Design and construction of an electric chisel for underwater applications

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DOI: http://dx.doi.org/10.6036/7693

1. INTRODUCTION

Underwater archaeology is becoming an established field of study and research in cultural heritage, thanks to the improvements of materials, technologies, and exploration methodologies [1].

The goal of underwater archaeology is to enhance and preserve the submerged artefacts without removing them from the seabed. The 2001 UNESCO Convention, in fact, defines as "all traces of human existence having a cultural, historical or archaeological character," all those artefacts that have been submerged for more than 100 years. These indications gave birth to new professional profiles, such as underwater archaeologists, in charge of safeguarding the archaeological heritage and carrying out proper maintenance operations. As a further consequence, the UNESCO Convention has generated the need for new working tools able to support the underwater archaeologists in their work [2].

In underwater environment conditions, the operative depth is a crucial factor for the choice of tools or devices. In particular, when the operations have to be performed at greater depths, underwater vehicles like remotely operated vehicle (ROV) or autonomous underwater vehicle (AUV) are the best solution. In relatively shallow waters, the direct intervention of underwater archaeologist is very common [3]. The typical tasks, such as recovery and restoration of a specific object or an entire archaeological site, are carried out through more or less the same procedures used on dry land.

In accord with the scope of this work, we will refer only to the devices aimed to support the archaeologists who work at shallow depths. These tools can be divided into two categories: hand tools or automatic tools (with either hydraulic or pneumatic actuation). In the first case, the operator handles precision instruments such as chisels, knives, or brushes, to remove biofouling encrustations on the remains [4]. This activity requires an extreme precision and strong manual accuracy. In the second case, especially when more complex and time-consuming operations are necessary (for instance, when very large areas have to be treated), instruments with hydraulic or pneumatic actuations are the preferred choice. Whether the actuation is hydraulic or pneumatic, there is the need of a support boat for powering the instruments - without any doubt, the logistical aspects of these interventions are very complex.

This paper describes the design and manufacturing stages of an electric underwater chisel, a technical solution aimed to solve some of the issues described above. In particular, we have realized a device aimed to support archaeologists during the cleaning of submerged structures. This device tries to combine the peculiarities of hand tools, such as precision and manageability, with the points of strength of automated tools, such as power and durability, removing the biggest obstacle linked to automatic tools, that is, the need for a support boat.

The paper is organized as follow: in the first part we will focus on the reasons that lead to the use of either manual or mechanical techniques. Then we will define the design specifications of the sealing, electronics, and manufacturing technologies. In the second phase, we will describe some manufacturing solutions based on 3D printing techniques that have been adopted to build specific components. The last section will describe the construction and testing of the prototype.

2. MATERIALS AND METHODS

The project goal was the creation of a battery powered underwater chisel that can be used for removing encrusting organisms from underwater structures.

In order to achieve this goal, we've defined the state of the art of the currently available automated underwater tools , which are mainly relying on pneumatic or hydraulic power. The choice of these types of actuation depends essentially on the intention of limiting as much as possible the use of electrical equipment in water, in order to ensure the safety of operators. However, such a choice increases the costs due to the use of complex devices, which require a constant connection with the support boat equipped with bulky power devices. The high power that these instruments are capable of supplying, together with their overall dimensions and their weight, are not satisfying the requirements of underwater archaeologists in terms of precision and accuracy. Moreover, the restorer is always constrained to the position of the boat, with all the negative consequences for his/her freedom of movement [5].

In order to avoid the drawbacks related to the presence of a support boat, and also to provide an effective tool for underwater restoration, we chose to realize a device with an electric actuation, despite the fact that such a device needs several precautions aimed to eliminate any risk for the operator. On the other hand, such a choice is able to ensure the manoeuvrability, precision, and durability needed to operate effectively in the restoration and cleaning of submerged structures.

In order to achieve a high safety level for the device, the case that contains the movement and percussion assemblies (which require direct contact with the diver) has been separated from the case containing the power supply and control unit. The two cases are independent and connected through a cable equipped with underwater-rated connectors. This solution allowed for reducing the weights and improving the handiness and the ergonomics of the instrument. The integrated electronic components allows for managing the power of the blow/shot, for controlling the charging and discharging of the battery, and for monitoring the operating parameters of the device, including the detection of any water infiltration. The materials and processing techniques used for the creation of the prototype allow for using the device in waters up to 50 meters deep - that is, where almost all of the submerged archaeological sites are located.

A thorough analysis of the percussion systems currently available on the market was carried out in order to identify the ones that were compatible with the design chosen for the instrument, in terms of constructive features, weights and dimensions, so that it could be used as a basis in the design and prototyping stages. In particular, the study of the kinematic mechanism of our percussion system allowed us to design and integrate some static and dynamic sealing components, capable of maintaining water-tightness up to 5 bar.

As for the module containing the electronics, an 10 Ah, low voltage (7,4V) lithium battery was included in the design, in order to ensure a back-up time of about an hour and a half of continuous use at maximum power. A proper design of the sealing elements and a pressure relief valve have been adopted to ensure the safety of the battery pack [6].

The manufacturing techniques employed for the first prototype are based either on conventional machine tools, or additive manufacturing (3D printing) [7]. The choice of the most suitable technology is dictated by the analysis of the functional characteristics of each component. In terms of design approach, it should be pointed out that the described techniques differ significantly among each other, both in terms of design delivery time and costs of implementation.

3. DESIGN

The first phase of the design concerned the analysis of the methodologies and the instruments currently used during the operations of underwater restoration. Commonly the encrustations are removed manually with steel spatulas of different sizes. To remove the most tenacious encrustations the archaeologist hammers the handle of the spatula with a mallet.

To set the parameters of the system, the maximum impact energy of 1J was calculated, corresponding to a blow struck with a mallet of 5 Kg at 0.64 m/s.

The underwater device has been designed starting from the pneumatic hammer assembly of an off-the-shelf hammer drill [8].

First, the assembly has been modified in order to disable the rotation of the main cylinder, since we are interested only to the percussive action. Then the main body of the underwater tool has been dimensioned to ensure the required handiness, making sure that the hammer assembly is perfectly fitted (Figure 1a).

We used SolidWorks [9] to model and simulate the system. The hammer is powered by a brushed DC motor, which delivers about 5000 impacts per minute with a maximum impact force of 1 Joule. A particular attention has been paid to the sizing of the vent holes required for the operation of the pneumatic hammer. Given the space constraints, two support elements for the hammer pipe have been carefully designed. These components present appropriate holes for the passage of the proper air flow rate at maximum power (figure 1b).

Several simulations have been carried out to verify the assembly procedure and to optimize the geometry, in order to reduce the number of components. A lesser number of components reduces the complexity of the tool, with positive effects in terms of maintenance planning and cost reduction. Right from the design stage, rapid prototyping techniques were used for the production of the most complex components.

The battery pack has been dimensioned to contain both the electronics and the Li-ion battery. A first knob controls the output power, while a second knob can be used to enable or disable the device (see section 3.2 for details). A wet mateable connector has been placed on a side for connecting the hammer body. Table 1 reports the technical data of the device.

3.1. DESIGN OF THE SEALING ELEMENTS AND STRUCTURAL SIMULATIONS

The water tightness has been ensured by a proper design of dynamic and static sealing elements. We defined the exact dimensions and materials of the grooves for the seal parts and the O-rings to be used. In particular, we have used NBR (Nitrile) O-rings for static seals and a single-acting polyurethane rod seal for the pneumatic cylinder [10], [11].

For the structural sizing, we have conducted a series of FEM simulations that allowed for the identification of the

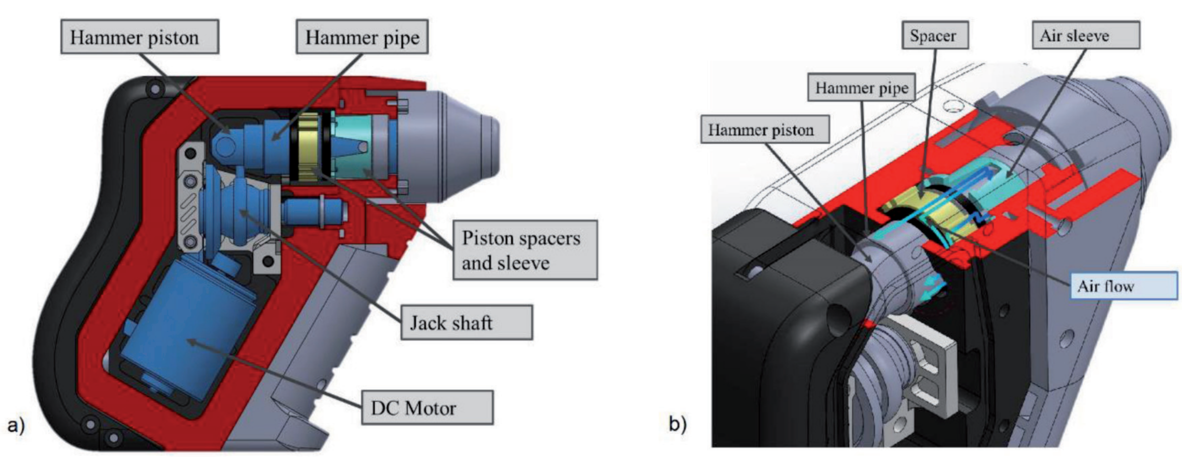


Fig. 1: CAD of hammer assembly and representation of air flow

areas to be stiffened. The prototype was firstly tested at low depths (5 bar), in order to avoid excessively burdensome conditions. For this reason, a number of FEM analyses using Delrin were conducted. This acetal resin is robust enough to ensure a good structural response at not very high pressures. The results show that the geometry does not return high stress values and the maximum deformation amounts to 0.2 mm. During the design of underwater components, it is important to remember that the deformation of the parts shall be limited, as strong deformations may result in a failure of the O-ring, leading to a complete or partial filling of water in the device.

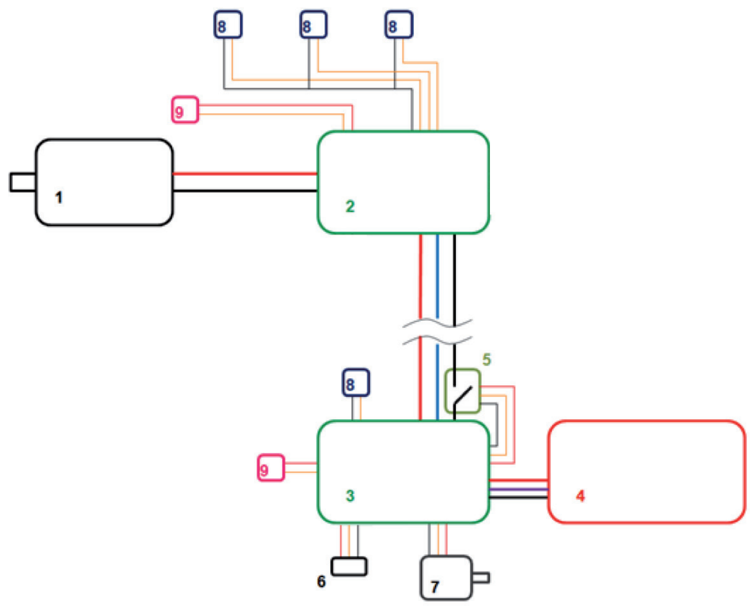


Fig. 2: Electronic layout

3.2. ELECTRONIC DESIGN

A schematic representation of the electronics used in the chisel is shown in figure 2.

The percussion system is driven by a DC Brushed electric motor (1), powered by a 7.4V, 10 Ah lithium battery (4). Two electronic boards are connected to each other and placed between the motor and the battery: the (3) in particular, inserted in the battery pack, in addition to managing the charge/discharge process for the lithium cells, allows for controlling the power supply through a pulse-width modulation.

The actuation system is composed of an analog Hall sensor (6) and by a knob that adjusts the relative position of a permanent magnet. By varying this distance, the detected magnetic field - and, therefore, the voltage read by the control board - may be adjusted. Therefore, by setting an appropriate threshold value, the percussion can be started or stopped. This solution was chosen because it reduces the risk of water infiltrations, as the sensor is placed inside the watertight casing of the batteries without any physical connection with the outer environment.

The rotation speed adjustment may be obtained by acting on a potentiometer (7) which, by adjusting the output voltage, allows for obtaining a reference against which the duty cycle and the power to be supplied may be set.

In order to ensure the proper functioning of the instrument - and, therefore, the operator's safety - a special safety system was designed. Water (8) and temperature (9) sensors are present both at the motor and the battery. The former are capable of detecting any infiltration, while the latter monitor the thermal conditions of the device during its operation. When water or extreme temperatures are detected, the electronic battery management board (3) acts on a relay (5) that decouples the power supply until the situation is normalised. The board also provides a data logging function that allows for evaluating the nature of the problem, if any. The connection between the two electronic boards is provided through three cables: two of these are dedicated to power, while the third establishes a one-wire communication connecting the two boards: in this way the board (3) can activate the relay and also record data from those sensors connected to the board (2) and placed near the motor.

Along the connection between the two boards, there is an underwater-rated connector that, in addition to the instrument, allows for connecting the battery pack to an external charger. In this way lithium cells may be charged without being removed from their housing.

Max. impact energy	1 J
Impact rate at maximum speed	0 – 2070 bpm
Rated speed	0 – 8000 rpm
Battery voltage	7.4 V
Battery capacity	10 Ah
Battery runtime at maximum power	90 min
Weight in air (hammer body)	2 Kg
Weight in water (hammer body)	0.5 kg
Weight in air (battery pack)	2.3 Kg
Weight in water (battery pack)	0.1 kg
Dimensions (hammer body)	175 x 215 x 62 mm
Dimensions (battery pack)	232 x 135 x 130 mm
Cable length	2.5 m
Bit holder	SDS-plus

Tab. 1: Underwater chisel technical data

4. RESULTS

Firstly, a first prototype of the instrument has been manufactured in order to assess its footprint and detect any interference or assembly issue. In particular, despite the computer simulation pointed out the absence of interferences among components during the assembly procedure, we built the physical models of the involved components through 3D printing, using a Makerbot Replicator 2X printer, based on FDM technology.

Therefore, it was possible to carry out all the tests described above in a short time, exploiting the full potential of rapid prototyping. During this stage, the assembly procedure for the parts has been verified and optimized, both on the battery pack and the main body.

The next stage was the creation of the functional prototype of the electric chisel. The structural sizing was done in order to allow for the optimal operation of the tool up to 50 meters deep.

The structural components of the main body have been realized by means of 4-axis CNC milling platform, from a block of acetal resin POM-C (Delrin), a material that fully meets the requirements of structural strength. This material is also known for not being hygroscopic, so it is perfectly suitable for use in underwater environment (Fig. 3a).

The construction of all the internal support parts for the drive train and the pneumatic cylinder, given the complexity of the shape, would have required a great effort in terms of time and costs, if conducted with conventional metal removal processes. Therefore, we opted for a Nylon powder sintering process, to be done with the 3D printer EOS Formiga P110 [12]. The analyses and tests have shown that the sintered components achieved excellent performances in the task for which they were designed. As an example, Fig. 3b shows some of the sintered components: an air sleeve and a spacer, along with the activation knob with integrated spring.

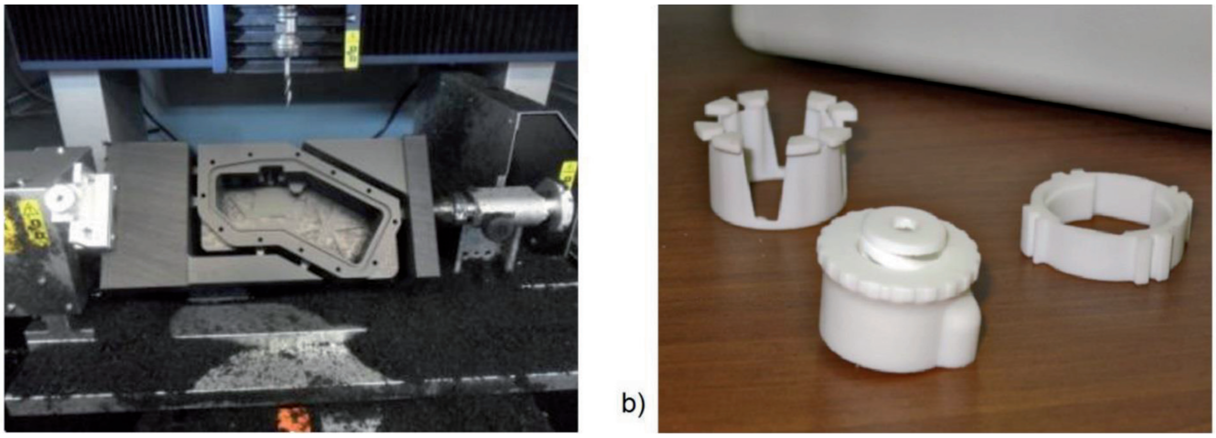
The battery pack was entirely manufactured by laser sintering of Nylon powders. This processing technique has allowed us to optimize the arrangement of the electronics, minimizing the number of parts to be constructed. Since Nylon is a hygroscopic material and the parts produced by laser sintering are characterized by porosity [13], the case has been treated with a two-component polyurethane paint, in order to saturate every pore present on the surface of the sintered component. This treatment ensures the water tightness up to a pressure of 5 bar during a prolonged immersion.

Figure 4a shows the tool complete with battery pack and stainless steel spatulas, while figure 4b shows an exploded view of the main body of the instrument.

4.1. TESTING

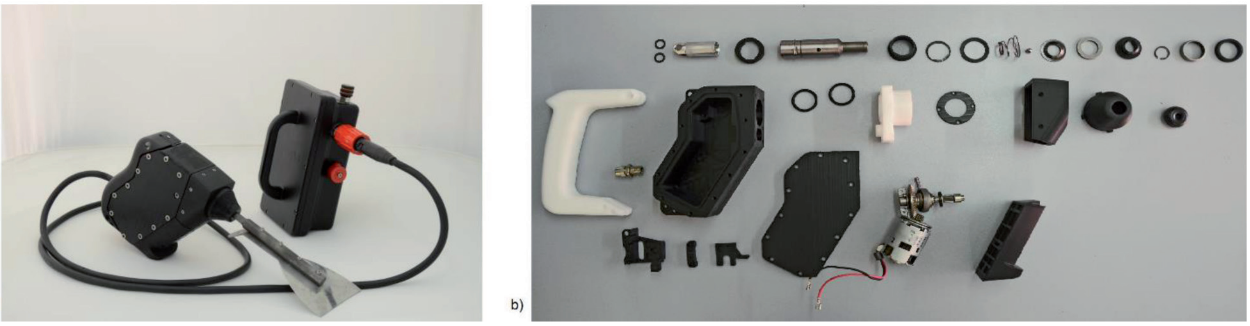
Firstly, the device was tested inside a hydrostatic chamber at a pressure of 5 bar to check its structural strength, then subjected to a series of laboratory tests in order to assess the various safety systems. In particular, the tests have confirmed that the choice of supplying the motor at 7.4V allows for maintaining the temperature below 50 °C after one hour of continuous operation, so that there is no need to use a heat sink or different materials, such as aluminium, for the case.

The field tests of the device were conducted at the submerged archaeological park of Baia (Naples, Italy). The experimental tests have shown the good performances of the device in terms of power and control, demonstrating its capability of removing even the toughest fouling without the use of conventional hand tools. The chisel is equipped with stainless steel spatulas of different sizes, so that different build-ups and surfaces



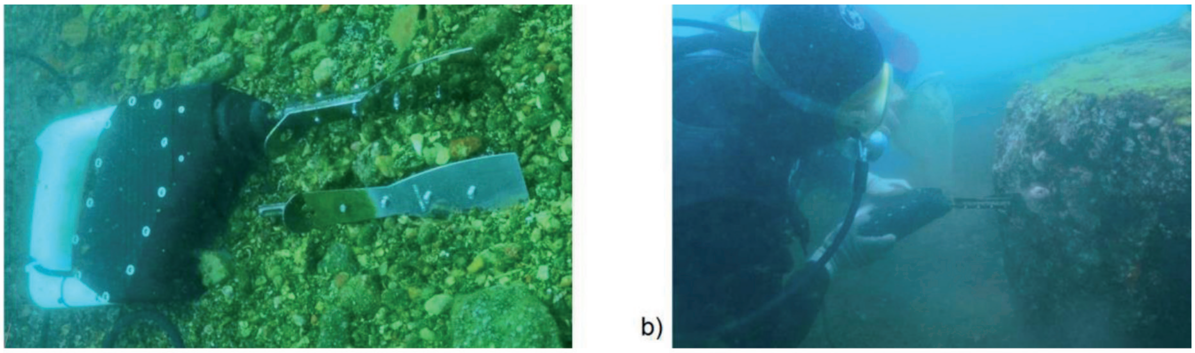
a) b)

Fig. 3: Result of main case milling (Delrin)and components produced by laser sintering



a) b)

Fig. 4: Electric chisel with battery pack and internal components



a) b)

Fig. 5: Hammer assembly, tested in underwater environment

can be treated (Figure 5a). The arrangement of the front handles, and the possibility of mounting different handles on the back, allowed the underwater restorers to use the device on different surfaces, since it is possible to grasp it in different positions (Figure 5b).

At the end of the testing phase, we didn't detect any leak or abnormal wear of the various parts.

5. CONCLUSION

In this paper, we have described the design and construction of an underwater power tool that may be used by underwater archaeologists for removing even the toughest fouling agents. During the design stage, we have used the most advanced CAD tools, while the prototype was built with traditional manufacturing and rapid prototyping techniques. These techniques allowed us to build the most complex components in a shorter time. The instrument was first tested in laboratory and then at the submerged archaeological site of Baia (Naples), where professional restorers have conducted a number of cleaning tests on underwater structures, each characterized by different natures and states of degradation.

The instrument has allowed for increasing the speed of execution of those cleaning operations that are currently carried out by hand, while ensuring at the same time the precision and accuracy needed when working on submerged archaeological finds. The tests conducted in situ have shown that the electronic management of the device, together with the high capacity of the battery, allow for a continuous operation for about 2 hours. Another positive outcome is that the tools (chisels and spatulas) require little time to be replaced in water, without the need to use hand tools.

With regard to future developments, we are investigating the possibility to integrate electronics and battery pack on the main body, in order to eliminate the cable and the related connectors. In this way we might improve the ergonomics of the device and reduce its overall cost.

ACKNOWLEDGMENT

This work has been partially supported by the Project "COMAS" (ref. PON01_02140), financed by the MIUR under the PON "R&C" 2007/2013 (D.D. Prot. n. 01/Ric. 18.1.2010).

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