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The Redesigned Serpens, a Low-Cost, Highly Compliant Snake Robot †

Askan Duivon [1], Pino Kirsch [1], Boris Mauboussin [1], Gabriel Mougard [1], Jakub Woszczyk [1] and Filippo Sanfilippo [2,*]

[1] Department of Mechanical, Electronic and Chemical Engineering, Oslo Metropolitan University (OsloMet), 0130 Oslo, Norway; askanduivon@gmail.com (A.D.); p.kirsch97@gmail.com (P.K.); mauboussinboris@gmail.com (B.M.); gabriel.mougard@gmail.com (G.M.); s357571@oslomet.no (J.W.)

[2] Department of Engineering Sciences, University of Agder (UiA), Jon Lilletuns vei 9, 4879 Grimstad, Norway

* Correspondence: filippo.sanfilippo@uia.no

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Abstract: The term perception-driven obstacle-aided locomotion (POAL) was proposed to describe locomotion in which a snake robot leverages a sensory-perceptual system to exploit the surrounding operational environment and to identify walls, obstacles, or other structures as a means of propulsion. To attain POAL from a control standpoint, the accurate identification of push-points and reliable determination of feasible contact reaction forces are required. This is difficult to achieve with rigidly actuated robots because of the lack of compliance. As a possible solution to this challenge, our research group recently presented Serpens, a low-cost, open-source, and highly compliant multi-purpose modular snake robot with a series elastic actuator (SEA). In this paper, we propose a new prototyping iteration for our snake robot to achieve a more dependable design. The following three contributions are outlined in this work as a whole: the remodelling of the elastic joint with the addition of a damper element; a refreshed design for the screw-less assembly mechanism that can now withstand higher transverse forces; the re-design of the joint module with an improved reorganisation of the internal hardware components to facilitate heat dissipation and to accommodate a larger battery with easier access. The Robot Operating System (ROS) serves as the foundation for the software architecture. The possibility of applying machine learning approaches is considered. The results of preliminary simulations are provided.

Keywords: snake robot; series elastic actuator; SEA; robotics

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1. Introduction

Snake robots are very promising for exploring terrains and environments that wheeled, legged, and tracked robots, as well as people may not be appropriate for. Snake robots, as real snakes, can move through a variety of ground formations. These include flat ground, pebbles, as well as gravel, and tree branches, among others, where robots with different mobility systems may encounter significant difficulties. Snake robots are also ideally suited for operations in restricted locations, such as pipe inspections or search and rescue (SAR) missions in earthquake-affected areas, because of their shape and size.

With such a broad range of potential uses, it is attractive to design a snake robot that is simple to construct, inexpensive, and does not require much equipment or time to put together. At the same time, such a robot must be able to navigate autonomously through unfamiliar and unmapped terrain while consuming as little energy as possible. Perception-driven obstacle-aided locomotion (POAL) may be characterised as snake robot locomotion in a cluttered environment where the snake robot uses a sensory-perceptual system to leverage the surrounding operational space and to identify walls, obstacles, or other external elements as a means of propulsion [1–3]. The development of POAL is considered to be challenging due to the complicated interaction between the snake robot and its physical surroundings. As a result, the use of series elastic actuators (SEAs) at the joint level is desirable to ensure passive environmental compliance, as well as the capacity to store and subsequently release energy resulting from collisions with surrounding objects.

To tackle these challenges, Serpens, an open-source and highly compliant multi-purpose snake robot with SEAs, was previously introduced by our research group [4,5] as a preliminary approach towards a low-cost and modular design. However, there are still a few unanswered questions. The prior assembly process for connecting two modules was based on small push-buttons that took up little space, but proved to be insufficiently sturdy for long-term usage. Because the SEAs of Serpens are not equipped with a physical damper, dampening is performed only through the control algorithm. This method saves weight, but increases the danger of component damage in the case of a control or power failure. Furthermore, battery packs have a limited amount of space, and owing to the closed form of the module enclosure, difficulties caused by overheating of the motor may represent a considerable risk.

This work contributes towards the mechanical and hardware redesign of Serpens' modules. In the newly proposed design, which was recently outlined in [6], an eddy current damper (ECD) was added to the SEA, and the assembly mechanism gained a more reliable self-locking slide mechanism. The arrangement of the components inside each module was updated to accommodate a larger battery pack, which provided a longer operational time. Furthermore, the risk of overheating was countered with a novel heat dissipation approach. From a control perspective, the software architecture was designed based on the Robot Operating System (ROS) [7]. The results of preliminary simulations are provided.

The paper is organised as follows. A review of the related research work is given in Section 2. In Section 3, the main contributions of this work regarding mechanical, hardware, and control design are presented. In Section 4, the mathematical model of Serpens' elastic actuator system is outlined. Successively, the possibility of applying machine learning approaches is considered in Section 5. In Section 6, preliminary simulation results are outlined. Finally, conclusions and future works are discussed in Section 7.

2. Related Research Work

This section reviews related research work that summarises the state-of-the-art in mechanical design. The review focuses solely on SEA-equipped modular wheel-less snake robots. Snake robots must overcome several impediments to move across a variety of terrains and attain great flexibility while expending minimal energy. One design approach that seems to be promising but has only been explored by a few research groups [8–10] is to build a robot with a smooth outer surface and SEAs. The smooth outer surface enables the snake robots to navigate diverse types of terrain where wheeled, legged, or tracked robots may become stuck. SEAs have a high passive compliance with the environment, which reduces the risk of harm to the robot and simplifies the control algorithm. Furthermore, SEAs enable the snake robot to store energy in its joints.

SEAs were introduced in [11] as a means of achieving compliant motion and force control with traditional gear-motor-driven actuators. Thereafter, the design and control of SEAs has been exploited in the fields of legged locomotion, humanoid robots, and manipulators. Regarding snake robots, only a few examples exist. Nansai et al. presented a design in [8] where rotational springs between two gear stages are used as a means of storing energy. By using universal joints with two motors, movement in the three-dimensional space becomes possible with the help of SEAs. Due to the necessity of having a very lightweight robot, the motors in this design are very small and the SEAs provide the ability for a high power output working towards the goal of a climbing or jumping snake robot. In [9], Rollinson et al. presented the *SEA Snake*, a very compact snake robot with one-degree-of-freedom (DOF) joints, as well as elastic actuation for compliant motion and fine torque control. The proposed SEA consists of a rubber elastomer, which is bonded between two tapered plates and torsionally sheared during actuation. In [12], the design, fabrication, and modelling of this compact, high-strength series elastic element designed for use in snake robots were presented, which was able to achieve mechanical compliance and energy storage that was an order of magnitude greater than traditional springs. Koopaee et al. introduced another design variant for SEAs in [10] where a water-jet-cut polyurethane-based elastic element was used. In this case, the SEA consists of one inner ring and one outer ring connected by four s-shaped blades, which provide elasticity. What is notable about this approach is the low cost of the manufacturing process and the fact that this module may also be integrated into existing snake robots. A low-cost approach was also followed by our research group in the design of Serpens [5], where the output gear of the motor of each SEA is connected to the shaft of the joint via two bent translational springs inside the gear and a ring that connects the springs with the output shaft.

3. Proposed Design

This section presents the choices made in terms of hardware, mechanics, and software for the redesign of Serpens. In particular, this work focused on the revamping of the joint modules, while the head and the tail modules are beyond the scope of this paper. Each module shares the same design and is composed of the same components.

3.1. Hardware Design

The redesign of Serpens relied exclusively on low-cost commercial off-the-shelf components. Special attention was given to the fact that Serpens is easy to manufacture by choosing parts that do not require many modifications to fit the intended purpose of the snake robot. For this reason, the same torque-controlled servo motor that was adopted in the first prototype of Serpens [5] was chosen: the Dynamixel XM430-W210-T produced by Robotis. Two optical absolute encoders were used to measure the angular difference between the motor and the load side of the SEA. One encoder was embedded inside the motor, the other one on the shaft of the joint. The encoder linked to the load was an AMT20 Series from CUI devices.

Each module of Serpens is powered by a battery pack consisting of three 18650 lithium-polymer cells with 3 Ah and controlled by an OpenCM9.04 motherboard mounted on the OpenCM485 expansion board, both produced by Robotis. The TDK InvenSense ICM-42605 inertia measurement unit (IMU) with a 3-axis gyroscope and a 3-axis accelerometer was used to determine the current state of the module. It provides the orientation of each module, as well as information about the surface on which the robot is moving (i.e., by evaluating the acceleration, conclusions about the frictional forces may be drawn). The IMU sensor could also be used to provide information about the surface on which the robot is moving. Terrain identification has been an important topic for wheeled autonomous vehicles [13]. For example, a method to classify terrain based on vibrations induced in a robot rover by wheel–terrain interaction during driving was presented in [14]. An accelerometer installed on the robot structure was used to monitor vibrations. During an offline learning phase, the classifier was trained using labelled vibration data. Linear discriminant analysis was used to identify terrain classifications such as sand, gravel, and clay in real-time. On a laboratory test-bed and in outdoor circumstances, this technique was experimentally proven on a four-wheeled rover. Similarly, a method for terrain categorisation based on vibrations created in the robot's body was outlined in [15]. The vibrations were measured perpendicular to the ground surface by an accelerometer installed on the robot. The fast Fourier transform (FFT) and the power spectral density (PSD) were used to compare data representations in an experimental setting. A simpler and more compact representation based on features computed from raw data vectors, as well as a combination of this representation with the PSD were also suggested. A support vector machine (SVM) was used to learn and classify the data. Analogously, a terrain categorisation method based on 3D vibrations caused in the robot structure by wheel–

terrain contact was described in [16]. The robot's IMU was used to acquire acceleration information in three directions. The vibration properties of the known topography were then learned. The annotated three-axis vibration vectors were transformed into a frequency domain using the FFT. Normalisation was then used to obtain the training feature vectors. An upgraded back-propagation (BP) neural network was employed to obtain the mapping correlations between the vibrations and the terrain types, taking into consideration the peculiarities of the surroundings. Finally, categorisation testing was carried out on five different types of environments: concrete, grassland, sand, gravel, and mixed. Similar approaches could be adopted to effectively achieve POAL on different terrains.

The gears between the motor and the shaft of the joint were 3D printed. The shaft of each joint adopted two Igus iglidur JFM-0812-09 sliding bearings.

To dampen the rotation of the shaft in case of a sudden release of the SEA and prevent damage to any components, the new prototype of Serpens employs an ECD. It consists of the ITS-MSM-1811 electromagnet from Red Magnetics and a 2 mm-thick aluminium plate with a symmetric cut-out of 120° opposite the magnet to save weight.

3.2. Mechanical Design

The redesign of Serpens followed the same philosophy of the first prototype [5], which was based on the following principles:

- Minimalism: To make the robot inexpensive, easily customisable, as well as fast to manufacture, only commercial off-the-shelf (COTS) components or 3D-printed parts were used for the design;
- Screw-less assembly mechanism: To ease the connection of the robot's modules, a screw-less assembly mechanism was designed in a very reliable and robust manner;
- Symmetry and modularity: To facilitate the interaction with the environment, a symmetric design was adopted for each module. Moreover, identical modules were arranged as links to facilitate manufacturing. Each module is independent in terms of energy provision and control. This enables the user to add or remove modules at will.

An exploded view of the joint module design is shown in Figure 1. As shown in Figure 2, the redesigned module consisted of a prismatic shell, which facilitates locomotion, increases stability, and enables compact placement of the inner components. To provide better heat dissipation from the motor, a passive cooling mechanism was considered. A thin aluminium sheet, which was connected to one side of the motor, guides heat through a small slot in the shell to the outside of the module.

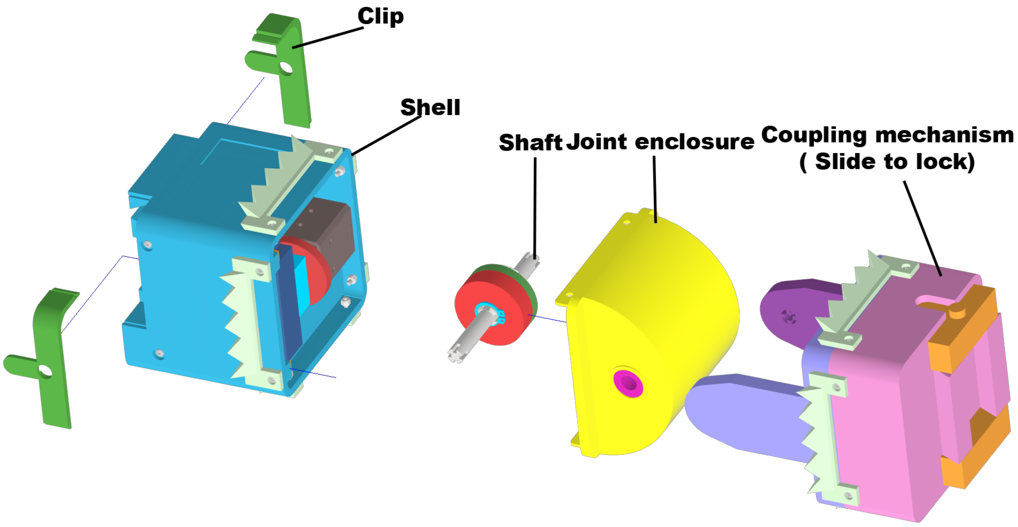


Figure 1. An exploded view of the module to describe the assembly of all parts.

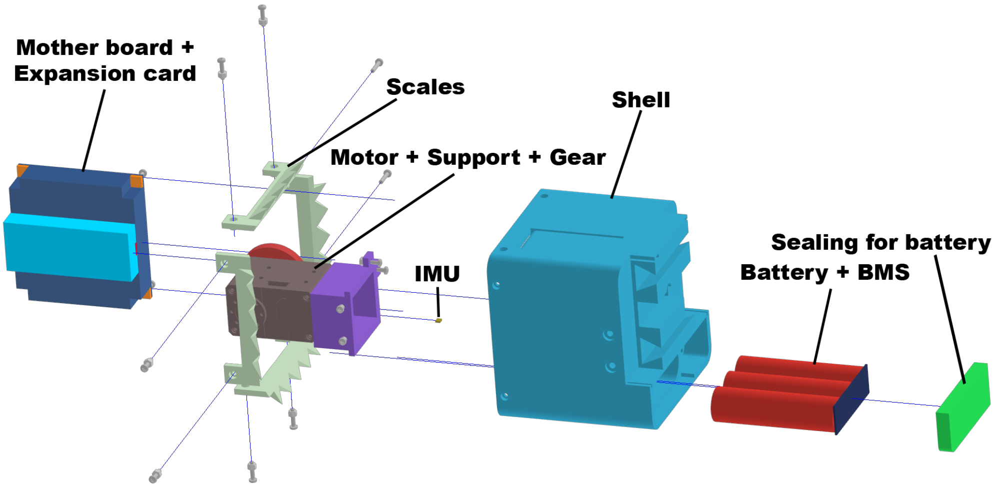


Figure 2. An exploded view of the prismatic shell and its components.

To enhance durability, a new coupling mechanism was developed. As shown in Figure 3, a new screw-less assembly mechanism was introduced based on a slide-to-lock approach, where a male component with the shape of a triangle fits into a female part with the shape of a triangular slide. To lock the connection in place, two spring-loaded arms, one on each side of the mechanism, block any translational movements. In addition, the slide-to-lock allows for realising different connections, such as pitch connection, yaw connection, and pitch–yaw connection. It only requires turning a quarter of the joint arm to change the connection.

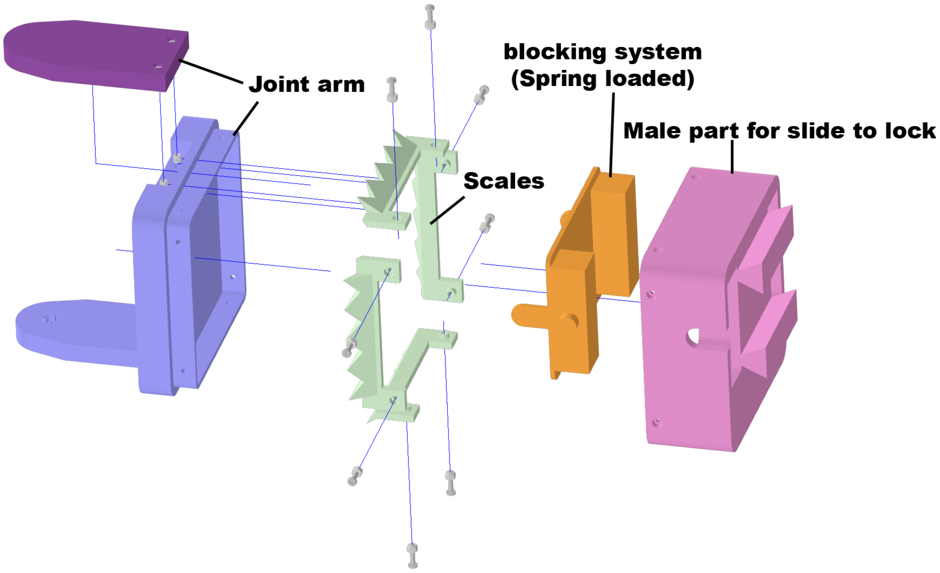


Figure 3. An exploded view of the coupling mechanism (slide-to-lock) and its components.

To facilitate locomotion in diverse surroundings, Serpens is now equipped with scales, which allow for a manual change of the material and of the orientation to adapt to multiple situations.

As the previous iteration of Serpens, the robot is equipped with an elastic actuation system, as shown in Figure 4. The design of the SEA was adopted from the first Serpens robot since it is an easy-to-build and space-efficient concept. The elastic actuation makes it possible to increase compliance with the surrounding environment, as well as to achieve higher robustness and energy efficiency [17]. The joint module of Serpens is characterised by the parameters in Table 1. The maximum number of modules that can be used was calculated according to our previous findings [18]. Let M be the number of modules of the snake. An upper bound of M was computed by considering the maximum motor torque that can be exerted on the module. We considered as the worst case the snake robot completely outstretched. In this situation, the maximum torque τ_{max} of the first module has to overcome the moment due to the weight w of the whole snake robot as defined in the following equation:

$$\tau_{max} > \frac{LMw}{2} \implies M_{max} = \left\lfloor \frac{2\tau_{max}}{Lw} \right\rfloor. \quad (1)$$

In our case, the maximum number of modules was 7. Therefore, the maximum snake length was 1470 mm.

A visualisation of the assembled snake robot is shown in Figure 5.

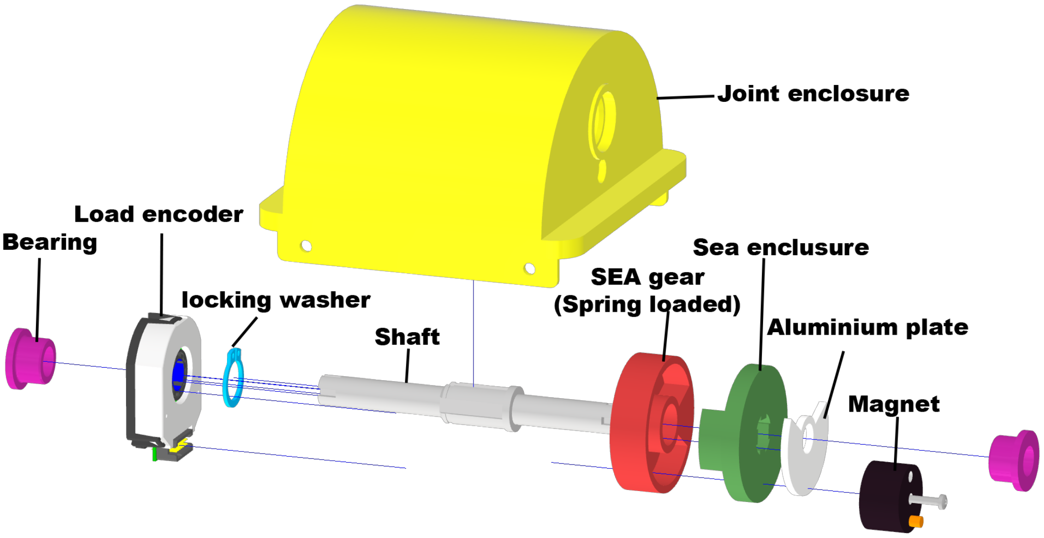


Figure 4. An exploded view of the joint and its components.

Table 1. Parameters of a Serpens joint module.

Parameter	Value
Weight	∼550 g
Width/height	90 mm
Length between joint axes	210 mm
Degrees of freedom	1
Max joint travel	±90°
Max continuous joint torque	3.0 Nm (at 12 V)
Max joint speed with no load	77 RPM (at 12 V)
Operating temperature (actuators)	−5 °C∼80 °C
Price	USD ∼ 500

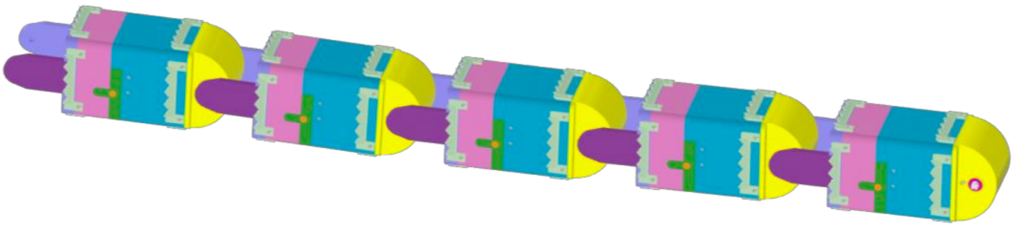


Figure 5. A visualisation of multiple Serpens modules.

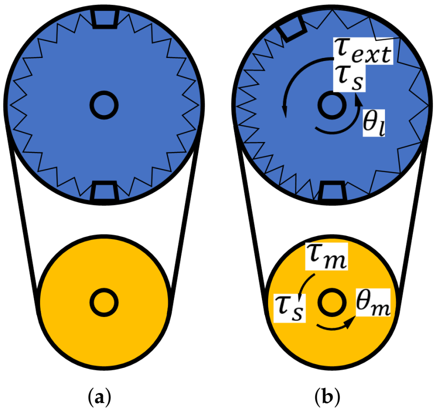
3.3. Software Design

As for the previous iteration of Serpens, the *Robot Operating System (ROS)* [7] paired with the *Gazebo* simulator [19] were adopted to design the software architecture. The RViz (ROS visualisation) visualisation tool was used in addition to ROS and Gazebo to visualise and monitor sensor data obtained in real-time from the simulated environment. These choices were based on our previous research experience [20–22]. To control the SEAs of Serpens, a two-feedback-loop position-control algorithm was previously proposed by our research group [23–25]. The inner controller loop was implemented as a model reference adaptive controller (MRAC), while the outer control loop adopted a fuzzy proportional–integral controller (FPIC). The performance of the presented control scheme was demonstrated. However, the efficiency of the proposed controller is dependent on the initial values of the parameters of the MRAC controller, as well as on the effort required for a human to manually construct fuzzy rules.

4. Mathematical Model and Kinematics

4.1. Mathematical Model of the Elastic Actuator

In this article, we focus exclusively on the control of a single elastic actuator. The corresponding schematic representations for Serpens' elastic actuator system are shown in Figure 6 [23]. There are two gears with gear ratio $N = Nl/Nm$, where Nl and Nm are the number of teeth for the load and the motor gear, respectively. Motor torque (τm), spring reaction torque (τ_s), and external torque (τ_{ext}) are depicted in these graphs. Figure 6a illustrates the system when there is no external force/torque, while Figure 6b illustrates the system affected by an external action.



(**a**) (**b**)

Figure 6. Elastic actuator system: (**a**) without external force/torque; (**b**) compressed/tensed by external action.

External disruptions have an impact on the entire system from the motor (d_m), as well as from the load (d_l). By denoting the motor angular position as θ_m, the load angular position as θ_l, the rotor inertia as J_m, the motor damping coefficient as D_m, the stiffness coefficient of the spring as K_s, the spring damping coefficient as D_s, the load inertia as J_l, and the load damping coefficient as D_l, the mathematical model of the elastic actuator system is obtained:

$$d_m + \tau_m - N^{-1}\tau_s = J_m\ddot{\theta}_m + D_m\dot{\theta}_m, \tag{2}$$

$$\tau_s = K_s(-N^{-1}\theta_m - \theta_l) + D_s(-N^{-1}\dot{\theta}_m - \dot{\theta}_l), \tag{3}$$

$$d_l + \tau_s + \tau_{ext} = J_l\ddot{\theta}_l + D_l\dot{\theta}_l. \tag{4}$$

Equation (2) shows the relationship on the motor side among the motor torque, the spring torque, and the motor angular position. The spring torque, τ_s, is obtained by Equation (3). The interaction among the spring torque, the external torque, and the load angular position is illustrated by Equation (4).

4.2. Kinematic Model of the Whole Robot

In the literature, there are examples of kinematic models developed for snake robots. Notable studies were presented in [26,27]. However, to the best of the authors' knowledge, only limited studies exist regarding the kinematic model of a snake robot with series elastic actuators. In [28], the authors presented the equations of motion of a modular 2D snake robot with SEAs moving in a vertical plane. The kinematics of such a 2D modular snake robot were presented in an efficient matrix form, and Euler–Lagrange equations were constructed to model the robot. Furthermore, external contact forces, which are required for simulating pedal wave motion (undulation in the vertical plane), were taken into account using a spring–damper contact model, which, unlike previous approaches, can be utilised to describe the impact of multiple contact points. The pedal wave motion of the robot was simulated using such a contact model, and the torque signal measured by the elastic element from the simulation and experiments was utilised to demonstrate the model's validity. Furthermore, the pedal wave locomotion of a such robot on uneven terrain was also described, and an adaptive controller based on torque feedback in the gait parameter space with optimised control gain was presented. The suggested controller's efficacy was demonstrated in simulation and experimental settings, as the robot successfully climbed over a stair-type obstacle without any previous knowledge of its position at a speed of at least 24.8% faster than non-adaptive motion.

Our work focuses specifically on the design, prototype, and simulation of a single module of the snake robot. The kinematic model of the whole snake is beyond the scope of this paper. We leave this as future work.

5. Possibility of Applying Machine Learning Approaches

Control algorithms for path planning of snake robots in unknown and unstructured settings must be developed with a focus on optimisation for environment adaptation and energy efficiency. Machine learning (e.g., deep learning) techniques may have great potential for such a challenge, according to current robotics advances [29]. Machine learning tasks are frequently divided into three categories based on how the learning process is carried out: supervised, unsupervised, and reinforcement learning (RL). The perhaps most-studied categories within robotics are supervised learning and RL. In supervised learning, the robot is presented with the correct behaviour, which must then be learned and generalised. Robot learning from demonstration [30] is an especially relevant sort of supervised learning since it is frequently easy to demonstrate the desired behaviour to the robot via teleoperation. In RL, the robot actions are assessed by an objective function, and the learning is carried out through interactions with the environment. To learn, the robot must trade off exploration and exploitation. Reference [31] provides a comprehensive study of RL in robotics. It is obvious that some form of adaptation/learning is desirable for snake robots. There has been some work on machine learning for snake robots [32,33], with the majority of the effort concentrating on optimising the control parameters for propulsion. These exploratory studies showed that machine learning can potentially be used for snake robots. With the recent improvements of deep convolutional structures (i.e., deep learning) [34], prospective applications to snake robots for path planning have become even more appealing. Deep learning allows computational models with several processing layers to learn various degrees of abstraction for data representations. Deep learning uses the backpropagation technique to describe how a machine should adjust its internal parameters that are used to calculate the representation in each layer from the representation in the previous layer, revealing the detailed structure in massive datasets. Convolution can be used for image classification by "sliding" a "filter" over the image, and "locomotion convolution" might be performed in a similar way by "sliding" a "propulsion filter" along the snake in various settings to pick the configuration that offers the highest propulsive efficiency. To the best of the authors' knowledge, no other snake robot techniques have been created in the prior literature. Creating such a mechanism would be a significant contribution.

5.1. Overview of Machine Learning Approaches for Snake Robot Locomotion

This section provides an overview of machine learning algorithms for snake robot locomotion. There are just a few publications in the literature related to this topic. The use of RL for the generation of locomotion patterns of snake-like robots as hyper-redundant systems, for example, was presented in [35]. In [36], an automated design strategy based on genetic programming (GP) was described to achieve the fastest feasible (side-winding) locomotion of simulated limbless, wheel-less, snake-like robots. The search space of the GP was reduced by modelling the snake robot as a system with identical morphological links and by automatically defining code fragments that were shared among (and representing the correlation between) the evolved dynamics of the vertical and horizontal turning angles of the robot actuators. Empirically obtained results proved the emergence of side-winding locomotion from relatively simple motion patterns of morphological links. The presented method was validated in terms of robot robustness, which was defined as the capacity of a robot to maintain its velocity in an unforeseen environment. This research might be seen as a first step in creating actual snake robots that can operate robustly in challenging conditions. Only the concepts of adaptability and robustness, however, have been studied in the literature thus far. To the best of the authors' knowledge, no equivalent techniques for leveraging roughness in the terrain as a means of propulsion (POAL) have been developed yet.

5.2. Proposed Control Approach Based on RL

To tackle the challenges related to our previous work [23–25], an alternative approach based on the use of methods that do not assume a priori knowledge was successively presented [37]. In particular, a novel controller was presented based on the use of an artificial neural network (ANN) that was trained with reinforcement learning (RL) by applying proximal policy optimisation (PPO). The adopted control architecture was organised in a hierarchical manner. Considering the standard functions and capabilities of guidance, navigation, and control (GNC) [38], the RL algorithm was applied to the control block, as shown in Figure 7. The proposed control scheme is shown in Figure 8. The input signals were the motor angular position θ_m, the motor angular velocity, $\dot{\theta}_m$, the load angular position, θ_l, the load angular velocity, $\dot{\theta}_l$, the load desired angular position, θ_{ld}, the error between the load desired position and the load actual position, $\varepsilon = \theta_{ld} - \theta_l$, and the error derivative $\dot{\varepsilon}$. The output signal was the motor torque τ_m. For further details on the proposed RL algorithm, the reader is referred to [37].

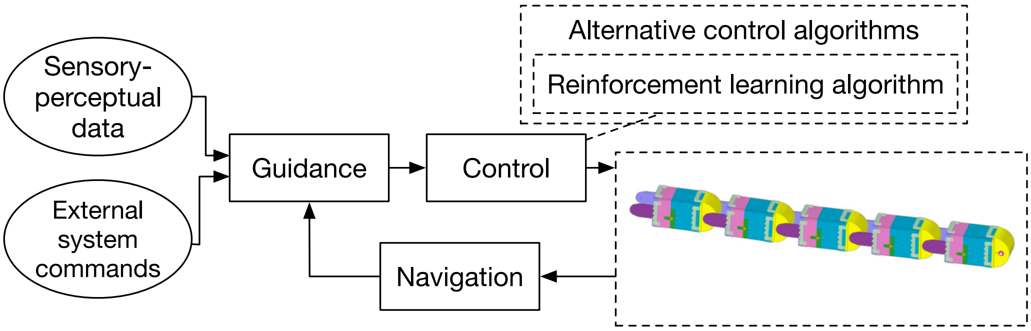


Figure 7. The idea of developing a novel low-level controller based on the use of an artificial neural network (ANN) that is trained with reinforcement learning (RL).

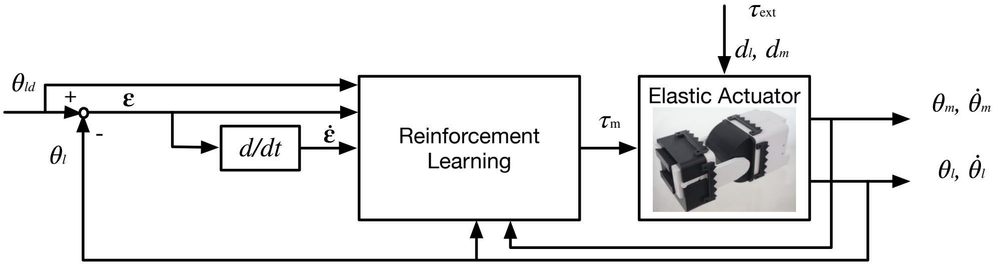


Figure 8. The proposed reinforcement learning system controller.

6. Experimental Results and Simulation

The 3D-printed robot module is shown in Figure 9. Preliminary simulation results are presented in this section. In this initial work, the scope of the simulation was to perform an exploratory test of the simulated model. The considered elastic actuator was simulated in Gazebo, as shown in Figure 10. It should be noted that in this preliminary simulation, the kinematic representation of one module was simulated. The simulation environment also shows the real-time plots related to the applied torque from the motor, the joint angular position, and the joint angular velocity. The proposed simulation framework makes it possible to develop different control algorithms and test them in a safe environment.

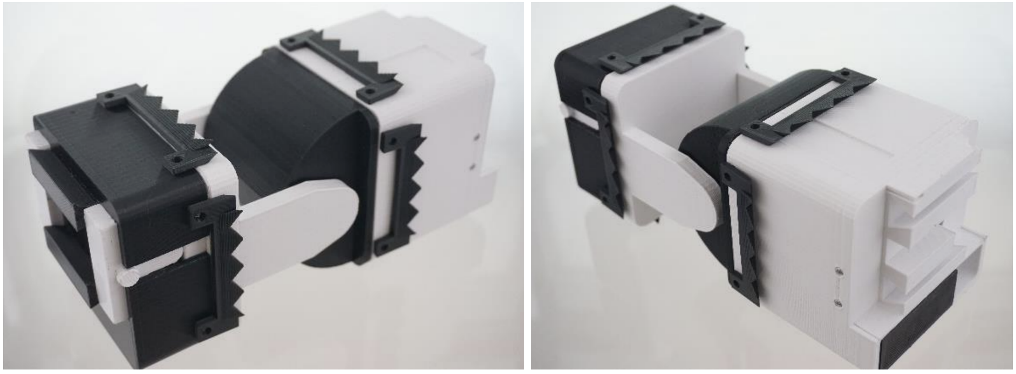

(**a**) (**b**)

Figure 9. The 3D-printed robot module: (**a**) slide-to-lock side; (**b**) battery side.

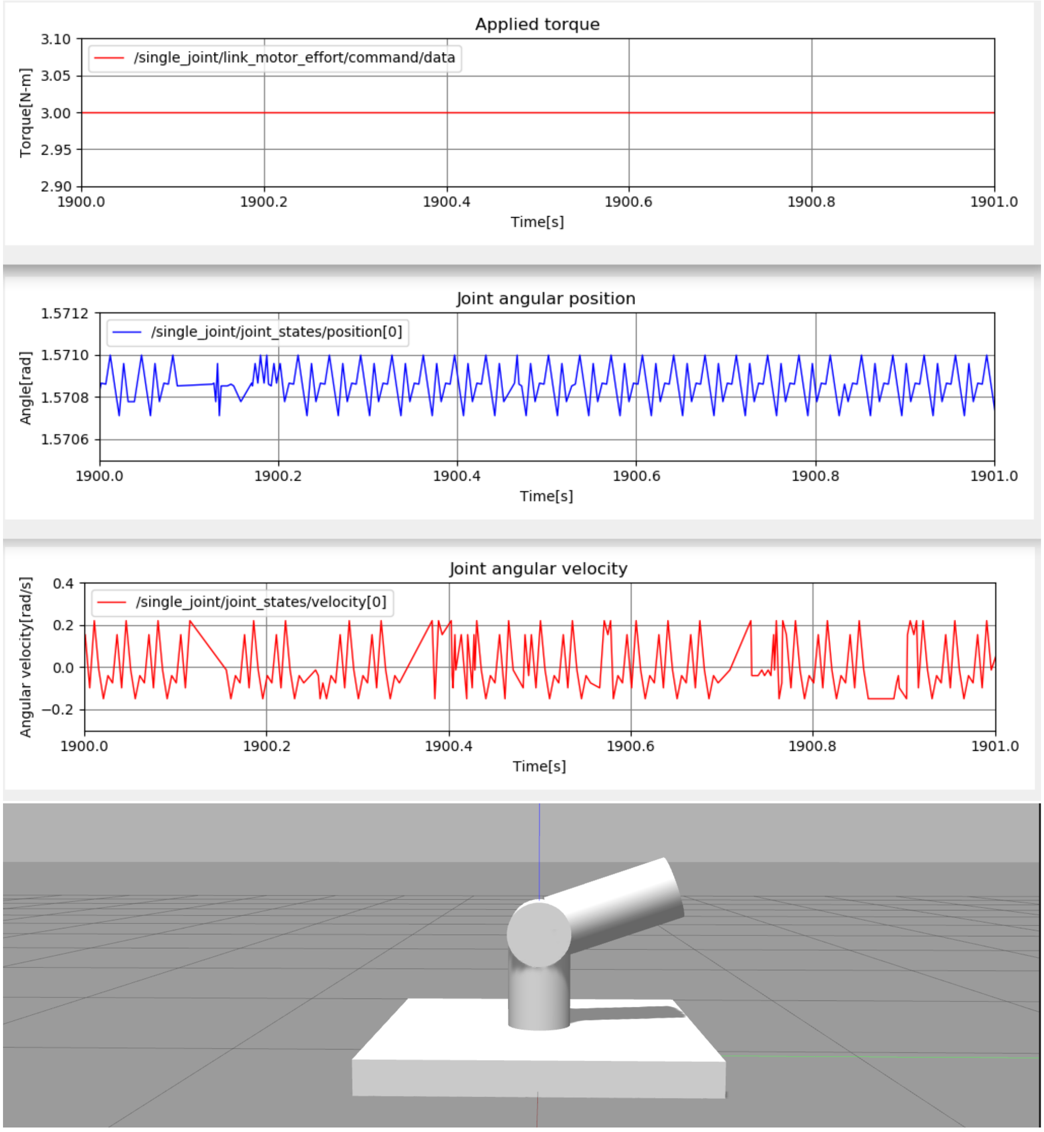


Figure 10. The elastic actuator is simulated in the Gazebo environment.

7. Conclusions and Future Work

This study proposed a redesign of Serpens, a modular, low-cost snake robot featuring series elastic actuators (SEAs) and a screw-less assembly mechanism. In comparison to the first prototype of Serpens [5], the main benefits of the new design iteration regard mechanical improvements. In fact, the newly developed mechanical design includes an eddy current damper (ECD) as part of the SEA, a sturdy screw-less assembly mechanism with a slide-to-lock approach, and a new layout for the components inside each module, allowing the use of a larger battery. The maximum number of modules is seven, while the maximum snake length is 1470 mm. As part of this new prototyping phase, the new module of Serpens was assembled and refined from a mechanical perspective. Our preliminary simulations focused on a first feasibility study of the proposed framework. The software architecture was built on top of the Robot Operating System (ROS). Successively, the possibility of applying machine learning approaches was outlined. The findings of preliminary simulations were provided. Regarding the achievable speed, load capacity of the robot, and energy balance, more experimental tests are required to estimate the real values.

The contribution and novelty of this work compared to existing solutions of other snake robots relied on the low-cost prototyping approach. Commercial off-the-shelf (COTS) components were used exclusively. The robot modules can be 3D printed, making rapid prototyping incredibly cost effective and quick. A screw-less construction system enables the dependable and sturdy connection of modules and reconfiguration of the robot.

Future work on the mechanical and hardware design of Serpens might look at possible alternatives to the chosen commercial off-the-shelf (COTS) components, such as employing a smaller motor in conjunction with a higher gear ratio, to reduce the weight/size of the modules. By modelling heat flow and optimising the cooling strategy, the motor's heat dissipation may be enhanced. The snake robot would be more resilient if the joints were water-proofed, allowing it to be used in a wider range of settings. Future research will focus on developing the kinematic model of the whole snake and on obtaining a more accurate simulation. Furthermore, to achieve optimal performance in a wide range of possible environments, the control design of Serpens could include the adaptation of multiple different gaits such as lateral undulation, side-winding, pedal wave locomotion, and finally, perception-driven obstacle-aided locomotion (POAL). It would also be worth considering the assessment of the proposed redesigned module regarding steering [39], path planning [40], the possibility of combining locomotion with grasping [41], and the opportunity to employ machine learning [42].

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Abbreviations

The following abbreviations are used in this manuscript:

POAL	Perception-driven obstacle-aided locomotion
SEA	Series elastic actuator
RL	Reinforcement learning
ROS	Robot Operating System
ECD	Eddy current damper

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