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Design and simulation of a wireline core drilling device for near-shore applications

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Abstract. The PROTEUS project involves the construction of a self-propelled and floating amphibious machine for near shore geological surveys. In this context, the development of a wireline core drilling device was tackled, evolving with respect to existing models and responding to the specificities of the new application. In the preliminary phase, comparative research was carried out both through market research and through reverse engineering activities on core drill models deemed suitable for the purpose, thus identifying the functional priorities and criticalities of the existing material through the ex-post analysis of the subject elements to wear and tear. Once the requirements of the new core drilling device were formalized, the constructive layout was defined, giving priority to functions such as sample management, interlocking and rapid disengagement from the drilling actuation system. The construction details of the mechanical coupling profiles were then optimized by simulation in a multibody software environment, in order to ensure full functionality even in harsh environments, typical of the application, making an advancement with respect to the previously identified reference solutions. Finally, the executive design of the component was carried out by introducing the corrections deriving from the simulation results and considering different solutions in relation to the material adopted and its production needs through machining processes.

1. Introduction

The current activity takes place in the context of the PROTEUS project, which is focused on the design and construction of an amphibious platform for near shore geological prospecting activities [1,2]. Such platform is aimed at facilitating and reducing the costs of drilling and exploration activities due to its characteristics, such as flexibility, compactness and ability to move on different surfaces. Such machines are expected to gain interest in the future due the increasing relevance of seaside installations, especially near shore ones, for applications frequently related to energy generation and use such as underwater data centers [3,4], wind farms whose growth is undoubted worldwide [5], wave energy extraction [6] and in general for site characterization [7].

In line with modern machine design criteria, modeling and simulation activities have been extensively performed to virtually prototype all machine subsystems and control logic [8], thus reducing development time, aiming to provide a near-finished prototype while reducing calibration and correction activities, which can occur in case of the first exemplary of a new machine; the semi-final design of the machine is shown in Figure 1.

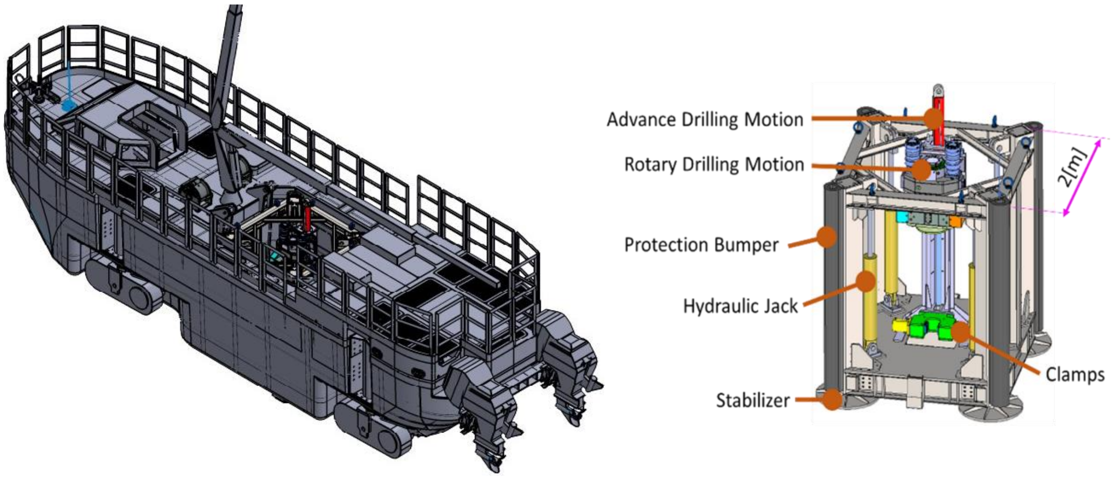

Figure 1. Overview or PROTEUS prototype: amphibious platform (left) and underwater drilling unit (right). The drilling unit is hosted at the centre of the platform and can be lowered to the seabed on occurrence. Note that the vehicle is equipped with both tracks for ground movements and outboard motors for marine propelling.

The characteristics of PROTEUS machine suggests that optimizing its ability to perform site characterization through the extraction of core samples requires the adoption of the so-called wireline technology; as known in literature [9] such technique presents a number of advantages in comparison with other surface-driven rotary drilling technologies, main one being the ability to reduce tripping pipe time.

In the Wireline drilling technique, pipes with an external diameter from 90 to 150 mm and thicknesses between 8 and 12 mm are used instead of drilling rods. Each pipe typically 1500 mm long has a conical thread at the ends (female at one end, male at the other as can be seen in Figure 2/a); in this way the pipes can be assembled in series in order to achieve arbitrarily large drilling depths such as visible in Figure 2/b . The tube acts as a drilling rod by dragging the excavation tools placed at one end into rotation, but also arms and supports the walls of the hole made. A fluid, pressurized water, is injected into the pipes, which performs the role of lubricant and coolant during excavation. The flow rate of pressurized water is typically at least three to four times higher than the volume of excavated material and ensures its removal in the form of sludge emerging from the hole on the surface. As can be seen in Figure 2/c and in Figure 2/d, tool change operations, sampling and more generally interventions on the bottom of the hole are carried out by lowering a bayonet quick coupling or other similar organ using a winch, which allows manipulation and transfer of tools and components along the tube.

Among the equipment that can be installed on the system, there are different types of tools and instruments such as the CPTWD (Cone Penetration Test While Drilling) equipment visible in Figure 3 or other equipment that allows to create cores of the soil. So, one of the requirements of the any wireline and-effector adopted is to enable the possibility to host different tools and to provide easy insertion and recovery of them.

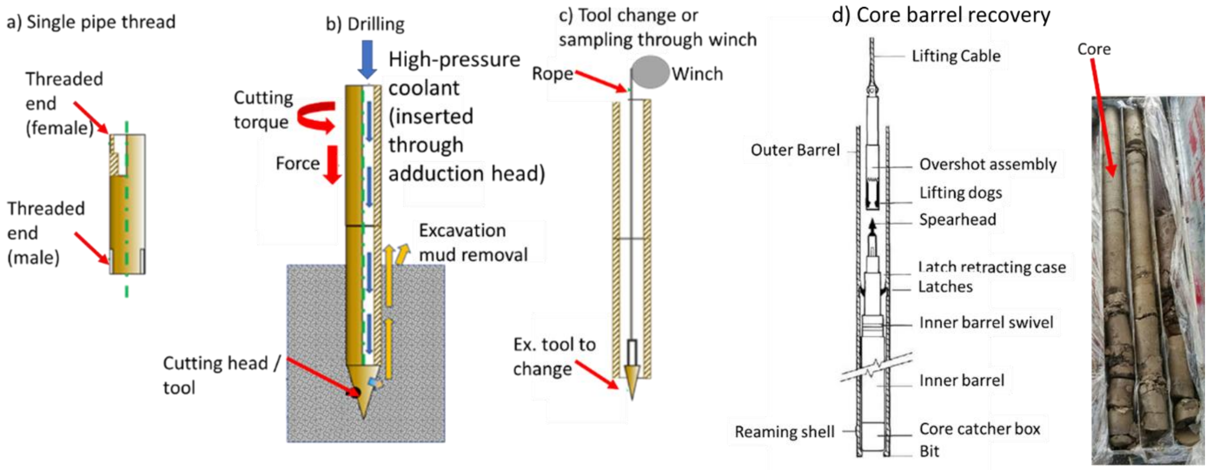

Figure 2. Single threaded tube (a), tubes assembled during drilling (b), tool change or sampling through wireline winch d) core barrel recovery [1].

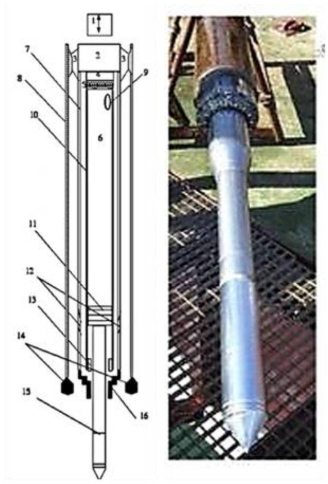

Figure 3. Cone Penetration Test While Drilling equipment to be installed on the PROTEUS platform.

Wireline core drilling is used to carry out excavations, mining research, polluting research, soil coring; this system allows to quickly lower a core barrel to the bottom of the hole and recover it without removing all the others driving rods. The recovery of the core barrel takes place through a catcher device, lowered by means of a steel cable connected to a winch, which is hooked in depth to the core barrel. This technique is usually suitable for any soil. Once that the device is outside of the drilled hole, it is possible to dismantle the tool, or extract the core and in general to perform needed operations. Such assembly takes the name of overshot connector; various designs are available, most of them being proprietary; certain of them also enable other type of operations while in the drilling hole depending on the setting of hydraulic mechanisms and valves installed on it.

There are two categories of core barrel heads as we can see in Figure 4 one is the one where the core barrel has a pointed shape (Figure 4/a) while the other is the one where the catcher has a pointed shape and the hollow core barrel as per Figure 4/b. The core barrel can be fixed or idle, it basically depends on the soil to be analyzed, if it is rocky or crumbly. Generally, as far as the thrusts are concerned, they do not exceed 5 tons and for the shots they do not exceed 12 tons. The rods remain in the hole until the tip needs to be replaced. This has great cost advantages when drilling deep holes for mining exploration.

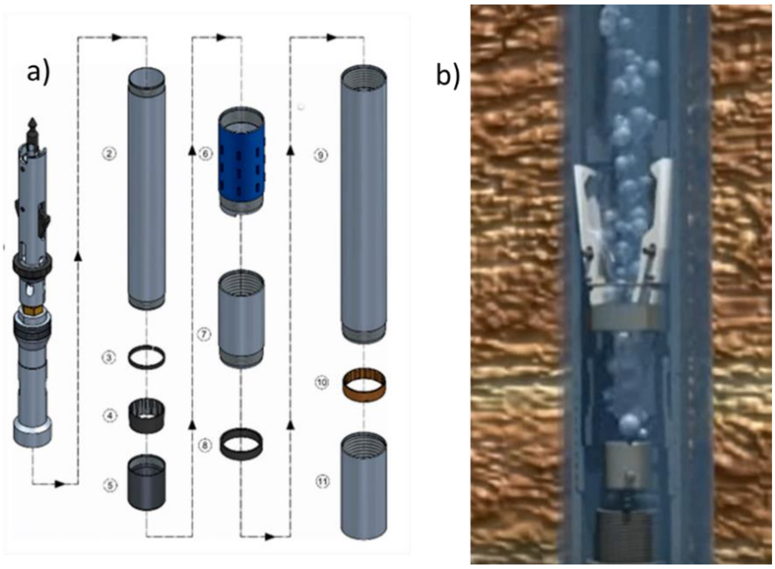

Figure 4. Overshot assembly – commercial units (Tecso [10] and Sandvik [11]).

2. Examination and re-engineering of an existing wireline tooling system

One of the main priority of the PROTEUS project was to search for technologies suitable for the purpose to create efficient and suitable cores. According to the know-how on the sector of the authors of the present text, it has been decided to use a previously tested and widely used (see Figure 5) core barrel to make Wireline cores. Such device dates back to the early 2000s and was produced in a reduced number of units by a local manufacturer, the original design being property of a small enterprise; 2D original drawings were also available. A first examination (see Figure 6) showed not only that is was partially degraded by wear and corrosion due to intense use, but also that certain parts were upgraded in comparison with existing 2D drawings, probably due to in-use modifications and improvements. Also, certain details (undercut profiles) suggested that the production activity had to include complex operations, such as manufacturing of multiple subparts, welding and additional machining. Due to the undoubted value of the device overall layout and design, it was decided to operate an operation of reverse engineering including measurements, CAD creation, resistance and holeshot connection verification, and proposal of alternative solutions.

Figure 5. Wireline assembly in use (courtesy Dott. Ing. Massimo Sacchetto [12]).

Figure 6. Dismantling of wireline drilling unit. Head assembly and drilling device (left) and catcher device (right).

Reverse engineering was carried out to reconstruct the core barrel and the various worn and damaged equipment. The reproduced core barrel can be seen in Figure 7, in this figure the two types of core barrel can be seen, the fixed one in Figure 7/a and the so called "idler one" in Figure 7/b used for different types of soil. The fixed one is directly coupled to the tube in which the core drilling is carried out; therefore, while the external tube turns, the internal core barrel also turns. In the idle core barrel, the head of the core drill is always set in rotation by the external tube, but the tube in which the core drilling is carried out is supported by a series of bearings; this enables to isolate the inner pipe – idler - from rotation, while the core is produced by simple axial force. Both solutions are needed for the PROTEUS machine, and the choice usually depends on the type of soil on which the drilling occurs.

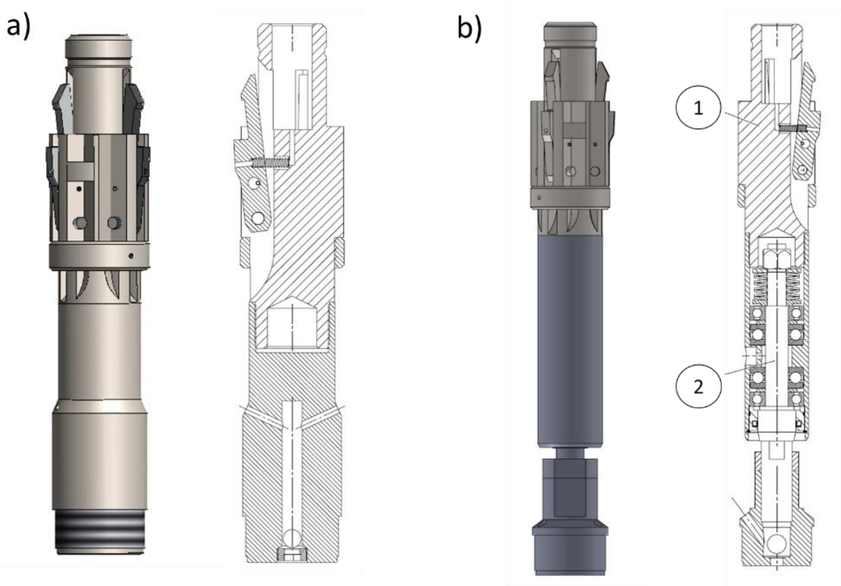

Figure 7. View of CAD reconstructed fixed (a) idler (b) devices.

Figure 7 shows a section of the idler core barrel, which is composed of two parts, the first is marked with the number 1 which is the head of the core barrel and the second marked with the number 2 which is the section to make the sampler idler. The head of the core barrel is machined in such a way as to house three teeth, which have two main functions:

- the first is to engage on the external tube in order to transmit the motion to the sampler thanks to the aid of some springs
- the second is to grab the fisherman during the re-leveling phase of the core.

When the teeth are in contact with the outer tube, they are slightly extracted thanks to the action of the springs, which act on each tooth; in this case they transmit torque, performing the same purpose as a key. Spring stiffness and preload is selected in order to achieve full opening with disengaged tools (see Figure 8), while opposing moderate resistance to compression during the connection phase (see Figure 11)

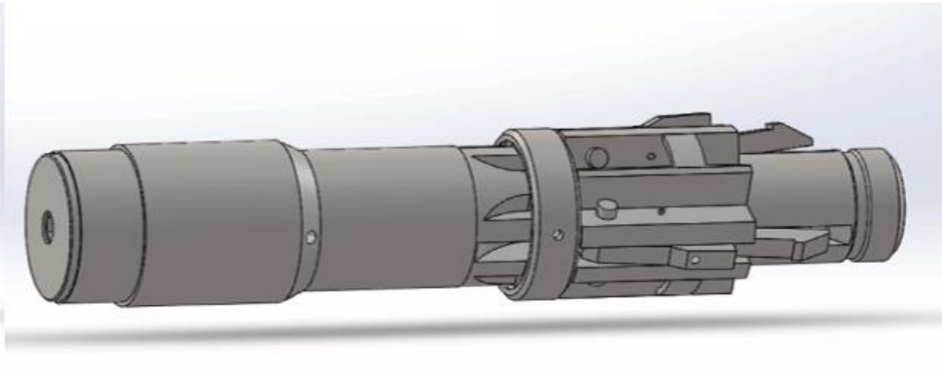

Figure 8. View of the disengaged tool: the teeth are kept fully opened by the springs.

Figure 9/c shows the section where motion is transmitted from the external tube to the internal core barrel. The position of the core barrel in the axial direction is ensured by a stop so that the teeth engage in the appropriate grooves on the external tube. The rotation torque is applied to the external tube set by a rotary motor assembly visible in Figure 9/d. Due to the design of the system, the core barrel engages on the external tube only through two of the three teeth available to the core barrel through the grooves that can be seen in Figure 9/a; also, the section view highlights the complexity of construction of a similar device, since turning is simply not possible. The results from former simulation activities carried out by the same authors of the present activity [8] have been adopted to quantify the maximum solicitations on the device, especially those related to torque transmission (see Table 1) which has been estimated at the maximum value of 16000 Nm.

Table 1. Effort on drilling end-effector depending on selected speed.

Scenario	Unit	High drilling speed	High drilling torque
Drilling speed	Nm	4000	16000
Rotation speed	RPM	140	35
Axial speed	m/s	0.02	0.02
Axial force	N	10000	10000

The external tube used in the PROTEUS project has a diameter of 127 mm, presents a thread section which is needed in order to create a column of pipes during deep drilling. For both core drills, the idle and fixed cores have sealing gaskets in order to prevent the core from leaking out during the sample re-leveling phase.

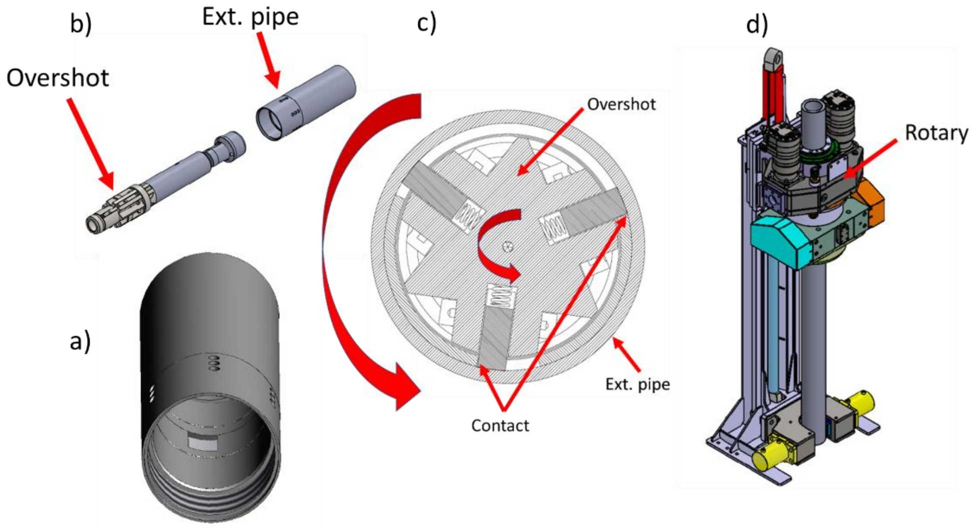

Figure 9. Transmission of torque and motion through the external pipe.

The overshot recovery unit (catcher) has also been reproduced, as shown in Figure 10. The overshot recovery has the purpose of picking up the core barrel when he has finished sampling the soil. It is lowered by a winch from the top of the pipes.

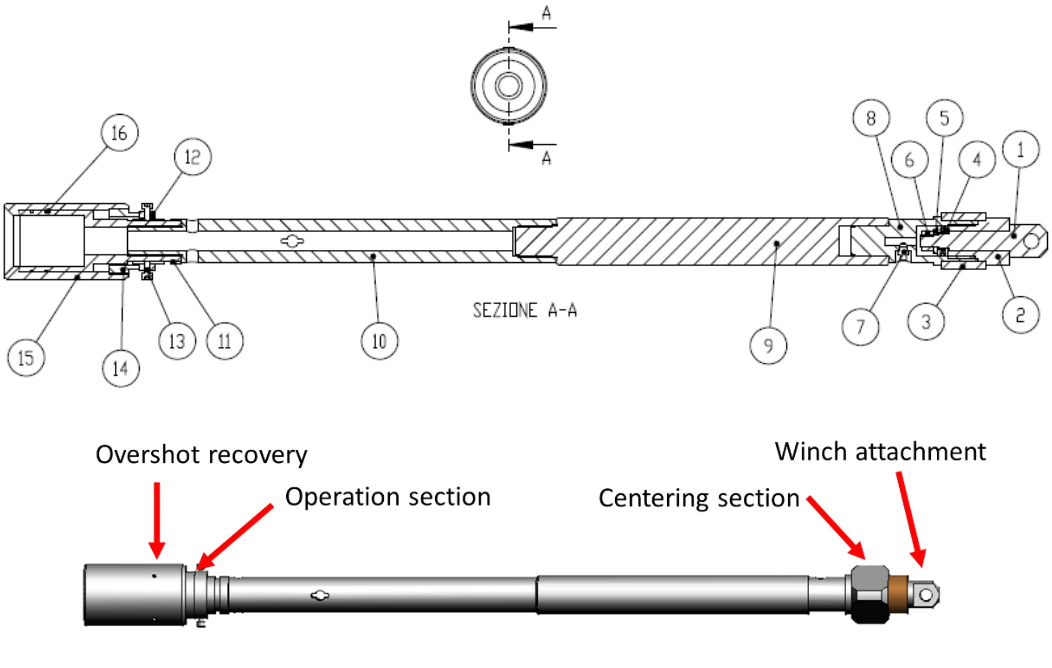

Figure 10. Overshot recovery unit (catcher).

The overshot recovery assembly is composed of a recovery bell which has the purpose of grasping the teeth of the core barrel during the re-leveling phase, a maneuvering section to release the teeth engaged for the release phase from the core barrel, another centering area to avoid undercuts of the angler and to prevent it from getting stuck in the pipes; upper parts hosts the hook for the winch.

When recovery of tool or sample is necessary, the overshot unit is lowered from the top of the pipe column by means of a winch, when it arrives on the core barrel the teeth are released from the external tube and hook onto the angler allowing the recovery of the core barrel as shown in Figure 11.

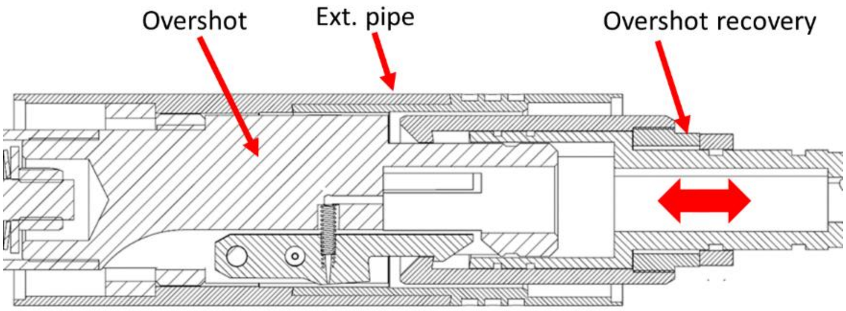

Figure 11. Tool – catcher assembly: section view of connection phase.

Figure 12 shows a section of the assembly, in particular the contact area of the three teeth, highlighted in green, with the recovery bell. The contact is ensured by the springs.

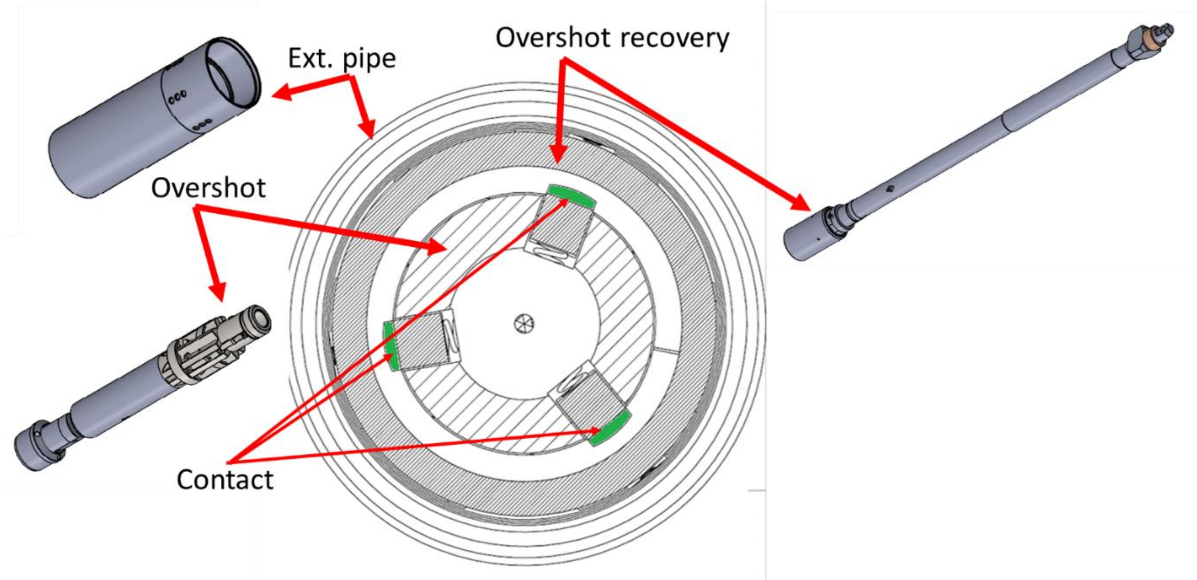

Figure 12. Gripping section.

The overshot connection needs the sliding of the teeth inside the bell in a very harsh environment, since the drilling occurs under pressure of water contaminated by drilling debris, it is necessary to ensure that the connection is not hindered by the increase of friction in comparison with steel/steel clean contact. For this reason, a simulation has been performed. Figure 13 shows the trend of the contact forces of a tooth in the various gripping positions and the directions of these. To carry out this analysis we used the Solidwork Motion software, this software allows us to animate the CAD model, and then extrapolate the information we need, for example the contact forces. After having inserted all the constraints between the various components, the constraints that the software had to simulate were left free, for example the movement of the grips, the descent of the overshot recovery. To simulate the descent of the overshot recovery, a dummy linear motor, with a speed of 20 mm/s in order to simulate the descent of the overshot recovery with a winch. In addition, the springs were inserted to simulate the movement of the grips; according to the dismantled devices, it has a stiffness of about 8 N/mm, which appeared a

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suitable compromise between the need to keep teeth open and the possibility to have a smooth connection during catch phase.

A friction contact model between the various components was adopted and two scenarios were made, the first with a friction coefficient of 0.25 between the two steel surfaces while the other simulation was performed by increasing the friction coefficient to 0.5, this latter to take into account degraded conditions such as mud present during the use phase. Finally, the analysis was performed by finding the contact force module and their direction for each point of contact between overshot recovery and overshot. In both simulations, the results show the occurrence of a moderate force, which is expected to be suitable for smooth connection, since its value is significantly lower than the force due to weight of the catcher assembly itself (approx. 30kgs), even considering water flotation.

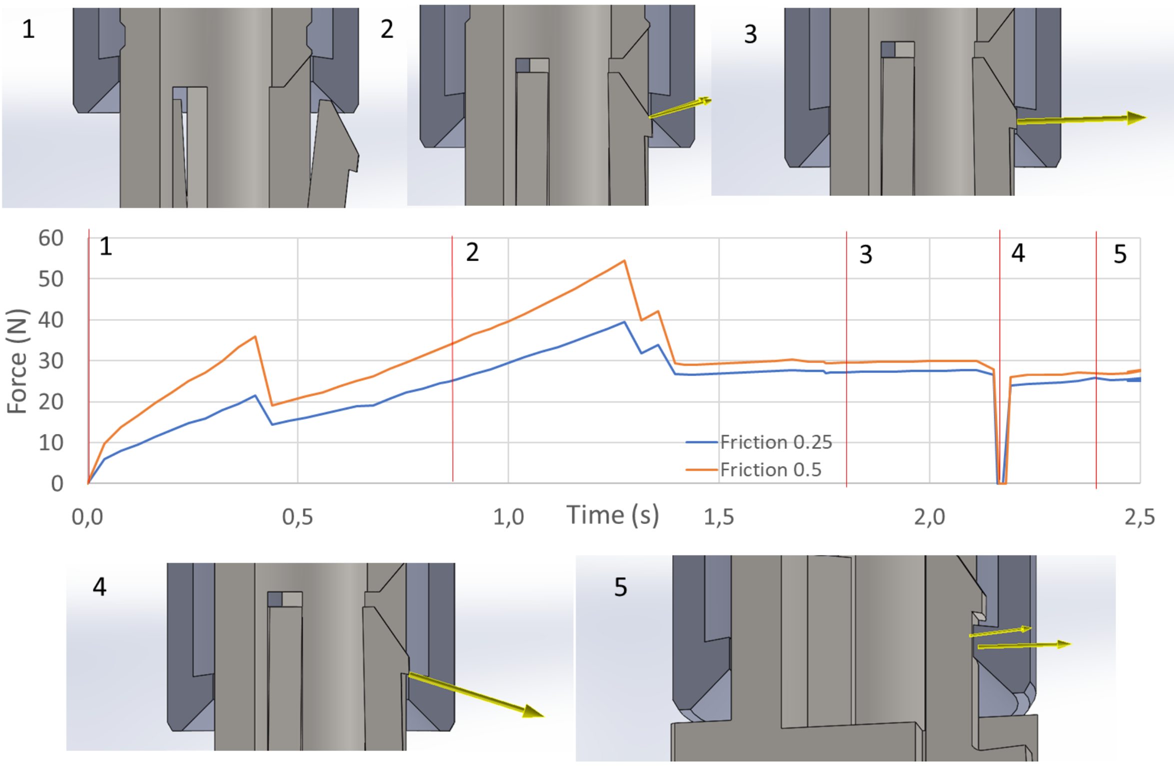

Figure 13. Trend of forces.

In addition, a finite element analysis was performed, both of the core barrel and of the recovery bell. Figure 14 shows the mesh created for the various elements.

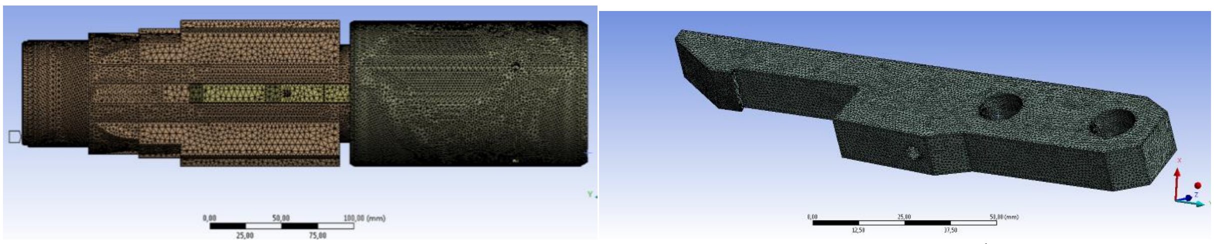
Figure 14. Mesh generated on the components for FEM analysis. Elements are 2nd order tethraedric.

Assuming that the core detachment is typically the most demanding phase of the whole catching process, a 1500 N axial force was applied to the recovery bell, a value than that which would occur in working conditions, the value of which has been estimated to be around 700 N. Figure 15 shows the analysis of the results calculated with the Ansys software, the maximum stress is approximately 85 MPa, significantly lower than the yield strength of any steel.

Finally, Table 2 shows a preliminary selection of steel alloys suitable for device construction; such list has been built through consultation with suppliers, considering the minimum required mechanical properties listed in ISO10097 [13].

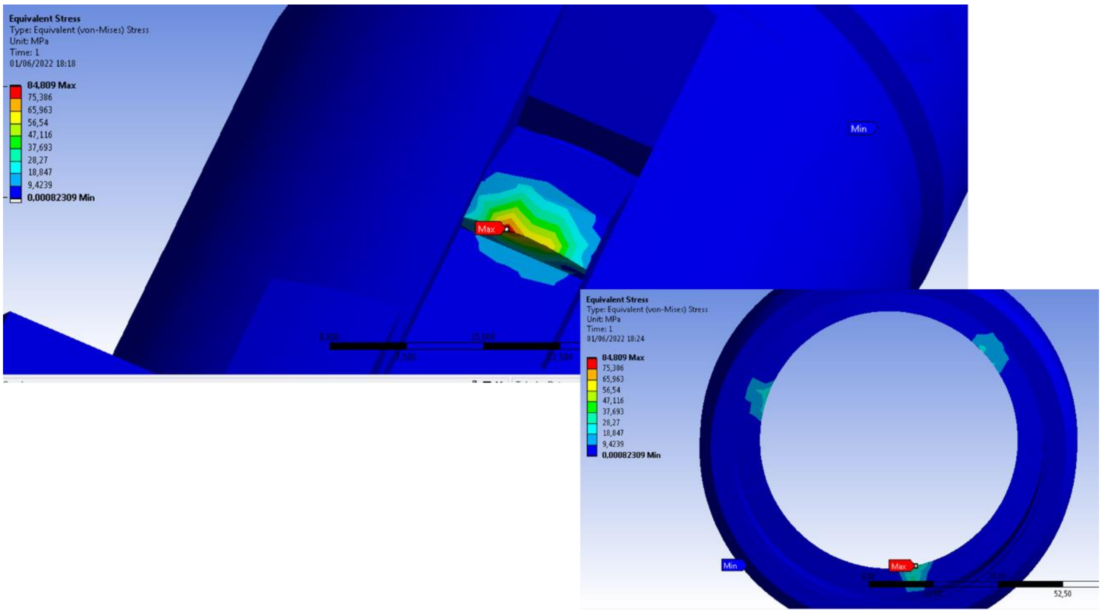

Figure 15. Results of FEM analysis on the catching device.

Table 2. Preliminary analysis of candidate materials for device construction.

Material (steel)	Yield stress (MPa)	Tensile strenght (MPa)
XJY950 (42CrMo)	950	1050
30 CrMnSiA	815	945
Si135	1080	1110
N80 type1	550	690

3. A proposal for revamping of the assembly

To make the system less expensive and reduce mechanical processing, we have to modify the core barrel head. In the current system, only two teeth are engaged on the angler to transmit motion, so we decided to reduce the teeth to two and avoid numerous milling operations. This solution is expected not to affect the overall torque transmission – since, as seen, it occurred on 2 teeth also if 3 were installed, but of course centering qualities during catch may be affected. It has been decided to experiment such design, considering the potential for a series production; a prototype will be therefore needed for on-field testing and assessment.

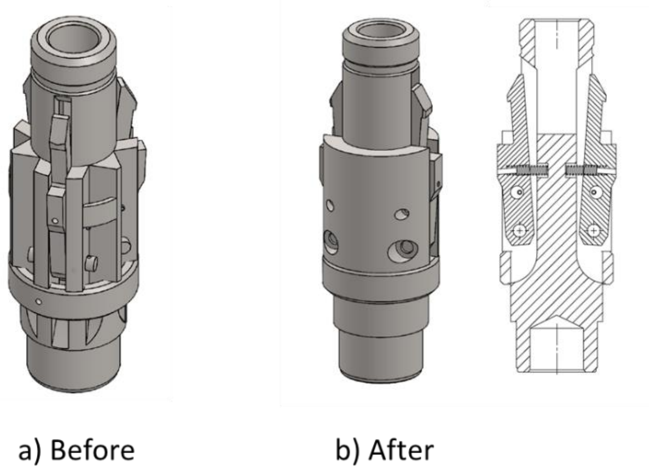

Figure 16. Head assembly group before and after revamping activity.

Figure 16 shows the core barrel head before and after the modification. Figure 16 b shows the core barrel after modification, almost all milling operations have been eliminated, making the component easy to make and reducing the costs associated with mechanical machining. The gripping teeth thickness has been increased so that they have greater grip on the recovery bell; the criteria has been to maintain the contact area at the same value between original and new solution (see Figure 17).

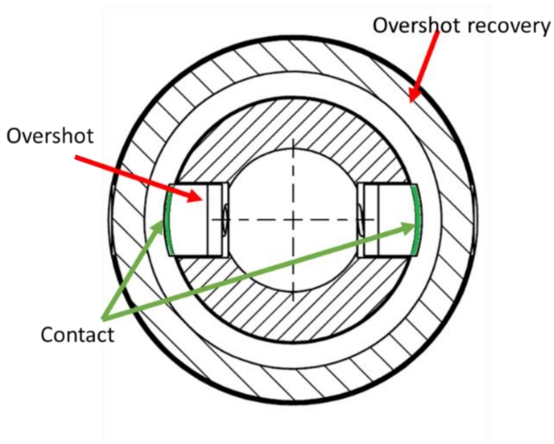

Figure 17. New gripping section.

For this modified overshot the same spring as the original overshot was used to give the grips the same reaction force. Also in this case the analysis was performed with two coefficients of friction to see how the contact forces change; again, we can see that the module of the contact forces increases as the friction coefficient increases, maximum value of the axial force being comparable.

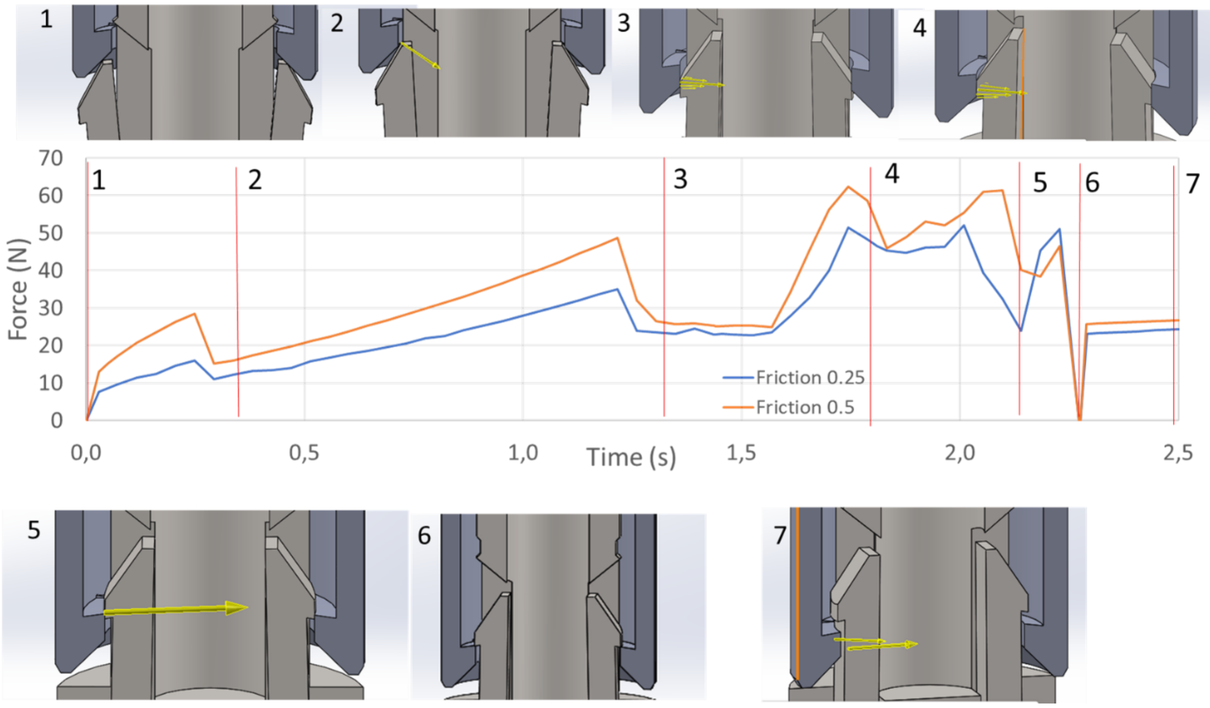

Figure 18. Contact forces trend.

Figure 18 shows the trend of the contact forces of a single tooth in the various gripping positions. Also for this modification a finite element analysis was performed, Figure 19 shows the mesh created for the tooth.

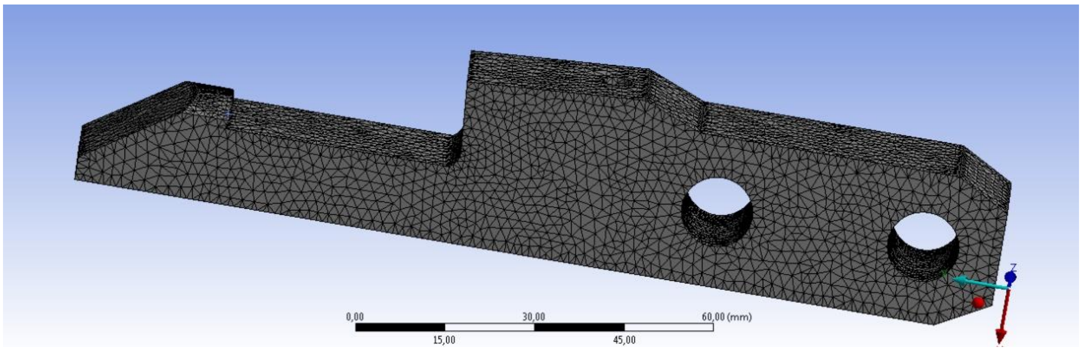

Figure 19. Tooth mesh.

Figure 20 shows the tension present on the tooth, the maximum tension in this case is about 28 MPa, this is because the contact with the bell is expected to be almost perfect.

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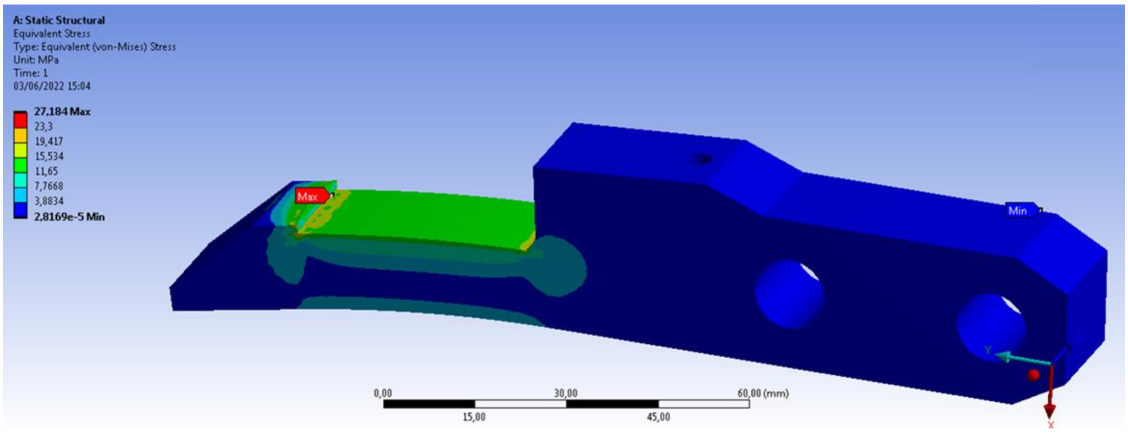

Figure 20. FEM analysis results.

Moreover, to improve grasping, we have thought of creating a tooth that follows the shape of the core barrel, so that the contact does not occur precisely on the edges but occurs uniformly over the entire surface. Figure 21 shows the optimized tooth with rounded outer surfaces.

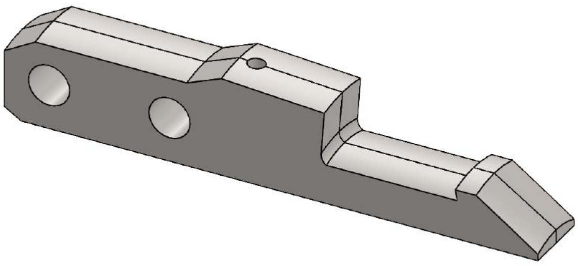

Figure 21. Tooth with optimized surfaces.

4. Conclusions and final remarks

The definition of the PROTEUS prototype needed to take into account a number of relevant requirements in order to ensure economic, flexible and efficient operation in any application field. The wireline tool is the key factor to ensure reduced time waste in case of sample coring and in case of cutting head substitution. A brief market analyses highlighted that there are different types of core drills, each of them characterized by some peculiarities. We have decided to redesign an existing core barrel by doing reverse engineering activities in order to valorize a device which was known for efficacy and easy operability, while not being covered by existing patents. A CAD model of the core barrel was reconstructed; as usual, the 3D model enabled the possibility of stress analysis and connection simulation, thus permitting to comprehend the role of the details of the existing part and to verify the expected forces. Simulations were conducted to optimize contact and understand the trend of forces in different catching scenarios. Finally, significant modifications were proposed to design a new core barrel to make it simpler and less expensive, increasing the reliability of the system as the number of components has been reduced. This core barrel will be reproduced in a mechanical workshop and tested during use.

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