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ORIGINAL PAPER

Design and development of a towfish to monitor marine pollution

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Abstract

Monitoring of marine pollution is currently being given a lot of importance as an aid to legislators for when it comes to protecting the environment. A clean marine environment is very important in order to sustain healthy life for all creatures and plants that live in the sea and beyond. The work presented in this paper includes work done within the project BIODIVALUE (Biodiversity and Sustainable Development in the Straits of Sicily) funded through the European Union Regional Development funds (ERDF) Italia-Malta 2007–2013. One of the project aims was to support the monitoring of pollution at sea in the Straits of Sicily, hence contributing to drawing future legislation at the national and European level. The project involved the study and analysis of maritime traffic in the Straits of Sicily and the water pollution produced by it. In particular, this paper presents the design, fabrication, and preliminary functionality testing of an underwater vehicle known as a towfish that can be used to monitor seaborne pollutants such as hydrocarbonsand nitrates. The towfish can also be used to measure seawater temperatures and conductivity at different depths and also to monitor jellyfish populations in the open sea.

Keywords Towfish · Structural design · Control · Marine pollution

Introduction and overview of the towfish design

A towfish is an underwater vehicle that is towed behind a surface ship. The towing line carries all the power supply and signal lines necessary for towfish control and for data acquisition (Schuch et al. 2006). In contrast with AUVs (autonomous underwater vehicles) (Yuh et al. 1999), a towfish is quite versatile when a large area of sea needs to be monitored. Towfish are used for a multitude of applications including military applications, commercial applications (Charles et al. 1993; Sawa et al. 2011) and for marine biology research (Edsall et al. 1989)

This paper describes the design of a positively buoyant pollution and marine species monitoring towfish so that elevators and ailerons are used to make it dive when under tow. This buoyancy characteristic together with a radio beacon enables recovery of the towfish in case of tow line failure. The elevators and ailerons are further used to control the pitch, roll, and stability of the towfish. The depth of dive is automatically controlled to a set value. Automatic control is used to reduce the work and operator concentration necessary during a mission at sea. In addition to active control against the rolling action, the ailerons and elevators of the towfish are at a small anhedral angle. This creates a passive anti-roll action by creating a corrective moment acting about the main longitudinal axis of the towfish. The stern of the towfish carries a rudder. The towline is attached to a towing lug that is welded to the main cylinder. For proper logging and mapping of pollutants and of camera images, the positional depth of the towfish is recorded by means of a depth sensor mounted on the underside of the towfish.

The position of the towfish is found by having a Global Positioning System (GPS) on the surface boat coupled with a commercially available sonar-based instrument that can be used to calculate the relative position between the surface boat and the towfish. The method on which the positioning instrument works is called the ultra-short baseline (USBL) method and is normally used for underwater positioning systems (Vickery 1998). It consists of a transceiver mounted under the towboat and a transponder placed on the towfish. A computer is used to calculate

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the position of the towfish measured by the transceiver. A sound pulse is transmitted by the transceiver and identified by the transponder, which then sends again its particular sound pulse. This pulse is then picked up by the transceiver, which measures the underwater angle and range. The transceiver contains within itself three or more transducers individually separated by a baseline of about 100 mm in order to calculate the angle to the underwater transponder by means of ‘phase-differencing’. Figure 1 outlines the vessel architecture and the general towfish system described above.

The towfish presented in this paper is designed to reach a maximum depth of 50 m below sea level. The main structural components of the towfish are a hemispherical head, a cylinder that carries the ailerons and towing lug, and a conical end that carries the elevators and rudder. Two other cylinders (cylindrical arms) on each side of the main cylinder are designed so that they carry cameras. A three-dimensional line diagram of the towfish is shown in Fig. 2a.

Conductivity, temperature, depth (CTD), nitrates, and hydrocarbon sensors are mounted on the underside of the towfish. These help to maintain the towfish stability during a mission. Figure 2b shows a photo of the fabricated towfish (Muscat et al. 2014). Table 1 gives the specifications of the towfish.

Structural design of the main components of the towfish

Two methods were used in order to structurally design the towfish. The main dimensions and thicknesses of some of the towfish components were calculated using Design by Rule (DBR) (Malta Standards Authority 2009). The principal failure mode of the towfish is failure due to instability or buckling, therefore the main thrust of the design was to address this kind of failure mode. Essentially, the towfish is a pressure vessel that is acted upon by external pressure due to sea

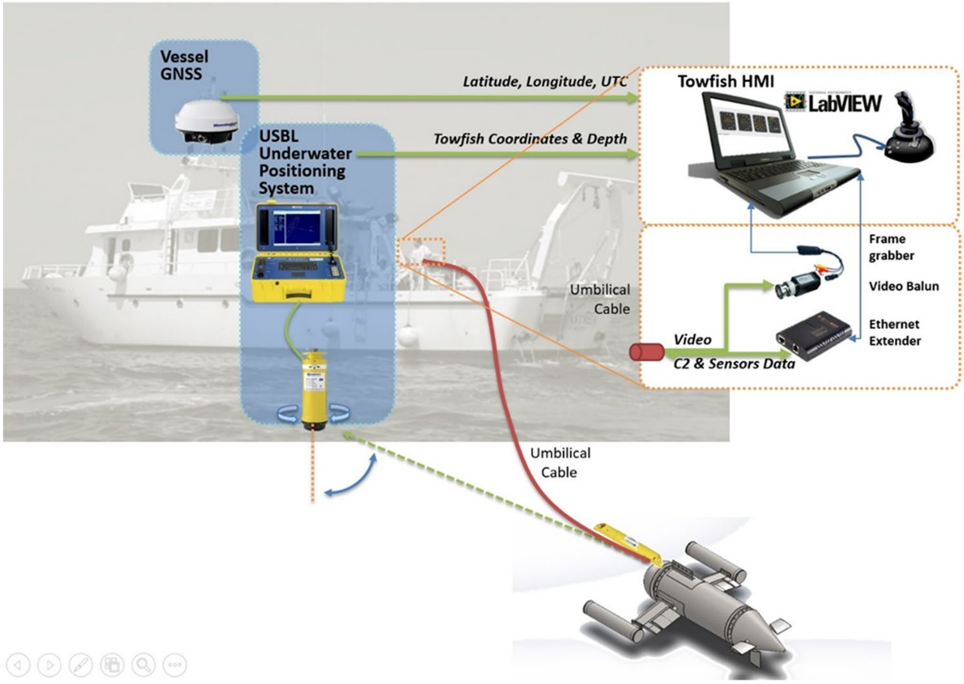


Fig. 1 Vessel architecture and general towfish system

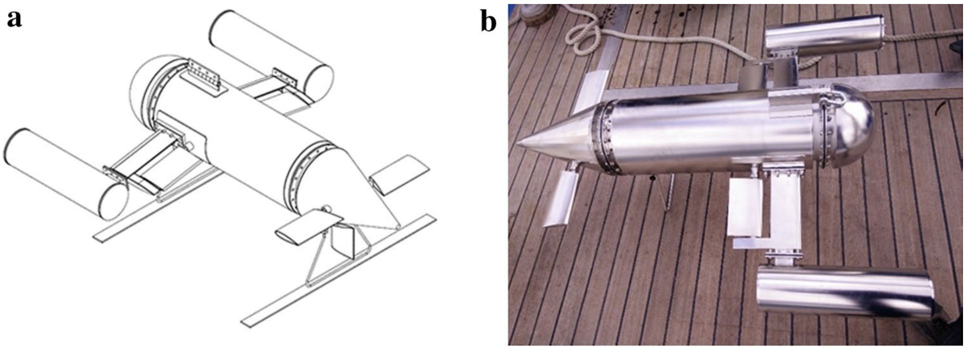


Fig. 2 **a** Line diagram of the towfish. **b** Photograph of the fabricated towfish

Table 1 Towfish specifications

BioDiValue towfish	
Length	1490 mm
Width	1253 mm
Height	499 mm
Material	Chrome-plated structural steel
Weight (including sensors)	75 kg
Maximum depth of dive	50 m
Nominal operating speed	5 knots
Sensors	CTD (conductivity, temperature, depth)
	Hydrocarbons
	Manufacturer: Chelsea Technologies Group Ltd
	Product: UviLux Sensor
	This sensor detects UV fluorescence; in particular, it is set to detect polycyclic aromatic hydrocarbons (PAH)
	Nitrates
	Manufacturer: Seabird
	Product: Satlantic Suna V2
	Its technology is based on the absorption characteristics of nitrate in the UV light spectrum. It has the capability of measuring nitrate and bromide trace
Control	Active control via computer interface on surface vessel
Data acquisition (pollution sensors)	Automatic via computer interface
Features	Positively buoyant
	GPS positioning and recording system
	Depth measuring and recording system
	On-board beacon for recovery in case of towline failure
	On-board sensor for internal humidity level
	Capability to mount a jellyfish camera
	Capability to mount a plankton recorder
Towing line	External nominal diameter 15 mm
	Nominal weight of 290 kg/km in air
	Nominal weight of 110 kg/km in seawater
	Minimum breaking load 10 kN

water depth and by other concentrated loads due to a number of structural connections. These structural connections are mainly the towing lug and the nozzle/bearing attachments for the ailerons' and elevators' bearing housings. Hydrodynamic drag and lift act on the ailerons and elevators and these forces create moment loads and also shear load actions on the main body of the towfish. Buckling checks that were outside the scope of Design by Rule were carried out by utilizing Design by Analysis (DBA) procedures found in the pressure vessel code EN13445-3 (Malta Standards Authority 2009). Structural design by analysis was implemented in the finite element analysis software ANSYS Mechanical (ANSYS 2011). Analytical fluid mechanics equations, computational fluid dynamics (CFD) software ANSYS FLUENT (ANSYS FLUENT ANSYS Academic Research FLUENT 2011) and SolidWorks (SolidWorks 2013) were utilized in order to calculate the hydrodynamic loads acting on the controlling surfaces and towing lug while the towfish is under tow. The ANSYS software mesh tools (ANSYS 2011) were used to create the required CFD mesh. A rectangular volume of sea water having the dimensions 15 × 5 × 5 m was used to model the flow over the towfish. This volume of water was tested to be large enough to contain the towfish and allow the flow to develop at its front and at its back ends. The towfish volume was then subtracted from this rectangular volume of water using Boolean operations. The towfish's front hemispherical end was modeled nearest to the front face of the rectangular volume of the fluid. The latter therefore became the water inlet area while the back face of the rectangular volume (nearest to the conical end of the towfish) became the water outlet area. The rectangular area upstream of the towfish was set to the free stream condition with the axial (relative to the towfish) velocity being set to a particular value for a particular Reynolds number, while the two other velocity components were set to zero. The rectangular area downstream of the towfish was set to a zero pressure constraint since the velocities at this area are unknown. Only half the towfish was modeled with the symmetrical face running parallel to the main longitudinal axis of the towfish cylindrical part. The nodes making up the surface area of the towfish were set with a zero velocity component in any given direction. This is known as the stationary wall condition. The other three remaining 15 × 5-m areas were set with the axial velocity equal to the freestream velocity while the other two velocity components were set to zero. The type of flow that characterizes the behavior of the fluid over the towfish is three dimensional, inviscid, has a mixture of laminar and turbulent flows at various geometrical points, and is incompressible since the flow medium itself (sea water) is incompressible in nature. Laminar flow is likely to occur near leading edges of the lifting surfaces while turbulent flow is likely to occur downstream along the towfish body. Turbulence was modeled using the k-ε model. The k-ε model was chosen for its robustness in modeling laminar and turbulent flows and because it is the most validated turbulence model. During the analysis, the mesh of the model was adapted and refined in the areas with higher pressure gradient in order to obtain a better pressure profile and aim for result convergence. Fluid dynamic analyses at different angles of attack of the ailerons were carried out. Maximum values for drag and lift were calculated at an aileron angle of attack of –20°. Unsteady flow and aerofoil stall occurred at angles of attack of –20° and beyond. The drag and lift forces calculated within the CFD analysis were used for the structural analysis and to calculate the value and direction of the resulting force on the towing lug when the aileron angle of attack was 20°. This is considered to be a maximum when the towfish is at a depth of 50 m. It was assumed that the towing lug will not be under tension when the towfish is rising towards the surface and that the buoyancy and towfish weight are neutralizing each other.

The towfish was designed using structural steel having a minimum yield stress of 235 N/mm^2 and a maximum tensile stress of 360 N/mm^2. These give a design stress of 150 N/mm^2 (Malta Standards Authority 2009). The towfish was designed to be painted with a marine protection paint so that allowance for corrosion was not used at the design stage. The tolerance on shape imperfections followed the specifications in Section 8 of EN13445-3 (Malta Standards Authority 2009). Section 16 of the same code was used to design the required reinforcement at the towing lug area and at the nozzle bearing attachments. The Design by Rule methods presented in (Malta Standards Authority 2009) were not always applicable to the design of the towfish components. These cases occurred at the bearing nozzle at the conical end and at the rectangular flange connection of the fixed wing assembly to the main cylinder at one end and to the cylindrical arms at the other end (Fig. 2a). The main cylindrical shell thickness was calculated to be 3 mm, while that for the cylindrical arms, conical end, and front hemispherical shell were calculated to be 2 mm. The latter value was used for the thickness of the fixed wing skin. Finite element analysis (FEA) software was used to model the lift and drag acting on each aileron. For this, three-dimensional beam elements were used. A reinforcement plate of 3-mm thickness was required for the towing lug region in order for the main cylindrical shell to be able to withstand the maximum towing force. The finite element models were used to check against excessive deformation or buckling in the regions around the nozzle and towlug connections with the main cylinder. In the finite element models, SHELL281 and BEAM181 elements were used in the software ANSYS Mechanical (ANSYS 2011). An elastic perfectly plastic material model was used in line with EN 13445 Part 3 Annex B. Partial safety factors on loads were used depending on the type of analysis. Both gross plastic deformation checks (GPD) and instability (I) checks using large deformation analysis were used for all the components of the towfish with the exception of the towlug region. Model mesh convergence was based on the von Mises stress. In all components, the maximum structural strain occurring in the FEA models when subjected to the maximum loads was less than 5%. The principles of the GPD check and I check as described in reference (Malta Standards Authority 2009) were therefore satisfied and the design of each component acceptable according to Annex B of EN13445 Part 3. Figures 3 and 4 show two models used to analyze the stress fields around the conical end and aileron regions, respectively.

Design by Analysis indicated that at the main cylinder flanges, there is the possibility that some plasticity would occur. The flanges are used in order to be able to open and close the towfish from both the hemispherical end and the

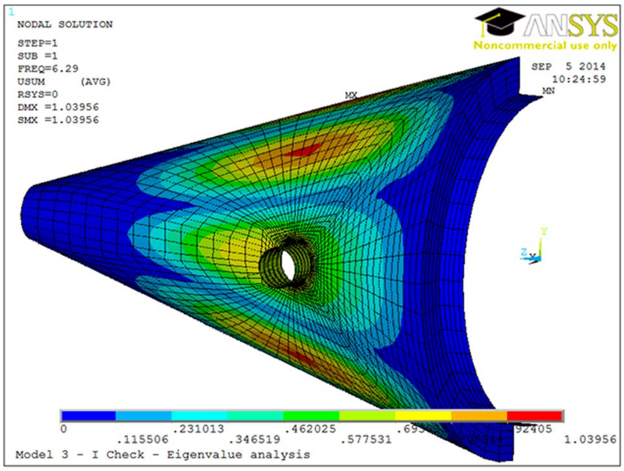


Fig. 3 Finite element model for the conical end region

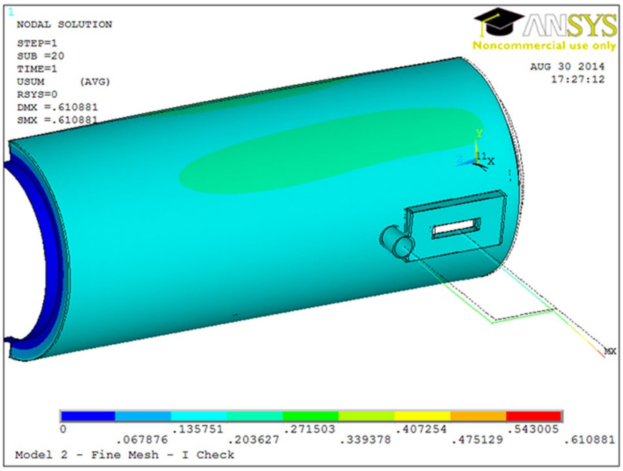


Fig. 4 Deformed model for the GPD check of the model that incorporates the aileron nozzle/bearing and a representation of the fixed part of the wing

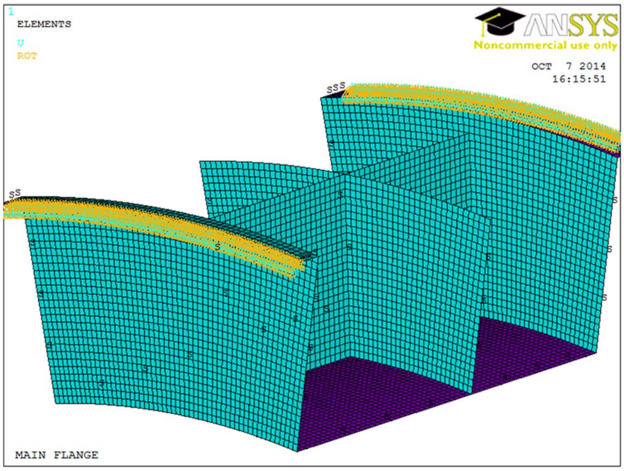


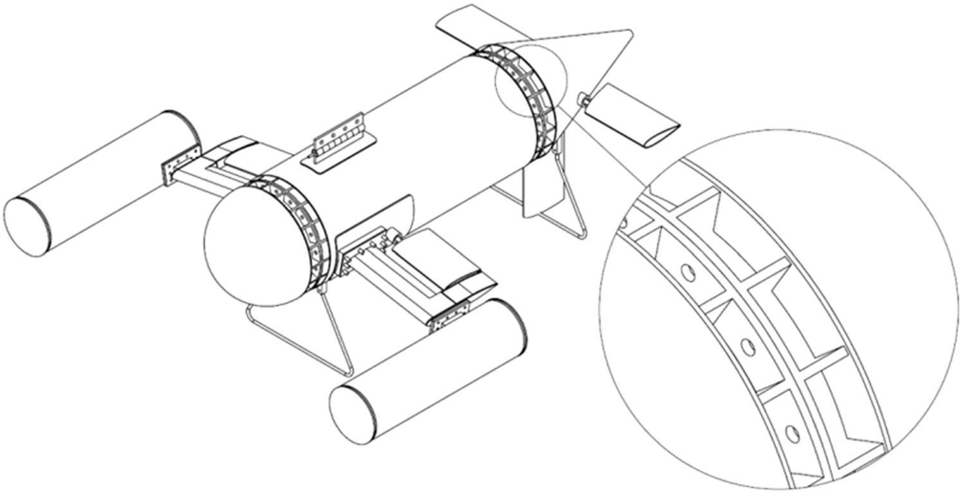
Fig. 6 Finite element plot for a single sector of the modified flange

conical end for the purpose of gaining access to its internal parts. Access is required to install the necessary hardware and perform any maintenance that would be required on the same hardware. The flanges were designed so as to offer a streamline flow as the towfish glides through sea water. Figure 5 shows a suggested modification for the flanges with the addition of a total number of 18 external short stiffeners or ribs around the circumference in the intermediate spaces between the bolts. These ribs increase the bending stiffness of the flanges so that plasticity at their root is reduced or even eliminated.

Figure 6 shows the shell finite element model of the new flange design. It consists of a 20° sector of the flange assembly including a single rib in order to take advantage of the cyclic symmetry of the model. The boundary conditions were applied by constraining the circular edges in all directions except that one of them was set free in the axial direction. Moreover, cyclic symmetry boundary conditions were applied on both edges of the sector, which are located on the radial edges as indicated with the 'S' symbol as shown in Fig. 6. The axial hydrostatic force, including safety factor, was applied on the circular edge, which was set free in the axial direction. Furthermore, the external hydrostatic pressure due to sea water pressure was applied on the section reducer. The model deformation was as expected and confirmed the applied boundary conditions and loadings. A mesh convergence analysis on the model of the flange was performed. The criterion for convergence was based on the maximum von Mises stress.

The nonlinear static analysis for the flange showed that the model remained fully elastic with its maximum strain lower than the 5% limit as allowed by the code MSA EN13445-3 (Malta Standards Authority 2009) for both the

Fig. 5 Main flange positions and the suggested modification



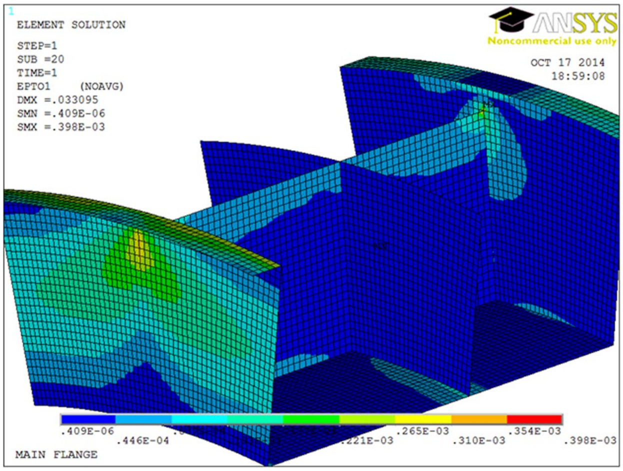


Fig. 7 The first principal structural strain distribution in the modified flange assembly with a maximum strain of 0.04% located in rib-reducer junction for the instability (I) check

instability check and the gross plastic deformation check (Fig. 7).

Actuators and control

There are three towfish aspects that the ailerons and elevators need to control. These are the rolling motion, the pitching motion, and the depth position. The two main ailerons (connected to the main fixed hydroplane) rotate independently from each other so as to be able to control the rolling action of the towfish. As they are the largest control surface on the towfish and can create a large lift, they are also used to control the depth of dive. Pitch control, however, is achieved by both the main ailerons and the tail elevators, creating a moment that will counteract any undesired pitch angle. The motion of the rudder is independent. It is used when turning and to steer the towfish away from the surface boat wake when taking surface or close to surface measurements. In order to control the angle of attack of the ailerons and elevators, a microcontroller receives the signals from the depth sensor and from the inclinometer and calculates a suitable angle of attack by means of a PI-PID controller.

Stepper motors have a high precision and small incremental movements so that they are used to control the ailerons. Step sizes of these motors usually are around 1.8°, so the use of a gearbox is normally required. For the towfish in this project, torque transmission is achieved by means of a 4-bar linkage, shown in Fig. 8.

The 4-bar linkage is used instead of a gear-box mainly because it increases the nominal value of the actuators' torque. It also makes up for machining tolerances and so eliminates the use of flexible joints. In Fig. 9 (left), the torque applied to the main aileron and the angle of rotation of the aileron are plotted as a function of the crank angle of the actuator (servo motor). It can be observed that for the angular working range of the aileron rotation of 1 to π (rad), the output torque has values greater than 5 Nm against the input nominal value of 3 Nm provided by the servo motor linked to the crank. Figure 9 (right) shows the rotation angle of the main aileron as a function of the rotation of the crank. It can be observed that the plot remains linear (constant transmission ratio) for the working range between 1 and π [rad].

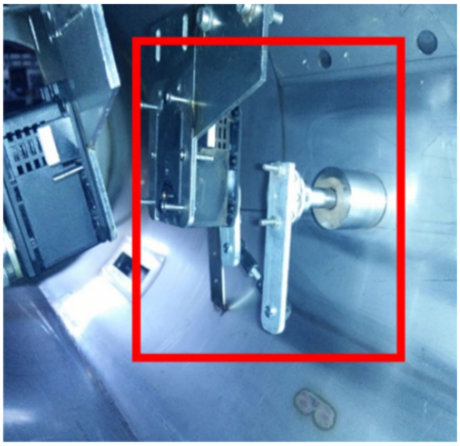


Fig. 8 The 4-bar linkage used to rotate the main ailerons. The photo shows the linkage inside the cylindrical part of the towfish

Figure 10 summarizes the actuators and sensors used to control the towfish and to collect data.

Towing line

The towing line carries the power supply and signal cables from the surface boat to the towfish in order to power up sensors, stepper motors, a video camera, and data acquisition boards. The type of cable required was determined by estimating the maximum towing force induced in the towing line (Cammarata et al. 2016; Delmer et al. 1983; Friswell 1995) and the electrical load in extreme working conditions. At a speed of 10 knots, the maximum towing force was calculated to be 2100 N. Using a factor of safety of 4 on the ultimate breaking load of the towing line, a cable having a MBL (minimum breaking load) greater than 8400 N was chosen. The electric energy consumption in extreme operating conditions, at a nominal DC voltage of 12 V, was calculated to be 360 W, such that the cable would be carrying a current of 30 A. In order to avoid excessive losses on the cable, whose approximate length is 600 m, alternating current (AC) was used (Wrinch et al. 2007). In this way, the root mean square of the current is about 1.5 A. An electrical

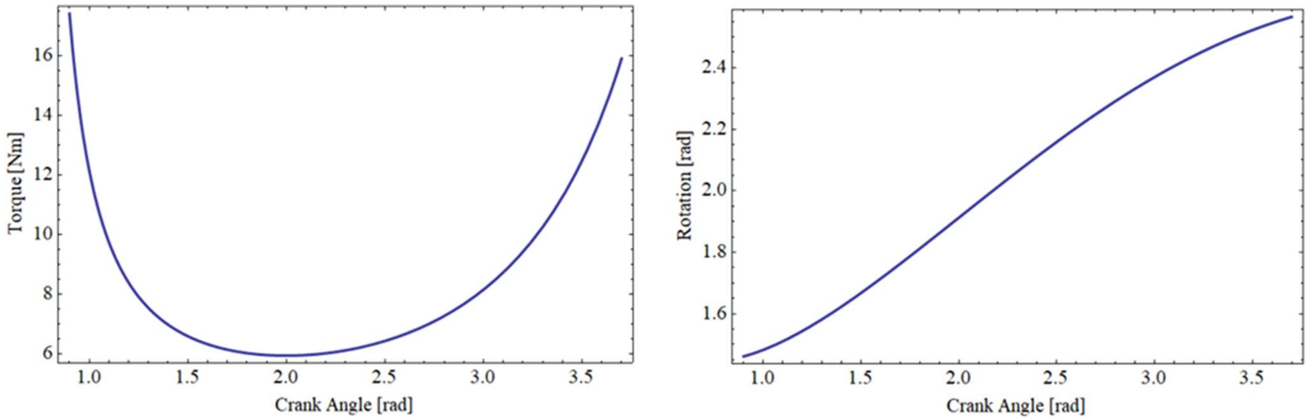


Fig. 9 (*Left*) Torque (nm) applied to the main aileron as a function of the crank angle (rad). (*Right*) Rotation (rad) of the main aileron as a function of the crank angle (rad)

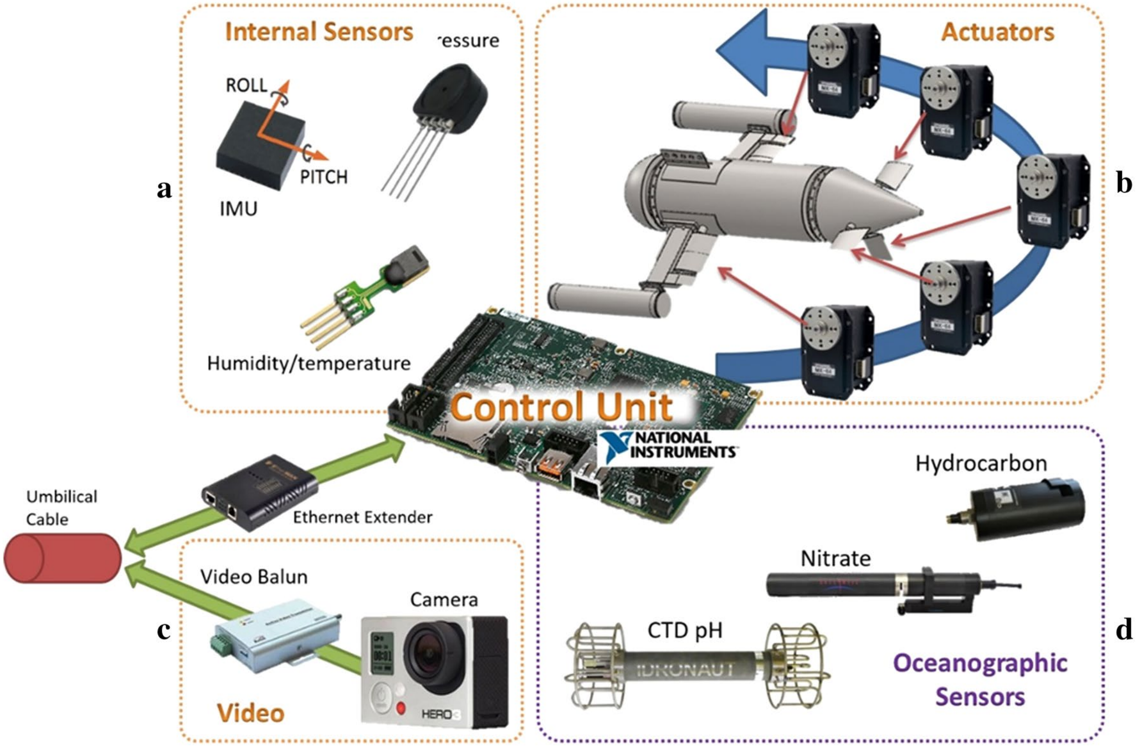


Fig. 10 Towfish architecture. **a** Group of sensors used for detecting any water infiltration inside the towfish or an abnormal increase of temperature. The inertial measurement unit (IMU) measures the pitch, roll, and yaw angles useful for the control of the vehicle. **b** The five actuators: two for the ailerons, two for the elevators, and one for the rudder. **c** The video components: a camera and a Video Balun, which avoids electrical disturbances. **d** Group of oceanographic sensors mounted outside the towfish, on the bottom. All of these electrical devices are managed by a control unit that sends/receives data to/from instrumentation on-board the ship through the umbilical cable. An Ethernet extender amplifies data as the cable exceeds 100 m

cable of 2 mm^2 (one for the inlet cable and one for the outlet cable) that can carry this current was chosen. For data transmission, the protocol used is CAN and so twisted pair-type cables have been used in order to avoid magnetic interference due to the power cable.

The towing line chosen (Cortland 2014) has an external nominal diameter of 15 mm, a nominal weight of 290 kg/km in air, a weight of 110 kg/km in seawater, and a minimum breaking load of 10 kN. These towing line properties affected the choice of the mechanical systems used to deploy the cable at the start of a mission and to recover the cable at the end of a mission. These mechanical systems include the winch and slip ring. The winch drum on the deck of the towing boat was designed to have a diameter that is larger than the minimum bending radius as specified by the towing line manufacturer. For this purpose, the diameter of the winch drum is 150 mm. The slip ring is the electrical device that allows the current to flow between the cable rolled around the winch drum and the cable entering the control unit on board the towing boat. The chosen slip ring can operate at voltages up to 1000 V and a current of 7.5 A. The electrical power from the towing boat was supplied at 220 VAC and a power management system made up of the following modules was designed:

- Vicor EN1C11: front-end AC with “passive power factor correction” and “auto-ranging function” that converts 220 VAC input voltage to 300 VDC.
- Vicor V300A12E500B: DC/DC switching block, which converts the voltage from 300 to 12 VDC.

These modules provide a power management system with high standards of performance in terms of robustness, reliability, and efficiency. For these modules, two electronic boards that can accommodate the devices have been designed and built. A suitable filter system has been integrated on the boards to meet the standards on EMC compliance. Different protection devices were also installed. Upstream of the AC supply, a differential circuit breaker has been provided, which has the double function to disconnect the towfish in case of a current surge or an earth fault. This provides safety for the towfish operator and for the towfish itself while adjustments are being made. Electronic boards have also been fitted with electrical fuses that offer protection against overcurrent. In addition to these, in order to monitor the correct operation of the power plant, the current sensor LEM HAIS 50-P and the voltage sensor 220 VAC—LEM LV 25-P have been used.

Control system

In order to successfully control the depth of dive and attitude of the towfish, a specific control system has been developed. The general architecture of the control system is made up of:

- Five DYNAMIXEL MX-64R motors having an output torque of 6 Nm (12 V). The motors include two actuators for the elevators, one actuator for the rudder, and two actuators for the stabilizers.
- Cables, connectors, and accessories for the motors;
- A control system that adjusts the trim and the depth position of the towfish.
- A data acquisition system that stores parameters used to control the towfish.

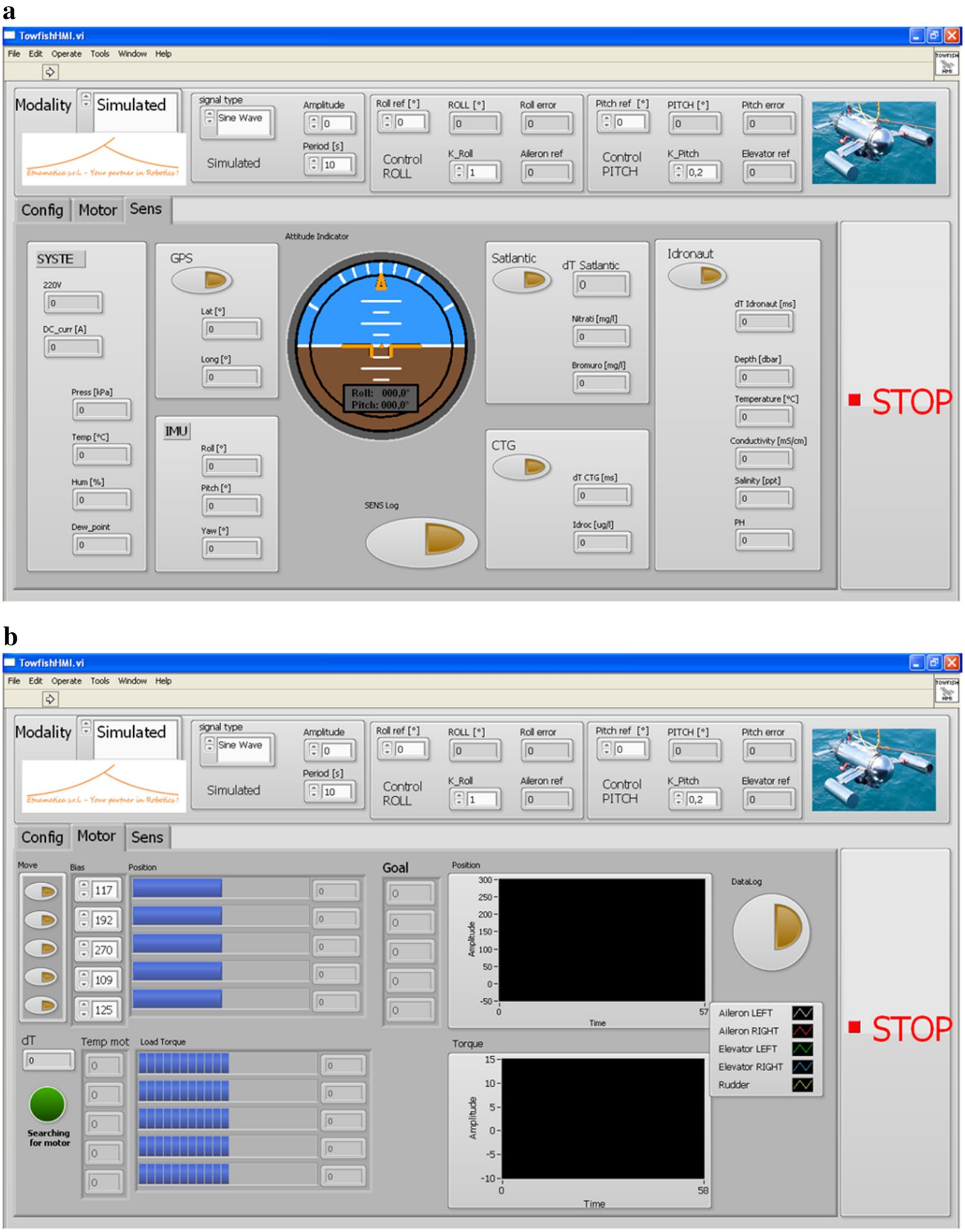
This system uses a National Instruments NI SB9636 board. The board integrates real-time processing, FPGA, I/O digital and analog interfaces, and the attitude and depth sensors so that adjustments to the aileron and elevator angle of attacks can be made to control the towfish. In order to facilitate the control of the towfish during a mission, a human machine interface (HMI) on board management system was developed. The HMI uses PC support based on the Windows operating system. The software interface (Labview 2013) is equipped with a controller that allows the user to interact with it in order to change the attitude parameters and towfish position, allowing the towfish to be manually controlled to modify the control parameters, to set a path trajectory for the towfish to be followed automatically, to collect data and to follow the jelly fish video camera shooting. The HMI is shown in Fig. 11a and b. As can be observed, it is possible to follow all physical parameters and data transmitted from the sensors. The desired pitch and roll to be followed during towing can also be set. A second interface provides for monitoring motors and to set flight paths or desired pitch angles. A third interface, not shown or described in this paper, pertains to GPS data, baud rate, parity, stop bits, flow control, as well as joystick input and log files for saving the data coming from the sensors.

Sensors

The proposed architecture provides the use of a sensor platform that allows the user to accurately determine the trim and the depth position of the towfish. In order to allow communication, considering a mean length of the umbilical cable of about 600 m, a suitable data transmission system based on devices “Ethernet extender” rate which allow bidirectional communication at high baud with the boat has been used.

The architecture is made up of a sensor board measuring system which determines, stores, and transmits the required towfish parameters. These include:

- Trim: inertial platform STM Inemo; this device allows the operator to get all the angles of pitch and roll of the towfish.
- Depth: obtained from the USBL Underwater Positioning System, Sonardyne.
- Speed: derived from the GPS on the boat.
- Temperature/humidity level inside the towfish: obtained using a Sensirion SHT75 sensor.
- Internal pressure sensor: obtained using Freescale MPX-H6300A6U.



a

Modality: Simulated

signal type: Sine Wave

Amplitude: 0

Period [s]: 10

Simulated

Control ROLL

Roll ref [°]: 0

ROLL [°]: 0

Roll error: 0

K_Roll: 1

Aileron ref: 0

Control PITCH

Pitch ref [°]: 0

PITCH [°]: 0

Pitch error: 0

K_Pitch: 0,2

Elevator ref: 0

SYSTE

220V: 0

DC_curr [A]: 0

Press [kPa]: 0

Temp [°C]: 0

Hum [%]: 0

Dew_point: 0

GPS

Lat [°]: 0

Long [°]: 0

IMU

Roll [°]: 0

Pitch [°]: 0

Yaw [°]: 0

Roll: 000,0°
Pitch: 000,0°

Satlantic

dT Satlantic: 0

Nitrati [mg/l]: 0

Bromuro [mg/l]: 0

CTG

dT CTG [ms]: 0

Idroc [ug/l]: 0

Idronaut

dT Idronaut [ms]: 0

Depth [dbar]: 0

Temperature [°C]: 0

Conductivity [mS/cm]: 0

Salinity [ppt]: 0

PH: 0

b

Modality: Simulated

signal type: Sine Wave

Amplitude: 0

Period [s]: 10

Roll ref [°]: 0

ROLL [°]: 0

Roll error: 0

K_Roll: 1

Aileron ref: 0

Pitch ref [°]: 0

PITCH [°]: 0

Pitch error: 0

K_Pitch: 0,2

Elevator ref: 0

Bias	Position	Goal
117	0	0
192	0	0
270	0	0
109	0	0
125	0	0

dT: 0

Temp mot	Load Torque
0	0
0	0
0	0
0	0
0	0

Position

Torque

Fig. 11 **a** Human machine interface (HMI): sensors interface. **b** Human machine interface (HMI): motors interface

- HD camera: GoPro 3 with baloon video for the transmission of the analog video signal.
- Cables, connectors, and accessories for the previous sensors.

The measuring system is also interfaced with the hydrometric sensors present on board the towfish: CTD sensor, hydrocarbon sensor, nitrate sensor (Idronaut).

Towfish testing

The design and fabrication phase of the towfish was followed by a series of tests to verify the towfish structural integrity and the correct operation of the actuators. In order to be able to collect and analyze the data of the testing campaigns, software called BioDiWare was developed. BioDiWare was used to analyze and compare data collected at different times and on different days during the year. BioDiWare collects all the results of the project BioDiValue and is divided into three categories: environmental analysis, maritime traffic, and cost of pollution. The section on environmental analyses is further divided into the following topics: waste analysis, biochemical analysis, and analysis of the data collected by the towfish. The latter section contains the data of all the campaigns carried out so far. The data that can be recorded are: depth of towfish, temperature, conductivity, salinity, pH, hydrocarbons, nitrates, and traces of bromide. The route taken by the towfish during one of the missions is shown through a Google map application. Clusters collect the points of the trajectory for a better visualization. Figure 12 shows the route of the towfish on its first campaign from the port of Augusta to Syracuse in Sicily. The points of the trajectory and the distance from the origin, expressed in nautical miles, are linked to the physical parameters recorded by the sensors. As shown in Fig. 13a and b, up to two parameters can be simultaneously displayed on screen. The data collected is used to monitor water pollution of critical zones and protected marine areas and to help biologists to define and come out with pollution models.

Some limited testing in data acquisition has been carried out at sea in order to test the sensors and the software developed for this purpose. The sampling rate is once every 5 s. The towfish has not yet been equipped with cameras to monitor plankton and jellyfish population. This is seen as a future addition to the towfish platform and to the BioDiWare software.

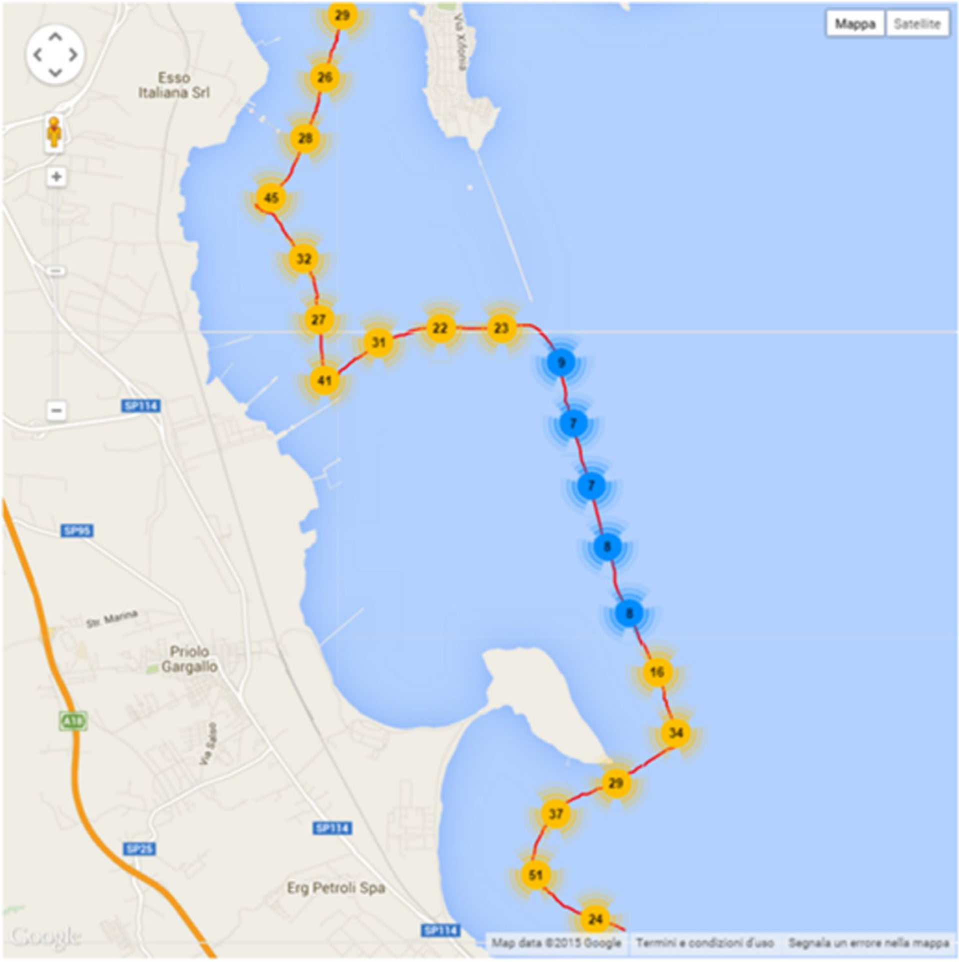


Fig. 12 The Towfish route on the first campaign from the port of Augusta to Syracuse

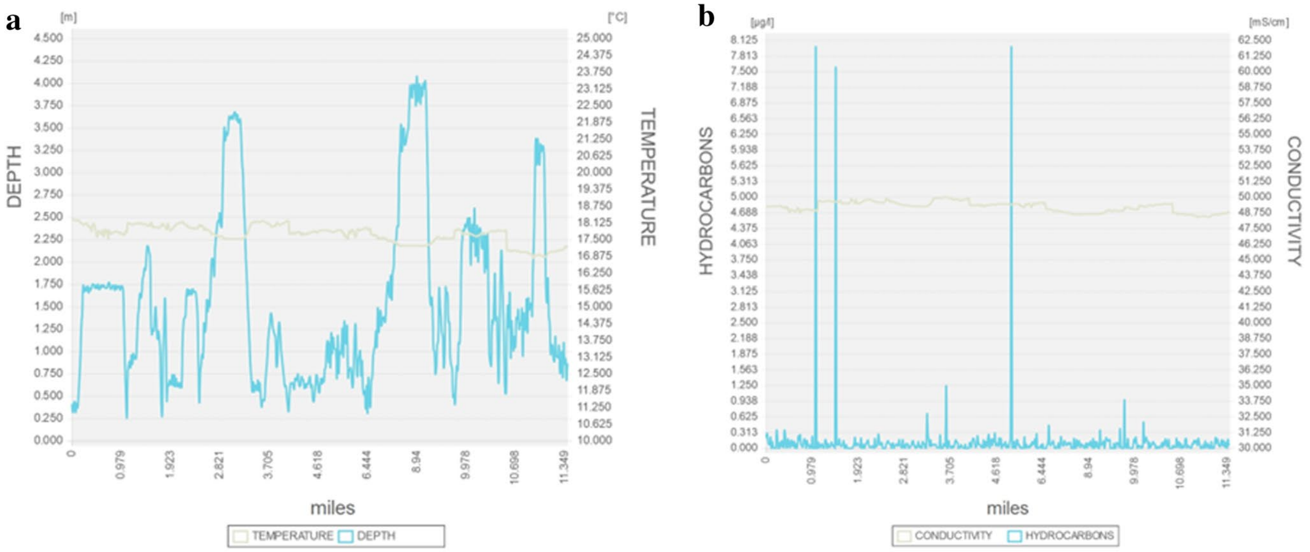


Fig. 13 **a** Temperature and depth plotted as a function of distance in nautical miles for the towfish route from Augusta to Syracuse. **b** Hydrocarbons and conductivity plotted as a function of distance in nautical miles for the towfish route from Augusta to Syracuse

Conclusions

In this paper we have presented an overview of the design, fabrication, and testing of an underwater towfish that can be used to monitor water pollution caused by maritime traffic in the Straits between Malta and Sicily. The towfish is equipped with sensors to monitor seaborne pollutants such as hydrocarbons, nitrates, and bromide as well as physical parameters like conductivity, pH, temperature, and salinity at different depths. The towfish can also be equipped with cameras to monitor plankton and jellyfish populations. Five actuators move two main ailerons, two elevators, and one rudder that allow the towfish to reach a given depth and to maintain the correct pitch and roll attitude. An umbilical cable connects the towfish to the surface towing boat. The towing boat supplies power to the towfish and acts as a base for controlling the towfish and for recording data. A control board and a human machine interface are used to determine, store, and transmit vehicle parameters as well as control the depth of dive, pitching, and rolling actions of the towfish. Software called BioDiWare was developed to record and analyze all data collected during the towfish missions. These data can be used to monitor marine pollution in critical zones and in protected marine areas as well as to help biologists to develop seaborne pollution models. The paper presents a towfish design that is not widely available at a commercial level and that gives more flexibility and control to marine biologists in their expeditions at sea covering large monitoring areas. Future developments of the towfish include adding a camera to monitor jellyfish populations, developing a plankton recorder, adding new sensors, and developing a micro plastic picker.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there are no conflicts of interest.

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