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A new flex-sensor-based umbilical-length management system for underwater robots

Ornella Tortorici, Cédric Anthierens and Vincent Hugel

Abstract—This work focuses on the automatic control of the length of a tether that links an underwater vehicle to the surface, with the objective to prevent the tether from becoming taut or getting entangled due to too much length being deployed. The solution proposed here consists of equipping the tether with a balanced buoy-ballast system that gives the cable a V-shape in the vicinity of the vehicle. This system offers a passive compliance by smoothing the movements of the tether and damping external disturbances. The tether length is adjusted by an active feeder on the surface, whose control relies on the reading of a flex sensor embedded in the V-shape portion of the cable. The experiments conducted on a real ROV in a pool allowed validating this mechatronic compliant-actuated system, which can adapt to the movements of the underwater vehicle while it executes longitudinal and curved trajectories.

I. INTRODUCTION

Underwater exploration is a promising and sensitive field which takes advantages of the manoeuvrability and reliability of remotely operated vehicles (ROV) [1], [2]. Those systems are linked to a control station by a tether that can transmit data and supply power if required [3], [4]. However, this link may apply undesired forces on the ROV [5], [6] that imply a limitation of the ROV mobility, an increase of its power consumption and disturbances on its trajectory [7]–[10]. All these constraints are even more important for the small and less powerful ROV which are widely used in shallow waters. Furthermore, a passive slack tether increases the risk of entanglement, drag on the seabed thus early wear [11]–[13]. In order to take advantage of the cables linked to underwater robots, a variable cable length is required.

One of the main challenges in underwater robotics is to provide more autonomy to the robots, whereas the cable length is mostly managed manually. There exist three main solutions in the literature to manage tethers: tether customization/instrumentation, use of a surface winch, or use of an underwater tether management system (TMS) whose function can be carried out by a second robot.

Tethers are often customized by buoys and ballasts to change their buoyancy, shape or behaviour [6], [14], [15]. Those systems are passive and their positive impact on the cable management is limited if they are not associated with an active control. Less commonly, cables are instrumented with external or internal sensors to measure their behaviour and shape. The measurement is done either on several specific nodes along the cable by inertial or tension

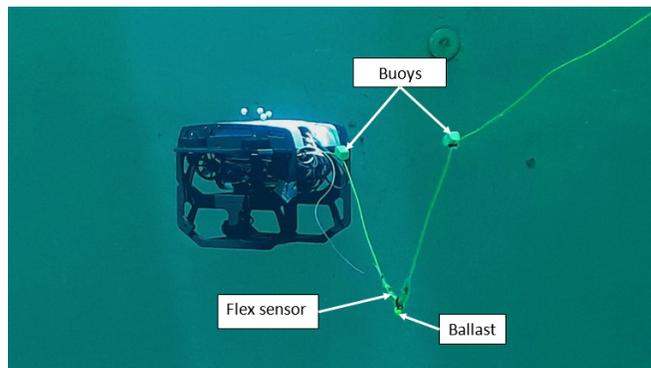


Fig. 1. Buoy-ballast compliant system mounted on neutrally buoyant cable.

sensors [6], [16], or continuously all along the cable through embedded fiber optic solutions [17]–[19]. The first solution generates irregular shape, whereas the second one can be very expensive. Surface winches are used to deliver /retrieve cable, and their control is often manual or simply based on cable tension [20], [21]. They are commonly placed on the surface vessel, but they can also be embedded on the ROV itself [14]. Tether management systems (TMS) are widely used for deep water systems [1], [22]–[24]. They behave as an intermediate system between the surface and the ROV that manages the portion of the cable connected to the ROV. A second ROV can also play the role of a TMS [2]. However, this solution adds a potential risk of collision between the robots.

This paper presents the design of an automatic cable management system to limit the undesired effects of the tether on the navigation of the ROV. The contributions of this work include the design of a mechatronic compliant-actuated system for a tether that is linked to an underwater robot, the associated length control management to maintain a semi-stretched shape of the tether, and experimental validations with the whole system connected to a compact underwater vehicle.

The paper is organized as follows. Section II details the proposed solution, including the mechatronic adaptation brought to the tether and the control scheme. Section III presents the experimental setup used for evaluating the cable management system. Section IV reports and discusses the experimental results. Finally, Section V draws the conclusions of the work.

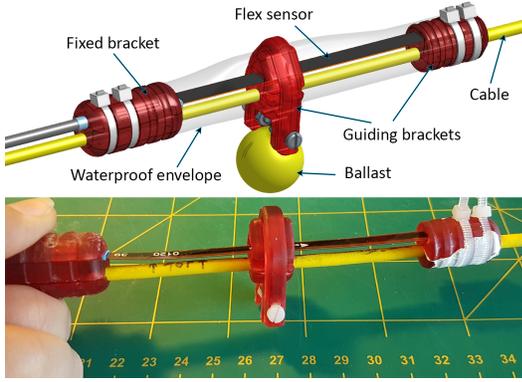


Fig. 2. Integration of the flex sensor on the tip of the V-shape buoy-ballast compliant system

II. METHOD

A. Mechatronics

The mechatronics of the system includes customization of the tether near the ROV vehicle to achieve passive compliance, and the design of an active feeder on the surface to automatically control the tether length.

The passive compliance is based on the local deformation of the cable created by two buoys and a ballast fixed on the cable, that give it a V-shape as shown in Fig. 1. This V-shape portion of the cable is symmetrically designed with the ballast in the middle of the two buoys to have a neutrally buoyant system. A flex sensor is mounted on the cable at the ballast place using a fixed bracket and guides along the cable (Fig.2). The sensor has a negligible bending stiffness. It is isolated from the water by a thin plastic envelope. The buoy-ballast system is placed in proximity to the ROV. The heavier the ballast, the stiffer the system, but the higher the drag force. The reactivity also depends on the stiffness. The deformed part of the cable must keep a V shape and not a droplet shape, so that the flex sensor provides a monotonous response with the deformation.

The buoy-ballast system is designed to smooth the movements of the tether and to damp external disturbances. Table I summarizes the specifications and the characteristics of the system that have been determined by simulation for a Fathom Slim tether from Blue Robotics that is neutrally buoyant in freshwater and has a low stiffness. Figure 3 shows the data acquisition chain of the flex sensor.

buoyancy	neutral
desired compliance	1 m
distance between buoys	min: 20 cm, average: 1.2 m
flex sensor model	FS-L-0095-103-ST (Spectra Symbol)
flex sensor size	11 cm long, 0.5 mm thick
buoy size	2.9 x 2.9 x 4.7 cm ³
buoy foam density	288 kg/m ³
ballast mass	76 g

TABLE I

SPECIFICATIONS AND CHARACTERISTICS OF THE BUOY-BALLAST V SHAPE SYSTEM ADAPTED FOR THE FATHOM SLIM TETHER.

The specifications for the tether feeder are the following,

- it must be able to pay out cable at the same speed as the ROV movements.
- in case the feeder system becomes inactive, it should not stop the movements of the ROV
- if the control of the ROV is lost, the feeder must be capable of trailing the ROV back to the surface vessel

Therefore, the feeder must be able to bear more than the ROV's dead weight in water, but less than the maximum ROV thrust. Here, the ROV is a BlueRov 2 from BlueRobotics that has a maximum forward speed of 1.5 m/s and a maximum forward thrust of 100 N. A strength of 11 N is necessary to drag it in water at 0.5 m/s. Furthermore, the feeder must have a smooth behaviour and be controllable at low speed. To ensure control, the length measurement must remain accurate and avoid any slippage, even with a wet tether.

The feeder structure is depicted on Fig. 4. The cable is fed in and out by transmission between two gears of the same diameter. One of the two gears is actively driven by a motor and the other one is passively driven by friction from the cable. This assembly is composed of machined parts, rapid prototyping parts (ABS) and off-the-shelf components. An incremental encoder on the passive gear measures the length of unwound tether. This part comprises a flange, a toothed gear and an encoder shaft guided in rotation by a bearing box. The toothed gear guarantees a good grip on the cable without the need to tighten it too much between the two gears. The drive gear is actuated by a DC motor with an integrated gearbox.

B. Control scheme

Modeling of the flex sensor. Since the resistor of the sensor is directly linked to its bending, a 3rd order polynomial fit between the output voltage and the distance between buoys has been drawn and identified (Fig. 5). The error between the experimental points and the fit is also plotted. The average error is 3 cm, and the maximum error is 7 cm. The experimental carried out to determine the fit showed a very fast response (1.26 s as time constant), a monotonic behavior and no significant hysteresis or phase shift.

The estimation of the distance by the flex sensor model is sent by the ROV to the feeder on the surface, which is actuated to keep an average distance between buoys. Because of the drag force, the gap between the buoys increases with the ROV speed. So the normal distance between buoys is set relative to the actual ROV speed. During the ROV motion, the feeder speed is controlled to regulate the desired average gap between both buoys.

Figure 6 describes the control block diagram of the feeder. The control of the feeder consists of a length control loop (proportional controller) that encloses the speed control loop (proportional-integral controller with anti-windup). The cable length is computed in the speed control loop so that it is accessible even when the length control is disabled. The desired speed, whether it comes directly as a controller input or from the length control loop, is first bounded to avoid

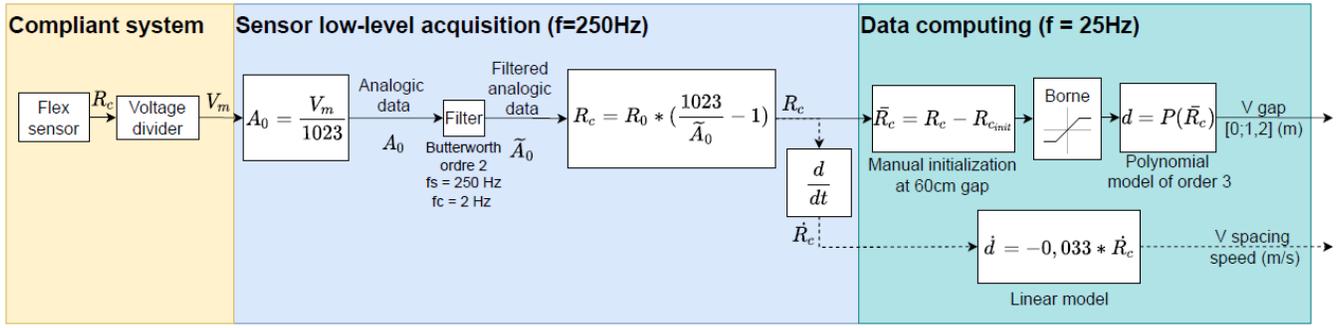


Fig. 3. Block diagram of the flex sensor data acquisition

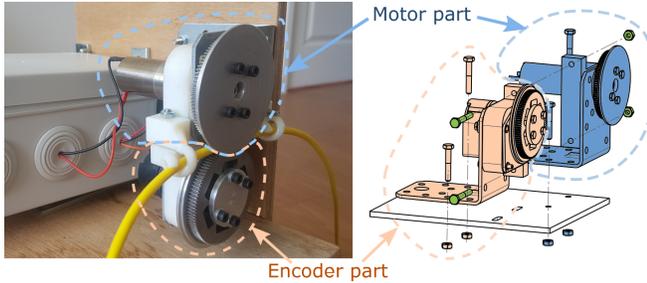


Fig. 4. Overview of the tether feeder, composed of a driving part and an encoder part.

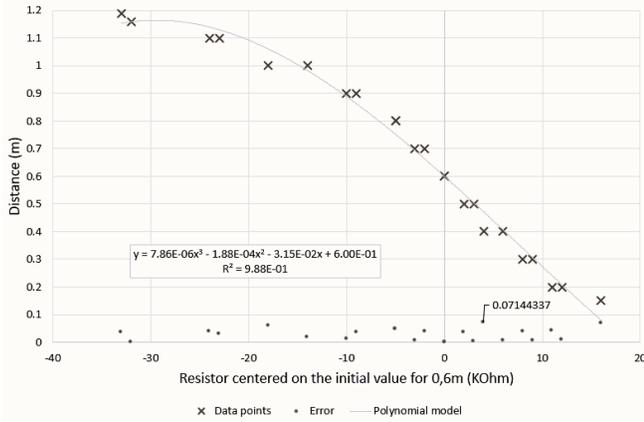


Fig. 5. Model of the distance between the buoys as a function of the centered resistance of the flex sensor with experimental data points.

overshooting the motor limits. It outputs a raw PWM signal, which is then bounded and smoothed by a low pass filter before it is transmitted to the motor control board.

The feeder can be operated in two ways to release the cable on request. Either it works sequentially, i.e. the length controller releases 2 m of cable when the V-system is getting taut (2 m of cable is reeled back after 10 s period when the V-system is loosed), or it works continuously and so the speed control loop releases the cable when the V-system lengthens, or reels it in when the gap between the buoys is less than the average.

III. EXPERIMENTS

For the experiments, the feeder is fixed on the edge of an experimental water tank (16 x 8 m pool with a maximum depth of 5 m) and is connected to the ROV through the 25 m long umbilical equipped with the V-shape buoy-ballast system. Figure 7 represents the global implementation scheme of the system.

The behaviour of the system is tracked by an underwater motion-tracking system, namely *Qualisys*, in addition to internal sensors. These data are used in post-processing to obtain the configuration of the cable, as well as the position and orientation of the ROV in the global frame.

In order to compare the behaviour of the system in different modes of the cable, two trajectories of the ROV were defined:

- a linear trajectory where the ROV goes forwards and then backwards
- a curvilinear trajectory.

They illustrate two configurations where the cable control should play an important role in relation to a high risk of cable snagging or entanglement. All these trajectories are associated with a 1.5 m depth control of the ROV. The ROV is controlled in open-loop to track these trajectories by setting the thrust level for each degree of freedom. Therefore, the observed trajectories are expected to be different depending on the mode of the cable, namely taut, slack or controlled. The controlled mode of the cable is tuned to keep an average distance of 0.65 m between the buoys with a tolerance of ± 0.05 m.

IV. RESULTS AND DISCUSSION

a) *Linear trajectory*: The cable control for this trajectory is illustrated on Fig. 8 for the three modes. The feeder appears to be quite reactive and smooth to wind/unwind the cable depending on the ROV motion and the distance between both buoys.

Figure 9 depicts the paths of the ROV projected onto the horizontal plane measured by the *Qualisys* system for the three cable modes. If there were no external disturbances at all, the path would be rectilinear. The ROV deflects slightly to the left when the cable is slack. This deviation is slightly larger in control mode and is observed both during its forward and backward motion. The deviation

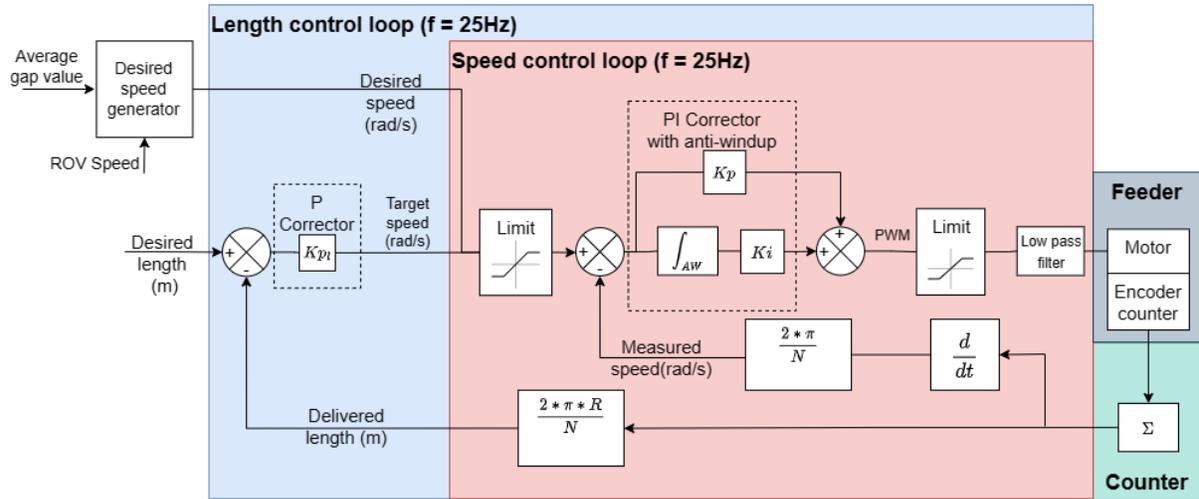


Fig. 6. Control block diagram of the feeder. The input is either a cable length value or a speed value.

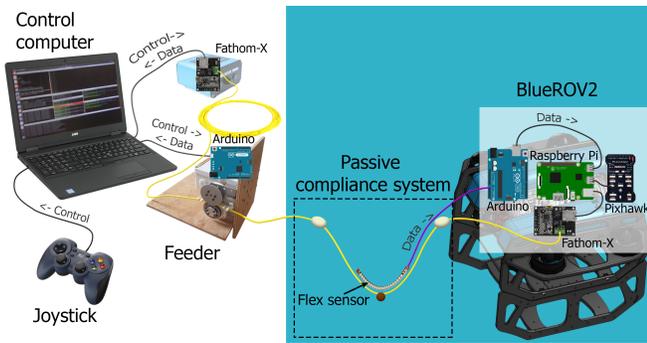


Fig. 7. Global implementation diagram of the system

is significantly greater in passive taut mode, approaching 90deg. Furthermore, the distance covered by the ROV is significantly shorter with the taut cable.

Figure 10 shows the evolution of the depth control of the ROV for the three modes. Only the control mode efficiently helps to regulate the ROV depth. The vertical thrusters work significantly more when the cable is not controlled than when it is controlled.

b) Curvilinear trajectory: To achieve a slalom shape, a forward thrust level of 25% is sent for 15s (between points 1 and 2), then a yaw command of 11.25% is sent in addition with a forward thrust level of 40% for 6.5s to turn to the right (between points 2 and 3), followed by a left turn with the same levels for 6s (between points 3 and 4), and finally a forward thrust of 25% for 4s (between points 4 and 5).

The compliant system keeps its V-shape and a reasonable distance between the buoys even when the ROV turns (Fig. 11). Figure 12 presents the behavior of the compliant system in the three modes. The feeder is also reactive and smooth to reel back the cable and manage the desired gap between both buoys.

For a flawless system without any disturbance, the yaw angle (Fig. 13) should be constant during the ROV straight line commands (before point 2 and after point 5). It should

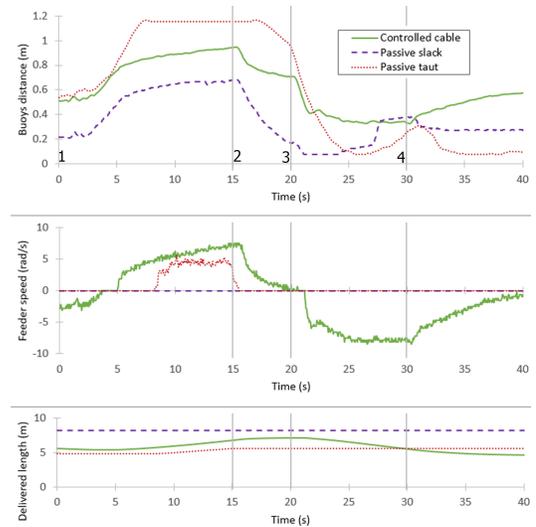


Fig. 8. Distance between buoys (flex sensor), feeder speed and unwound length of cable in control mode, passive slack mode and passive taut mode for forward-backward trajectory. (<https://youtu.be/owekUkN.UtM> for control mode, <https://youtu.be/1RTT23-USDY> for passive taut mode, <https://youtu.be/FG5iyNfjzck> for passive slack mode.)

also be linear during rotating commands (between points 2 and 3, then 3 and 4). There is a small deviation of about 20° to the right during the first straight line (2.6 m) command of the ROV for the passive slack cable. This deviation is oriented to the left and its absolute value is doubled with the controlled cable and doubled again with the passive taut cable. In fact, the cable is fixed on the left side of the back of the ROV, which induces a slight deviation to the left for the controlled cable both in straight line and during a right rotation. This deviation is much larger for the passive taut cable. The left rotation of the ROV appears to be less affected in the control mode and in the passive taut mode.

The impact of these deviations is observed on Fig. 14, which presents the ROV paths, projected onto the horizontal plane, for the three modes. The distances traveled are quite

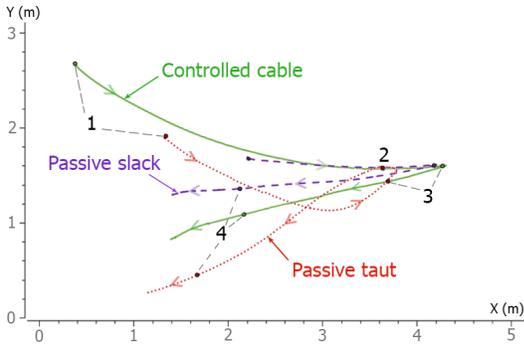


Fig. 9. Actual forward-backward trajectories of the ROV projected in the horizontal plane with cable control and with slack or taut passive cable. These paths are superimposed on point 2 for easier comparison.

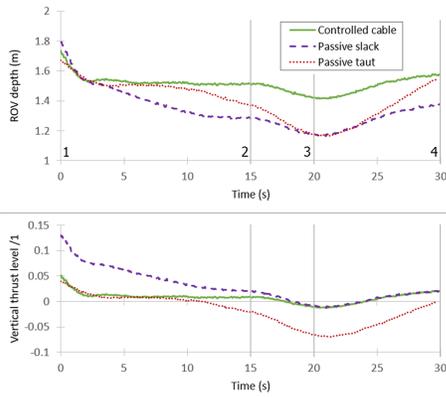


Fig. 10. ROV depth and vertical depth-control thrust in the three modes.

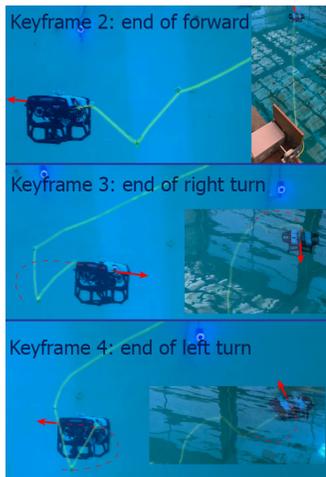


Fig. 11. Views of the overall system at different points along the curvilinear trajectory when the cable is controlled. The red arrows indicate the direction of motion of the ROV. (Video at <https://youtu.be/fy-JTc8PvIY>)

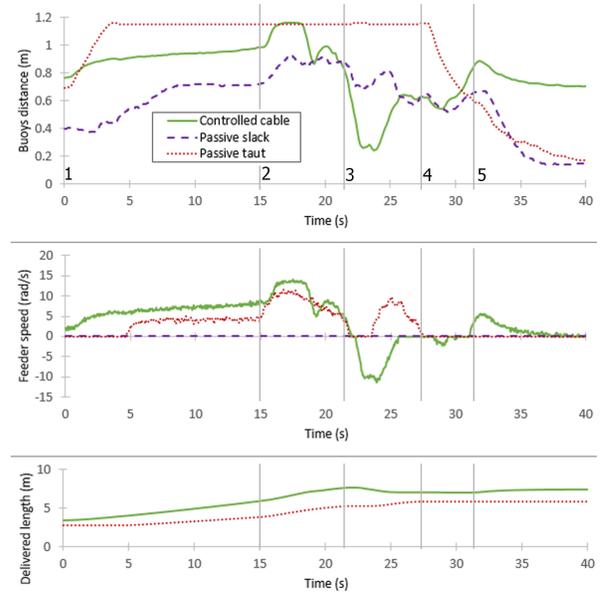


Fig. 12. Distance between buoys (flex sensor), feeder speed and unwound length of cable in control mode, passive slack mode and passive taut mode for the curvilinear trajectory. (Videos at <https://youtu.be/LR4BKfRSnM> for passive slack mode and at <https://youtu.be/74p5Bzee9kY> for passive taut mode.)

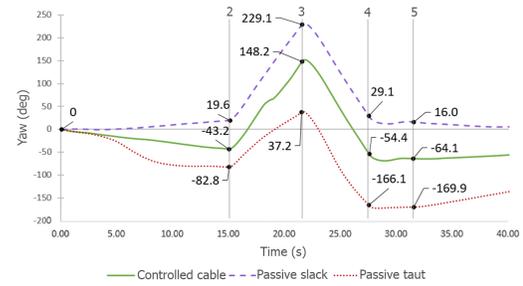


Fig. 13. Comparison of the yaw angle of the ROV (measured with its embedded compass) along the curvilinear trajectory when the cable is controlled or not. The angle was initialized to 0° at the beginning of the trajectories to facilitate their comparison. An increase of the angle represents a rotation to the right of the ROV.

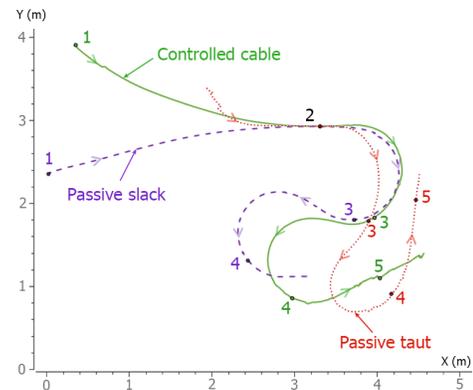


Fig. 14. Comparison of the actual curvilinear path of the ROV projected onto the horizontal plane, measured by the *Qualisys* system, with or without cable control. These paths are superimposed on point 2 for easier comparison.

close for the controlled cable and the passive slack cable. The turns are slightly different between these two modes. The path of the ROV with the passive taut cable is totally distorted. The first rotation to the right (between points 2 and 3) is very confined and the rotation to the left (between points 3 and 4) is quite irregular (much wider curvature in the middle than at the beginning and the end).

The experiments also showed that the control of the cable with passive compliance is effective in keeping the cable in a semi-stretched configuration, the delivered length being properly managed, and preventing the creation of cable loops and reducing the risks of snagging and tangles. The control mode generates a slight tension in the cable, which is transmitted to the ROV and results in a minor deviation in the trajectories of the system. This deviation could be avoided by fixing the cable closer to the center of gravity of the ROV. In addition, the passive compliance system appears to improve the stability of the depth control of the ROV.

V. CONCLUSION

This paper describes a mechatronic solution to automatically and actively manage the cable length of a ROV. The cable is equipped with a balanced buoy-ballast system, which creates a V-shape in the cable near the ROV and provides a passive compliance to it. The buoy-ballast system has been made for a specific tether, namely the Fathom Slim from BlueRobotics, but the design methodology can be used to equip other types of cables with different physical properties. The experiments show that the feeder is responsive enough with respect to the command speeds of the ROV, with no error or drift observed on the controlled cable length. Even wet, the cable does not slip through the feeder. Longitudinal forward-backward and curvilinear trajectories have been tested to validate the capability of the entire system to keep the cable in a semi-stretched configuration.

Future developments will focus on the implementation of the cable feeder on a surface vehicle (USV) and the monitoring of the semi-stretched configuration to use the cable as a means of proprioception for the estimation of the relative position between the vehicles. Synchronized navigation strategies between the ROV and the USV are also under prospect to have an optimized displacement of the vehicles in terms of energy consumption and seabed coverage in shallow waters.

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