An innovative Cleaning Tool for underwater soft cleaning operations

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***Abstract*— This work takes place in the framework of the EU FP7 funded ARROWS project. In ARROWS project, low-cost autonomous underwater vehicle technologies are adapted and developed to significantly reduce the costs of underwater archaeological operations, covering the full extent of archaeological campaign. The project aims to deal with underwater mapping, diagnosis and cleaning tasks. This paper, specifically, describes the development of a cleaning tool (CT) to be used in cleaning underwater archaeological sites. This cleaning tool will be exploited not only during research missions, but also for the periodic monitoring, controlling and maintenance activity of well-known underwater archaeological sites (e.g. periodic cleaning operations). In this paper, the design criteria, working principles, the design and the performance tests of the developed CT are explained in details. The performance results are discussed in the final section.**

Keywords—Autonomous Underwater Vehicle; Underwater Robotics; Underwater Cultural Heritage; Underwater Intervention; Cleaning Tool.

I. INTRODUCTION

The ARROWS project [1] challenge is to provide the underwater archaeologists with technological tools for cost-affordable campaigns. Several technologies, originally developed for military use and the Oil & Gas industry, have been successfully adapted to underwater archaeology (e.g. acoustic communication or sub bottom profiling). However, there is still a strong motivation for archaeologists to reduce the costs associated with underwater campaigns, otherwise impossible to perform without the support of private sponsors and/or foundations.

ARROWS project is funded by the European Commission in the framework of the FP7 call ENV-2012, challenge 6.2-6. The project is coordinated by the University of Florence (IT) and its consortium is composed of several research institutions and companies dealing with Underwater Robotics: CNR-ISTI (IT), Tallinn University of Technology (EE), Heriot-Watt University (UK), Edgelab s.r.l. (IT), Albatros Marine Technologies (ES), Nesne Elektronik (TR), TWI (UK), Soprintendenza del Mare Regione Sicilia (IT), Estonian Maritime Museum (EE). The ARROWS Steering Board is supported by a purposely created Archaeological Advisory Group (AAG), composed of European archaeologists whose task is to guide and follow all the strategic developments of the project. ARROWS adapts and develops user-friendly autonomous underwater vehicle technologies to reduce significantly the cost of archaeological operations, covering the full extent of archaeological campaign.

The project aims to deal with underwater mapping, diagnosis and cleaning tasks. In particular the presented paper deals with the development of an innovative Cleaning Tool (CT) for underwater applications. According to the archaeologists' experience, a "cleaning device" has been considered, instead of an excavating ones defined in [2] within this project. The guideline for the submarine findings plans to monitor the objects found without interacting with them in a mechanical way. For example, the objects found are left where they are, both for safety reasons and for economic ones (cost and low availability of storehouses on land). The excavation, according to the 2001 UNESCO Convention for the Protection of Underwater Cultural Heritage, is not a practice to be used for Underwater Cultural Heritage (UCH). In addition, the

978-1-4799-8736-8/15/$31.00

excavating activity would probably damage the stratigraphy of the area causing a loss of very important data. The underwater archaeologists would instead benefit a lot from the availability of a cleaning tool integrated with an underwater robot system. It is worth to note that the cleaning tool will be exploited not only during research missions, but also for the periodic monitoring and controlling of well-known underwater archaeological sites (e.g. periodically cleaning operations or evaluation of the changes of a site). In order to softly clean the focus area, this cleaning device should blow air/water to dissolve the sand or mud on the archaeological artifact and also suck dissolved sand or mud to remove these from the focus area.

Moreover, ARROWS is dealing with the development of a team of new heterogeneous Autonomous Underwater Vehicles (AUVs) to support archaeologists in all the phases (mapping, diagnosing, cleaning, and monitoring) of underwater campaigns. Three classes of new AUVs are developed according to archaeologists' needs. The innovative AUVs, developed in the framework of ARROWS, are:

- MARTA (MARine Tool for Archaeology) AUV: it is a modular AUV, easily adaptable to the various types of mission according to its configuration;
- U-CAT: small biomimetic (turtle-shape) AUV, usable for shipwreck penetration;
- A-sized AUV: small torpedo-shaped vehicle, easily manageable thanks to its reduced size.

Among these vehicles, only A-sized ROV and MARTA will be equipped with the CT and the archaeologists will be trained to use the innovative tools produced in the framework of the ARROWS project. The system effectiveness will be demonstrated in two places, different as regards the environment and the historical context, the Mediterranean Sea (Egadi Islands) and the Baltic Sea.

In this paper, initially the design criteria set by the underwater archaeologists and the engineering team are given. A concept of the cleaning tool is presented to fulfill the requests listed in these design criteria. The design is embodied and analyzed to evaluate its working performance against the design criteria. The design is then manufactured and used in the experimental test setup which is also described in this paper. The results of the tests are provided for the forces that the CT induces to the ROV during operation. Finally, the results are discussed by giving the remarks and conclusions.

II. CLEANING TOOL DESIGN PRINCIPLES

In the beginning of the ARROWS project, meetings were held with the engineering team and the archaeologists. During these meetings specifications of the CT were defined to formulate the design criteria for the engineering team. These criteria are:

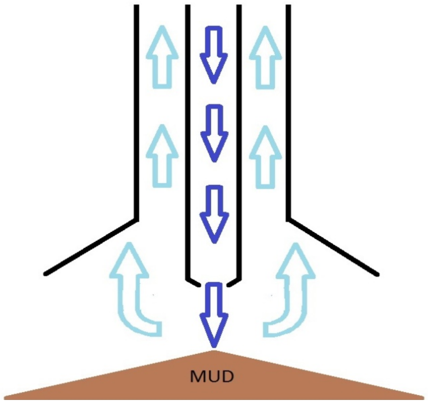
1. To have operating depth at a maximum of 100 m;
2. To be mountable on the ROVs;
3. To be run in ROV (Remotely Operated Vehicle) mode to receive external power;
4. Able to create water jets to dissolve the mud or dirt on the archaeological object and to suck the dissolved mud or dirt;
5. To be neutrally buoyant.

Complying with the design criteria, a working principle is derived by investigating various solutions and techniques. The working principle derived for the CT is presented in the next sub-section. The design of the CT based on this working principle is described following this sub-section. Finally computational fluid dynamics (CFD) analyses are carried out in order to evaluate the performance and to verify the calculations of the most critical part of the design, which is the ejector part. The results of the CFD analyses are provided to conclude this section.

A. Cleaning Tool Working Principle

In order to softly clean the underwater archaeological objects, sea water will be sprayed on the object to dissolve the mud or the sand on top of the object. As the mud or sand is dissolved in the water just above the artifact, a suction action will be required to suck away these dissolved particles to a further distance from the top of the object. In this way without touching the object or the sand on top of it with a solid body, the cleaning action will be completed. This idea is schematically provided in Fig. 1. The dark blue arrows show the water jet sprayed on the mud for dissolving it and light blue arrows show the suction line induced by the ejector.

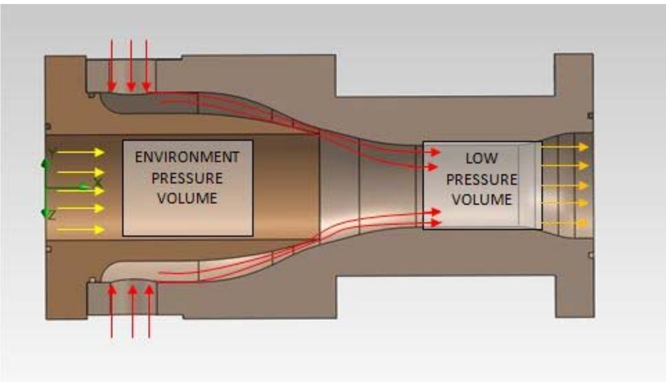
Fig. 1. Sketch of the general concept



Among the many solutions to accomplish the mentioned task, one concept was found to be wisest solution. The general working principle of the designed system is that a pump supplies water to both the nozzle for dissolving the mud on the archaeological object and to the water ejector as motive fluid for sucking the dissolved mud. Therefore, no sucked particles will move through the blades of the pump which results in a safer option for underwater mud cleaning service.

The critical part of the system, which is called the water ejector, increases the flow velocity in front of the inlet so that the pressure at the intermediate volume drops to lower values compared to the inlet pressure. This physical phenomena, which is called Venturi Effect [3], generates a vacuum and with this driving force, ejector sucks the carrier fluid with dissolved mud particles. Flow of the motive fluid to generate suction effect is denoted with red arrows and suction direction of the carrier fluid with particles is shown in yellow in Fig. 2. In our case, carrier fluid is seawater and as it flows, drag forces are introduced on dissolved particles tangential to flow streamlines. These forces compensate for the gravitational and buoyancy forces acting on particle motion and therefore, generated flow transports particles without letting them drop out of the flow line [4].

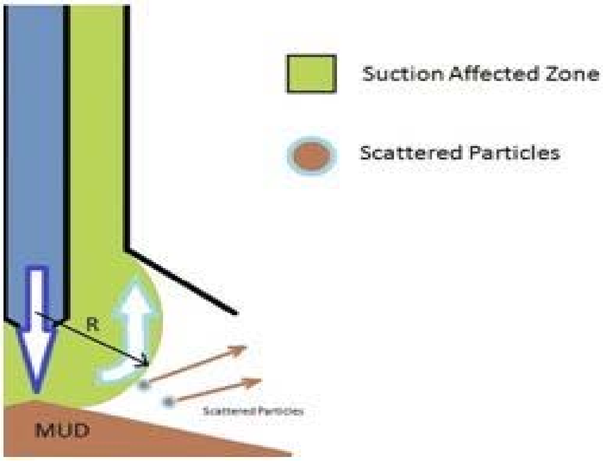
Fig. 2. Working principle of the water ejector



As explained in [4], to carry solid particles in a pipe, velocity of the carrying fluid is critical to have turbulent flow for the carrying fluid. Since Reynolds number has to be greater than 4000 for an internal flow to become turbulent, mean velocity of the internal flow has to be greater than 0.134 m/s through the 40 mm suction line. However, when heavier particles are carried and energy losses are considered in the outlet pipe, this value is then taken as lower limit and required velocities to compensate for the weight of the particles in water are determined by experimentation.

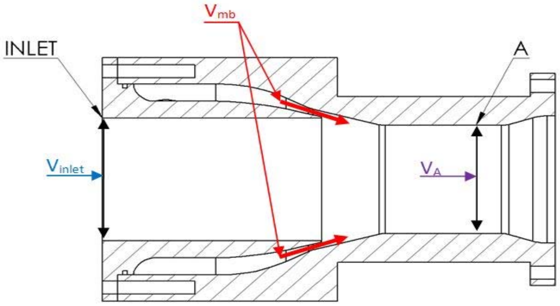
Another consideration in this design is to generate enough suction that system is able to collect mud piles that are located at 100 mm away from the suction inlet. This distance criterion is set to have a safe distance of the ROV with the sea floor. Additionally, as a result of the pressurized water from the nozzles, dissolved mud particles will be scattered. This phenomenon is shown in Fig. 3. Therefore, suction capability of the system has to be determined with respect to the suction range described from the center of the duct inlet, R in Fig. 3.

Fig. 3. Visualization of the action near the suction zone



Complying with the suction performance requirement, the mean velocity of the main flow for the carrier fluid is determined iteratively through CFD analysis and selected to be V_{inlet} = 3 m/s. Flow that is set at this value provides an effective suction at R in the range of 100 to 150 mm. Mean velocities within the ejector system are shown in Fig. 4 as; V_{mb}: motive fluid mean velocity, V_p: mean pump flow velocity VA: mean velocity at mixing chamber.

Fig. 4. Flow velocities inside the ejector



Pressure and flowrate of supplied water is determined to support both nozzles' water jet for spraying action and ejector's motive fluid, where V_{inlet} = 3 m/s. Therefore, calculations are then made for nozzles and ejector separately. For ejector, VA, V_{mb} and P_{mb} are first determined through iterations in CFD analysis. Then, V_{mb} and P_{mb} are used to find the nominal flowrate and pressure of the pump flow according to the equations expressed as

$$\frac{P_p}{\rho g}+\frac{V_p^{2}}{2g}+Z_p=\frac{P_{mb}}{\rho g}+\frac{V_{mb}^{2}}{2g}+Z_{mb} \qquad (1)$$

Since along the ejector there is no height difference, $Z_p = Z_{mb}$ and (2) is derived from (1).

$$\frac{P_p - P_{mb}}{\rho g}=\frac{V_{mb}^{2}-V_p^{2}}{2g} \qquad (2)$$

We can define head pressure in meters, h_p, as

$$\frac{P_p - P_{mb}}{\rho g} = h_p \quad . \tag{3}$$

The h_p pressure is the required pressure to be supplied by the pump. When (3) is substituted into (2) we get

$$2\times g\times h_p + V_p^2 = V_{mb}^2 \tag{4}$$

Due to continuity equation, which is $V_p A_p = V_{mb} A_{mb}$, we find V_{mb} as:

$$V_{mb} = \sqrt{\frac{2ghp}{1-\left(\frac{A_{mb}}{A_p}\right)^2}} \quad . \tag{5}$$

A_{mb} and A_p are cross-sectional areas of the motive fluid outlet and ejector inlet in which flow directions are along the normal of these cross-sections. A_s, V_{inlet} and V_A are determined through CFD analyses. V_{mb} is calculated by the continuity rule which is described in (6).

$$V_{inlet}\times A_{inlet} + V_{mb}\times A_{mb} = V_A\times A_A \tag{6}$$

After the V_{mb} is calculated, required pressure to be supplied, hp, is determined by (5). A resistance curve [5] for motive fluid outlet is constructed to be used in iterations for pump selection and design improvement.

Using (5), Table 1 is constructed to observe the pressure required to generate intended motive fluid velocity, which is V_{mb} = 13.4 m/s as calculated from (6). For convenience, only the vicinity of the required motive fluid velocity is represented in the Table 1.

TABLE I. REQUIRED PRESSURE TO SUPPLY MOTIVE FLUID MEAN VELOCITY

H (m)	Q (m^3/h)	Q (m^3/s)	Q (L/s)	Q (GPH)	V_{mb} (m/s)
9.000	12.300	0.003	3.417	3249.317	12.7
10.000	13.000	0.004	3.611	3434.237	13.4
11.000	13.600	0.004	3.778	3592.741	14.1

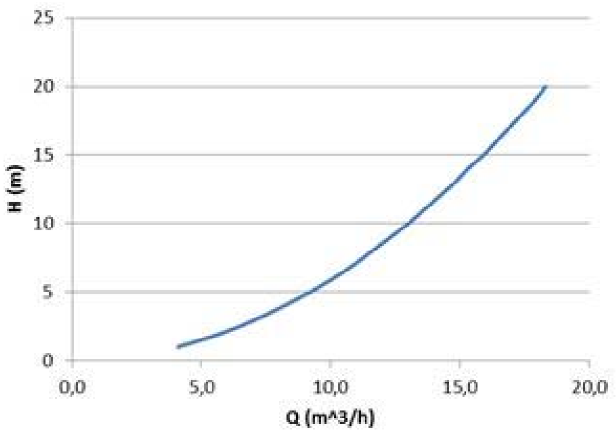
In order to have dissolved mud within the carrier fluid to be transported through the ejector, mud should have been dissolved by pressurized water from the nozzles. Pressurized water to the nozzles are also supplied from the same pump with same pressure as selected in the Table 1. Mud on the archaeological object is to be dissolved by peripherally guided 4-outlet-nozzle block with nozzle outlet diameters of 2 mm. This block is designed to spray a symmetrical flow over the mud on the archaeological object and at the same time, it does not let dissolved mud cloud to move away from the suction zone. The range of the nozzles is selected to be 100 to 150 mm. With respect to the mentioned design criteria listed above, Table 2 is constructed to visualize the mean velocity of the pressured water going off the nozzles and the required pressure for this action.

TABLE II. REQUIRED PRESSURE TO SUPPLY NOZZLE JET FLOWRATE

Hn (m)	Q_n (m^3/h)	Q_n (m^3/s)	Q_n (L/s)	V_{nozzle} (m/s)
9.000	0.600	0.0002	0.167	13.300
10.000	0.700	0.0002	0.194	15.500
11.000	0.700	0.0002	0.194	15.500

Data for 10 m Head in Table 1 and 2 are then superposed in Fig. 5 as a resistance curve of the combined ejector motive fluid and nozzle outlet to reveal the final characteristics of the required pump.

Fig. 5. Resistance Curve of the Motive Fluid



With respect to this information, impeller of the pump is chosen. When the impeller is selected, accordingly the electrical power requirement is set by taking the efficiency of the pump into consideration.

B. *Design of the cleaning tool*

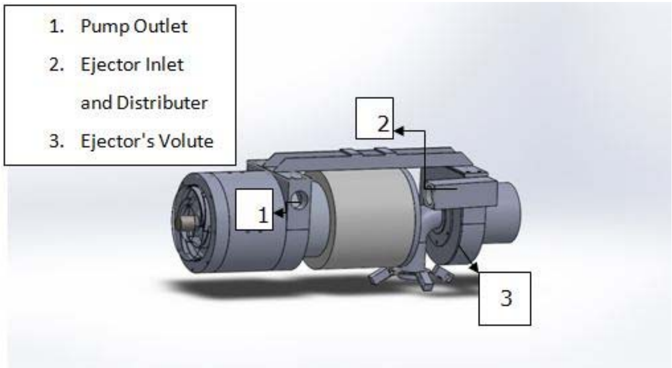
As provided in previous section, the suction line diameter of the ejector is chosen to be 40 mm and the inlet velocity is found in CFD analysis. The reason for this selection is to optimize the energy to be used in this suction action. A larger diameter will call for a larger energy input and therefore a larger pump in size and in capacity. Also throughout the suction line, the diameter of the suction line is kept constant in order not to have a stuck particle inside the suction line. According to the calculations described in previous section, pump requirements are determined. According to these requirements and specifications following stages are executed in design task.

- The suction line is designed to have a constant 40 mm diameter;
- A pump supplying 3600 GPH flowrate and 1 bar pressure is designed and integrated to the system;
- Ejector and nozzles are designed for optimum suction and dissolving action;
- Volutes for both pump and ejector are designed and implemented on the system to increase efficiency in transmitting flow and pressure.

CAD model of the final revision is presented in Fig. 6. The ejector is designed to have a volute at its inlet stage. Working principle of the system is realized with the main parts showing in Fig. 6 as the ejector, nozzles and the pump, which were described in the previous section. In addition, volutes are integrated to the outlet of the pump and inlet of the ejector to increase the efficiency of the system. The flow from the pump to the ejector system is initiated from 1 in Fig. 6, continued through 2, which distributes pressured water from the pump outlet to the nozzles and the ejector, and finalized with 3, which is the volute on the ejector to supply a uniform flow for the motive fluid.

The pump is designed and assembled to maintain 10 m Head (approximately 1 bar of pressure) while providing a flowrate of 3600 GPH at 2500 rpm of the motor.

Fig. 6 Final design for cleaning module

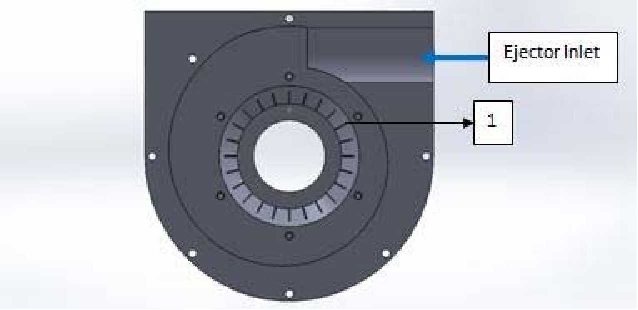


Impeller for this pump is chosen and manufactured for the specific requirements of the ejector and the nozzles. In order to choose the impeller, the resistance curve of the system and performance curve of the impeller are intersected at 1 bar pressure and 14 m^3/h flowrate complying with the previous design calculations.

The impeller is powered by a 1024 W PMDC motor. Motor is driven by 28 VDC and can reach up to 2600 rpm.

Using a volute, which is presented in Fig. 7, at the inlet to the ejector, a symmetrical flow with only one supply inlet is made possible. This resulted in having minimal number of connections for water flow from the pump to form the ejector motive fluid. Therefore, the weight and the Head loss of the system are reduced due to the reduced number of connectors and supply lines. The volute also provides homogeneous flow distribution along the ejector's bursting perimeter. Stationary blades are positioned in the bursting channel to direct the rotating flow into bursting flow. In Fig. 7, stationary blades are shown by 1.

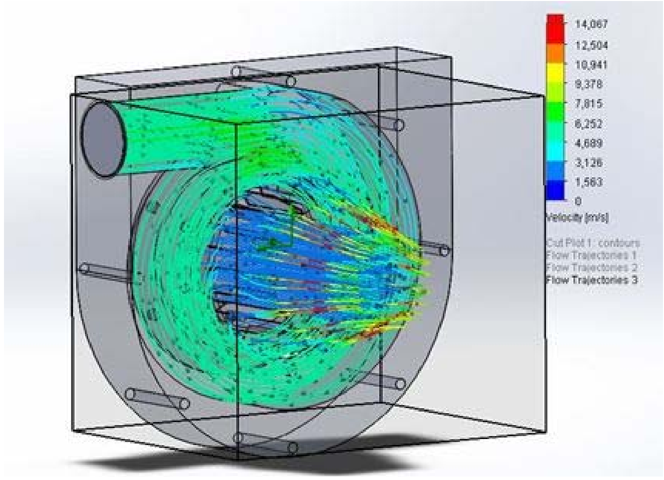
Fig. 7. Volute designed to maintain a homogeneous flow through the perimeter



C. *Analysis Results of the Cleaning Tool*

The design is evaluated with the environment conditions provided in [6] according to the performance parameters such as flow velocity, vacuum pressure, and head losses in flow analysis module of SolidWorks and one of the results for the design is given in Fig. 8. In Fig. 8, it can be observed that the flow through the volute into the ejector to create motive fluid is homogenous. The sucked fluid velocities through the ejector can also be observed to be around 3 m/s as it was specified for the design. It can be also observed that the stationary blades in the jet channel convert rotational flow into linear flow. Finally, according to ejector analyses, pump characteristics are verified.

Fig. 8. Velocity trajectories of motive fluid through the volute and sucked fluid through the ejector



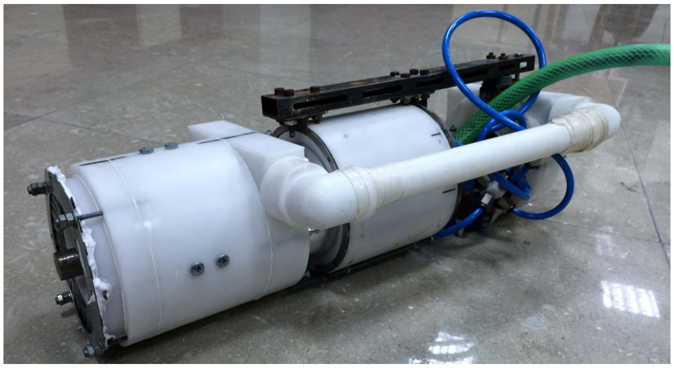
III. THE EXPERIMENTAL TEST SETUP FOR PERFORMANCE MEASUREMENTS

A working prototype for the CT is manufactured based on the specifications and calculations, which is shown in Fig. 9. Parts of the device are manufactured from aluminum alloy and Delrin due to their high strength to weight ratio. Aluminum is used in manufacturing the heat dissipation jacket of the motor casing and the blades of the impeller assembly.

With the integrated volutes in both sides, pump and ejector, the design has only one pipeline from the pump to the ejector and nozzles. Minimal amount of pipelines made the

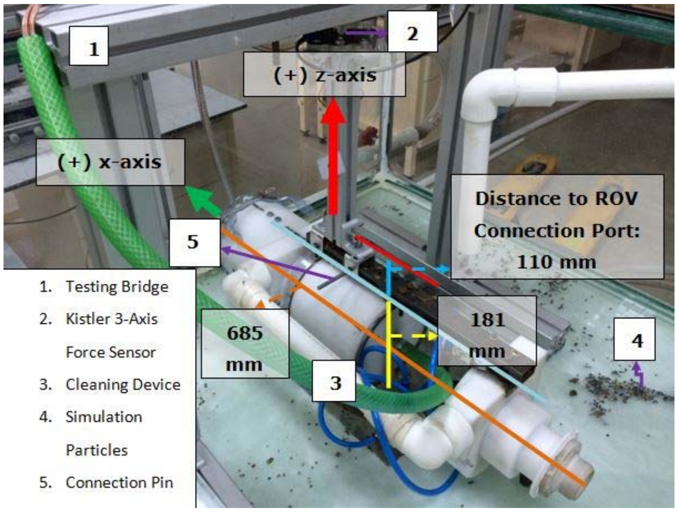
CT to be more rugged since it does less parts to be entangled to the objects in the environment.

Fig. 9. Overall system design



The experimental test set-up is presented in Fig. 10 and it is composed of a tank that contains clean water and particles to be dissolved and sucked (4), CT to be tested (3), the testing bridge (1), the force sensor (2) and the data acquisition system. Device is tested in a water tank, which has base area dimensions of 1.5 m x 1.5 m. A 3-axis force sensor from Kistler is used for force measurements. Force measurement data is acquired through a data acquisition card (DAQ) by Humusoft. Pump used for the device was designed within this study. The pump is powered by a 28VDC 36 A motor, having 1 kW nominal power.

Fig. 10. Experimental set-up and working axes.



Test Procedure:

The force sensor is activated and re-calibrated for its initial measurement to start at zero. The experiment is initiated with the measurement of the weight of the CT (including the pump, ejector and nozzles) by mounting it onto the force sensor when the water tank is empty. It is done by plugging the connection pins, denoted by (5) in Fig. 10, and then releasing the lifters below the device so that the weight is directly measured by the sensor without much noise. Then, the clean water inlet for the water tank is opened to fill the water tank until the water level reaches the red level drawn in the Fig. 10, which represents the ROV connection port. During the rise of water in the water tank, the forces measured by the force sensor along the z-axis are recorded to calculate the buoyancy force acting on the device.

After the buoyancy force calculations are completed, the pump is run at various DC voltage levels at 9V, 15V, and 24V and the measurements are recorded for the forces induced by the device along the x- and z-axes as indicated in Fig. 10. The reason to record only these axes is that the vehicle's head-tail direction is along the x-axis and the device ejects the water and the collected sand along the x-axis while sucks the water and sand along the (-) z-axis. In the measurements, the sampling rate for acquiring data is set to 10 Hz.

IV. PERFORMANCE TEST RESULTS OF THE CLEANING TOOL

The first test is conducted for measuring the weight of the CT and the buoyancy forces acting on the CT. Fig. 11 shows the forces acquired by the force sensor along the z-axis direction during this test. Initially the force readings are set to zero and then the CT is mounted on the testing bridge. Until about 1000 seconds, the CT is fixed onto the testing bridge and the forces during the fixing action can be observed. As the CT is fixed to the bridge, the water tank is started to be filled with water. After 2000 seconds the water level starts to reach the level of the CT and the force drop along the z-axis can be observed in Fig. 11 until the 7000th second when the CT is fully submerged in water. According to the test results, it is observed that the CT weighs about 171 N in air. As a result of the buoyancy forces acting on the CT, after the CT is fully submerged in the water, the force measured along the z-axis rises to -82 N from -171 N, which means the weight of the CT in clean water is 82 N.

Fig. 11. Experimental results showing change of weight during submerging

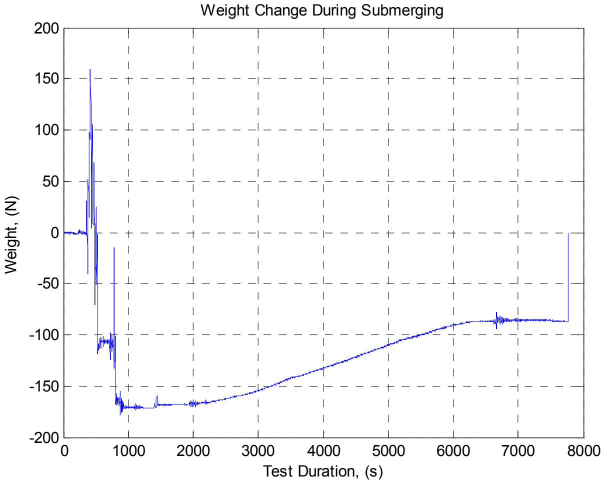
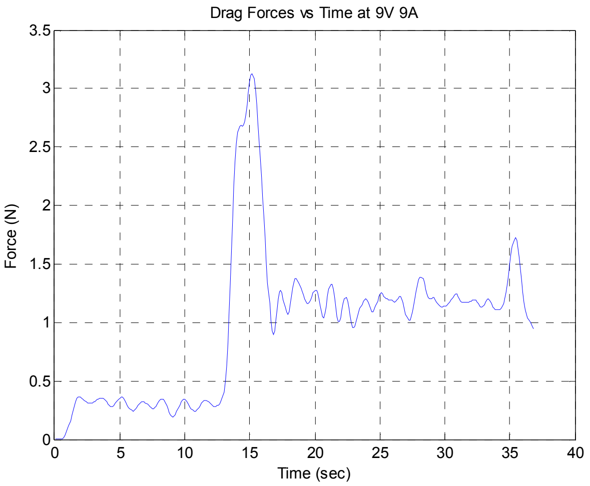


Fig. 12, 13 and 14 show the forces measured along the x-axis of the CT during the test from the lowest power to operate the system to the vicinity of the highest power achievable by the system, which is reached at 24VDC supplied to the pump motor. After an initial peak of force at 9 VDC, force in (+) x-direction settles at 1.3 N as it can be observed in Fig. 12. Therefore, forces acquired along x-axis is in the range of 1 to 3 N. During the continuous operation condition, the forces applied on the ROV by the CT reaches a maximum of 1.3 N.

Fig. 12. The experiment result for forces acting along x-axis at 9 VDC (filtered @ 10 rad/s)



Data presented in Fig. 13 represents the system running at a mid-level power range when the pump motor is run at 15 VDC. Initially there is an overshoot that reaches to 6 N and then it is settled to just below 3 N in steady-state operation.

Fig. 13. The experiment result for forces acting along x-axis at 15 VDC (filtered @ 10 rad/s)

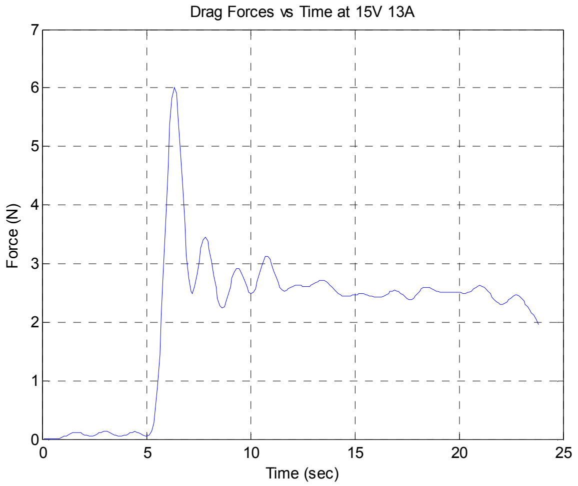
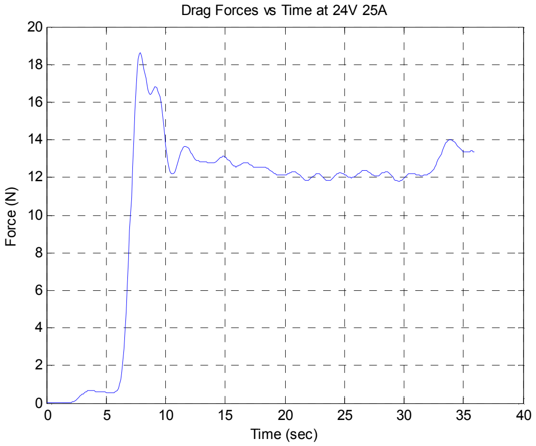


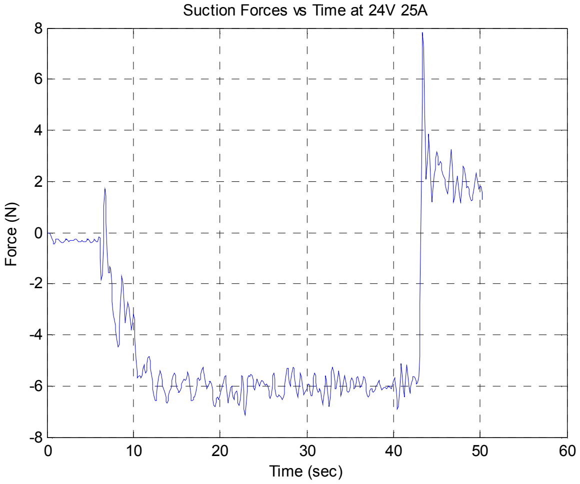
Fig. 14 shows performance of the system around its maximum range of power at 24 VDC and 25 A. The overshoot of forces happen initially at a maximum of just above 18 N. The forces induced by the CT to the testing bridge are at about 12 N during the steady-state operation.

Fig. 14. The experiment result for forces acting along x-axis at 24 VDC (filtered @ 10 rad/s)



During operation, the CT also applies forces to the test bridge along the z-axis direction due to unsymmetrical flow directions. This phenomenon is explained by momentum equations presented in [2]. Since these forces can result in a drift of the ROV in operation, forces along the z-axis direction were also acquired in tests and processed to be used in real operations as control input for the controller of the ROV. Fig. 15 shows the suction forces applied on the testing bridge along the z-axis direction. Since the forces in every run shows similar trends with different magnitudes, only the suction forces at 24V and 25A is presented in this paper. The forces measured along the z-axis direction are (-)2 N, (-)5 N, and (-)6 N respectively from the lowest to the highest power supplied to the pump motor.

Fig. 15. Experiment result for forces acting along z-axis at 24 VDC (filtered @ 10 rad/s)



V. FINAL REMARKS AND CONCLUSIONS

The work presented in this paper is carried out to develop an innovative CT for underwater applications. The main idea was to design a CT that can dissolve the mud over an underwater archaeological object and suck the dissolved mud over the object. To fulfill this task, a water ejector combined with a pump and a set of nozzle was considered. This design was chosen to eliminate the chance of failure during operation and decrease maintenance costs. Since the design and testing stages are executed in iterations of loops, prototypes are manufactured and tested to verify the engineering calculations based on design criteria, which was set by archaeologists and AUV design team.

The design has low number of parts and connectors with lighter materials. Furthermore, there is no reduction of cross-section in the ejector. As a result of this, any particle that is able to pass through inlet can go out from the outlet without getting stuck in the ejector. An impeller is manufactured to provide required flowrate to the nozzles and ejector at the same head pressure. Therefore, by using the designed pump, a flow control unit listed as an improvement in the intermediate design evaluation is no longer required. The weight of the system in air is 171 N. On the other hand, buoyancy force acting on the final design is 89 N. The chosen PMDC motor has a heavy commutator which results in a weight of 3 kg underwater. Underwater weight of the system has to be decreased by possibly adding 82 N of buoyant force generated by external buoys. Nevertheless, these external buoys will increase the dimensions of the system. In order to decrease the weight of the system in water, a lighter in weight BLDC motor having same mechanical power output at rated speed can be chosen for future studies. Also a particle filter can be added to the pump system to secure to supply line from any blockage.

As concerns the further developments of this work, the developed CT will be customized to be mounted on the ARROWS vehicles: its sea testing is scheduled for the beginning of Summer 2015.

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ACKNOWLEDGMENT

This work has been supported by the European ARROWS project, that has received funding from the European Unions Seventh Framework Programme for research, technological development and demonstration under grant agreement no 308724.