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Towards active self-management of umbilical linking ROV and USV for safer submarine missions

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Abstract: This article focuses on the active management of the umbilical of a Remotely Operated Vehicle (ROV) for shallow water exploration. The objective is to increase the ROV maneuverability by exploiting the mechanical model of the cable that links the ROV to an Unmanned Surface Vehicle (USV). The efforts applied on the umbilical are studied in simulation. The numerical models implemented under Simulink™ and Vortex™ are used to define new strategies of control for the winch, the USV and the ROV in order to manage the umbilical.

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1. INTRODUCTION

Underwater umbilicals are used to link a submarine Remotely Operated Vehicle (ROV) to a control unit or a Human-Machine interface usually placed on board a vessel or ashore (Christ and Wernli (2007)). They can transmit data in real time in both directions, i.e. orders (top-down) and measurements (bottom-up) in order to operate in the best conditions. Umbilicals can also provide power supply to increase the ROV autonomy (Ajwad and Iqbal (2014)).

Though it can be useful to keep a physical link attached to the ROV for safety reasons, umbilicals have drawbacks that are inherent to their mechanical properties. Indeed, underwater umbilicals undergo drag forces when they move, which impacts the ROV motion. Such disturbances can slow down the ROV, and generate significant trajectory changes in the presence of strong water stream (Bevilacqua et al. (1991), Soyulu et al. (2010)). The tether inertia is also to be considered as a parameter that impacts the ROV mobility (Fang et al. (2007)). The tether length defines the size of the ROV's workspace. A large workspace involves a very long cable, which is heavy to manage. The maneuverability of the ROV is also reduced due to its interaction with the umbilical (McLain and Rock (1992)). The more compact and less powerful the ROV, the greater the impact of constraints on the robot.

Nevertheless, tethered compact ROVs are very useful to inspect shallow waters close to the coast (Pacunski et al. (2008)). Unfortunately they have to face other hazards coming from the interaction with the environment. Shallow waters are often turbulent especially within the surf area where waves and water streams are generated due to the rugged seabed. In addition, when the ROV navigates close to the hilly seabed, seaweeds can represent natural obstacles the umbilical could get entangled with (Fig. 1). The cable should not be left dragging on the seabed to prevent early wear or damage (Drumond et al.

(2018)), and to avoid sand clouds that may alter the ROV vision and disturb the natural environment.



Fig. 1. Natural obstacles that can impact the umbilical - ROV picture from OpenROV (2015)

These traditional issues related to umbilicals and to the exploration of shallow waters suggest to address three main challenges:

- Provide the ROV with a larger exploration workspace with respect to the surface vessel.
- Actively manage the tether in real time in order to limit hazards related to the environment (entanglements, drag force, loops, ...).
- Roughly estimate the position of the ROV with respect to the surface vessel at low cost thanks to the identification of tether properties and the feedback of the ROV inertial sensor.

To achieve these goals, an underwater observation system is used. It is composed of three modules, namely a compact ROV (BlueROV 2 from BlueRobotics™), an Unmanned Surface Vehicle (USV) shaped as a catamaran boat equipped with a smart winch, and an umbilical linking the ROV to the USV (Fig. 2).

To allow ROV missions to run smoothly, even in the presence of the umbilical and its potential disturbances, the tether length is intended to be managed through collaborative control of the

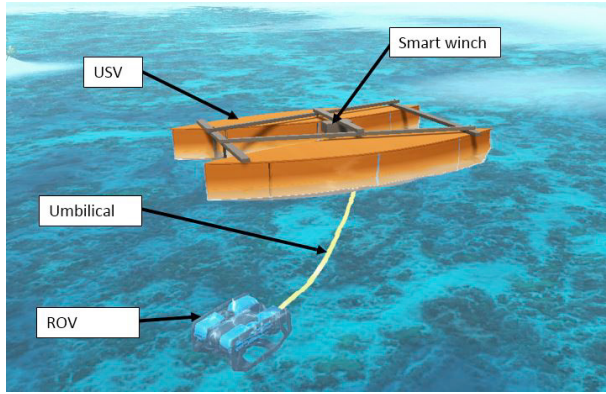


Fig. 2. System overview with ROV, USV and umbilical

USV's movements and the winch actions. A successful mission is characterized by a smoothly moving ROV and minimal energy consumption of the whole system.

Section 2 presents the mechanical model of an underwater cable by studying its mechanical parameters. These parameters determine the shape of the cable and affect the forces applied at each end. This section presents the experiments conducted to evaluate the bending and torsion stiffness along with the type of numeric model selected to simulate cable behaviour.

Section 3 focuses on the shape of the cable and on the forces it transmits to the ROV during missions. The cable is simulated in MatlabTM/Simulink by validating the values of the mechanical parameters presented in section 2. Then the action of the umbilical on the movements of the ROV is studied depending on the cable's length and shape.

Section 4 addresses the way to control the winch and the USV to provide the ROV with the suitable length of umbilical.

Section 5 discusses the results and provides directions for future work relating to the management of the system.

2. MECHANICAL MODEL OF THE UMBILICAL

A numerical model of the cable mechanics is useful to estimate the cable shape, and makes it possible to simulate loops (Gay Neto and de Arruda Martins (2013)) and entanglements that may occur in the tether. It provides the torques and the forces at the attachment points which significantly impact the ROV maneuverability.

An alternative to the model presented here would be to instrument the cable. One solution named *Smart Tether* (Frank et al. (2013)) is based on IMU sensor nodes embedded in the tether itself that give the shape and the motion of the cable in real time. However these nodes induce an irregular shape along the cable, which causes problems for winding. A second solution (Duncan et al. (2007)) is based on the very promising technology of optic fibers braided within the umbilical. The optic fibers use the interferometry properties (Sagnac effect) to monitor the curve of the whole cable in 3D in real time. The drawback of this solution is its very high cost – about 200 000 euros for 50 m length – that restricts its use to defense applications. A similar solution was used with an underwater agent-based detachable tether system (Yu et al. (2004)) with a very short cable.

To manage the umbilical, additional components such as buoys and ballast, or intermediate cables connected by tether manage-

ment system (Rigaud (2015)) can be used as dampers to avoid undesired forces on the ROV due to waves/currents. As they are mostly used for deep-sea applications, they are not adapted for shallow water missions.

Provided the cable shape is a catenary curve, the forces applied on both ends can be easily computed through a mathematical model (Irvine (1981)). The catenary model refers to a non-rigid flexible cable whose weight in water is greater than the buoyancy force. Nevertheless, usual cables are characterized by a bending stiffness that must be taken into account.

2.1 Mechanical parameters of the umbilical

To compute the shape and forces of the cable, the model has to take into account the actions from the water (buoyancy, stream, drag), the reactions at both ends from the USV and the ROV, inertia, gravity, and the internal forces due to stiffness and elasticity (Blintsov (2017)). Moreover, the entire tether is assumed to move freely underwater between the attachment points to the USV and the ROV.

The constant parameters, such as cable section, density and total length determine weight and buoyancy. The bending and torsion stiffness determine the internal forces. The drag coefficient provides information on the influence of stream and drag force on the umbilical. Drag coefficient values can be obtained from empirical tables (Bourget and Marichal (1990)).

Some data – section area, density and total length – are given by the manufacturer or can be directly determined. The unwound cable variable length is given by the winch controller.

Since the cable in the study is fifty meter long it is reasonable to neglect the length variation. The difference of water pressure applied all along the cable is small enough to neglect the cable compressibility. This is why the cable volume and buoyancy, thus density, are assumed to be constant.

The identification process was conducted on two kinds of two-wire cables.

- **Cable 1** is quite rigid, has an external radius of $4.8 \cdot 10^{-3} \text{ m}$ and is neutral in water. It was designed to supply power to the Tortuga underwater robot (SubseaTech (2018)) that features a large thrust-to-weight ratio.
- **Cable 2** is less rigid, has an external radius of $2 \cdot 10^{-3} \text{ m}$, is floating and only transmits data.

The bending stiffness reflects the resistance of the cable against bending deformation. It was obtained by hanging the cable at one end, giving it a loop-shape, and pulling it down by a known mass, M , attached to the other end. The curvature diameter D at the neutral fiber was measured via the internal curvature diameter and via the cable diameter d , as shown in Fig. 3. The bending stiffness K_b of the cable is given by Eq. (1):

$$K_b = \frac{M \cdot g \cdot L_0 \cdot D \cdot \pi}{360}, \quad (1)$$

where g is the standard gravity, L_0 , the distance between the mass attachment point and the point of the cable of greatest curvature. The obtained bending stiffness is related to a 1 meter length cable. The numerical results of the bending stiffness are presented in Tab. 1.

Depending on external forces and ROV motion, the cable may be twisted. Therefore, the twist stiffness, which is generally much higher than the bending stiffness is considered. A dedi-

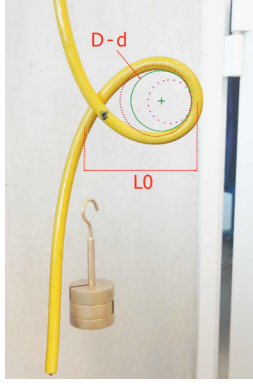


Fig. 3. Experimental characterization of bending stiffness

	Cable 1	Cable 2
Radius ($10^{-3}m$)	4.8	2
Density (kg/m^3)	1000	932
Bending stiffness ($N.m/deg$)	$1.43 \cdot 10^{-4}$	$0.2 \cdot 10^{-4}$
Torsion stiffness ($N.m/deg$)	$6.37 \cdot 10^{-4}$	$3.26 \cdot 10^{-4}$

Table 1. Mechanical parameters of the two cables

cated experimental procedure was implemented to identify this parameter. The cable is stretched with a given tension between two fixed brackets while a perpendicular tray is fastened to the cable to create a symmetric cross in a horizontal plane (Fig. 4). Each mass that is suspended at the end of the tray rotates it to generate a twist angle θ on the cable. The linear torsion stiffness, K_t , is the ratio between the deviation angle and the torque applied by a specific mass.

$$K_t \theta = \frac{M \cdot g \cdot b \cdot \cos \theta}{L}, \quad (2)$$

where L is the cable length and θ is the angle between the equilibrium position of the tray with a mass M and without mass (horizontal) and b is the half length of the tray. By measuring the angle θ for given mass values, the coefficient K_t is obtained for each cable. The numerical results of torsion stiffness for 1 m length are presented in Tab. 1.

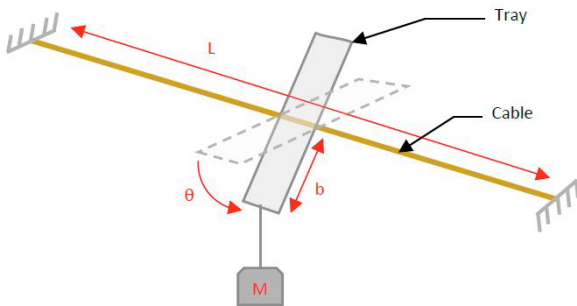


Fig. 4. Experimental characterization of torsion stiffness

2.2 Tether model and simulation

The knowledge of internal and external efforts applied on the cable and the knowledge of the shape are crucial to improve the ROV control and localization accuracy. Numerical simulation allows testing the cable behavior between the two robots.

There are two main methods to model cable dynamics (Blintsov (2017)): lumped-mass-spring (Buckham and Nahon (1999))

and segmental (Eidsvik and Schjolberg (2016)). The first method models the umbilical as mass points joined together by massless elastic elements. The forces are determined at the mass points and are described by differential equations. This approach is very useful for elastic cables but requires large computational resources. The segmental method describes the cable as a continuous system and numerically solves resulting partial differential equations. These two methods focus on the cable dynamics in simple environments with few forces : gravity, buoyancy, hydrodynamic drag, environment inertial force (expressed through added masses), axial tension, twisting force and bending force.

The segmental method was selected here in order to simultaneously validate the mechanical model itself, hence the mechanical parameters involved in the shape and forces at both ends, and the way to simulate it.

To validate the segmental model, the static behaviour of a 1.6 m long catenary was simulated and compared in shape and effort to the analytical curve and its theoretical forces. In this configuration, the attachment points (A and B) are at the same height and 1.3 m apart (Fig.5). The model is composed of 32 bodies which are 5 cm long and linked together through gimbal joints.

The maximal gap between the catenary curve and the segmental model run on Simulink does not exceed 0.08 %, so it validates the segmental model and thus the simulator in terms of geometry for static behavior.

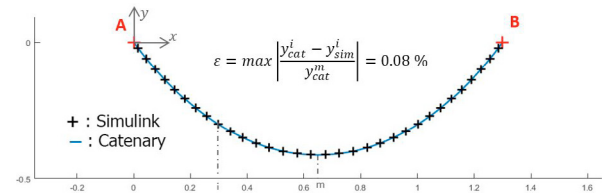


Fig. 5. Cable simulation compared with catenary curve

To confirm this result, the results given by both models were also compared in terms of effort by focusing on the Horizontal Tension (T_h) and Vertical Tension (T_v) at point A (Tab.2, Eq.(3)).

$$\begin{cases} T_h = a\mu g \\ T_v(x) = T_h \sinh\left(\frac{x + \Delta_x}{a}\right), \\ \Delta_x = \frac{x_b - x_a}{2} - x_b \end{cases} \quad (3)$$

The catenary parameter, a , depends on the positions of A and B and on the cable length. The linear density of the cable is denoted by μ , while Δ_x is the horizontal offset from the ordinate axis and x_a , x_b are the x-coordinates of points A and B, respectively.

	Catenary equations	Numerical model
T_h (N)	0.5594	0.5597
T_v (N)	-0.7845	-0.7848

Table 2. Tension at point A for both models

From these results, the shapes and forces can be considered similar between catenary and Simulink models, taking into account the numerical inaccuracies of computations. This allows validating the cable model without stiffness.

To validate the mechanical parameters values experimentally determined, the results of the segmental simulation were compared with a real case.

To do so, the model of a 1.6 m long cable suspended at both ends in the air was reused. The manipulation is carried out in a vertical plane against a white board and the initial conditions at both ends imply a horizontal tangent curve. Only the force reaction at both ends and the gravity act on the cable (Fig.6)

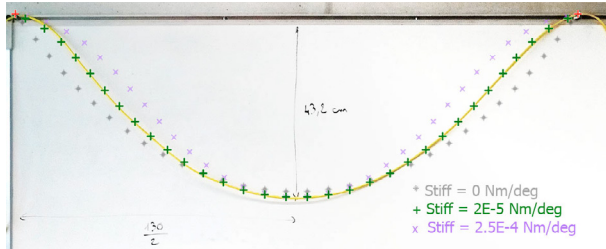


Fig. 6. Model validation with real Cable 2.

The mechanical parameters used are those of cable 2, which are detailed in Tab. 1. They are considered as constant in time and space. Since this is a planar experiment, only bending stiffness, density and volume are involved and taken into account in this case.

To highlight the impact of the bending stiffness on the shape, the curve of a more rigid cable, $2.5 \times 10^{-4} \text{ N.m/deg}$, than the real one and a non-rigid such as a catenary, 0 N.m/deg were plotted. Figure 6 shows these 3 superimposed curves with the real shape of Cable 2. It shows that the simulated model with the identified value of bending stiffness fits well the real shape unlike the two other models.

This part of study confirms the interest of the segmental model and the physical sense of the mechanical parameters identified (at least the bending stiffness that was evaluated and modelled the same way as twisting stiffness).

Another physical parameter which plays a role in the cable shape is the winding persistence that gives a spiral shape to the free cable. It is due to the stress in the cable during some winding phase or process. This parameter is modeled in Simulink as an angular equilibrium position of the free cable. It was not implemented during simulation because experimental tests suggest it is a second-order effect for Cable 2.

3. SIMULATION PROCESS

Once the segmental model of cable validated, the objective is to simulate the behaviour of the umbilical that links the ROV to the USV during a mission. The goal is to compute the efforts applied by the umbilical onto the ROV that may impact its movements. In addition, the configurations that could lead to entanglements are researched.

VortexTM was selected to simulate the whole system composed of the USV, the umbilical and the ROV (Fig.7). This software solution features a model of the sea environment where the seabed, waves and stream can be set. A graphical rendering is given to have an overview of the simulated experiment. In addition, many detailed data related to geometric shape of the umbilical and the forces applied onto it due to the ROV, the USV, the gravity/buoyancy and the water stream are also available.

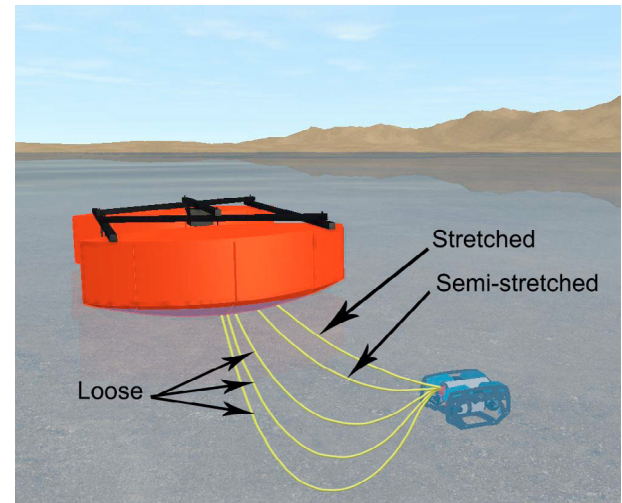


Fig. 7. Vortex simulation - Several lengths of umbilical

Vortex allows modelling the umbilical as a flexible object through its dimensions (length, diameter), inertia parameters (mass, density, inertia), bending stiffness, torsion stiffness, and elongation. To do so a wizard can help to adjust these parameters from physical parameters such as the number of wires, their Young's modulus, and the radius for instance.

The size of elements (5 cm max here) can be set like the damper coefficient of joint which is often used to help the simulation to converge. Within an underwater environment, the objects motion are quite slow whereas the water works as a natural damper. Then the damper coefficient of joints is defined larger than zero but is not determined physically.

First the efforts of the umbilical applied onto the ROV in a static mode are computed i.e. all the system stands still and then with only the ROV moving forward at a constant velocity.

As depicted on Fig.7, several lengths of umbilical were defined to run the simulation. Preliminary studies led on the segmental model run in Simulink show that, for a given configuration, the bending stiffness does not act on the vertical effort applied by the umbilical onto the ROV whereas the torque and especially the horizontal tension are increasing as the umbilical is stiffer (Fig.8). Note that the forces are expressed in the ROV reference where the axis X is positive in the forwards direction and Y axis is positive upwards.

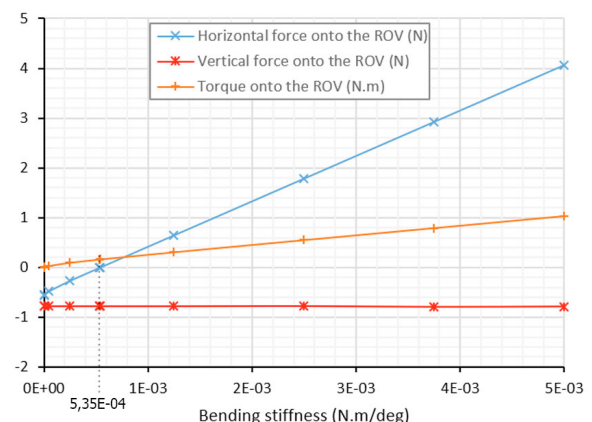


Fig. 8. Force onto the ROV as a function of bending stiffness

It means that according to the value of the bending stiffness of the umbilical, it could be better to increase the horizontal distance between the ROV and the USV to reduce the horizontal force applied onto the ROV. The cable needs space to have a free shape, but of course it implies that the ROV will have to overcome a higher drag force while moving. Moreover, a free shape may generate entanglements and could not help anymore for localization.

This is the reason why the determination of a specific configuration is investigated by adjusting the length of the umbilical, according to the coordinates of the ROV and USV, in order to minimize the horizontal and vertical forces and also the torque applied onto the ROV. It was named the semi-stretched configuration.

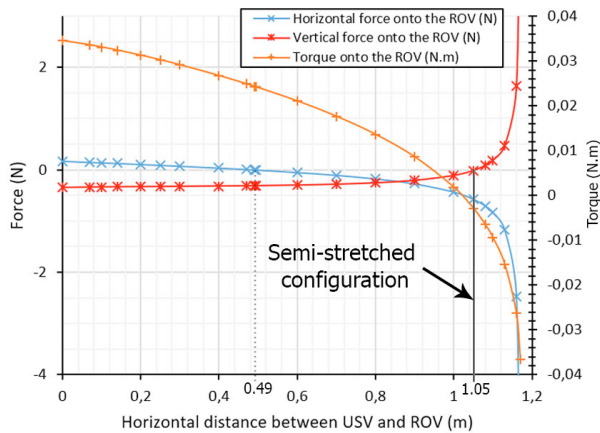


Fig. 9. Forces applied by the umbilical onto the ROV as a function of horizontal distance between the ROV and the USV

The efforts applied in this configuration are depicted on Fig.9 and are computed from the segmental model run with Simulink. The horizontal distance between the ROV and USV is drawn along the horizontal axis, while the ROV depth and the cable length remain constant. The semi-stretched configuration is defined when the vertical tension vanishes. It means that, in the case of a sinking cable, the umbilical would be tangent to the horizontal at its lowest point - which is the attachment point of the cable onto the ROV.

This configuration is interesting to reduce the efforts generated by the umbilical onto the ROV in order to keep a good maneuverability of the ROV. It implies to provide the ROV with the suitable length of cable to let it move around without undergoing a too large drag force due to the moving cable. Moreover a too long unwound umbilical may drag on the seabed, get knotted or hamper the motion of either the USV or the ROV.

4. CABLE MANAGEMENT

The system, being composed of a ROV (6 DOF) and an USV (2 DOF) equipped with a cable winch, can be considered as over-actuated with respect to the cable. Indeed, to control the length of the cable to reach the semi-stretched configuration, the system can operate in several ways. For example, to make the cable looser, it can be unwound from the winch or the USV or the ROV can move to reduce the distance between them.

The required mission of the ROV, the energy savings or the environmental conditions (wind, waves, hazards risk) will determine which strategy to follow. The simulation run with

VortexTM will help to choose a suitable strategy of cable management.

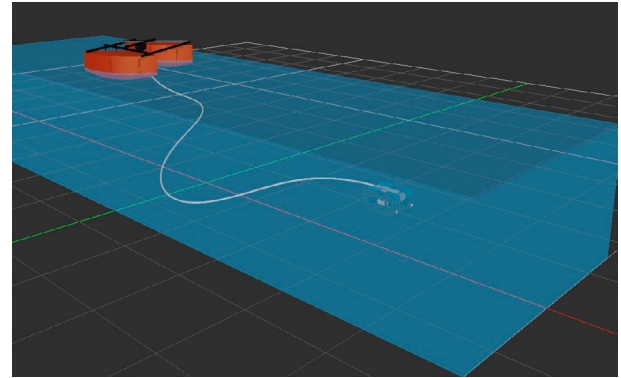


Fig. 10. Screenshot of Vortex software : Case of study with a too loose umbilical

As shown before, the semi-stretched configuration is interesting for several reasons, especially to avoid the risks involved in a configuration such as the one shown in Fig.10 with a too loose cable. But, regarding the efforts applied by the cable onto the ROV, the tolerance on this configuration is very low. Indeed, as the cable passes this configuration when stretched, the increased forces obstruct the ROV from moving forward. Disturbances due to waves, wind and uncertainties about ROV or USV displacements may easily lead the ROV into this critical configuration.

The cable management must prevent this to enable the ROV to move without being hampered by the umbilical's behaviour. So a 4-modes winch controller is suggested. The USV should mostly remain on the spot whereas the ROV will move further to explore a targeted area. In this case, the first mode consists in releasing quickly a large amount of cable to let the ROV reach the targeted area. The second mode is idle where no action is done on the cable winch to keep the cable length constant. The third mode consists in winding the whole cable to help the ROV move back to the USV docking space. In this step, the direction towards the USV is constrained by the tightened cable whereas the ROV drives its propellers backwards to contribute to the motion. Finally the last mode is to keep the cable close to the semi-stretched configuration. To obtain this mode, the implementation of a sensor on the cable is needed to detect when the desired configuration is about to be attained. It implies to create a compliant controller that uses tension sensor of the cable as a feedback.

Since it is considered that the cable has no elongation with regard to the maximal force that can be applied on its both tips, the cable winding cannot rely only on its own properties to be compliant. So to introduce a certain controllable compliance between the USV and the ROV, it is suggested to shape the cable as a spiral along a short piece of cable near the ROV to allow it to get longer under tension. In such a way, an elongation sensor will measure the change of length of this compliant part to give a value about the tension on the cable thus the force applied by the cable onto the ROV. The development of this solution is in progress and would be submitted during the forthcoming year.

The cable tension measurement will be used as feedback to control the winch in order to continuously get closer to the semi-stretched configuration i.e. to supply the ROV with the

just suitable length of cable. This opens to promising perspectives about the ROV localization.

5. CONCLUSION

This paper has described a method to identify the bending and twisting stiffness of an underwater cable, and proposed a way to model its mechanical behaviour. It has also shown how stiffness influence the forces at both attachment points (ROV and USV). The semi-stretched configuration has been introduced to reduce the efforts applied onto the ROV. Even if a neutral cable generates low forces, it is still interesting to stay close to the semi-stretched configuration to prevent the cable from dragging on the seabed and thus getting entangled with obstacles.

The studied system composed of an USV, an embedded winch, an umbilical and a ROV offers several ways to manage the cable close to the semi-stretched configuration. To do so a compliance is required. This is why next study will focus on a tension sensor placed close to the ROV to supply the winch controller with a signal feedback.

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