted, that the hardened steel ring has a tendency to dig into softer steel which makes separation force unrepeatable. Further external torque or bending has some effect on release forces, which may be due to non-symmetric modified rings or minor geometrical errors in ring-groove geometry. Altogether the system seems to be very sensitive to accuracy of geometry.

A simple in-house developed slip-ring assembly, see Figure 7, is used to transfer electricity to the rotating spindle for the spindle solenoid and active drill tool functions. There are five isolated lines in the slip ring. For prototyping purposes the rings are made of brass and brushes are made of spring steel. One ring has a split to be used for absolute spindle position detection.

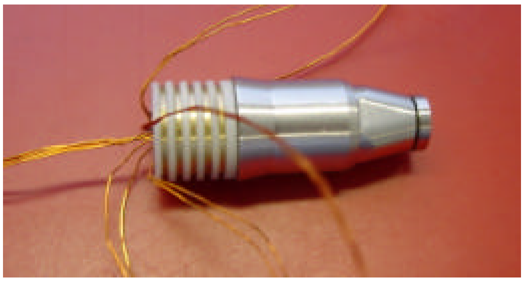

Figure 7. Slip-ring assembly.

The spindle, manufactured mainly from steel, is mounted on a sledge (manufactured of aluminum) that moves up and down along a linear slide. For effective use of volume the drilling motor is located aside the spindle and below the sledge and the motion is transmitted with train of gears. Absolute spindle position is detected with the aid of a split in the slip ring. The split in the ring is detected as a break in electrical current. After this signal spindle position is calculated from incremental encoder mounted to the end of the spindle motor.

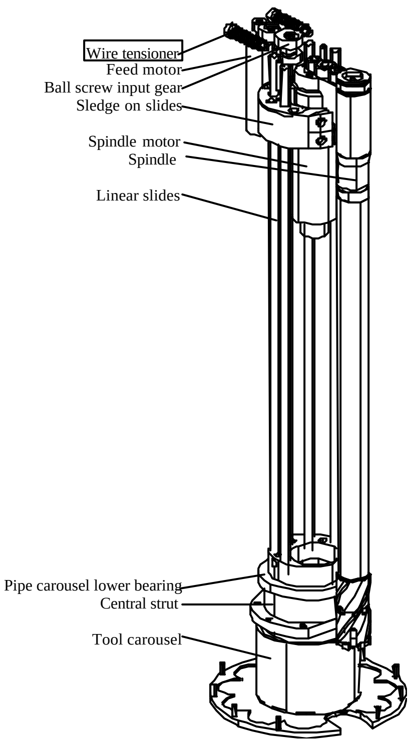

Figure 8. Linear feed system.

Linear Feed:
Linear feed, moving the sledge and spindle up and down, is realized with a thin ball screw, rotated with an electric motor, and a ball nut that is mounted on the spindle sledge. The sledge is guided by four ball splines that run along four guide rods. Drilling force +/- 100 N is measured with a load cell attached to the lead screw. The load cell can measure only compressive force and therefore the lead screw is pretensioned to 100 N. Axial load on the screw is carried by two thrust bearings and radial load is carried with two needle rollers. See Figure 8.

Axial position of the sledge is measured with the aid of a linear potentiometer constructed of 0.3 mm thick stainless steel wire giving resistance approximately 0-8 ohms over measuring range. To maintain constant tension in the wires they are tensioned with two compression springs.

Drill Pipes:
The drill pipes, constructed of aluminum, are located in a pipe carousel. Inside diameter of the pipes is 13 mm, outside diameter is 15 mm, and the three-ended helical flute outside the pipe has 17 mm outer diameter. Couplings in the ends of pipes are made of steel and present the same design as the spindle coupling, but without any securing means.

Connection between the pipes happens by pushing them together until the locking ring snaps into the groove. The three ended flute is symmetric and so the pipes can be connected in any of the three possible orientations. Disconnection of two drill pipes from each other happens when the clamping mechanism holds the lower pipe and spindle pulls the upper pipe apart. Then the locking solenoid in the spindle is opened by a command and the sledge is driven to upper position. During elevation of the spindle a mechanical de-coupling mechanism separates the pipe from the spindle and leaving it into the pipe carousel. A tool is separated from the pipe by first driving the tool into the tool carousel and locking it in there. Then the pipe is pulled with the aid of the sledge apart from the tool.

For enhanced or special sampling actions two power lines are routed through drill pipe couplings to allow use of possible active drilling tools in the end of drill string. These possible tools include, for example, percussive tools and ultrasonic tools. DR. T C NG and Holinser Group have already developed a design for a suitable active percussive tool in University of Hong Kong. Also special measuring instruments can be mounted in tools for measuring temperature, contact force, etc.

Pipe carousel:
The pipes are located in a pipe carousel, which has a skeleton-like appearance with thin vertical bars and slotted disks at both ends. The design allows the spindle to be located and move inside the carousel which saves a lot of volume. The pipes are not mounted positively to the carousel, but sit in the slots surrounded by structures above the upper disk and around and below the lower disk. The rotation of the carousel is actuated with Maxon d13 motor located outside the carousel and a gear rim connected to the upper end of the carousel. The carousel is positioned to the correct angular positions with two limit switches and index pins; one for each pipe indexing and one for absolute position indicator. In the bottom of the carousel there is a slot through which the drilling happens. In order to prevent inadvertent falling of a pipe into the slot, two spring-loaded pushers add some friction between the pipe and pipe carousel.

Tool Carousel:
The tools, which also double as sample containers, are stored in a tool carousel. There are 11 storage cups for the tools. The tools are mounted to the cups with a bayonet-like passive mechanism. The tool is inserted to the carousel with combined and controlled feed and tool rotation. With the aid of an aligning pin the tool finds correct position in the carousel and three flat springs snap over upper edge of drilling bits holding the tool. For removing the tool it is rotated so that a bulge in the side of the tool lifts the spring above the edge and sets the tool free. Coupling between the tool and string is similar to pipe connections. The locking between the carousel and the tool makes it possible to disconnect the tool from the string simply by pulling. Actuation and position sensing of the tool carousel is similar to that of the pipe carousel, except that the Maxon d10 motor is located inside the carousel support. See Figure 9. for carousels.

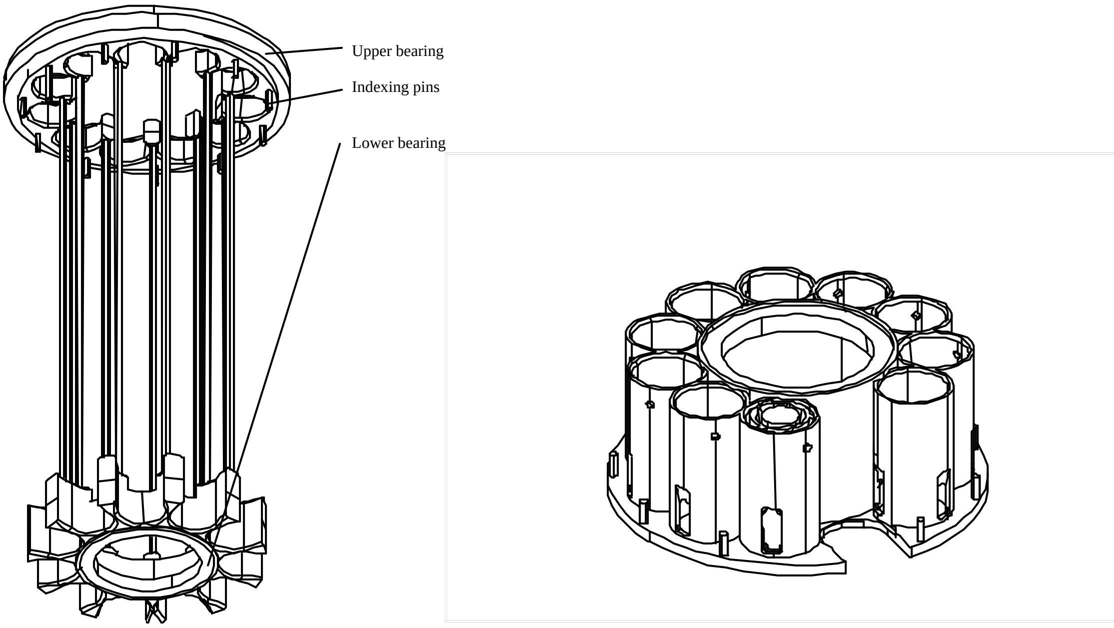

Figure 9. Pipe carousel and tool carousel.

String holding device:
A string holding device, located between tool carousel and lower end of linear slide system, is used to hold the lower pipe in place during pipe connection or disconnection. Clamping of the pipe is done at both sides of the string with two paws, shown in Figure 10, are coated with soft rubber-like high-friction material to accommodate helical flute of the drill pipes. The paws are attached to linear slides and the linear movement and clamping force is provided with two independent cam mechanisms located on the both sides of the string. Geometry of the cam is such that the clamping force approaches infinity as the travel approaches to its maximum. The two clamping motors are driven in an electronically synchronized way to guarantee that the paws will clamp the string with equal forces and in the middle of drilling axis. Position of each slide is measured with a linear potentiometer.

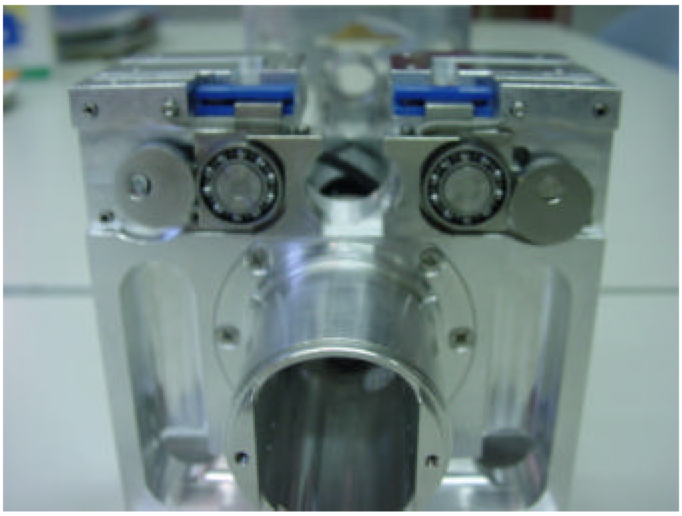

Figure 10. String holding mechanism.

For coupling and de-coupling of the pipes the string holding device must provide a 100 N linear holding force which with a friction co-efficient of 0.25 needs a clamping force of 400 N. Arm of the clamping force will remain minimum 0.5 mm which gives the needed torque in the cam axle 0.2 Nm. With Maxon RE d13 118430 motor and gear Maxon 110 316 (max. torque 0.3 Nm) a 400 N clamping force is reached already with a 0.75mm force arm, or with 0.5 arm a 600 N clamping force is achieved.

Tools

In the beginning of the project it was considered whether to use hammering action to chip the material or not. From mechanical point of view it was considered whether to develop a hammering system on the drill - even two meters and 10 couplings above the drill bit, or to fit a miniature hammering device inside a drill pipe. From electrical point of view the power need for such hammering device was considered. From scientific point of view it was considered whether the interesting remains of possible fossils would be found from sediment layers of sand stone and lime stone-like materials, or do we really need to drill into hard rock like granite. After these considerations it was decided to produce this first prototype without hammering action and rely on cutting and grinding based removal of material. For this purpose very hard and sharp diamond-like drill bits would suit the best. If for scientific reasons carbon-based materials can not be used, boron-nitride hard-alloy would provide a good replacement. For this prototype the tool bits are made of industrial hard-alloy Sandvik DZ05 having HV30 hardness on Vickers scale.

The tool used for sampling duplicates as a drilling bit and a core drill, as shown in Figure 11. The tool is designed to drill a 17 mm diameter hole into rock material and to contain a 9 mm diameter and 20 mm long core inside it. A crown that carries out the cutting is constructed of six cutting bits made of hard alloy. During drilling a core develops inside the drill while the bit crown chips material. Chips are conveyed to the surface by the external helical profile. Once the coring section is full, the head cutter chips the core top. The effect is that the bit penetrates deeper into the material always holding a 20 mm core of the current depth. When the desired depth has been reached, the core is broken apart from base material with the aid of a wedge-shaped core lifter by lifting and turning the drill. This action is similar to that used with conventional rock-core drills. For sampling of sand or other similar loose soil, specially designed flaps will be mounted next to the core lifter to hold sample inside the tool during lifting. Total of nine tools are stored in the tool carousel and they are intended to penetrate into rocks of hardness similar to limestone and sandstone. In this configuration, the DSS will carry individual tools for each sample to be acquired during a single trip between the lander and the sampling location. A fresh tool will be attached to the drill string before each sample acquisition, and then subsequently detached with the sample inside.

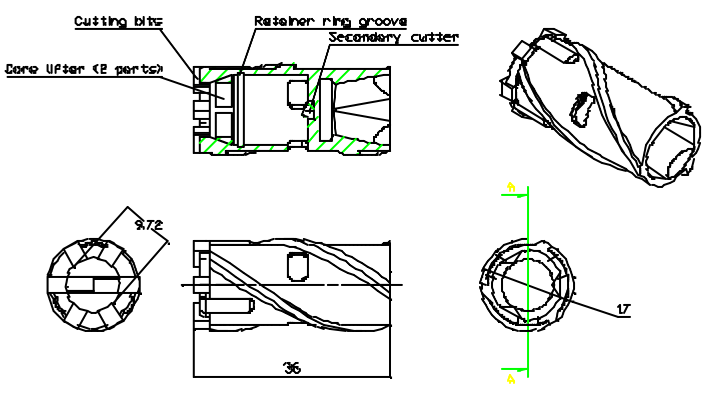

Figure 11. Tool design and prototypes (missing drill bits here).

Preliminary tests with different types of cutting tools were carried out in early stage of project. The tests show cutting power that would collect a rock core 10 mm in diameter and 15 mm in height within few hours. Quick tests were carried also on very hard and abrasive Finnish granite and results indicate, that with given thrust and power it would be possible to collect similar rock core in a time frame of tens of hours, however, durability and selection of drill bit material will be a critical issue. The tools that were tested were as following, see Figure 12.:

• ¬6 and ¬16 mm impregnated diamond core drills for cutting of glass
• ¬16 conventional hard-alloy-tipped drill for hand-held hammering drills (Hilti)
• ¬16 mm hard-alloy tool for metal cutting (¬4 mm core)
• ¬16 mm custom made hard alloy core drill (Terätrio)
• a concept of two surgical knife blades rotating at ¬16 mm radius (~¬14 mm core)
• some tools were tested also with the aid of sonic vibrations, but without any success

Hole	Drill bit	Material	Speed RPM	Force N	Hole depth/mm	Speed mm/h	Duration h
1	diamond Ø16	Marble	30	24	8.8	0.3 .. 2.5	4
2	hard alloy	Marble	30	25	12.1	2.6	5
3	"Hilti"	Marble	30	25	17.6	1.9	14
4	diamond Ø16	Marble	30	24	16.6	1 .. 2.2	8
5	hard alloy	Marble	30	25	17.8	2.6	6.5
6	diamond Ø6	Marble	30	24	11.1	0.5 .. 2.1	6
7	diamond Ø6	Marble	60	24	13.2	0.7 .. 2.4	6
8	diamond Ø16	Marble	60	24	15.1	1 .. 2.2	8
9	diamond Ø6	Limestone	30	24	6.7	0.3 .. 3.9	4.5
10	diamond Ø16	Limestone	30	24	10.6	1.7 .. 3.4	5
11	knife blades	Limestone	30	25	3.4	6	0.5
12	sonic hard alloy	Limestone	30	12	4.3	1.5	Different
13	sonic hard alloy	Limestone	30	12	6.1	1.5	sonic
14	sonic hard alloy	Limestone	30	12	2.3	1.5	vibration
15	Terätrio	Limestone	30	27	9.8	18	0.5
16	Terätrio	Granite	50	high	0.9	3	10 minutes
17	Terätrio	Granite	120	high	6.2	36	10 minutes
18	Terätrio	Granite	120	27	2.3	2.2	1.3
19	sonic knife blades	Granite	30	12	1.5	0.2	2
20	knife blades	Granite	30, 120	12	1	0.2	3
21	Terätrio	Granite	120	45	3.1	2.0	1.5
22	Terätrio	Granite	120	45	12.9	0.2 .. 1.8	14

Figure 12. Some preliminary drilling test results, materials and tools.

For enhanced or special sampling actions two power lines are routed through drill pipe couplings to allow use of possible active drilling tools in the end of drill string. These possible tools include, for example, percussive tools and ultrasonic tools. DR. T C NG and Holinser Group have already developed a design for a suitable active percussive tool in University of Hong Kong. Also special measuring instruments can be mounted in tools for measuring temperature, contact force, etc. A concept to utilize ultrasonic vibration to enhance cutting action was also developed and tested. An ultrasonic transducer was developed to fit inside the drill pipe. The results show, however, that with given volume it was not possible to gain reasonable mechanical amplification for vibration and required electrical input power requirement became too high. An ultrasonic transducer in this size turned out to be useless.

<u>Preparation for anomalies</u>
The worst case accident to happen for the drill would be the one that would seize entire rover preventing it from returning back to the lander or carrying out any other tasks. This can happen if the drill string gets stuck in the borehole, or the drill system fails to separate drill pipes from each other.

To be prepared for such accident, the drill system is capable of leaving the entire drill string into the borehole as the rover backs away from the borehole. This is possible since the DSS has a long vertical slot in the front side of the structure, right in front of the active drill pipe. Also designs of the pipe carousel, clamping system, pipe holders, and tool carousel are such that the pipe can be abandoned and the rover can be backed away.

1. In case the drill string should get stuck in the ground the drill first pulls with full power in hope to separate one of the couplings on the string. If one coupling opens the string retraction can proceed in the preplanned manner. If none of the couplings opens, it means that the uppermost pipe is stuck in

the ground. Then the securing wedge on the spindle is released and the spindle is separated from the string, after which the rover can back away.

2. If a coupling between two pipes is stuck, those can not be stored in the carousel. In that case both of them must be abandoned by releasing them from the spindle and leaving them into the borehole.

3. If the coupling on the spindle is stuck, only one pipe can be used and the length of the pipe limits the possible sampling depth.

4. In case the tool gets stuck on the pipe only this one pipe and this one tool can be used, but the rover maintains its moving capability.

Development and prototyping

The entire drilling system was designed with IDEAS 3D modeling software, which was of a great help when fitting all moving parts and components inside the limited volume. At certain stage of development and modeling it was decided that instead of continued visual modeling a hardware-model would provide more concrete playground and faster progress. The 3D model was translated into a STL-file that was used to produce a plastic model of the most important parts (roughly 30 pieces) with fused deposition modeling (FDM) method. This plastic prototype was fitted with all mechanical motions, not electrically driven though, which clearly exposed potential interference and tight places.

Some of the part placement, like the micro switches, were done first with the plastic model and only then transferred to the computer model. Also all of the mountings and screws were designed with the prototype first. This approach appears to be very fast and efficient. However, a couple of things that should have been done in this time were left to wait for final model, which later turned out to be a mistake. Details like the pipe holder (that prevents a pipe from dropping from the carousel into the drilling hole), tool cleaning brushes and complete wiring design, turned out to be extremely difficult and took a lot of time at the stage where there was not the time reserved. In general details like these, and also all new features, should be prototyped and tested simultaneously during designing to avoid surprises in assembly and integration phase.

Testing

The drill performance is to be tested on a set-up constructed of a platform and a 2 m long transparent plastic tube. The soil sample to be drilled into is prepared into the tube and the drilling system sits on the platform, mounted either on a separate jig or on the roving vehicle. Drilling speed and thrust are measured with drill’s own instrumentation, while torque-measuring system is mounted to the jig. The sample to be prepared will consist of dry sand with varying grain size and compactness, added with occasional boulders of marble, lime stone and sand stone. Aim of tests is to determine drilling speed, power and forces, and to demonstrate capability to obtain samples from desired depth and from desired materials.

Vacuum compatibility and qualification for space

This device is merely an advanced proof-of-principle model; operations of which still require development for better efficiency and reliability. The model is constructed of commercial and self-manufactured components, but its operation does not rely on any special parts or materials that could not be made space-qualified.

On mechanical point of view the design lacks launch locks that might be necessary for a space instrument, and mass can still be reduced by another ~0.5 kg with optimized structural design. Effects of thermal expansion, thermal balance, and protection against dust must be studied carefully to guarantee operation of the drill in space environment.

Lessons learned

Pipe Couplings

Round-edged trihedron design familiar from robot wrist/tool interfaces appears to suit well for automated connections between parts.

A split ring, or a C-ring, for securing of the coupling, although simple in design and easy to use, has some disadvantages related to clinging and possibly to ring orientation.

Drilling tests

With a rotary core drill, 30 N thrust, 30 RPM, without hammering action, core diameter ~10 mm and depth ~15 mm, using hard-alloy cutting tool bits, it takes a few hours to take a sample from a soft rock like marble or lime stone. For hard rock like granite it takes a time frame of tens of hours, but durability and selection of drill bit material would be a critical issue. For hard rocks rotation speed has a great effect, the faster the better.

General

3D Volumetric development together with rapid prototype modeling techniques is a very efficient and fast way to design complex systems with moving parts.

Prototyping and testing of mechanical subsystems already during design phase is very important. Nothing should be left to be invented with the final hardware.

Pay attention for design of wire harness, especially if it is moving.

Conclusions

The work presented here produced the first prototype of a small mobile robotic drilling device capable to extend and retract an extendable drill string reaching up to two meters into soil. Scaling the device smaller a lighter and smaller drill can be developed, or if desired to drill deeper, a bigger scale drill with similar actions could be constructed. With this size, and especially with scaled-down devices, volume available for drill motors sets certain limits for applicable drilling power and speed. Lessons-learned section indicates some of the development targets that should be considered for the next generation of the prototype.

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