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SPiraling Intelligent Robotic Underwater monitoring pLAtform (SPIRULA) - towards repeated, high density and low-cost seafloor monitoring

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***Abstract*—Repeated multi-modal seafloor observations over an extended period of time have significant applications in marine biology, chemistry and geology. Reducing the logistical effort, cost and complexity in monitoring technology for such tasks, will help to increase accessibility and availability of relevant long-term monitoring data. To this end, a new design concept, the SPiraling Intelligent Robotics Underwater monitoring pLAtform (SPIRULA), is introduced and evaluated. The key idea for SPIRULA is the combination of a static lander and a mobile autonomous vehicle, which is permanently tethered to the lander. Through shared data and energy between the two sub-systems SPIRULA can be made robust, small and with reduced complexity. By unwinding and winding from a passive drum with a taught tether the SPIRULA vehicle is forced on a circle involute path around the SPIRULA lander, which can be analytically described and used during system design and for navigation purposes. Spiraling paths have shown to be efficient in terms of coverage, for instance, a tether length of approximately $20\,\mathrm{m}$ allows already for a monitoring coverage of $1200\,\mathrm{m}^2$ around the lander. Given a conservative estimate of the energy expenditure of the SPIRULA system and a desired survey area of $1200\,\mathrm{m}^2$ at a constant speed along the path of $0.5\,\mathrm{m/s}$ it can be shown, that a total energy storage of $10\,\mathrm{kWh}$ would provide the system with the ability to conduct between 38 to 82 surveys depending on the sensor suite used. Those surveys can then be spread over days to months to provide a first step towards repeated long-term environmental monitoring on the seafloor with SPIRULA.**

***Keywords* - long-term seafloor monitoring, autonomous underwater systems, spiral surveys, ROS2, micro-ROS**

I. Introduction

A robust seafloor monitoring system that enables repeated surveys of an area of interest over extended periods of time (weeks or even months) is valuable in various marine applications, such as medium and long-term observations of environmental changes and their effects on the local ecosystem. Other potential applications include the long-term monitoring of gas seeps and the observation of dynamic seafloor processes over long time periods. Furthermore, the deployment of high-precision seafloor mapping capabilities with a limited footprint in terms of both size and budget has the potential to enhance accessibility and availability of relevant ocean floor data.

With the SPiraling Intelligent Robotics Underwater monitoring pLAtform (SPIRULA) we aim to develop a system that offers an affordable, robust, and compact (basic dimensions can be found in table I) solution for such tasks. Figure 1 illustrates the concept which is comprised of two key components, a static lander as the base and an autonomous underwater vehicle for larger area coverage. This hybrid structure enables the utilisation of the superior temporal monitoring capacity of static landers, along with the enhanced spatial monitoring of mobile platforms. Additionally, tethering the vehicle to the lander will provide added protection against system loss under often hard to predict environmental conditions during long deployments. At the same time the tethered system allows a significant reduction in size and complexity of the vehicle due to reduced onboard energy, computational and, as explained below, navigational instrumentation requirements.

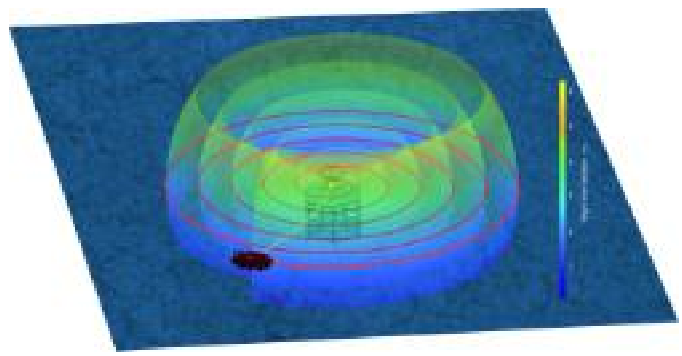

Figure 1. Figure showing the SPIRULA concept with circle involute path and achievable involute planes (see eq. (2)) for tethered SPIRULA vehicle at different heights from tether drum.

The tether is wound up on a passive drum, which will constrain the vehicle to follow a circle involute path, as shown in Fig. 1, around the lander under the assumption of a taught tether. This has several advantages: 1) The followed path can be analytically computed and used as an inexpensive navigation solution. 2) Tethering the vehicle reduces the risk of system loss. 3) Spiralling paths have been shown to be more efficient in covering a specific area for observation and

Table I
SPIRULA PROTOTYPE SYSTEM BASIC DIMENSIONS

Lander	Diameter	2 m
	Overall Height	1.5 m
Vehicle	Length	1 m
	Height	0.4 m
	Width	0.6 m
	Dry weight	37 kg

sampling purposes [1], [2], [3], [4].
Logarithmic spirals have been shown to be efficient paths for robot search tasks [1] and Archimedian spirals have been used in metrology [2] and the reconstruction of patchy distributions [3] due to its sampling efficiency. Circle involute curves have been shown recently to be optimal scan paths in surface topography [4].

In the underwater domain Pizarro et al. [5] have applied the spiralling survey concept. They constrained divers on circle involute paths to generate fast, structured and repeatable optical surveys for visual 3D reconstruction of the ocean floor. Tanaka et al. [6] demonstrated the first robotic application for constrained motion on a circle involute path and showed that it is possible to predict the motion of the vehicle within reasonable error margins by utilising information from the tether alone. Furthermore, they presented the first prove of concept of such a system in the field [7].
In order to develop SPIRULA we adapted and extended the works by Pizarro et al. [5] and Tanaka et al. [6], [7]. Instead of relying on a conventional remotely operated vehicle (ROV) as mobile platform, we have designed a purpose-built vehicle that has been optimized for unwinding and winding from the drum. A streamlined body design, as illustrated in Fig. 3 a), will result in a drag reduction compared to a standard ROV geometry. A dedicated thruster will be used to tension the tether, which enables the full thrust range of the remaining thrusters to be used for vehicle control. Additionally, a rotational joint at the tether thruster enables out of plane spiraling motions with minimal roll disturbances.

II. Concept of Motion

Assuming the vehicle is attached to a tether, which is wrapped around a drum with a defined radius R_D, neglecting the tether radius ($R_T << R_D$) and presupposing that the tether remains under tension during the operation of the system, we can state that the vehicle is constrained to move on a curved plane. This plane constitutes the sum of the involutes of the drum's circle for different altitudes relative to the drum's vertical center. The following geometric relations are extensions of the planar descriptions given by Pizarro et al. [5].

Given R_D, the angle α between the horizontal axis and the tangent to the drum circumference located at the point where the cable starts to wind/unwind around the drum (see Fig. 2) and the vehicle's height relative to the drum's vertical center Δh_D (see Fig. 4), we can define the position of the attachment

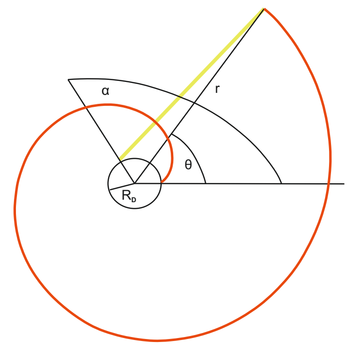

Figure 2. Relevant parameters for unwinding a tether (yellow) from a drum of radius R_D.

point of the cable on the vehicle in cylindrical coordinates (r, θ, z) as:

$$\begin{aligned} r(\alpha, \Delta h_d) &= \sqrt{R_D^2(1+\alpha^2) - \Delta h_d^2} \\ \theta(\alpha) &= \alpha - \arctan(\alpha) \\ z &= h_D + \Delta h_D \end{aligned} \tag{1}$$

By transforming (1) into Cartesian coordinates the following space curve $s_c(\alpha, \Delta h_D)$ is formed:

$$\begin{aligned} s_c(\alpha, \Delta h_D) = \langle & r_H(\alpha, \Delta h_D)\cos(\theta(\alpha)), \\ & - r_H(\alpha, \Delta h_D)\sin(\theta(\alpha)),\ h_D + \Delta h_D \rangle \end{aligned} \tag{2}$$

with h_D being the height of the drum over the seafloor.

Based on the assumption of $\Delta h_d = 0$ additional operational parameters such as path length L_f, survey time t_S and approximate survey area A_S can be defined. The path length L_P can be calculated as [5]:

$$L_P = \frac{R_D}{2}\ \alpha^2 \tag{3}$$

To compute the overall path length, which the vehicle is traveling for a given R_D and cable length L_C we first compute the final radius r_F:

$$r_F = \sqrt{L_C^2 + R_D^2} \tag{4}$$

and the final tangential angle α_F:

$$\alpha_F = \sqrt{\left(\frac{r_F}{R_D}\right)^2 - 1} = \frac{L_C}{R_D} \tag{5}$$

By inserting (4) and (5) into (3) we can compute the final path length L_F:

$$L_F = \frac{L_C^2}{2R_D} \tag{6}$$

Assuming a defined and constant velocity along the path $v_\parallel = const.$ one can also calculate the survey time t_S as:

$$t_S = \frac{L_F}{v_\parallel} = \frac{L_C^2}{2R_D v_\parallel} \tag{7}$$

Now given a desired survey area A_S and (4) one can define a relation between desired area, drum radius and cable length by assuming the total covered area can be approximated by a disc of area A_S:

$$A_S = \pi(L_C^2 + R_D^2) \tag{8}$$

If we assume the monitoring task will be based on visual information sampled by a downward looking camera, we can define a visual footprint b, which depends on the angle of view of the camera β and the vehicle's altitude h [5]:

$$b = 2h \tan\left(\frac{\beta}{2}\right). \tag{9}$$

Usually b will be different along and across the robot's path, so that one can define $b_\parallel$ and $b_\perp$. Additionally, one can define the number of views n of a specific scene point by:

$$n = \frac{b}{\Delta}, \tag{10}$$

with Δ being the displacement between frames. The displacement between frames along the path $\Delta_\parallel$ can be computed based on the velocity of the vehicle along the path $v_\parallel$ and the sampling period of the camera T_{cam}:

$$\Delta_\parallel = v_\parallel T_{cam}. \tag{11}$$

This means that in turn, the desired along path velocity can be computed based on the desired number of times a specific scene point should be sampled, as well as the camera specifications of along path footprint and sampling period:

$$v_\parallel = \frac{b_\parallel}{n T_{cam}} \tag{12}$$

The displacement across the path $\Delta_\perp$ can be computed by:

$$\Delta_\perp = \frac{b_\perp}{n} \tag{13}$$

To ensure sufficient coverage across the path $b_\perp$ should be bigger than the spacing between revolutions of the circle involutes S_r:

$$S_r = 2\pi R_D \tag{14}$$

Given the parameters R_D, L_C, A_S, h and $v_\parallel$ the circle involute paths can be designed according to the specific application. A parametric calculation scheme for the above shown parameters is provided as jupyter notebook under https://github.com/ChMeur/SPIRULA_ParameterComputation.

III. System Design

The SPIRULA system comprises an in-house written software framework together with a combination of custom designed hardware and commercially available pressure housings, basic electronic components and sensors.

BlueRobotic's 4-inch Aluminum tubes are used as electronics enclosures. Three enclosures are joined together to form one T-shaped enclosure via a central aluminum block with forward, backward and downward oriented O-ring flanges. This configuration anchors the whole system, and the origin of the central aluminum block provides a convenient and stable reference point for the vehicle coordinate frame. The forward and downward facing tubes are capped with acrylic domes to facilitate camera ports, while the endcap of the backward looking tube houses all connectors and penetrators to interface external systems with the vehicle electronics. Additionally, two 3-inch Aluminum enclosures from BlueRobotics are used to house four battery packs. The central electronics and battery enclosures, as well as the six thrusters are all suspended by a frame made out of high density polyethylene as shown in Fig. 3 b). A PLA 3D printed hull encloses the frame as shown in Fig. 3 a) to reduce drag and decrease risk of entanglement.

The SPIRULA vehicle is equipped with four battery packs, each providing 270 Wh, and a Nvidia Jetson Orin Nano, which provides guidance, navigation and control functionalities in ROS2 [8]. A STM32-based microcontroller board is used for interfacing with actuators and facilitates communication with the main computer via micro-ROS [9] in accordance with the concept developed in [10]. In its basic sensor configuration as shown in Fig. 3 d) the vehicle will employ a DVL (DVL A50 from WaterLinked) for velocity measurements, a USBL system (AvTrak Nano from Sonardyne) for surface positioning and communication purposes and as a payload, two cameras, one forward- (low light HD USB camera by BlueRobotics) and and one downward-looking (Alvium 1800 U-2460c from Allied Vision) with a lighting system (Lumen Subsea Light from BlueRobobtics). In addition the vehicle will carry a CTD (CTD48 from Sea and Sun Technologies) with a port for one additional environmental sensor, and a multi-beam sonar (Oculus M750 from Blueprint Subsea). However, the system is designed to be modular, allowing for the addition or replacement of payload components.

The SPIRULA vehicle employs a total of six T200 thrusters from BlueRobotics, from which five are dedicated for motion and attitude control. Two thrusters are allocated for surge and yaw directions, while the remaining three thrusters are used for heave, roll and pitch control. A sixth thruster, the tether thruster, is located on one side of the vehicle and is dedicated solely for tether tensioning. This enables the full thrust range of the remaining five thrusters to be used for vehicle control. The vehicle is configured and ballasted so that the center of mass is in line with the tether thruster, which provides additional stability. Furthermore, by attaching the tether thruster via a rotational joint it is possible for the vehicle to wind and unwind at different heights without significantly compromising roll stability. It is therefore possible to consider a number of different monitoring scenarios as illustrated in Fig. 4, where the vehicle can start at a safe distance from the seafloor with an initial survey, move then to a baseline survey at the same height of the SPIRULA lander and follow up with a detailed survey very close to the seafloor in case relevant features have been detected.

With regard to the SPIRULA lander, an early concept can be

Figure 3. a) rendering of SPIRULA vehicle with tether thruster and rotational joint. b) SPIRULA frame and thrusters during buildup. c) early concept of SPIRULA lander with drum. d) basic payload sensor suite for SPIRULA vehicle.

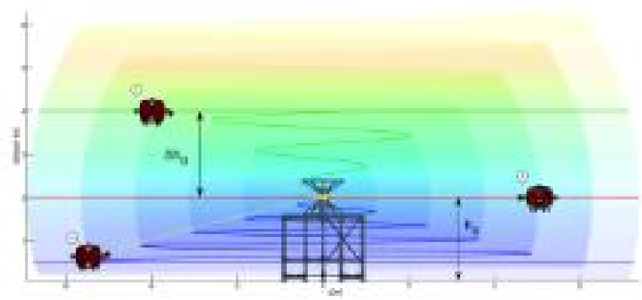

Figure 4. Vertical cross section for 3 circle involute paths varying in height from tether drum and enabling different measurement scenarios: 1) initial environmental mapping at safe altitude, 2) baseline survey at drum height, 3) detailed high-resolution mapping of points close to the seafloor.

observed in Fig. 3 c). In comparison to the design presented in [7] we extend the possible tether length, by enabling layered winding on the cable drum. Furthermore, we design the lander as a multipurpose platform that serves as a sensor and computation hub, vehicle garage, and mission control center. In order to enable these functionalities, the lander will be equipped with batteries that will provide approximately $10\,\mathrm{kWh}$ of energy, which will be used, besides covering the lander's own power requirements, to recharge the vehicle through the tether. Furthermore, the lander will be equipped with a Nvidia Jetson AGX Orin for payload sensor processing, navigation, high level decision making and mission control. The whole system is designed for target depths of up to $300\,\mathrm{m}$ targeting shallow applications on continental shelfs.

To ensure reliable self-sustained operation of the SPIRULA system, an autonomy framework is set up as shown in Fig. 5. The framework is distributed among four principle computing units, two microcontroller boards and two single board computers, which are either situated on the SPIRULA vehicle or the SPIRULA lander. The communication between lander and vehicle is ensured via ethernet through the tether. The STM-based low power microcontroller on the lander will be used as a scheduling manager to wake up the SPIRULA system for a user-defined number of surveys within the operational period and send the system back to sleep after each survey to conserve energy. The Jetson AGX on the lander will be used to perform computationally heavy tasks such as simultaneous localization and mapping (SLAM) or 3D reconstruction. Additionally, higher level decision making and planning will be carried out to ensure safe operation, manage the available energy and possibly facilitate adaptive sampling. For scientific data, edge processing can be also carried out to provide preliminary results right after recovery or via acoustic communication. On the vehicle side, the Jetson Nano is used to run the control and local state estimation algorithms as well as interface with the two cameras. The control framework constitutes a cascaded dual loop system with the inner loop controlling the tether tension via feedback force or visual feedback from the connection to the thether thruster. The outer loop establishes the 5 degree of freedom control for the SPIRULA vehicle, where roll and pitch will be regulated to zero, while surge, heave and yaw will either be formulated as a trajectory tracking, path following or waypoint tracking problem. The desired wrenches are then forwarded to the STM32-based microcontroller board that facilitates the control allocation and directly interfaces with the T200 thrusters.

State estimation and environmental sensing for the purpose of mapping and localization will be set up in a flexible manner to cater to the various user defined scenarios for long-term measurements. For highly precise navigation and geo-localization of sensor data, multi-modal SLAM [11] can be utilized, while for long term energy sensitive measurement scenarios state estimation algorithms can be used that solely rely on the tether based observation as shown in [6]. Furthermore, state estimation based on inertial sensor data aided by the DVL and/or USBL [12] can be used as a trade-off between energy demand and accuracy.

IV. Energy Budget

To gain insight into the operational capabilities of the SPIRULA System for long term monitoring it is essential to understand the energy budget of the system. We provide initial estimates of the expected performance regarding energy consumption for the system based on the total energy supply from the lander ($10\,\mathrm{kWh}$) and a rough estimate of the expected energy consumption by the system. Table III presents the average and maximum energy consumption for all relevant parts of the SPIRULA system. The energy demand for the thrusters is based on a preliminary analytical drag estimation for the SPIRULA vehicle.

Given the relevant parameters in Table II the Reynolds number of the SPIRULA vehicle can be calculated as:

$$Re = \frac{\rho u L}{\mu} = 477240.0 \approx 4.77 * 10^5 \tag{15}$$

Based on this Reynolds number and following [13] for cuboids with rounded edges, a reasonable assumption for

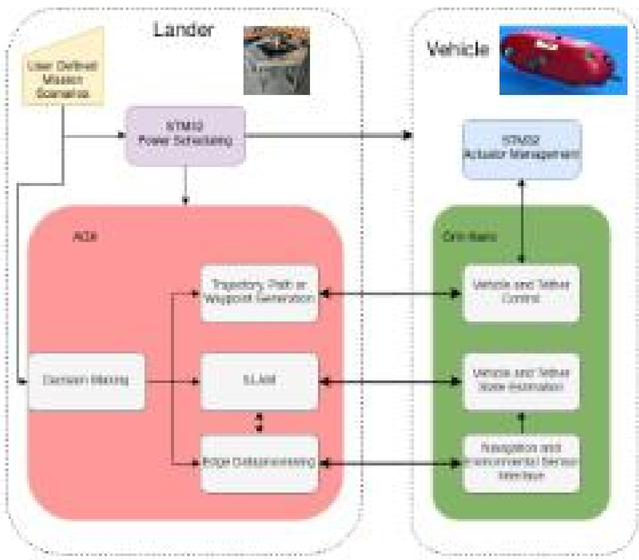

Figure 5. Autonomy framework for SPIRULA system: The autonomy framework is distributed over four different computing units running either ROS2 or micro-ROS: purple - STM-based low energy microcontroller with timer (micro-ROS) / red - Nvidia Jetson AGX (ROS2) / green - Nvidia Jetson Orin Nano (ROS2) / blue - STM32-based microcontroller board (micro-ROS).

Table II
RELEVANT PARAMETERS FOR DRAG ESTIMATION

vehicle surge velocity u	$0.5\,\mathrm{m/s}$
vehicle characteristic length L	$1.095m$
dynamic viscosity sea water at $20\,^{\circ}\mathrm{C}$ μ	$0.001\,09\,\mathrm{Ns/m^2}$
density seawater ρ	$1025\,\mathrm{kg/m^3}$

the drag coefficient would be $0.3 <= C_d <= 0.5$. This is also corroborated by drag coefficients listed by Hoerner [14]. However, the SPIRULA vehicle hull approximates more a bullet shape, which should decrease drag. At the same time the vehicle does not have a smooth surface facing the flow, but rather several blunt protrusions due to the forward looking sensors at the front of the vehicle. We thus decided to calculate with a conservative estimate of $C_d = 0.6$. Given this drag coefficient the assumed drag can be calculated as:

$$F_d = \frac{1}{2} C_d \rho A u^2 = 9.225\ N \tag{16}$$

With u and ρ as in table II and a reference surface area of $A = 0.12m^2$. The assumed drag will form the baseline to calculate the thruster demand based on the mapping between thrust output and energy input provided by BlueRobotics[1]. We further increase the assumed thruster demand to $15\,\mathrm{N}$ to account for roll, pitch, yaw and heave stabilization.

Based on (8) one can calculate that a tether length of $20\,\mathrm{m}$ allows for the coverage of an area of approximately $1200\,\mathrm{m}^2$.

[1] https://bluerobotics.com/store/thrusters/t100-t200-thrusters/t200-thruster-r2-rp/

Table III
ENERGY DEMANDS FOR RELEVANT PARTS OF SPIRULA SYSTEM

actuators	6 thrusters (15 N)	50 W
hotel load	Nvidia Jetson AGX Orin	15 W (60 W max)
	Nvidia Orin Nano	7 W (15 W max)
	Ethernet Switch	0.7 W max
	IMU	0.52 W
	DVL	4 W (35 W max)
	USBL	30 W max transmission
	Camera (forward looking)	1.1 W
payload	Camera (downward looking)	4 W
	4 Lights	15 W max per light
	CTD	0.5 W
	Imaging Sonar	10 W (35 W max)
	total	182.82 W (291.82 W max)

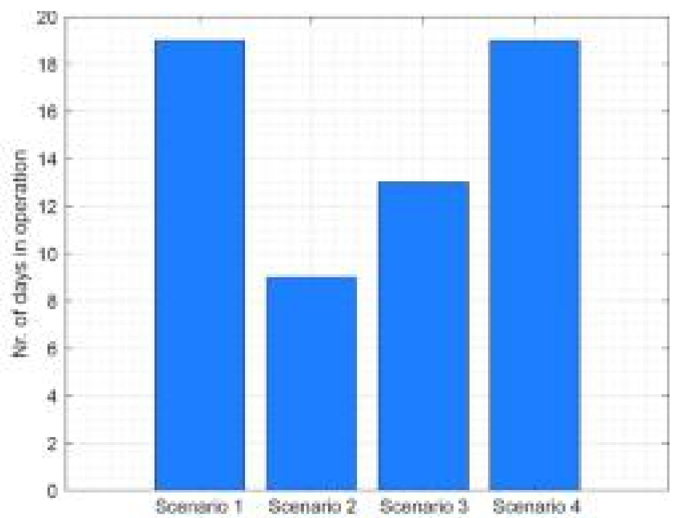

Figure 6. Energy considerations regarding the SPIRULA vehicle. Possible days of deployment based on estimated power consumption for various scenarios: Scenario 1 - two surveys with all payload sensors per day, Scenario 2 - four surveys with all payload sensors per day, Scenario 3 - 1 survey with all payload sensors and 4 surveys with only CTD per day, Scenario 4 - 1 survey with all payload sensors per week and 4 CTD surveys per day

Assuming a constant vehicle speed of $0.5\,\mathrm{m/s}$ the time required for a single survey, constituting the full unwinding and winding of the tether along the circle involute without any height deviations ($\Delta h_D = 0$), is estimated to be $1\,\mathrm{h}\ 6\,\mathrm{min}$. A conservative estimate of power consumption as summarized in table III allows for the calculation of the number of surveys and henceforth, depending on the deployment and sensing scenario, the number of deployment days as shown in Fig. 6, which vary in their usage of payload sensors. Given the conservative estimates of power-consumption, the maximum number of surveys that can be conducted, using the total energy storage from the lander, i.e. 10kWh, when all payload sensors are running for each survey is 38. Conversely, 82 surveys can be conducted when only the CTD is used.

V. CONCLUSION AND FUTURE WORK

By combining a static lander with a mobile autonomous vehicle the SPIRULA system promises to utilize both the temporal monitoring capacity of static landers with the enhanced spatial monitoring of mobile platforms. Tethering the SPIRULA vehicle permanently to the lander provides the vehicle with protection against system loss and provides added energy and computational capabilities to the SPIRULA vehicle, which in turn reduces the complexity and size of the mobile part of the system. The winding and unwinding of the tether from a passive drum forces the vehicle on a circle involute path if the tether is kept taught at all times which can be computed analytically and used for state estimation. Further analytic relationships between key design parameters such as cable length, drum radius and covered area can be established and optimized for a given application. A preliminary and conservative energy budgeting has further shown that the system is at least capable of between 38 and 82 surveys depending on the sensors used, showcasing the capability for repeated long-term surveys.

Future development steps include in-water tests with the SPIRULA system to investigate the static and dynamic behavior of the winding/unwinding from the drum at different lengths and heights and the capability to keep the tether taught at all times. In that regard we will investigate possible feedback control scenarios based on sensor data providing information about the tether. Furthermore, we will investigate the predictive performance of the tether angle on the vehicle position and on how to measure the angle reliably. We also aim to derive an integrated multi-body dynamics model for SPIRULA vehicle and tether to be used for control and state estimation purposes, as well as for simulations. Finally, we will extend the hardware design to a $3000\,\mathrm{m}$ capable version for future deep sea experiments.

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