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Authors	Jose A. Silva Rico, Shigeo Hirose, Hiroya Yamada, Gen Endo, Koichi Suzumori
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A Novel Long-Reach Robot with Propulsion Through Water-Jet

Jose A. Silva Rico[1], Shigeo Hirose[2], Hiroya Yamada[2], Gen Endo[1] and Koichi Suzumori[1]

***Abstract*— Long-reach robots offer good performance developing tasks in areas where the access is difficult or dangerous. Due to their multiple degrees of freedom, they are able to adapt easily to different environments. These robots base their locomotion to two different elements: tendon cables or fluid pressure elements. Normally these robots are divided in sections and each section has its independent degrees of freedom. Therefore, if the length of the robot increases, the number of sections increases as well. This also means an increment in the diameter for each section and a more complex control for the whole system. In this paper we introduce the concept of a novel water-jet long-reach robot, which allows increasing the length of the robot without affect its number of elements, control complexity and diameter. Due to its characteristics, it is possible to use this robot in different environments, confined or opened spaces. We test the performance of the first prototype in different scenarios in order to validate our concept.**

I. INTRODUCTION

In recent years, the development of long-reach robotic arms has increased due to the need of perform different tasks from a secure distance or in order to avoid damaging the surroundings by using conventional systems. These robots can be found in different kind of configurations, but in general they are grouped in two categories: serpentine and continuum robots. Both kind of robots are able to produce smooth curves, similar to snakes, elephant trunks or tentacles [1]. On one hand, the serpentine robots are comprised of high number of rigid links which are connected each to other with discrete joints [2][3][4][5][6]. On the other hand, continuum robots do not posses rigid links nor joints. In this way they are able to generate even softer curves and reduce the number of mechanical elements [7][8][9][10]. Besides, because of the large number of degrees of freedom they possess, these robots have better performance in real-world environments compared with conventional rigid-link arms robots, which normally require previous preparation of their surroundings to avoid interferences in their workspace.

For this kind of robotic arms, it is important to keep a high ratio between their length and their other dimensions, as well as lightweight. Thus, mechanical elements of large size, like motors or compressors, are located at the base of the robot. Basically, two different approaches have been developed to transmit the power from the base to the rest of the body of the robot. The first one is through tendons and the second one is through fluids. The former is the most common for serpentine robots [2][3][4]. While continuum robots use tendons, fluids or both [1][11].

Continuum robots, whose actuation is transmitted through tendons are also classified as extrinsic. These require a central backbone to ensure tendons remain with tension which also offers support to the arm [11]. These backbones consist of springs [8] or concentric flexible tubes [10]. Those continuum robots, where fluid is used to transfer power, are known as intrinsic. This fluid is contained inside bellow elements [9] or pressure tube elements [7] and, through the change of their inner pressure, these elements supply the actuation and give structural support.

Serpentine and continuum robots are divided in sections. For the former each section is equivalent to a rigid link. Thus, in order to increase its flexibility or to generate softer curves, it is necessary to increase the number of links and reduce their length. By doing this, the number of tendons and its diameter increase as well as the complexity of the system. In contrast, continuum robots possess theoretically infinite degrees of freedom in each section, which allow compliance in their entire sections and section can be actuated through finite degrees of freedom. By the addition of more sections, the length of the robot as well as the dexterity to adapt to complex curves increases.

For many applications where long-reach robots are used, the most important part of the robot to be controlled is the tip, because at the tip is located the tools or sensors used for the task. However, some tasks require introducing the tip of the robot to confined environments and carry out its mission far away from the access point. This could be a problem because, as was mentioned above, current configurations tend to increase their diameter when their length is increased. The exception to this rule are those robots that are intended to control just a few sections at the distal part of the robot [12][13]. The problem with the latter is that in some occasions, it is difficult to move forwards the distal part of the robot from its proximal part. This mainly happens when the passive part has high compliance and large length.

In this paper, we propose a novel long-reach robot design. This design increases considerably the ratio between the length and the diameter of the robot to an order larger than 1000 to 1, reduces the complexity of its elements and use a more straightforward control. This design uses hydraulic power to generate the motion of the robot, although unlike current designs which keep the fluid confined inside tubes or bellows, our system requires a continuous flow in order to generate thrusting force through water-jet. We present the design of our first prototype and some experimental

[1]Jose A. Silva-Rico, Gen Endo and Koichi Suzumori are with the Department of Mechanical and Aerospace Engineering, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo, 152-8552, Japan, `silvarico.j.aa, endo.g.aa, suzumori.k.aa@m.titech.ac.jp`

[2]Shigeo Hirose and Hiroya Yamada are with Hibot Corp., 5-9-15 Kita Shinawaga, Shinagawa-ku, Tokyo, 141-0001, Japan, `hirose, yamada@hibot.co.jp`

evaluation done in order to prove the concept.

A. WATER-JET PROBE CONCEPT

As mentioned before, the use of long-reach robots have extended for different tasks, mainly to develop mission in confined environments or to move through unstructured areas in order to deploy its end-effector far away from the base of the robot. However, the current systems have a limitation to increase the length/diameter ratio in order to keep the ability to move the distal part of the robots forwards.

With the purpose of generating propulsion in the distal part without the need of increasing the diameter of the robot, we consider the use of water-jets at the tip. Currently it is possible to find robotic [14][15], industrial [16] and amusement [17][18] systems which use water-jet to generate their motion. The robotic systems display good positioning control, but their size is not small enough and these can just perform their motion if they are immersed completely in water environments. Industrial systems have great power and are able to propel long and slim devices, but they lack control and are limited to move in confined structured environments. Finally the amusement systems have high power and are able to move in different environments with high dexterity, but they are big and their control is complex, this control is done directly through the sensing and motion of the body of the user, who is riding the device.

Considering the pros and cons of the systems cited above, we decide to use high pressure pumps to generate flow of water and transfer it through hoses like the industrial and amusement systems; in addition to the implementation of variable vectorial thrust forces, similar to the one used in robotic systems; and finally we consider using an attitude sensor at the tip to simulate the sensing that users have in the amusement systems and use these data for the control.

II. WATER-JET PROBE DESIGN

A. Mechanical Design

In order to produce water-jets to generate the thrust force in our system, we use three high pressure net-wire hoses, each one with a length of 40 m and inner and outer diameters of 3 and 6.5 mm respectively. Each hose possesses a nozzle of 0.8 mm of diameter at the tip, which is directed backward with an angle of $\pi/4$ rad respect to its longitudinal axis. The three hoses are attached adjacently in a circular pattern where the nozzles are directed outside the pattern with a $2\pi/3$ rad angle offset. This configuration is displayed in Fig. 1. The three hoses together have a diameter smaller than 30 mm. Three high pressure washer machines (IRIS OHYama: FBN-401) are used to generate the flow of the water. The specification of the washer machine is shown in Table I. This kind of washer consists of an axial piston pump of two cylinders propelled by a universal motor, and is aimed at domestic operation and normally is used with alternating current. Besides, it does not possess any control for the motor other than on-off. For this reason, it was decided to switch from alternating to direct current and regulate the speed of the motor through Pulse Width Modulation (PWM).

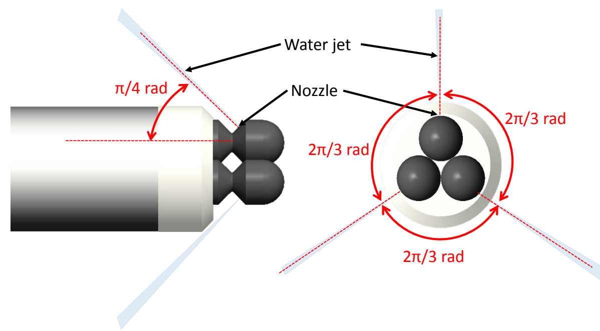

Fig. 1. Arrangement of the water-jet nozzles at the tip of the robot

TABLE I
HIGH PRESSURE WASHER SPECIFICATIONS

Work Pressure	6.0 MPa
Max. Flow Rate	270 l/h
Power	1000 W
Rated voltage	AC100V

B. Electronic Design

With the aim of controlling the motor of the washers, and in this way regulate the flow of water, we used one motor driver 1XH Power Module (Hibot Corp.) for each motor. With these motor drivers we generate a PWM from direct current, which can be provided from batteries or a power supply. The processing to generate the input signals for the motor drivers and their synchronization is done through the controller board TITechSH2 (HiBot Corp.). In order to generate these signals, the micro-controller processes the information from two different sources: a Joy Stick Controller and another controller board with an Inertial Measurement Unit (IMU) embedded. The former is a 3 axes type Joy Stick 30JH (Sakae Co.) which provides three independent proportional signal defined by the user. The latter is a TITech M4 (Hibot Corp.), this device includes and IMU that is used to calculate the attitude at the tip of the system. The information of the IMU is processed and adapted to be transfered through CAN bus cable to the TITechSH2. It was decided to use CAN bus because by using this standard it is possible to have effective communication through long cable and reduce the effects of high electromagnetic noise in the environment.

The cable used for the communication is a shielded multicore cable of 50 m length, internally this cable has two pairs of two twisted cables. One pair of twisted cables transmits the CAN-High and CAN-Low signals, one cable from the other twisted pair is used as ground for the CAN communication and finally the remaining cable together with the shield are used to transmit power to the TITechM4. A diagram with the general description of the electronic system is shown in Fig. 2

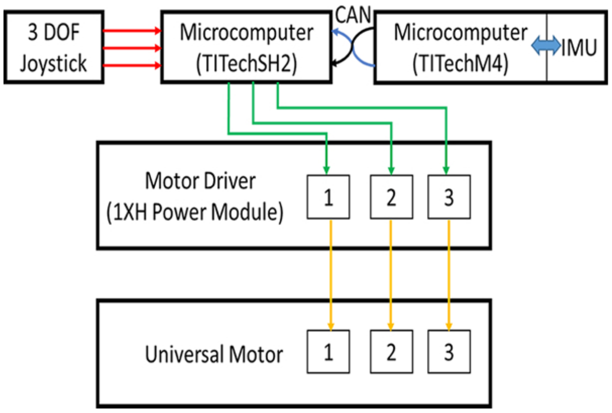

Fig. 2. Schematic of electronic elements

C. Control Design

The motion of our system is done by controlling the individual forces generated by the three water-jets located at the tip of the probe. As is displayed in Fig. 3, the total resultant force F_T, which is the force that directs the motion of the system, is the vectorial sum of the water-jet thrust forces. Besides, in the same figure it is possible to notice that the resultant thrust force could have positive, negative or null components for the X and Y axes, but just positive values for Z. In order to generate a straightforward control we decide to locate a local reference system at the tip of the hoses, as is illustrated in Fig. 4, where the X-Y plane is facing backward of the hose. For that reason, the X axes of the joystick and the tip of the robot point to opposite directions in this figure. Therefore, the direction of the thrust force in the X-Y plane is established directly with the orientation of the joystick, and finally the magnitude of the thrust force is established by the value of the Z axis in the joystick.

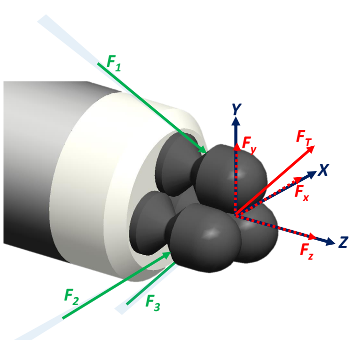

Fig. 3. Thrust force (green) and resultant forces (red)

We found that it is possible to direct the total thrust force projected in the X-Y plane by using just two water-jets at the same time, in this way it is possible to reduce the energy consumption of the system. If we want to locate the projection of the total force between lines a and b, it is only necessary to synchronize the flow of streams 2 and 3; between lines b and c, streams 1 and 3; and between lines c and a, streams 1 and 2 (see Fig. 4). Beside these conditions, there are other three specific cases when just one stream is necessary, and these are when the joystick is pointing in the same direction as lines a, b or c, and the streams that generate the thrust force are 2, 3 and 1 respectively. Finally, there is one special condition when the three jets are used and the three of them have the same flow. This happens when the joystick is located at the center, it means with zero values in X and Y.

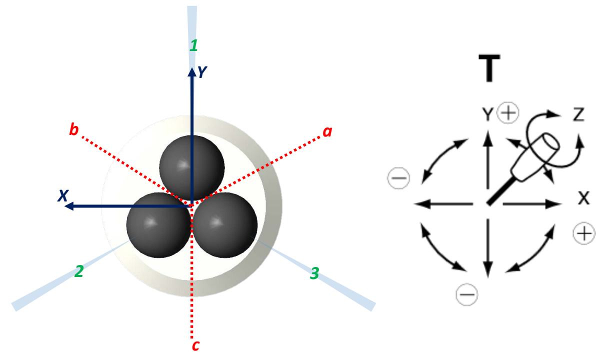

Fig. 4. Selection areas y joystick control

A crucial part for the control of the system is the synchronization of the motors. A correct synchronization allows us to have soft and continuous movement of the tip of the robot. Fig. 5 shows the PWM's required for each motor to generate a circular trajectory with the tip of the robot. The movement done with the joystick to generate this pattern is a counterclockwise rotation motion, which starts from the X axis. In a subsequent section, we will explain in more detail how the PWM profile was obtained. It is important to mention that this chart is valid only if the robot is orientated as is shown in Fig. 4. This is because our system does not possess any kind of propulsion to control the rotation in the longitudinal axis and due to the tip being capable of moving in three-dimensional space, it is almost impossible to keep this orientation. For that reason, we use the IMU at the tip of the robot to calculate its attitude and in this way use these data as a feedback to adapt our local reference system to the real conditions of the robot.

Fig. 6 illustrates a case of how the reference system for the control is defined. In order to define the control reference system (yellow), we use an inertial reference system or ground (black) and the local reference(red), which is located at the tip of the robot and follows its position and orientations. The control reference system share its origin with the local system. Y_C is parallel to Z_G. Z_C is contained in the plane that contains Y_C and Z_L and is orthogonal to the former. Finally X_C is orthogonal to Y_C and Z_C. In this way, the plane X-Y of the control reference system is orthogonal to the ground all the time and is perpendicular to the plane that contains the longitudinal axis of the tip.

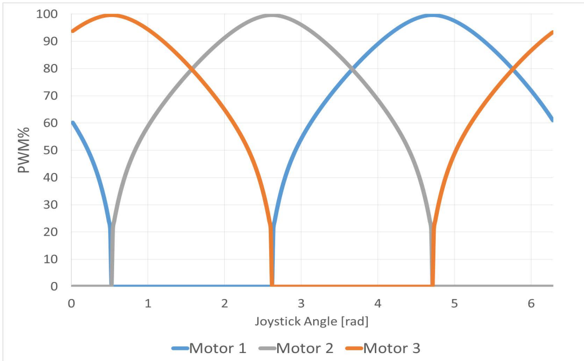

Fig. 5. PWM synchronization to generate circumference

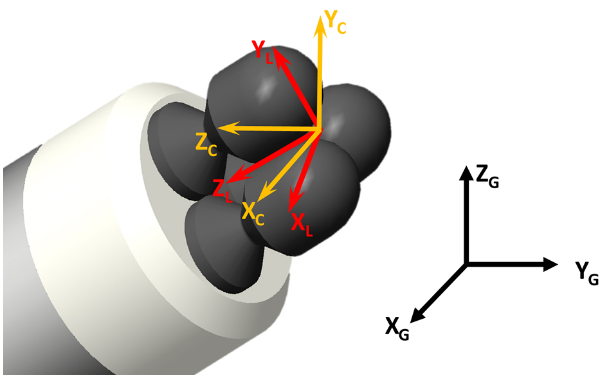

Fig. 6. Inertial reference (black), local reference (red), control reference (yellow)

III. PROOF OF CONCEPT

A. *Thrust Force Regulation*

Our system uses water-jet as propulsion, for that reason it was important to figure out the way we can regulate it and what are the most important variables to consider to improve its control. The PMW duty is the element in our system which we can regulate dynamically, for that reason, we carried out experiments to find the relationship between the thrust force and the PWM duty. Fig. 7 shows the results. For this experiment we measure the thrust force generated by just one stream of water. Several experiments were carried out and they showed good repetitiveness because the force varies slightly or not at all in each experiment. Besides, we were able to regulate the thrust force in a straightforward way. The motor starts to rotate with a minimal PWM duty of 16% but the thrust force starts to be sensed from a duty of 20%. This late starting behavior was considered in the chart shown previously in Fig. 5. The maximum force generated for the water-jet was 3.6 N. Taking this into account and referring to Fig.3, the maximum lateral force in our system is 2.54 N and the maximum force in the longitudinal direction is 7.64 N.

Another variable that is important to consider because it is related directly with the thrust force, is the pressure inside the hose. Furthermore, the pressure can drop considerably in hoses with small diameter and long length. Experiments were carried out to measure the pressure after the pump and just before the nozzle and in this way measure the drop pressure in the system. The results are displayed in Fig. 8. As it can be observed in the figure, although the hose has long length and small diameter, the pressure drop is not so large the maximum drop pressure found in this experiment was around 5%. This indicates that at least for this configuration it is not necessary to worry about the drop pressure. Besides, it was found that the maximum pressure generated in our system is about 5 MPa, which does not exceed the limit pressure of any of the components.

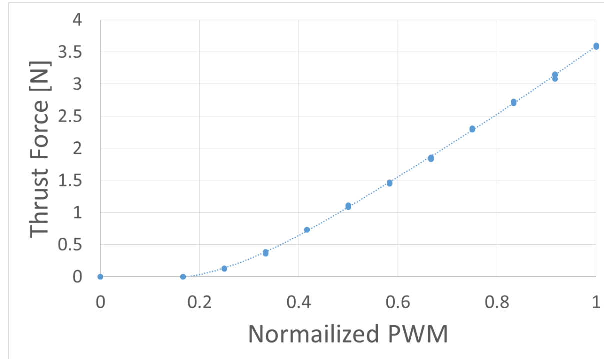

Fig. 7. Normalized PWM vs. Thrust force

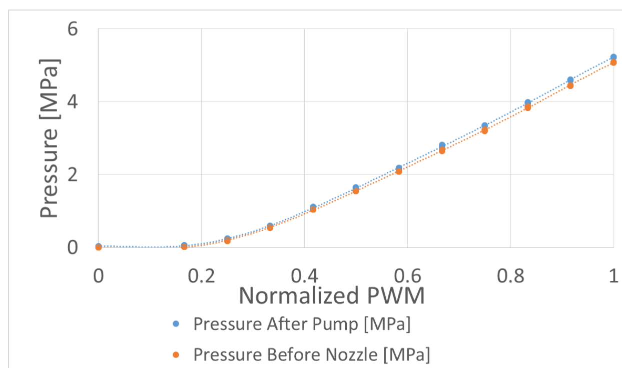

Fig. 8. Normalized PWM vs. (Pressure after pump & before nozzle)

B. *Motion of the robot*

We also tested the control design that was explained before. For this test, we fastened the robot in a point located 30 cm behind from the tip, after that the robot was controlled in order to generate a circular trajectory in clockwise direction, as it is shown in Fig. 9. In this figure the rotation of the robot is counterclockwise because the images were taken from the front. With this test we were able to verify that our control strategy works, as well as the correction done with the data acquired from the IMU. Besides this test, other experiments were done in an open area, these experiments were done to verify its movement while trying to reach two different targets, a sequence of images of this task are shown in Fig.

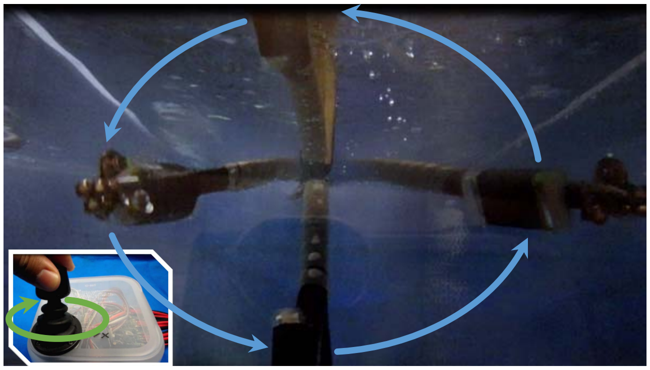

Fig. 9. Verification of the generation of circular path.

10. In this experiment we tried to keep the body of the robot in contact with the ground as much as possible, in this way the friction force between the hose and the ground tended to develop its maximum value. Therefore it was difficult or in some cases even not possible to move the system forward in straight line. For this reason we used a snake-like locomotion tactic, which enabled us to reach the targets. Afterwards, we tested the ability of keeping the tip of the robot gliding in the air, a sequence of images of this experiment is displayed in Fig. 11. This task was possible, but the control of the robot is extremely sensitive due to the lack of dragging forces. Thus, even with a small force applied to the side, it was exhibited significant movement.

Besides the experiments on ground, some experiments inside water were carried out. Because the surroundings were more homogeneous and the conditions did not change so much, we were able to measure the average maximum linear displacement of the system in water, which was around 0.5 m/s. In addition, we tested its control inside the water. For this test we place several targets, at the bottom of the pool and floating nearby the surface, Fig. 12. The motion inside the water was simpler compared to the test on the ground, since there was not necessary to adopt any kind of special motion to overcome lack of mobility due to friction. Besides, the control in three-dimensional space inside the water improved considerably, because the dragging force generated by the water avoided hasty movements, and all the targets were reach easily.

IV. Discussion

The proposed long-length robot is the first design of this kind of robots that uses water-jet as propulsion. With this design, it is possible to increase considerably the length/diameter rate. Additionally, the control of the robots is straightforward compared to the control of other long-length robots. Its simple mechanical design allows reducing the number of parts and thereby it can be used in different kind of environments without the necessity of adaptation in the system or extra elements for its protection. Furthermore, it

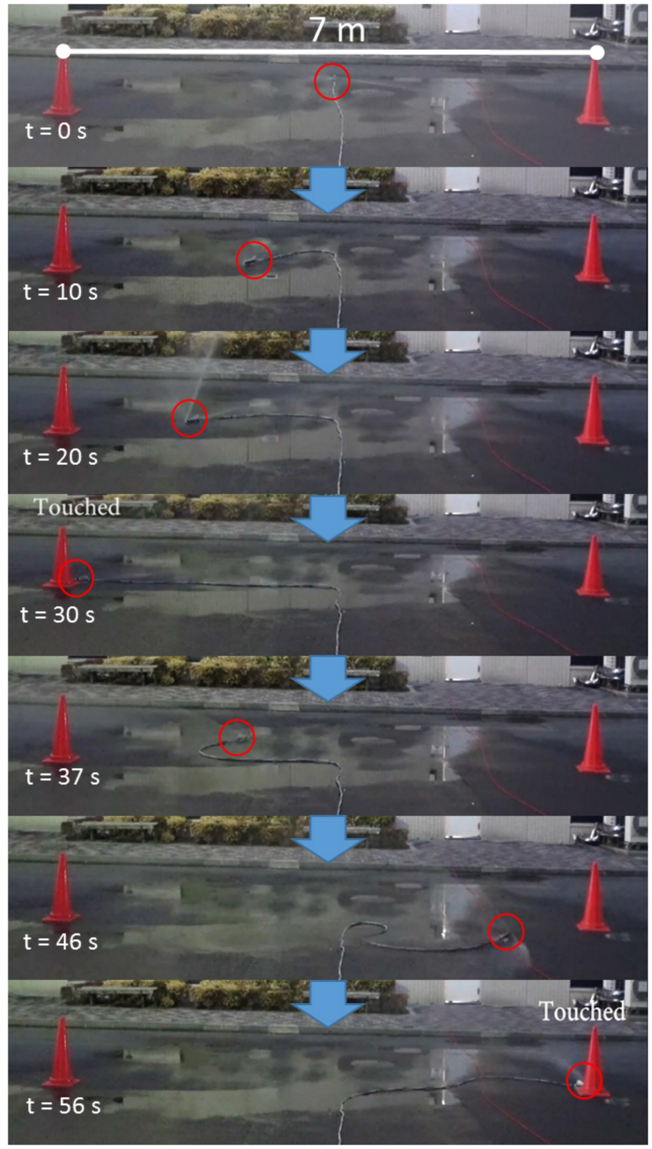

Fig. 10. Targeting objectives with snake-like motion on the ground

Fig. 11. Test of motion in the air

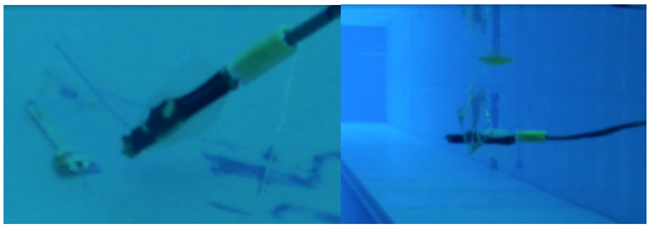

Fig. 12. Experiment in aquatic environment. Target at the bottom, left. Target nearby the surface, right

has displayed good dexterity in the different scenarios where it has been tested.

In the experiments, two different kind of water sources were used: tap water and water in a tank. Even though the tap water has an initial pressure, this pressure did not increase considerably the thrust force of the system. In fact, due to some fluctuations in the flow and pressure in the tap water, the behavior of the system showed slight variations. Therefore, in order to avoid these variations, it is preferable to use a more stable source or a source which we have control of its variables. Despite the appearance that the system uses a lot of water, the maximum consumption of water per pump is 2.1 l/min at maximum duty. Therefore, it is possible to keep running the system for relatively long periods of time without the need of a large reserve of water.

The robot generates enough thrust force to move all his body without problem in aquatic environments, but on the ground or air this force could be insufficient to develop all the needed tasks. However, we consider this problem can be solved by using high performance and more powerful pumps. Because as we mentioned above, the high pressure washer used to probe the concept is aimed for domestic applications.

In order to have a better controllability, it was proposed the implementation of an IMU at the tip of the robot in order to detect the orientation of the robot and use these data as a feedback for the synchronization of the pumps. Currently we are using only the attitude data from the IMU, but if we use other data from the IMU, such as acceleration or angular velocities, there is a big possibility to improve the control of the robot by implementing a PID control and in this way, there is a big opportunity to resolve the sensitivity problem that appeared when the robot was operated to glide in the air. Nevertheless, this kind of robot is a good candidate to be use as a inspection robot and it is possible to use other sensors that the current controller board has or connect new ones, like a camera.

V. CONCLUSIONS

We proposed and tested the concept of a novel water-jet long-reach robot which has considerably larger length/diameter rate compared with the current robots. Due to its simple and compact design, it is possible to use it in several environments as well as confined or open areas without the need of any modification. We proposed a control for this robot that allows it to develop motion in three-dimensional space in a straightforward way. The first prototype has shown promising results and there is still many different possibilities to improve its performance.

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