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Underwater Power Tools for In Situ Preservation, Cleaning and Consolidation of Submerged Archaeological Remains

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Abstract: In situ protection and conservation of the Underwater Cultural Heritage are now considered a primary choice by the scientific community to be preferred, when possible, over the practice of recovery. The conservation of the artefacts within their environmental context is essential in fact for a correct interpretation of archaeological presences and to preserve their true value intact for future generations. However, this is not an easy task because modern technological equipment is necessary to make the work carried out by underwater restorers and archaeologists faster and more efficient. To this end, the paper presents three innovative underwater power tools for the cleaning, conservation, and consolidation activities to be performed in submerged archaeological sites. The first one is an underwater cleaning brush tool for a soft cleaning of the underwater archaeological structures and artefacts; the second one is a multifunctional underwater hammer drill suitable to be used as a corer sampler, chisel, or drill; the last one is an injection tool specifically designed to dispense mortar underwater for consolidation techniques of submerged structures.

Keywords: in situ preservation; product design; underwater archeology; underwater cultural heritage; underwater power tools

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1. Introduction

The study of the degradation phenomena affecting underwater archaeological sites has become a topic of growing interest especially in recent years thanks to an articulated implementation of the UNESCO conventions, i.e., 1970 (prevention of illicit traffic), 1972 (World Cultural and National Heritage), and 2001 (Underwater Cultural Heritage), aimed to protect the underwater heritage. In particular, the 2001 UNESCO Convention on the Protection of the Underwater Cultural Heritage [1–3] established that in situ preservation should always be considered as a first option when dealing with underwater archaeological remains (Rule 1). In situ preservation is not a simple process, but it ensures the conservation of the pieces [4], and as long as they are protected underwater, they hold valuable historical, archaeological, and natural data [5–7]. On the contrary, their extraction supposes a chemical alteration because the conditions of their surroundings vary from the marine environment to a terrestrial environment [8]. The definition of such principles and recommendations for the protection and in situ conservation of the submerged archaeological sites has led to the rise of a plethora of innovative techniques and technologies that cover a wide range of applications [9–15] for this burgeoning sector. The cleaning, consolidation, and restoration activities must in fact be entirely carried out underwater through the adoption of techniques and materials chosen in the relation to the specific conditions of the submerged environment.

In this context, in order to carry out the cleaning and conservative restoration operations to artefacts visible and preserve them, one of the main issues is represented by their biodeterioration due to the proliferation of biological colonization of pest microorganisms (biofouling) [16–19]. In order to overcome this issue and preserve the state of conservation of the submerged structures, underwater restorers and diving archaeologists [20], by combining the restorers' skills to those of professional divers, operate in the submerged environment to carry out cleaning, maintenance, and consolidation operations in the underwater archaeological areas that need to be restored. For all these operations, underwater archaeologists use "terrestrial" tools, such as ice axes, scrapers, chisels, scalpels, sponges, and sweeps, adapted to the submerged environment. As a consequence, there is a need for modern technological equipment to make the work carried out by underwater restorers and archaeologists faster and more efficient. Nevertheless, despite this need, at the moment, devices specifically designed to support the work of underwater restorers are not available on the market.

To this end, the paper presents three innovative underwater power tools for the cleaning, conservation, and consolidation activities to be performed by the underwater restorers in the submerged environments. In particular, the first one is an underwater cleaning brush tool for soft cleaning operations on underwater archaeological structures; the second one is a multifunctional underwater hammer drill suitable to be used as a corer sampler, chisel, or drill; the last one is an underwater injection tool specifically designed to dispense antimicrobial mortars that allow to prevent biological growth.

These innovative underwater power tools have been developed in the context of the MaTaCoS (Advanced materials and technologies applied to the conservation of the underwater cultural heritage) research project [21] funded by the Italian Ministry of Economic Development (MISE). This project aimed to develop innovative tools and methods for the protection of Underwater Cultural Heritage, with particular regard to in situ cleaning, consolidating, and monitoring procedures. The developed tools have been tested by end-users, i.e., underwater restorers and professional divers, during the conservation activities carried out in the underwater archaeological site of Peschiere di Sant'Irene (Briatico, Italy).

2. Materials and Methods

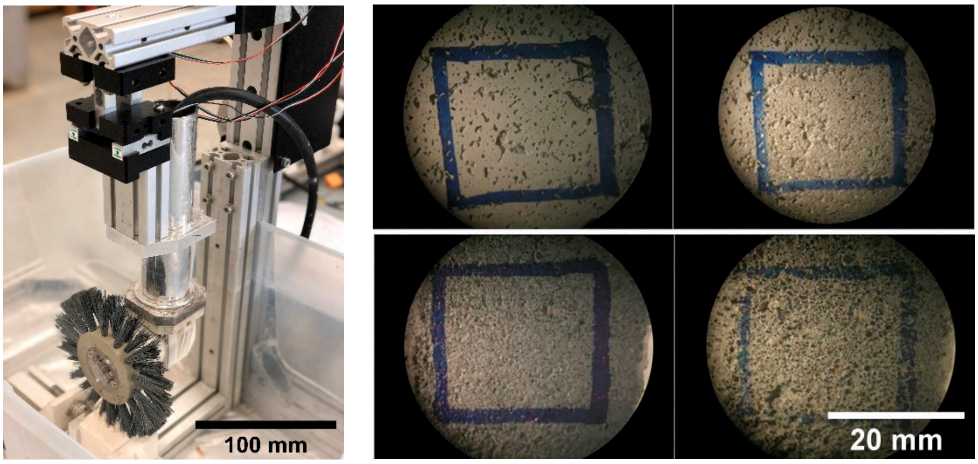
As mentioned above, one of the major stages of the post-excavation conservation-restoration procedure [22,23] consists of the cleaning of biodeteriogens and encrustation from underwater structures through the adoption of traditionally used handheld instruments, such as brushes, spatulas, chisels, and scalpels. In the last years, some instruments have been developed to speed up the operations that underwater restorers have to perform in order to remove calcareous and carbon-based residues from submerged artefacts. In particular, a first study took place in Italy in 2001 with the "Restoring Underwater" project, launched by ISRC (Superior Institute for Conservation and Restoration, now ICR), aimed at the study and experimentation of instruments, materials, methodologies, and techniques for the restoration, conservation, and in situ display of ancient submerged artefacts [15]. The study started with the restoration of the *vivaria* of the Roman villa of Torre Astura (Nettuno, Italy) and subsequently, in 2003, it continued in the Baiae Underwater Park (Naples, Italy), where, over the years, the restoration of sectors of certain buildings in the protected marine area has been carried out. In particular, a pneumatic micro-grinder tool, based on the modification of a surgical orthopaedic stainless-steel drill actuated by compressed air [15,24], and a pneumatic tank to inject mortar underwater through a pipe [15,24] were prototyped and tested. Nevertheless, the use of pneumatic instruments is not the best solution since they require pipes, pressure tanks, and sometimes a support boat equipped with an air compressor with relative generators, which demands more time and a greater effort by the operators for the handling of the equipment. Furthermore, in the submerged environment, pneumatic tools could jeopardize operators' safety because their exhaust bubbles usually obscure the divers' visibility and often cause compression waves that result in diver nausea [25].

In order to overcome these limitations and give underwater restorers greater freedom of movement and better visibility, electric underwater prototypes for cleaning operations were developed in the context of the CoMAS project [11–14] ("In situ conservation planning of Underwater Archaeological Artefacts"). In particular, prototypes of an electric cleaning tool were designed and tested to make the work carried out easier and faster of the cleaning operations conducted on structures and artefacts that are lying on the seabed of archaeological underwater sites. Although field tests received positive feedbacks from underwater restorers and archaeologists who used the proposed tools, some issues were raised mainly regarding devices' ergonomics, in-air and in-water weight and battery replacement. Furthermore, the manufacturing process of tools' waterproof aluminium cases required a long production time followed by a complex assembly stage of electronic components and wires.

Taking into account these limitations and end-users' needs and expectations, this paper proposes three novel underwater power tools that, compared to those currently proposed as the state-of-the-art, are end-products, not prototypes. Their development processes, in fact, were characterized by a design for manufacture and assembly [26–28] approach that allowed to achieve an easier assembly stage, a faster production process, better performances in terms of power and autonomy, and a higher level of technology with a patented in-water battery replacement system [29]. In particular, the proposed innovative power tools are:

- Underwater cleaning brush tool that features a 650 Kv brushless motor and an ergonomic lightweight design that makes more efficient and faster the cleaning operations carried out underwater by restorers to perform a soft cleaning of the submerged archaeological structures and artefacts.
- Underwater multifunctional hammer drill that features a standard SDS (Slotted Drive System) chuck that allows the use of stainless-steel drill bits, core bits and chisels for the removal of dense encrustations.
- Underwater injection tool that features an aluminium mortar cartridge and an 18 V brushed motor to extrude mortar through nozzles of different shapes and sizes. This feature, along with the ergonomic handle, significantly reduces the restorers' arm and wrist efforts needed to perform consolidation activities.

The product development process of the proposed tools started with an analysis and simulation stage aimed to better understand the context of use and define functional, technical, and performance requirements. To this end, an appropriate test rig (Figure 1a) was built to simulate, through laboratory experiments, the different conditions of use carried out by end-users in the submerged environment. As depicted in Figure 1a, the experimental test rig essentially consists of a plastic water tank and an aluminium support plate structure equipped with a cleaning brush tool. In particular, the support plate can be adjusted in height to fit different specimen dimensions. This rig has four bending-beam load cells that allow to measure the forces (pushing force applied on the workpiece and tangential forces) acting on the device during operations, current consumption, RPM (revolutions per minute) and operating temperature of the motor. Furthermore, to evaluate the effects of cleaning on different types of material, various specimens (mortar, gelcoat, steel) have been prepared. Each of them has been subjected to a cleaning cycle with variable operating parameters with different brushes. The effects of the bristles' action have been evaluated by visual inspection through an optical stereo microscope (Figure 1b), and for each test, the motor's operating parameters have been acquired.



(a) (b)

Figure 1. Test rig designed to simulate the cleaning process (**a**). Specimens before, on the left, and after, on the right, the cleaning operations (**b**) (University of Calabria 2020).

The large amount of acquired data allowed to identify the correct type of brush and the most suitable engine (in terms of performance and current absorption). The resulting analysis was fundamental for a complete determination of the technical requirements in order to optimize the design of the power tools and to size the electronics and battery pack. The results also provided useful indications on the correct rotational speed of the brushes and the best type of bristles for each application, in order to maximize the effectiveness of cleaning without damaging the artefact. As a result of rig tests, the diameter of certain brushes has been reduced from 120 mm (40 mm length bristles) to 80 mm (20 mm length bristles) to minimize bristles bending due to water drag. The results of two types of brushes are reported in Table 1. In particular, long bristles can be used at low speed for a soft cleaning action, while short bristles allow faster speeds and can be used when a more powerful cleaning action is required.

Table 1. Test rig results for 120 mm brush M1 (grit 320) with the original 120 mm diameter compared to brush M2 with the reduced 80 mm diameter at speed V1 (500 RPM), V2 (1000 RPM), V3 (1500 RPM) and with a brush pressure against sample surface given by vertical movement of the tool by a distance of 1/4 of bristle length (S3), 1/8 of bristle length (S2), 1/16 of bristle length (S1). Reduced brush diameter ensured lower power consumption and increased vertical force along with lower tangential force due to lower bristles bending. This behavior was even more evident for more flexible bristles.

		M1 Brush 120 mm			M2 Brush 80 mm		
Speed	**Brush Pressure**	**Current (A)**	**Vertical Force (g)**	**Tangential Force (g)**	**Current (A)**	**Vertical Force (g)**	**Tangential Force (g)**
V1	S1	1.24	91	35	1.20	150	41
	S2	1.29	209	211	1.25	352	86
	S3	1.33	158	196	1.27	536	102
V2	S1	2.6	117	276	2.55	256	78
	S2	2.93	276	357	2.70	456	125
	S3	3.03	276	422	2.83	625	254
V3	S1	5.86	221	291	5.45	280	95
	S2	6.26	181	176	5.86	369	156
	S3	6.35	165	743	6.03	568	335

The same test rig has been used to test the percussion cleaning system. Various marble and tuff specimens were subjected to cleaning cycles varying the material of spatulas and chisels (AISI 316L, AISI 420, PH-4 steel) and the impact energy. During the tests, the effectiveness of the cleaning and its effects on the substrate has been evaluated and the operating parameters of the motor have been recorded. Table 2 shows the results related to the current consumption during chiselling at the three motor speed levels and relevant bit impact rates (in Blows Per Minute, BPM). This study made it possible to identify the operating parameters suitable both for cleaning, coring, chiseling, and demolition operations.

Table 2. Test rig results for chiseling at no load (device with no tool attached) and at full load (chiseling on a concrete block).

Speed (RPM)	BPM	No Load Current (A)	Full Load Current (A)
8500	1800	3.5	3.8
13,800	2900	5.8	7.8
22,000	4650	8.2	12.6

Two brushless motors have been considered to fit out the underwater tools. Although similar in dimensions, the two motors have different constant velocities (Kv). It is measured by the number of revolutions per minute (RPM) that a motor turns when 1 V (one volt) is applied with no load attached to that motor. In order to correlate the motor operating parameters with the forces (primarily the torque), an appropriate dynamometer test bench has been set up through which different brushless motors, depicted in Table 3, have been characterized.

Table 3. Motor tested on the dynamometer.

	Motor A	Motor B
RPM/V	1050 Kv	620 Kv
Poles	1.5Y	4
Voltage (max)	22.2 V (6S)	18.5 V (5S)
Current (max)	160 A	110 A
Power (max)	3100 W	1750 W
Current (no load)	1.4 A	1.87 A
Diameter	39 mm	39 mm
Length	84 mm	78 mm
Shaft	5 mm	5 mm
Weight	490 g	365 g

These tests made it possible to extract the characteristic curves (Figure 2) of each engine (torque–RPM and torque–current curves) for different operating speeds. Based on these curves and the data recorded on the cleaning test rig, it has been possible therefore to select the most suitable motor for the specific power tool. As shown in Figure 2, the 620 Kv motor ensures enough torque at low speed, as required in cleaning operations by means of radial brushes while 1050 Kv motor lets drill bits reach the max speed of 1400 RPM (i.e., 23,500 RPM on motor).

Figure 2. 1050 Kv motor (blue zone) and 620 Kv motor (red zone) working range compared to cleaning brush and drill speeds.

3. Results

The restorers' needs analysis along with test rig result evaluation and components design optimization resulted in the development of three underwater power tools suitable for the cleaning, conservation, and consolidation activities.

3.1. Underwater Cleaning Brush Tool

As abovementioned, the underwater cleaning brush tool (Figure 3) has been developed to makes the operations carried out by underwater restorers faster and more efficient. The tool is very efficient in performing a rough cleaning of the submerged archaeological structures by removing the loose deposits and the various marine organisms that reside on their surface.

Figure 3. The underwater electric cleaning brush tool with integrated battery (Tech4Sea srl 2020).

The cleaning tool is characterized by a modular design, which consists of the following main elements: a transmission module consisting of two aluminium components containing chuck bearings, a mechanical seal, and a transmission bevel gear; a power module with a cylindrically shaped aluminium case containing brushless motor and electronic control components of which the rear end is attached to the quick-release battery pack. The modular design allows for the configuration of the tool according to the restorer's needs. In fact, it can be used as an angular cleaning brush, or as an angular grinder, sharing the same design and electronics, which differ only by the installed motor.

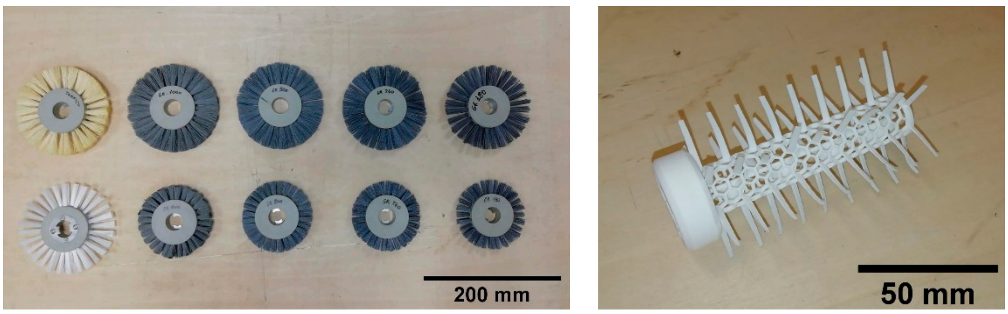
As detailed in Table 4, the cleaning tool has been equipped with a 620 Kv brushless motor that allows a no-load speed between 1000 and 1500 RPM. Speeds can be selected by means of a 3D printed magnetic switch placed in an easily accessible position on the tool side. Another switch allows to turn on and off the device. These no-contact magnetic switch buttons increase the safety of the tool because there are no moving parts that need a seal [30].

Table 4. Technical data of the underwater cleaning brush tool.

Cleaning Brush Tool	
Dimensions, body (l × w × h) *	286 × 78 × 135 mm
Dimensions with integrated battery (l × w × h) *	398 × 99 × 140 mm
Quick release brush attachment:	
Standard tool attachment	M14 × 2
Tool speed:	
Speed 1	1000 RPM
Speed 2	1500 RPM
Maximum power	400 W
Battery	Li-Ion 5 Ah
Voltage	18 V
Tool Weight **:	
in air	2.60 kg
in water	1.40 kg
External battery pack weight:	
in air	1.90 kg
in water	0.85 kg

* without handle; ** without battery.

During the design and development phase, the needs and suggestions of the end-users were taken into consideration in order to improve its usability in the underwater environment. The underwater cleaning tool, in fact, features a quick-release brush attachment system that allows to change the brush in a few seconds, with one hand, without the need of a separate key tool. In particular, it consists of a modular design that fits various commercial radial brushes (Figure 4a), made of nylon and abrasive nylon, and of the natural Tampico fiber, and 3D printed axial brushes (Figure 4b) that have been specifically designed to facilitate restorers' activities while cleaning narrow cavities.



(**a**) (**b**)

Figure 4. The full set of radial brushes (**a**) and the 3D printed axial brush designed to clean narrow cavities (**b**) (Tech4Sea srl 2020).

The cleaning tool is powered by an 18 V, 5 Ah Lithium-ion battery pack. Two different battery packs have been developed: the first one is cable-connected to the device, the second one is integrated directly on the tool's main body through a quick-release connector. In particular, a cable-connected battery case allows a lighter, handier, and more compact device, with a battery pack that can be attached to the operator's belt. The integrated battery pack, on the other hand, fits the restorers' need for a simple one-hand battery replacement: by sliding the 3D-printed stainless-steel sleeve, the operator can change the battery pack in a few seconds. Underwater restorers can hold the tool with one hand, nevertheless a second knurled aluminium handle can be placed on the device's side (Figure 3) to ensure more precise control. A removable stainless-steel cover protects the operator's hand during cutting operations.

Furthermore, the stainless-steel, 3D-printed quick-release chuck can be used to install, along with an add-on bracket, a frontal cup brush suction device (Figure 5). The suction mechanism, activated by a centrifugal pump, keeps the contact between brush and surface by allowing the user to clean a larger area than that covered by using radial brushes. Furthermore, this device improves the operator's visibility by vacuum away dust and particles through a flexible hose. In particular, the pump impeller has been developed according to a one-dimensional design method [31] for a radial flow pump. This method allows to design the blades' profile and the volute cross-sections by considering the following: spindle speed; water flow (i.e., 60 m^3/h); prevalence (i.e., 10 m); the motor's power and torque; blade material yield strength; and the velocity triangles at impeller inlet and outlet.

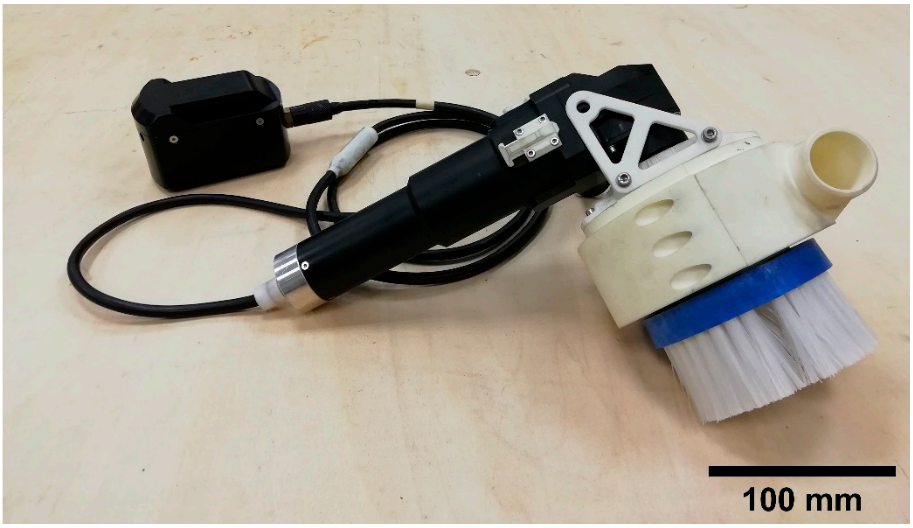
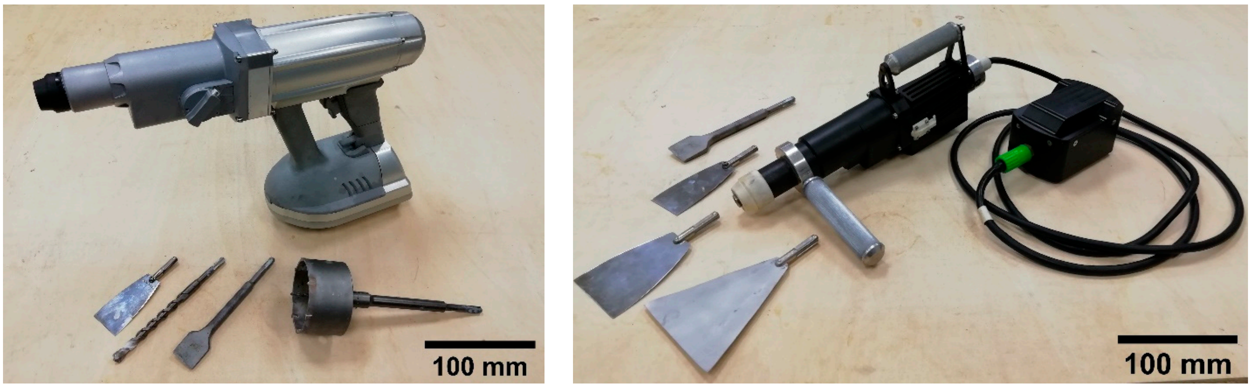


Figure 5. The cleaning tool with the suction brush accessory (Tech4Sea srl 2020).

The device body is made of an anodized 6 series aluminium alloy, manufactured by means of three- and five-axis Computer Numerical Control (CNC) milling machines. The same technology has been used for battery packs and handle manufacturing. Moreover, a hybrid manufacturing process has been carried out in which 3D printed parts, made through Direct Metal Laser Sintering (DMLS), have been post-processed with CNC machining to achieve higher accuracy and smoother surface finish. The use of metal 3D printing allows to make a stronger component composed of a smaller number of complex parts, at a fraction of the conventional cost. The device's dimensions and performance are shown in Table 4.

3.2. Underwater Multifunctional Hammer Drill

If the cleaning brush tool is an efficient solution for a quick rough removal of the loose deposit and the various marine organisms that reside on the surface of the submerged archaeological structure, the use of hammers and chisels is much more effective in the removal of the dense and strong encrustations. To this end, an innovative multifunctional underwater hammer drill (Figure 6a) has been developed for drilling holes and collecting samples by coring. Furthermore, it can be used as a chisel to support restorers in the removal of the strongly encrusted organisms present on underwater structures. In particular, the user can switch through the three different operating modes, i.e., hammer-drill, drill-only, and chisel-only, by means of a selector knob placed on the left side of the device. This feature, along with the SDS-plus chuck, makes the device suitable for different applications to be carried out in the underwater archaeological sites such as the removal of the strongly encrusted organisms present on the surface of underwater structures and artefacts; core sampling into stone, masonry, concrete, and inconsistent seabed (with percussion only to preserve stratigraphy); and underwater drilling. These different modes share the same hammer mechanism, which consists of a piston moved by a wobble bearing whose rotation produces reciprocating motion of the piston itself, compressing the air inside the working chamber in the spindle cylinder [32]. Thus, generated air pressure propels a steel striker towards the anvil in the front end of the cylinder, resulting in a stress wave through the device bit. The hammer mechanism is driven by a 3100 W brushless motor that allows an impact rate of 0–4650 BPM with an impact energy of 3.2 joule and a spindle speed of 0–1400 RPM. In addition, the motor torque allows to core standard 100 mm diameter concrete samples. The tool is powered by an 18 V, 5 Ah Li-Ion battery pack that, by means of an underwater pluggable electrical connector and a patented battery switching mechanism [29], can be replaced underwater.



(a) (b)

Figure 6. Underwater hammer drill (**a**) and underwater compact impact cleaning tool (**b**) (Tech4Sea srl 2020).

To meet restorers' needs, a more compact underwater hammer drill tool has been designed (Figure 6b), too. This tool integrates a simplified percussion system without rotation, that allows for cleaning with chisels and spatulas and to take core samples on incoherent seabeds, sharing the same battery pack with the brush cleaning tool. The device's body is made of anodized 6 series aluminium alloy, manufactured by means of three- and a five-axis CNC milling machines. The one-piece handle has been manufactured by 3D printing in order to reduce the number of parts. The components related to the spindle assembly with quick-release SDS chuck have been manufactured by means of a hybrid manufacturing process in which the 3D-printed SDS attachment, made through DMLS process, have been manufactured on a semi-finished cylindrical part made with a CNC machine. All the parts have been then post-processed with CNC machining to achieve higher accuracy and smoother surface finish. Table 5 contains the hammer drill's technical data while Table 6 contains those for the impact cleaning tool.

Table 5. Technical data of the compact chisel underwater cleaning tool.

Underwater Compact Chisel	
Dimensions (l × w × h) *	373 × 82 × 150 mm
Tool attachment	SDS-plus
Impact energy (max)	2.5 J
Impact rate	0–4800 BPM
Power	1000 W
Battery	Li-Ion 5 Ah
Voltage	18 V
Tool Weight **:	
in air	3.80 kg
in water	2.20 kg
External battery pack weight:	
in air	1.90 kg
in water	0.85 kg

* without handle; ** without battery.

Table 6. Technical data of the rotary hammer underwater tool.

Underwater Rotary Hammer	
Dimensions (l × w × h) *	536 × 154 × 367 mm
Tool attachment	SDS-plus
Impact energy	3.2 J
Tool speed	0–1400 RPM
Impact rate	0–4800 BPM
Drilling capacity:	
wood	30 mm
steel	13 mm
concrete	26 mm
concrete (with coring tools)	68 mm
Power	1200 W
Battery	Li-Ion 5 Ah
Voltage	18 V
Weight:	
in air	9.40 kg
in water	3.57 kg

* with battery pack.

3.3. Underwater Mortar Injection Tool

The developed mortar injection power tool (Figure 7) aims to facilitate the structural repair of underwater artefacts that reduce their resistance after the removal of encrustations. The demand for a handy, lightweight device has been met by developing a compact, cordless hand-held tool. As depicted in Figure 7, the underwater tool consists mainly of an anodized aluminium waterproof body containing the electric motor along with a gearbox reducer, battery, and electronic components. The mortar is stored in a 0.5 L cylindrical anodized aluminium cartridge screwed to the threaded connector placed on the device's front end. The injected material is compressed in the cylinder by means of a piston head moved by a stainless-steel rack. The rack's pinion is driven by a DC brushed motor that, by means of a 215:1 reduction ratio planetary gearbox, provides 225 kg pushing force to easily extrude even dense compound. Rack speed can be continuously adjusted from 0–6 mm/s through a knurled knob housed on the left side of the device. Whereas extrusion is performed through a magnetic switch trigger system [30] placed on the handle whose shape and dimensions have been defined under the guidelines for hand tool ergonomics [33]. The handle, in fact, ensures a high grip and a proper hand grip–forearm angle so that the user's wrist remains in its neutral position by preventing work-related disorders.

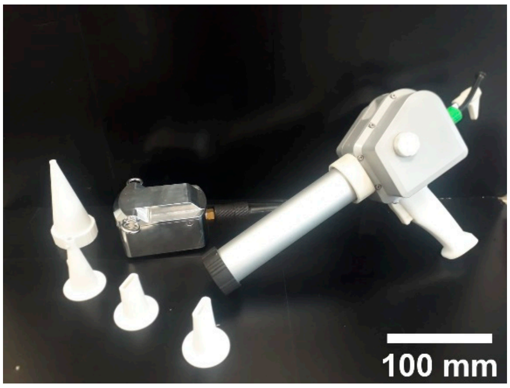


Figure 7. Underwater mortar injection tool (Tech4Sea srl 2020).

Different sized nozzles (Figure 7) have been designed and prototyped through additive manufacturing technology to meet restorers' needs. In particular, these nozzles differ in exit cross-section size and shape, while converging angle has been kept around 12° to facilitate mortar flow sliding. The waterproof aluminium case contains an 18 V, 2 Ah Lithium-ion battery pack. Thanks to an underwater pluggable electrical connector, it can be recharged underwater. When a mortar cartridge is finished, it can be replaced by a release mechanism that allows users to manually withdraw the piston head pulling back the rack end through a plastic handle. Rack withdrawal is possible thanks to a spring button placed on the right side of the aluminium case that places the last planetary reduction stage ring gear at idle, leaving the rack's pinion free to rotate in the opposite direction.

The tool's main body has been manufactured in aluminium by a five-axis CNC machine. The same technology has been adopted to manufacture the nylon ergonomic handle. Furthermore, small complex-shaped parts, such as rack sliding guides, electronic components' support frame, switch trigger, and nozzles, have been fabricated through additive manufacturing technologies. The tool's technical data can be found in Table 7.

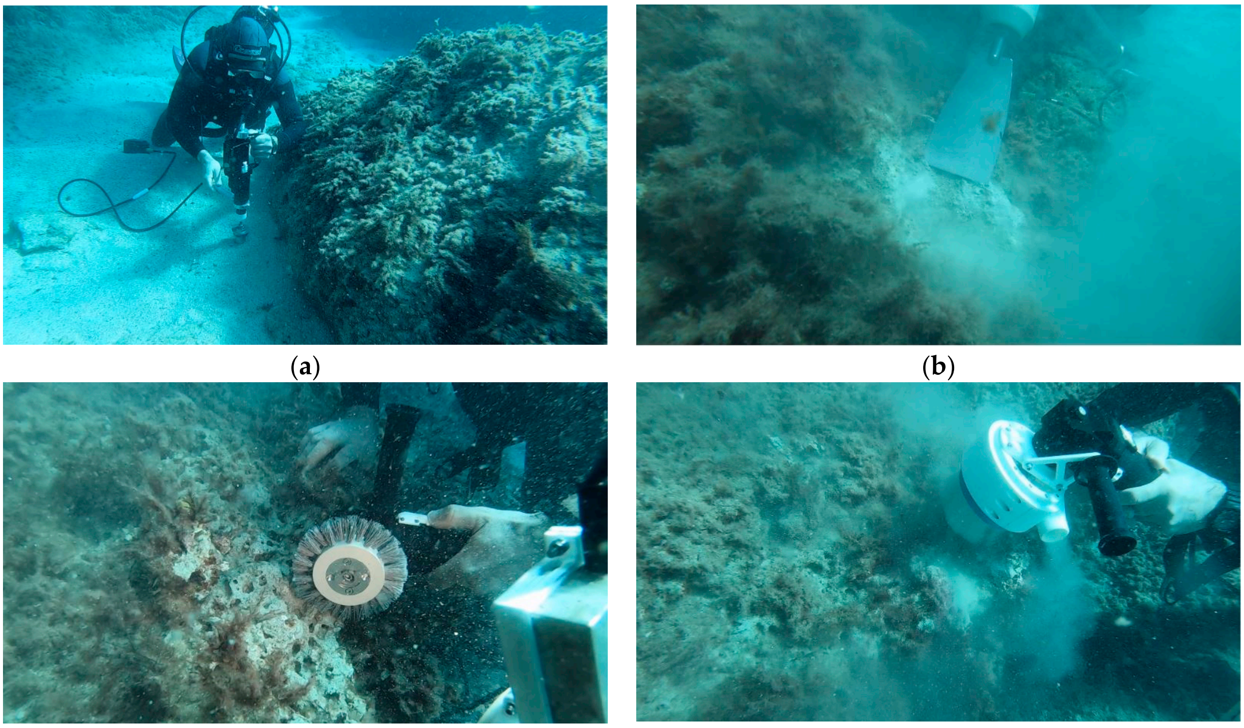
Table 7. Technical data of the underwater mortar injection tool.

Mortar Injection Tool	
Dimensions (l × w × h)	420 × 148 × 261 mm
Maximum pulling force	225 kg
Piston speed (with no load)	1–6 mm/s
Extrusion speed:	
Circular nozzle 4 mm	50–330 mm/s
Circular nozzle 8 mm	12.5–83 mm/s
Circular nozzle 12 mm	5–33 mm/s
Cartridge capacity	0.52 L
Battery (integrated)	Li-Ion 2 Ah
Voltage	18 V
Weight in air	3.65 kg
Weight in water	1.55 kg

3.4. Field Tests

Before performing field tests, each device has been tested within a hydrostatic chamber, at a pressure of 10 bar for 30 min, with the power turned off and on in order to assess structural strength, waterproof and safety capabilities, working temperature, and battery life.

The in situ testing campaign has been carried out in the underwater archaeological site of Peschiere di Sant'Irene (Briatico, Italy) on a large limestone rock worked by the ancient Romans to dig tanks for fish farming. These tanks, connected by semi-submerged canals that were used for the re-circulation of water and the supply of nutrients to the fish, are still well preserved today and are an example of an underwater archaeological site. The tools have been used and tested by underwater restorers in different phases of the cleaning, restoration (Figure 8) and consolidation (Figure 9) activities carried in the underwater archaeological site. The end-users involved in the field tests expressed their satisfaction with the results achieved in terms of efficacy and usability. The developed underwater tools are in fact easy to use and allow restorers to operate underwater with better results in terms of speed of freedom of movement.



(**a**) (**b**) (**c**) (**d**)

Figure 8. Underwater devices' test: multifunctional hammer drill for coring operation (**a**) and impact chisel cleaning (**b**); cleaning tool with radial brush (**c**) and with suction brush add-on (**d**), (Tech4Sea srl 2020).

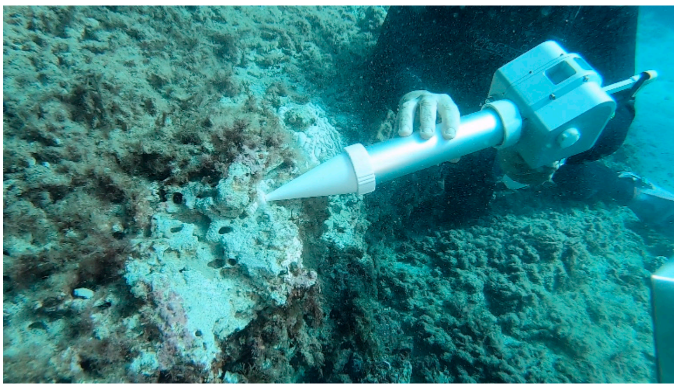


Figure 9. Test of the mortar injection tool (Tech4Sea srl 2020).

4. Conclusions

This paper presented the results of the MaTaCoS project achieved in the development of underwater power tools for in situ preservation, cleaning, and consolidation of underwater archaeological sites. In particular, three novel tools have been designed, prototyped, and tested to make the work carried out by underwater restorers easier and faster during the operations conducted on structures and artefacts that are lying on the seabed of submerged archaeological sites. The first one is an underwater cleaning brush tool that makes the work carried out by underwater restorers to remove biofouling from the surface of the submerged archaeological structures and artefacts faster and more efficient. The second one is a multifunctional underwater hammer drill suitable for drilling holes and collecting samples by coring. Furthermore, it can be used as a chisel to support restorers in the removal of the strongly encrusted organisms present on underwater structures. The last one is an underwater injection tool that allows a quick extrusion of mortar for consolidation techniques of submerged structures.

As further developments, the devices' power and ease of use can promote their future applications in the industrial field, e.g., for the maintenance of underwater structures, underwater demolition, and underwater drilling activities. The developed underwater tools, in fact, have been tested by professional divers during their fieldwork in order to collect their opinions and suggestions to orient the next improvements. In particular, the cleaning brush tool has been equipped with cutting disks in order to be used as a grinding tool on steel parts. The participants to this preliminary test expressed positive opinions about the proposed tools especially for their capability to be ready for immediate use, for example in case of emergency response, without the need of a support vessel. Furthermore, the lack of a power cable also offers greater freedom of movement to divers.

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