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Proposal and Basic Experiments of a Piping Inspection System Based on Water-Jet

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***Abstract*— After the incident in Fukushima nuclear plant, the access to several critical areas was damaged. Thus, the monitoring of them turned difficult. In order to keep tracking the status of these areas, it has been proposed to insert sensors through piping that is located nearby the element of interest. However, these pipelines have many restriction, like small diameter, changes of direction, elements that block access, etc. and none of the existing technologies have the capability of going through the piping while carrying the required sensors. In this paper we report a proposal of a new system, whose propulsion is based on water-jet. This device shows good possibilities to fulfill the requirements of carrying out the desired task. The design of this proposal aims to solve the limitations observed in the experiments done with a current technology, which are also described briefly. Basic tests done with the prototype developed are shown as well.**

I. INTRODUCTION

All the infrastructures require inspection and maintenance in order to keep them working in good condition, without interruptions or limiting these as much as possible. However, nuclear power plants facilities require especial care due to the hazardousness of the materials they contain and the long-term damage that the leakage of these materials represent to the environment and people. For this reason, most of the times, special systems are used to carry out this task. These devices could be teleoperated or have some degree of autonomy.

Even now, the design of the systems that are going to be used inside nuclear facilities is a difficult task, due to the harsh conditions these should tolerate, as well as the complex design of the installations where they should carry out their task. However, many different systems have been created to perform their duty in specific places inside the nuclear facilities[1], [2], [3], [4], [5], [6], [7]. Although most of these systems are not able to operate properly if the environment is not prepared specifically for them in order to deploy their task. This means, these systems can not be deployed if any unusual event considerably modifies the facilities.This situation could happened in case of accidents, as happened in Three Mile Island and Chernobyl, or natural disasters, as in Fukushima Daiichi.

In case of unexpected situations, the requirements of the systems could vary a lot, depending of the incident and which section of the infrastructure is damaged. The inspection to carry out the reparation or the decommissioning must be done carefully in order to avoid exposure of dangerous materials to the surroundings. Moore [1] described the importance of the usage of robotic systems in the decommissioning in Three Mile Island facilities. However, if we consider the incident in Fukushima Nuclear plant, this case is even more complicated, because the earthquake and the tsunami that followed it, did not just damage the nuclear plant facilities, but also damage the infrastructures located around, which functioned as backup. Without any extra support, the explosions of the reactors were unavoidable. These explosions damaged the buildings structure and the access to many critical areas.

Many different technologies have been used in order to carry out the decommissioning of the Fukushima Nuclear reactors [8]. Nevertheless, a problem that many of the systems developed so far have faced, is the limitation to access to confined areas. For instance, the access to some sections is only possible through pipelines. Even though currently many different technologies have been developed to inspect inside piping in nuclear plants [9],[10],[11], none of these devices is capable of moving in piping with an inner diameter smaller than 20 mm, as well as deal with obstacles presented in pipelines, such as: reductions, elbows, valves and so on.

In this paper, we propose a system to access some sectors of the Fukushima Nuclear Plant through its piping and negotiate different kind of obstacles. Initially we will define the requirements for this task and analyze different technologies used currently for similar duties. Then we describe the experiments done to figure out the feasibility of some existing technologies and with the results, a proposal for a new device is done. Finally, some conclusions will be directed and future work will be suggested.

II. REQUIREMENTS

As mentioned before, due to the occurred explosions in the reactors of the Fukushima Nuclear facilities, the access to many important sections was blocked and the current robotic systems are not able to access them. Besides, even more important than entering these sections is their monitoring

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in order to know the current situation and prevent more damages. Therefore, considering the difficulties and danger that represents reopening these areas, a plan of introducing special sensors through the pipelines to monitor the status of this areas have been addressed.

The planning of this project is carried out by the International Research Institute for Nuclear Decommissioning (IRID), IRID provided the schematic of a couple of pipings considered to introduce the sensors and are displayed in Fig. 1 and 2. On the one hand, Fig. 1 shows a pipeline whose pipes has an inner diameter which varies from 40 to 25 mm. Besides the reductions to couple the pipes of different diameter, there are three elbow connectors, two T connectors and one orifice plate, whose minimal diameter is 6 mm. On the other hand, the diameter of pipes in Fig. 2 vary from 25 to 20 mm and there are eight elbow connectors and one orifice plate of 6 mm diameter. Both cases have an average total length of 13 m and the end of the pipings are elevated a couple of meters with respect to the start.

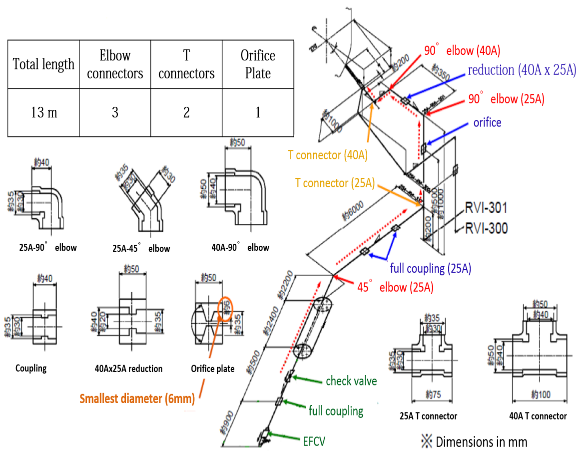

Fig. 1. Schematic of pipeline 1 in Fukushima Nuclear Plant. Diameters from 40 to 25 mm

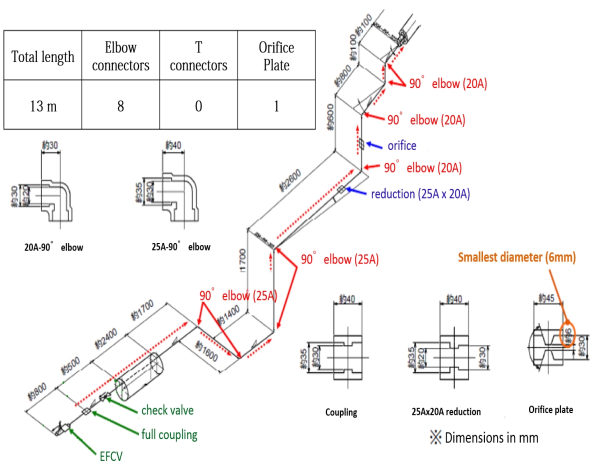

Fig. 2. Schematic of pipeline 2 in Fukushima Nuclear Plant. Diameters from 20 to 25 mm

Based on the conditions of the pipings mentioned above, we will define basic requirements for the system which should support the insertion of sensors to the end of the pipings. The requirements considered for this design are:

- The system should be made of elements with high resistance to radiation and endure harsh conditions.
- The device should be slim enough to access pipelines with a diameter smaller than 20 mm.
- It should be able to drill through the orifice of 6 mm. located in the pipings.
- It should be able to negotiate different obstacles, move in piping oriented vertically and propel itself through at least 13 m of piping.

III. CURRENT INSPECTION AND MAINTENANCE SYSTEMS

For tasks inside pipelines system, where different difficulties could be present due to the small diameter of the pipes, sharp curves and elements oriented in vertical position, many robotics system have been developed. Some examples are the robots proposed by Kuwada [12], which implements snake-like motion for its locomotion; Mazumdar [10], whose design is targeted for nuclear power piping systems and is propelled by water-jet; Choi [13], which requires compressed air to push the robot to the front; Kishi [14], which works with pneumatic actuators by simulating the motion of an earthworm; and Kakogawa [15], which is a wheel-type in-pipe robot with a special mechanism to keep the contact between the wheels and the walls all the time and is able to negotiate T branches. All these robots, except Mazumdar's design, require contact with the walls of the piping to generate the propulsion force for their motion. Therefore, depending of their configuration, they have a maximum limit in the diameter of the pipes where they are able to move. In the case of the designs proposed by Kuwada, Mazumdar and Kakogawa, their actuators are located along their bodies. Thus, their dimensions increase and the systems are not small enough to fulfill the minimal required diameter. In addition, Mazumdar's robot must be completely immersed in fluid for its propulsion. Also, for the systems developed by Choi and Kishi, due to their configuration, these systems could present some problems in negotiating reductions or some connectors. Finally, none of them is able to pass through the orifice nor possess any tool to drill it.

None of the mentioned pipe inspection systems fulfills all the requirements. The main limitations are the small diameter of piping and the lack of tools to drill through the orifice. One solution that different systems have adopted to reduce their size is by placing their actuators at the base of the systems. This can be observed in extrinsic continuum robots [16]. In the last few years these robots have been developed a lot and have found a good market niche in the nuclear industry. Some examples are those developed by OCRobotics [4], [17].These robots have shown good performance in nuclear facilities and are able to carry some tools at the distal end. Unfortunately, this kind of robot has a disadvantage, if the length of the body increases, it is necessary to increase its diameter. For that reason, so far there is not a robot slim and long enough to fulfill the requirements.

Considering another kind of devices used just for maintenance in pipelines, there is a commercial solution used to cleanup mainly drainage pipe networks, which uses water-jet as propulsion as well as cleaning element [18]. With this technology it is possible to generate a propulsive force at the distal end of the device. The water-jet is generated with water that flows through a hose which is the main body of the device. The water is propelled via a high pressure pump, moves through all the hose and finally goes out through nozzles which generate the water-jet at the tip. The force generated through the water-jet is strong enough to move the entire device several meter inside the pipeline and overcome several changes of direction and reductions. Commercially, it is possible to find some special mechanical elements, which are attached at the distal end and by using the water-jet power, these elements are propelled in order to remove dirt that is not possible to remove just with the water stream. Some of this elements have an operation similar to a drill, but their length do not allow them to negotiate with elbow connectors.

From all the technologies considered, the one that is propelled with water-jet is the most promising. It is possible to find many different configurations for this device, that is, different kind of hoses, nozzles, etc. Even so, most of the configurations of this devices have a diameter smaller than 20 mm. Nevertheless, because this technology is used in drainage networks, its common usage is in pipelines with a inner diameter larger than 50 mm. For that reason we decided to test its performance in a condition similar to those we require.

IV. EXPERIMENTS

In order to evaluate the performance of the water-jet device, a test bed made of PVC pipes of 40 mm diameter with a total length of the piping of around 13 m was prepared. At the same time, another parallel piping with the same length but different diameter was installed. This second piping has a diameter of 25 mm in its first half and decreases to 20 mm for its second half (this reduction is done in the middle of the pipe locaten between the elbows E and F). The pipings reach a complete height of 6 m approximately, and contains 3 elbows of 45° (A, E, F) and 8 of 90° (B, C, E, F, H, I, J, K), their distribution is shown in Fig. 3. The reduction of the piping is located between elbow E and F.

For the experiment we used a high pressure hose with length of 15 m. This hose has an inner tube core made of polyester which is covered with stainless steel braid. The inner and outer diameter of the hose are 4 mm and 7 mm respectively, their nominal pressure is 15 MPa. Two different nozzles were tested, one with the smallest size and simple, and other which is recommended to negotiate elbow connectors. Both of them have eight nozzles that are distributed radially to their longitudinal axis and have a diameter of 8 mm. The difference between these nozzles are that the jointed nozzle has 4 links that are connected

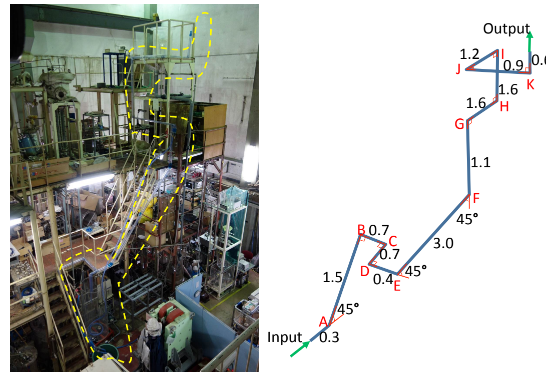

Fig. 3. Testbed and schematic, (length in meters)

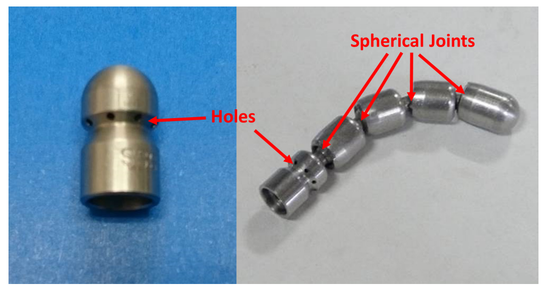

Fig. 4. Simple nozzle (left). Passive jointed nozzle (right).

in serial configuration with passive spherical joints. Fig. 4. The simplest nozzle was tested to figure out what are its limitations and because any possible adaptation is easier to apply to this nozzle.

In the experiments, the hose moved without problem in the first straight sections by applying a constant pressure. However, every time the tip faced an elbow, a pulsating pressure was necessary. This pulsating pressure shook the tip and with this motion, the tip could change direction. This change of direction was more difficult for the simple nozzle due to the lack of joints, which help to redirect the motion.

The system with the passive jointed nozzle was able to move through all the piping of 40 mm diameter without problem. However, a pulsating pressure was necessary even for the straight sections after the elbow G. This pulsating pressure makes the hose bends itself until it touches the walls, generating a motion similar to the locomotion of the robot developed by Kuwada [12]. On the other hand, with the simple nozzle, it was almost impossible to negotiate the change of direction from elbow D.

Due to the limitations observed in the piping of 40 mm with the simple nozzle, just the passive jointed nozzle was used with the other piping. In the experiments, the behavior of the system was similar to the previous piping until the tip reached the first elbow of 90° with an inner diameter of 20 mm (elbow G). The problem was that the minimal bending radius of the linkage in the jointed nozzle was larger than the radius of curvature of the elbow. Therefore, the nozzle was not able to pass through the elbow, Fig. 5. One way to solve this problem is eliminating some links from the nozzle. In this way, it is possible to reduce the radius of curvature slightly.

Fig. 5. Jointed nozzle stuck in elbow

Experiments to find the minimal pressure necessary to move the whole system through all the testbed were carried out as well. This was important because we noticed that even with the pulsating pressure, which generates special motion by propelling the body by the contact with the walls, there is a limit in how far the tip can penetrate, and this limit is related with the pressure applied. The minimal minimal pressure required to move the system through all the testbed was 8 MPa. This pressure generated a thrusting force at the tip of 8.5 N. In addition, we noticed that the higher the pressure, the less pulsating pressure was required to complete the testbed.

V. SYSTEM PROPOSAL

After analyzing the data obtained in the experiments, a selection of the best options for our device was done. These elements are: a drilling system, which will allow to penetrate through the orifice; a joint, which will allow a better adaptation to take the changes of direction; and finally a group of intermediate units, which we have called: whole stem drive, that will help to have a softer continuous motion of the whole system through the piping. Furthermore, a camera or sensor installed next to this nozzle, will allow us to gather information of the position and state of the device.

A. Drilling

Currently, there are different commercial nozzles that have rotational motion. These rotational elements are used to generate a distributed water-jet stream around the main head and they are used for the cleaning of pipelines. In order to have a better understanding of these rotational elements, a commercial part was modified by adding a drill-like element. This kind of devices generate the rotation by having a specific inclination and position in their water-jet nozzles. The disposition of the nozzles of the modified device are shown in the schematic in Fig. 6. We measured the rotational speed of the modified device, which reach around 1700 rpm. However, the torque of this element is quite small, due to the two pair of water-jets that act in opposite direction. The main reason of this is because this nozzle is aimed at generating a better distribution of the water stream around the tip, instead of generate a high torque. In our device, the direction of all the nozzles contributes to the generation of rotational torque.

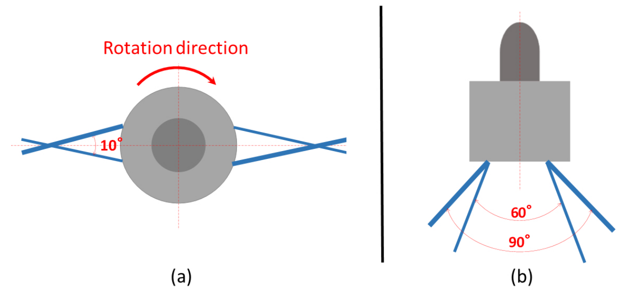

Fig. 6. a) Upper view of rotation device.(b)Lateral view of rotation device.

B. Joint

As mentioned in the previous section, the jointed nozzle has better adaptation when a change of direction is required. However, a large number of links could decrease the adaptability. Therefore, one spherical joint was added to our design. This joint is aimed helping the adaptation for the change of direction, as well as provide the degree of freedom required for the drilling. This concept is illustrated in Fig. 7

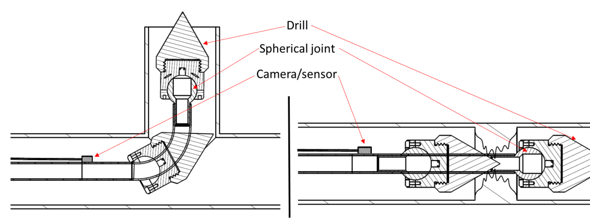

Fig. 7. Device changing direction (left). Device passing through obstacle (right).

With this concept, the adaptation and drilling rotation are considered in the same element, the spherical joint. In this way, it is possible to reduce the dimensions of the system. Additionally, because the drill rotates and is pushed forwards due to the water-jet, all the forces for the drilling are interacting just in the rotational part. This means, the drilling task should be independent from the forces that are interacting with the hose.

Based on this concept, a first prototype was designed, manufactured and tested. The elements and the assemble systems are displayed in Fig. 8. In the experiments carried out, this prototype was able to generate the water-jet to pull the hose. It was also able to incline slightly when it faced an elbow, but it did not produce the rotational motion for the drill. The problem with this prototype was that we expected that the water flowing through the hose and going out into the rotational unit would have distributed symmetrically and generated a uniform pressure around the spherical joint, as is shown in Fig. 9.a. However, what really happened was that due to the flow of the water, the rotational element was pushed forward, and this generated a contact between the rotational and fixed elements, which blocked any possible rotational movement due to the frictional force generated by the contact. Fig. 9.b shows the location of the points of contact.

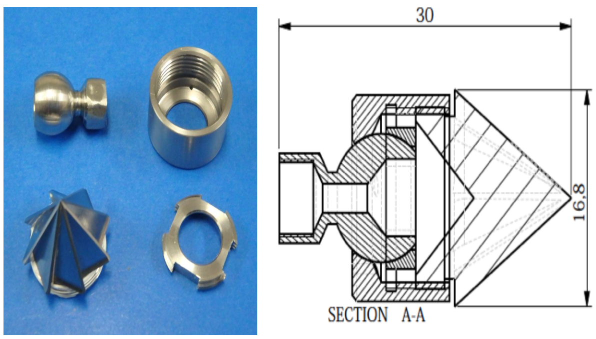

Fig. 8. Components device (left). Assembled unit (mm)(right) .

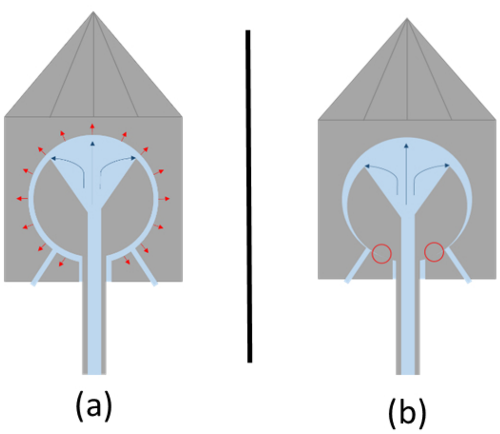

Fig. 9. (a)Expected behavior. (b)Real behavior

In order to solve this problem, the output of water in the spherical joint was modified, with the intention of trying to make a more uniform distribution of the outlets of water. The modified part is shown in Fig. 10.a. With this modification, the distribution of water improved and the contact between the rotation and fixed elements was avoided, Fig.10.b. Furthermore, the motion of the passive spherical joint was softened and the adaptation for the change of direction in the elbows improved. However, it is still not possible to generate a rotational continuous motion for the drill. Consequently, more improvements are necessary in the water outlet in order to get a more uniform distribution of water and its pressure. By doing this, the nozzle might be able to rotate by itself.

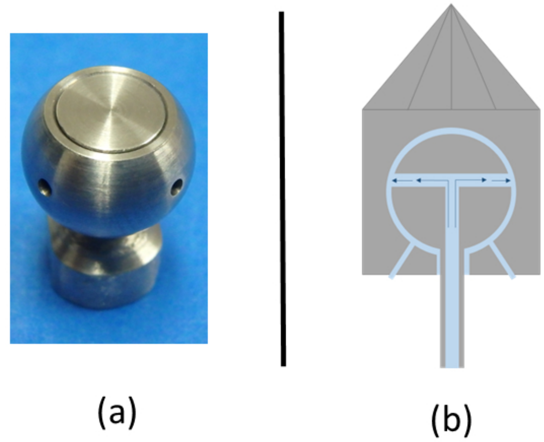

Fig. 10. (a)Modified part. (b)Schematic of modified unit

C. Whole Stem Drive

As mentioned previously, the motion of the system is less optimal the farther the system penetrates the piping, and a pulsating pressure is necessary. However, the motion generated due to the pulsating pressure has its limitations too. It does not work well if there are many continuous changes of direction. Because with many changes of direction the contact between the pipe and the hose will increase while it is pulling. as is shown in Fig.11.a. In order to solve this problem, the implementation of intermediate water-jet units was proposed. These units will help to generate more thrusting force along the hose, and in this way will be easier to negotiate continuous change of direction by using constant pressure and reducing the contact between the hose and the piping, as is shown in Fig.11.b. The thrust force for the intermediate elements should be the same for all of them or it should decrease the farther they are from the distal element. This is to avoid tangling the hose inside the piping. Because just one flow of water is used, the regulation of the thrust force will be carried out by changing the diameter of the nozzles on each intermediate unit. Because these intermediate units should work when they are inside the piping, we also consider a stop-ring element to avoid the flow in the elements outside the piping. This idea is displayed in Fig.12. A basic experiment with one intermediate water-jet unit was carried out, in this experiment the intermediate unit was placed five meters behind the distal end of the hose. The device showed improvement in its motion inside the piping, since the need of pulsating pressure was decreased slightly.

So far, we have not installed any sensor or camera to the system. Despite this, we do not consider this represents a big issue because we already possess a background knowledge on this matter due to other similar projects that our work group has developed, where the devices possess high flexibility and are deployed in underwater conditions.

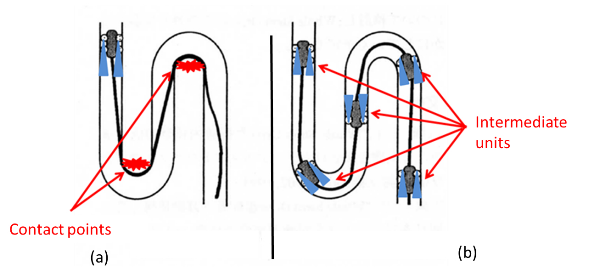

Fig. 11. (a)Just thrust force at the tip.(b)With intermediate thrust force

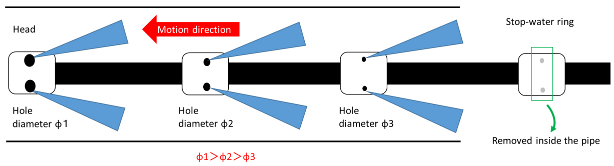

Fig. 12. Whole Stem Drive Concept

VI. DISCUSSION AND CONCLUSIONS

The incident in the Fukushima Nuclear Plant have brought too many new challenges to inspection systems. Thus, many systems need to be updated to fulfill the new needs. Taking this into account, we did a research of different inspection systems developed thus far. However, most of the systems are not able to negotiate piping with diameter smaller than 25 mm. This is due to the size of the inner elements they contain. Besides, those who can move through thin pipelines do not possess any tool to break through any obstacle if it is presented. Therefore, systems whose actuation elements are located at their base are more promising solutions. Nevertheless, the length of these devices are still limited.

After finding out that most of the automatic solutions do not fulfill the requirements of the task. The usage of water-jet technology for the maintenance of pipe networks was explored. This technology is not aim to be used in this kind of small diameter pipelines, because the common minimal diameter of the pipe in the drainage network is around 50 mm. Therefore, we tested its performance in similar condition to those we need and, in general, it showed a good behavior.Thus, the proposed system is based on the water-jet device, whose design is intended to solve some problems found in the current systems.

Some basic experiments were carried out with the first prototype. However, some issues were discovered. In order, to solve the issues, modification to the fist prototype were carried out. After the modification, the behavior of the system improved, but we are still not able to rotate the drill continuously with constant flow of water. For these reason, more detailed analysis need to be done, considering a better distribution and orientation of the outlets of the water.

Besides the proposal of the drilling nozzle at the tip, it was proposed using a whole stem drive to improve the motion of the system through the piping. Experiments to test the performance with one intermediate nozzle were carried out and showed promising results. However, it is necessary do more meticulous analysis and experiments to the intermediate units, with the aim of finding the optimal distance between each unit, and trying to reduce the pressure fall along the hose. Additionally, it is necessary to find the relationship between the diameter of the nozzle on each unit respect to its position in the hose, in order to generate the same thrust force in all the units.

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