Serpens, a low-cost snake robot with series elastic torque-controlled actuators and a screw-less assembly mechanism*

Filippo Sanfilippo[1], Erlend Helgerud[1], Per Anders Stadheim[1] and Sondre Lieblein Aronsen[1]

***Abstract*— Even though a few examples of elastic snake robots exist, they are generally expensive and tailored to custom-made hardware/software components that are not openly available off-the-shelf. In this work, *Serpens*, a newly-designed low-cost, open-source and highly-compliant multi-purpose modular snake robot with series elastic actuator (SEA) is presented. *Serpens* features precision torque control and stereoscopic vision. Only low-cost commercial-off-the-shelf (COTS) components are adopted. The robot modules can be 3D-printed by using Fused Deposition Modelling (FDM) manufacturing technology, thus making the rapid-prototyping process very economical and fast. A screw-less assembly mechanism allows for connecting the modules and reconfigure the robot in a very reliable and robust manner. By combining the rapid-prototyping approach with the modular concept, different configurations can be achieved. By using a low-cost sensing approach, functions for torque sensing at the joint level, sensitive collision detection and joint compliant control are possible. The concept of modularity is also applied to the system architecture on both the software and hardware sides. Each module is independent, being controlled by a self-reliant controller board. The software architecture is based on the Robot Operating System (ROS). This paper describes the design of *Serpens* and presents preliminary simulation and experimental results which illustrate its potential.**

***Index Terms*— snake robot, series elastic actuator, SEA, ROS.**

Fig. 1: A real snake locomoting in a cluttered environment (top); *Serpens*, the proposed low-cost ROS-based snake robot with series elastic actuator (SEA), precision torque control and a screw-less assembly mechanism (bottom).

I. Introduction

In nature, limbless organisms like snakes may exploit rocks, stones, branches, obstacles, or other irregularities in the terrain as a means of propulsion to achieve locomotion [1]. This remarkable ability allows biological snakes to be exceptionally adaptable to various types of environments. Snake robots that can replicate this range of behaviour could enable a variety of possible applications for use in challenging real-life operations and hazardous or confined areas that conventional robots (i.e. wheeled, tracked and legged) and humans are unable to access, such as explorations of earthquake-hit areas, pipe inspections for the oil and gas industry, fire-fighting operations, and search-and-rescue activities (SAR) [2]. Snake robot locomotion in a cluttered environment where the snake robot utilises a sensory-perceptual system to exploit the surrounding operational space and identifies walls, obstacles, or other external objects for means of propulsion can be defined as *perception-driven obstacle-aided locomotion* (POAL) [3], [4]. The development of POAL is known to be challenging because of the complex interaction between the snake robot and the adjacent cluttered environment. From a control point of view, achieving POAL requires to precisely identify potential push-points and to accurately determine achievable contact reaction forces. Accomplishing this with traditional rigidly-actuated robots is extremely demanding because of the absence of compliance.

To facilitate the control complexity for robots that interact with unmapped and dynamic environments or need to navigate rough terrains cluttered with obstacles, compliant motion and fine torque control on each joint is desirable. Consequently, intrinsically elastic joints have become progressively prominent over the last years. Commonly, elastic joints are considered to outperform rigid actuation in terms of peak dynamics, robustness, and energy efficiency [5]. Even though a few examples of elastic snake robots exist [6], they are generally costly to produce and tailored to custom-made hardware/software components that are not openly available off-the-shelf.

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In order to give researchers a novel snake robot that is inexpensive, easily customisable, and fast to fabricate, a newly-designed low-cost, open-source, and highly-compliant multi-purpose modular snake robot with series elastic actuators (SEA) is introduced in this work. The presented snake robot is named *Serpens* ("the Serpent", Greek Ὄφις) after the homonym constellation of the northern hemisphere. *Serpens* is shown in Fig. 1. *Serpens* features compliant torque-controlled actuators and stereoscopic vision. Only low-cost commercial-off-the-shelf (COTS) components are adopted to achieve a sustainable prototyping process. The robot modules can be 3D-printed by using Fused Deposition Modelling (FDM) manufacturing technology, thus making the rapid-prototyping process very economical and quick. A screw-less assembly mechanism allows for connecting the modules and for reconfiguring the robot in a very reliable and robust manner. By combining the rapid-prototyping approach with the modular concept, different configurations can be achieved. A low-cost sensing approach enables functions for torque sensing at the joint level, sensitive collision detection and joint compliant control are possible. The concept of modularity is also applied to the system architecture on both the software and hardware sides. Each module is independent, being controlled by a self-reliant controller board. The software architecture is based on the Robot Operating System (ROS) [7].

The paper is organised as follows. A review of the related research work is given in Section II. In Section III, we focus on the description of the mechanical overview. A software/hardware overview is described in Section IV. In Section V, some preliminary simulation and experimental results are outlined. Finally, conclusions and future works are discussed in Section VI.

II. Related Research Work

To achieve locomotion in a cluttered and irregular terrain, a snake robot must be able to adapt its body motion to the environment. This requires that the robot can sense environment contact forces acting along its body [8], [9]. The works in [8], [10]–[13] present snake robot designs featuring contact sensing capabilities. However, the vast majority of snake robots that have been designed so far adopt traditional gear-motor-driven actuators. This requires a very high degree of awareness of their surroundings to achieve POAL. When adopting traditional gear-motor-driven actuators, this implies that a very precise mathematical model that includes the interaction between the snake robot and the surrounding operational environment is needed. Furthermore, when considering POAL the high reflected inertia of rigidly actuated robots can cause possible collisions that may damage both the robot and the environment.

To avoid the risk of rigid collisions, an alternative approach is inspired by the ability of biological mechanisms to accurately achieve compliance (passively and/or by precisely control torque). Based on this idea, series elastic actuators (SEA) were introduced in [14] as a means of achieving compliant motion and force control with traditional gear-motor-driven actuators. Thereafter, the design and control of SEA has been widely exploited in the fields of legged locomotion [15], humanoid robots [16] and manipulators [17]. Regarding snake robots, different methods of achieving compliant motion by controlling the torques exerted by the joints of the robot were presented by the Robotics Institute at the Carnegie Mellon University [18]. These control strategies are implemented on a snake robot that includes SEA and torque sensing at each joint, and demonstrate compliant locomotion that adapts to the robot's surrounding terrain. This work is very pragmatic and has shown some success. However, the underlying idea is based on a relatively simplistic oscillation and adaptation of the torque to the surrounding obstacles. We hypothesise that exploiting full knowledge of the robot's configuration and surrounding environment can be more beneficial and can produce more reliable results with hopefully better performance. Moreover, the proposed robot design adopts financially demanding components and the software is not completely open-source.

To the best of our knowledge, a 3D-printable highly compliant multi-purpose modular robot that features SEA, precise torque control, open software/hardware and a screw-less assembly mechanism has not been released yet.

III. Mechanical Overview

In this section, the mechanical overview of *Serpens* is depicted by highlighting the the mechanical design, the proposed screw-less assembly mechanism and the adopted SEA. This novel design is exclusively based on a 3D-printing process with *polylactic acid* (PLA) through FDM with the exception of a limited number of elements such as springs, nuts, bolts, bearings and electrical components.

A. Mechanical design

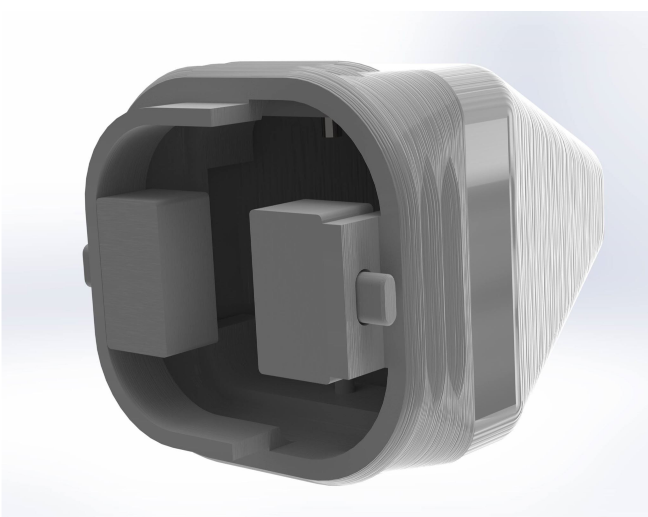
The construction of *Serpens* consists of similarly designed modules that are shown in Fig. 2 and include a head module, a varying number of joint modules, and a tail module.

Serpens allow for realising different connections, such as pitch, yaw and pitch-yaw. The pitch connection allows *Serpens* for moving only in 1D, forward or backward. The yaw-connecting configuration makes it possible to move *Serpens* like real snakes with all the joints rotating around the yaw axis. The pitch-yaw-connecting configuration enables *Serpens* to have some modules that rotate around the pitch axis and others around the yaw axis respectively. This makes it possible to achieve new locomotion capabilities, like winding side-way, rotating and rolling [19].

An exploded view of the joint module design is shown in Fig. 3 and it includes a screw-less assembly mechanism, a micro-controller, an actuator, an elastic gear, a rotary encoder, a bearing mechanism and a battery-pack. The proposed design enables the assembly process to be performed in an uncritical manner with respect to ordering and rotation of joints, while contributing to a better weight distribution throughout the body.

(a) The head module of *Serpens* with the *Intel RealSense D435* stereoscopic camera.

(b) One of the joint modules of *Serpens*.



(c) The tail module of *Serpens*.

Fig. 2: The head, joint, and tail modules of *Serpens*.

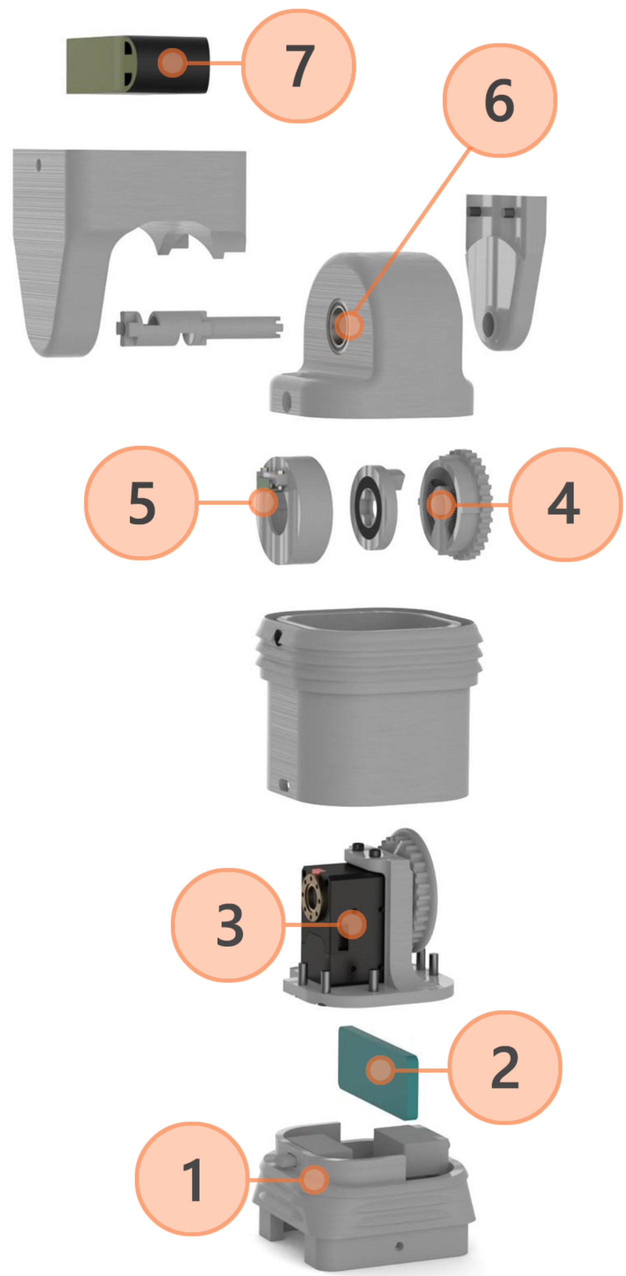


Fig. 3: An exploded view of a joint module. (1) screw-less assembly mechanism; (2) micro-controller; (3) actuator; (4) elastic gear; (5) rotary encoder; (6) bearing; (7) battery-pack.

B. *Screw-less assembly mechanism*

As shown in Fig. 4, a screw-less assembly mechanism is proposed for *Serpens* to easily interconnect each joint module through the adoption of specifically designed push-buttons. Each button consists of two springs that locks an oval cylinder in place when triggered. This novel mechanism makes it easier to access the battery-pack and the micro-controller of each module without requiring any tools. A complete dismantling of the modules is easily achievable with the removal of a few screws.

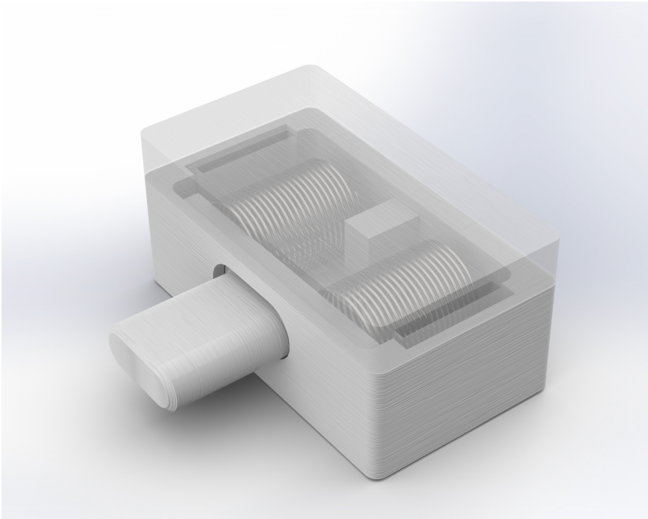


Fig. 4: The proposed screw-less assembly mechanism: it consists of three components with two springs orientated in the direction of the pin placed under the enclosure cover.

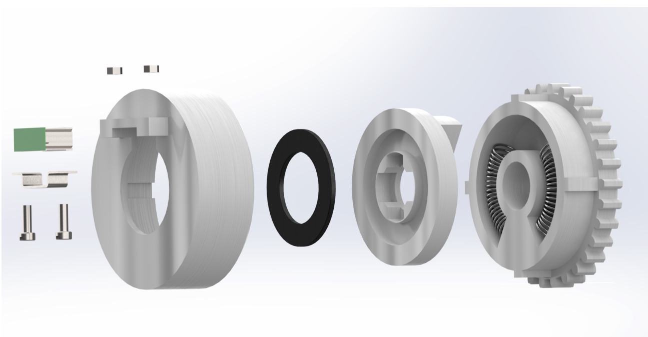


Fig. 5: The proposed design of the elastic gears for *Serpens*: the housing (left) with the encoder connected, the base (middle) with the magnetic rotary ring attached, and the cogwheel (right). The shaft (not depicted in this figure) runs through all parts. Compression springs are placed in the chamber of the cogwheel on each side of the outset of the base, providing passive-compliance.

C. Series elastic actuator (SEA)

A newly designed series elastic actuator (SEA) is embedded in each joint module. This makes it possible to achieve passively-compliant motion and precise torque-control. Each SEA deliberately introduces compliance via a compression-spring between the motor-gearbox and the load [20], and so has intrinsic low impedance. As shown in Fig. 5, the design of the elastic gear consists of a housing case with the encoder connected, a base with the magnetic rotary ring attached, a shaft, and a cogwheel. The intermediate element is connected to the shaft and works as a transmission between the cogwheel and the shaft itself. The cogwheel is connected to the actuator through a gear mechanism, where passive-compliance is provided by placing compression springs on each side of the outset of the base, in the chamber of the cogwheel. An encoder is employed to precisely monitor the misalignment/deviation of the compliant mechanism.

IV. Software/Hardware Overview

A. Open-source software

In line with the overall low-cost approach of *Serpens*, an open-source software framework is designed for the low-level control. To design the software architecture, the Robot Operating System (ROS) [7] is adopted. ROS is designed as a meta-operating system for robotic applications. The primary goal of ROS is to provide a common platform to make the design of capable robotic applications quicker and easier. Some of the features it provides include hardware abstraction, device drivers, message-passing and package management. In conjunction with ROS, Gazebo 3D simulator [21] can be adopted to accurately and efficiently simulate robots in complex indoor and outdoor environments. Gazebo also provides a robust physics engine, high-quality graphics, and convenient programmatic and graphical interfaces. In this perspective, ROS serves as the interface for the robot model of *Serpens*, while Gazebo is used to simulate both the robot and its operational environment. In addition to ROS and Gazebo, the RViz (ROS visualisation) [22] tool can be adopted to visualise and monitor sensor information retrieved in real-time from both the simulated scenario as well as from the real world. Other benefits for developers are the ROS community-driven support and the stable release-cycle of distributions (a new version is released every year, while a new long-term support (LTS) version is released every second year). Moreover, ROS offers an excellent interface to hardware components such as different micro-controllers and other peripheral hardware, e.g. actuators and sensors. The choice of ROS for the design of the control architecture makes it possible to extend the modular concept to both the hardware as well as the software of *Serpens*.

B. Hardware Overview

The control of *Serpens* is dependent on feedback from the actuators regarding position, velocity and torque. This feedback must be provided by the low-level controller of each actuator. For the design of *Serpens*, the *Dynamixel XM430W-210T*, a COTS actuator produced by *ROBOTIS* is selected for each joint module to meet these demanding requirements. This particular actuator provides the aforementioned data as well as additional feedback for temperature and input voltage. In addition to offering the required feedback, the *XM430W-210T* has a sturdy construction with full-metal gears and a metal body, while being able to deliver a stall torque of 3.0N.m (at 12.0V, 2.3A) in a operating temperature of -5°~80° [23], which is considered sufficient in regards to the applications and the future development of *Serpens*. The chosen actuator communicates through a half duplex asynchronous serial Transistor-Transistor Logic (TTL) communication and also facilitate for daisy-chaining, which provides a simple connection structure for multiple actuators.

For implementing the low-level control and the interception of feedback, a micro-controller is required at the joint level. To facilitate the integration with the ROS-based

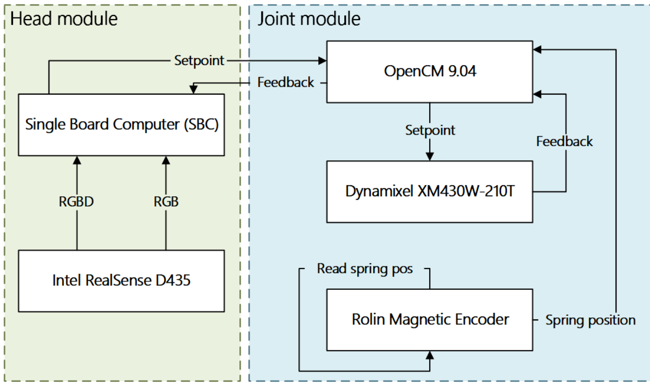


Fig. 6: The interface between the head module and each generic joint module.

architecture of *Serpens*, the *ROBOTIS OpenCM 9.04* micro-controller is embedded in each joint module. The *OpenCM 9.04* is a 32-bit *Cortex-M3* core micro-controller compatible with ROS. The form-factor of the *OpenCM 9.04* (27mm x 66.5mm) is a crucial parameter for the selection of this specific micro-controller for *Serpens*, given the limited physical space in the presented design of the joint module. In addition, since the high-level control can be centralised in a single-board computer (SBC) possibly located either in the head or in an external computer, while the low-level control is distributed to the micro-controllers embedded in each joint module, the computing power provided by the *OpenCM 9.04* is adequate for designated applications. The interface between the head module and each generic joint module is shown in Fig. 6.

C. Encoders

The proposed SEA are designed for passive-compliance, as described in Sec. III. Each joint module of *Serpens* is fitted with a rotary incremental encoder that is connected to the *OpenCM 9.04*. The encoder is vital to the control of each SEA, as it provides feedback for the absolute position of the load. In particular, a *RoLin* encoder system is adopted [24] for *Serpens*. The *RoLin* component level encoder system consists of a readhead and a magnetised ring. The actuator is a periodically magnetised ring with a pole length of 2 mm. Axial reading of the ring is adopted for *Serpens*.

D. Single-board computer and stereoscopic camera

The head-module is designed to be fitted with a single-board computer (SBC) and a stereoscopic camera. The implementation of the SBC is proposed to handle the high-level control of *Serpens*. To enable visual feedback of the surroundings of *Serpens* while traversing unknown terrains, a camera is also fitted into the head module. In particular, a reasonably small stereoscopic vision system is embedded because of the limited space in the design and the need for range detection. The proposed solution utilises a standard COTS *Intel RealSense D435* [25], a low-cost stereo vision camera comprising two depth sensors, an Red-Green-Blue (RGB) sensor, and a infrared projector. A considerable benefit of the *Intel RealSense D435* device is the *realsense2_camera* [26] package available for ROS, which provides a ROS-compatible interface to the *D400-series* from *Intel*, as shown in Fig. 7

E. ROS-based low-level architecture

The proposed ROS-based software architecture is illustrated by using a node-graph in Fig. 8. This shows a simplified view of the nodes and topics used to control n joints of *Serpens* in the current preliminary implementation. The nodes are represented as ellipses, while the topics are depicted as rectangles. The arrows represent publishers and subscribers, where an arrow directed towards an ellipsis or rectangle indicates a subscriber and an arrow directed outwards indicates a publisher.

The controller node can run either on an external computer or the SBC embedded in the head module. This node provides all high-level control for *Serpens* and acts as a hub for sensory data, such as the depth-sensor data collected by the *Intel RealSense D435*. As described earlier in this section, each joint module is provided with an embedded micro-controller (*OpenCM 9.04*) that is responsible for low-level control of the designated in the structure. Each of the boards acts as separate nodes in the ROS network architecture. In addition of being responsible for the low-level control, each joint module controller board also collects the feedback from the *XM 430W-210T* actuator and from the *RoLin* rotary incremental encoder. Each micro-controller implement a running ROS-node. This is shown in Fig. 8 as */serial_node_n*, where n denotes the micro-controller-index corresponding topics for each joint.

V. Simulations and Experimental Results

A simulation experiment is performed to highlight the behaviour of the proposed SEA of *Serpens*. As shown in Fig. 9, a scenario of a terrain cluttered with cylindrical objects is simulated. The entire body of *Serpens* is constrained by obstacles. The controller-node in the external computer intercepts the feedback through a subscriber and

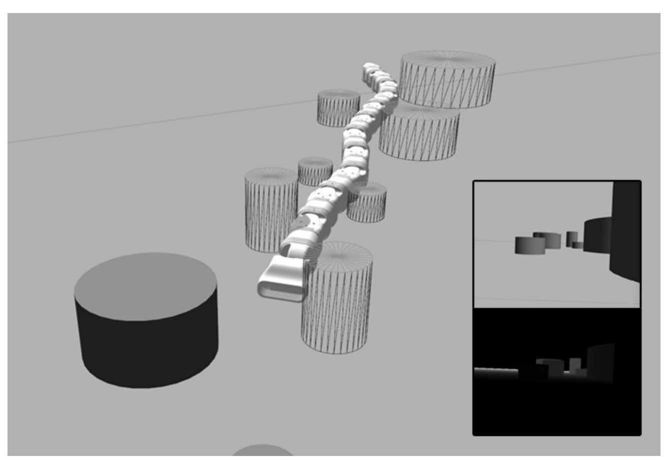


Fig. 7: The simulated Gazebo environment showing *Serpens* in a pitch-yaw configuration, and the output of the simulated RGB- (top) and RGBD (bottom) channels from the stereoscopic camera visualized through RVIZ.

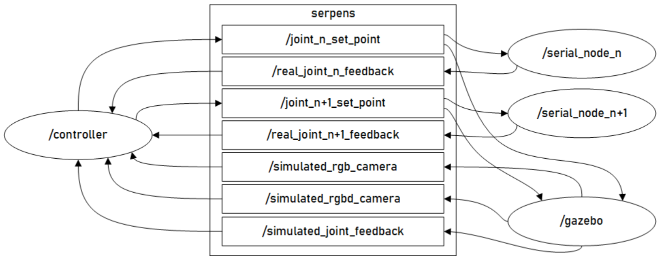
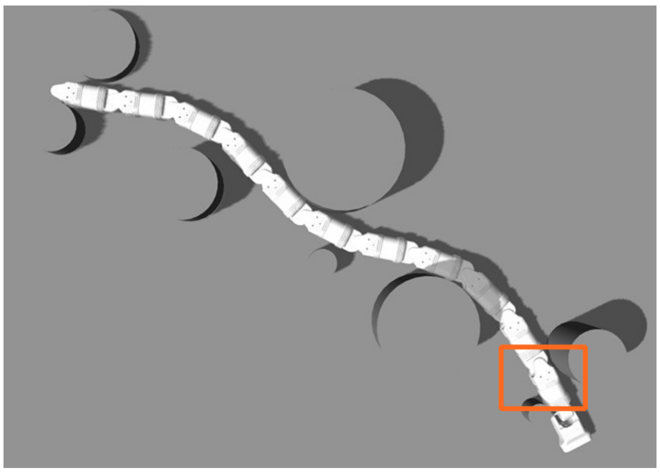
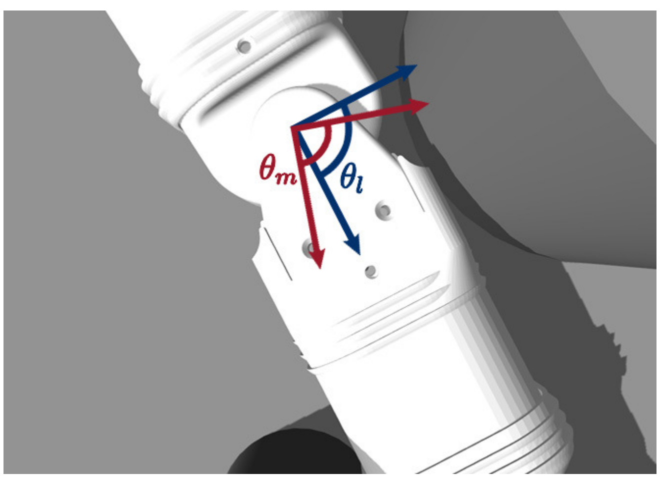


Fig. 8: Node-graph showing the structure of nodes and topics contributing to the control to both the simulated and physical robot.



(a) The input signal as outlined in (1) for the desired position (θ_d) is adopted to control the highlighted joint module close to the head.



(b) A zoomed view of one of the joint module while colliding with obstacles. The motor position θ_m is allowed movement through passive-compliance despite of the load position θ_l being blocked by external obstacles.

Fig. 9: The entire body of *Serpens* is constrained by cylindrical obstacles.

continuously publishes the desired position (θ_d) governed by the following equation:

$$\theta_d = A sin(2\pi(t + n\xi)), \quad (1)$$

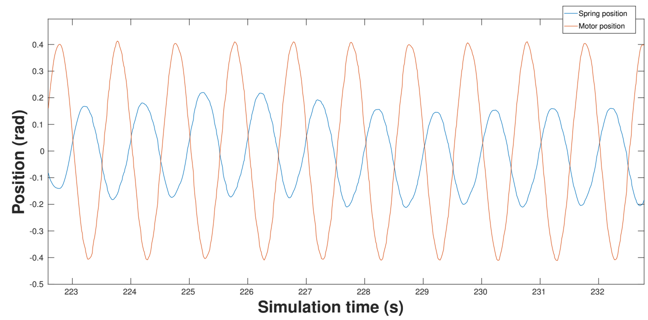


Fig. 10: The deviation over time between the motor gear position and the spring reference position.

where t is the time of the ROS-clock, n is the index of the joint to be controlled, and ξ is the spatial frequency. The oscillatory motion of the joint module determines collisions of the corresponding link with the adjacent obstacles. These collisions are accommodated through the high level of compliance offered by the SEA of *Serpens*. The motor position θ_m is allowed movement through passive-compliance despite of the load position θ_l being blocked by external obstacles. The consequential deviation over time between the motor gear position and the spring reference position is shown in Fig. 10.

VI. Conclusions and Future Work

Serpens, a low-cost snake robot with elastic joints, torque-controlled actuators and a screw-less assembly mechanism was presented in this paper based on a modular design and on the use of the Robot Operating System (ROS) [7]. The design of the robot relies exclusively on low-cost commercial-off-the-shelf (COTS) components. Fused Deposition Modelling (FDM) manufacturing technology is adopted for 3D-printing the robot modules with *polylactic acid* (PLA), thus making the rapid-prototyping process very fast and economical. A screw-less assembly mechanism makes it possible to assemble the modules and reconfigure the robot in a very reliable, fast and robust manner. A low-cost sensing approach is adopted to allow for torque sensing at the joint level, sensitive collision detection and joint compliant control. These characteristics make *Serpens* very suitable for the interaction with unmapped and dynamic environments or for traversing terrains cluttered with obstacles. The system architecture also follows the concept of modularity on both the software and hardware sides. Each module is independent, being controlled by a self-reliant controller board. The choice of ROS for the implementation of the control framework enables researchers to develop different control algorithms for perception-driven obstacle-aided locomotion (POAL) in a simulated environment with Gazebo. This integration makes the development of control algorithms more safe, rapid and efficient. Preliminary simulations and experimental results were presented to illustrate the potential of the proposed design. Additional experiments and simulations are presented in [27].

As future work, the design of reliable control algorithms for the proposed elastic joints will be investigated. Indeed, the design of robust and effective low-level control approaches is essential to enable the achievement of POAL for real-world applications. To achieve this, the current low-level software architecture of *Serpens* must be complemented with a hierarchical organisation by considering the standard functions and capabilities of guidance, navigation, and control (GNC). This would allow for extending the snake capabilities and responsiveness to external stimulus [28].

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