

# A robust two-feedback loops position control algorithm for compliant low-cost series elastic actuators\*

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**Abstract**—Elastic joints are considered to outperform rigid joints in terms of peak dynamics, collision tolerance, robustness, and energy efficiency. Therefore, intrinsically elastic joints have become progressively prominent over the last years for a variety of robotic applications. In this article, a two-feedback loops position control algorithm is proposed for an elastic actuator to deal with the influence from external disturbances. The considered elastic actuator was recently designed by our research group for *Serpens*, a low-cost, open-source and highly-compliant multi-purpose modular snake robot. In particular, the inner controller loop is implemented as a model reference adaptive controller (MRAC) to cope with uncertainties in the system parameters, while the outer control loop adopts a fuzzy proportional-integral controller (FPIC) to reduce the effect of external disturbances on the load. The advantage of combining the FPIC and the MRAC controllers is the possibility of achieving independence with respect to imprecise system parameters. A mathematical model of the considered elastic actuator is also presented to validate the proposed controller through simulations. The operability of the presented control scheme is demonstrated. In closed-loop the load swing is rapidly confined and eliminated thereafter.

## I. INTRODUCTION

When considering motion generation and control, actuators are key enabling components with properties that greatly impact the overall performance of any robotic system. Conventional actuators are guided by the traditional principle of “the stiffer the better” [1], [2]. Stiff actuators have high bandwidth which makes them suitable for position, speed control and trajectory tracking in constructed environments. However, in unknown environments, these rigid actuators can be damaged by undesired interaction with obstacles. Furthermore, most low-cost electric motors, which are used in robot actuators, have poor torque density at low speed and have to operate in high speed to obtain high torque density [2]. This challenge is traditionally addressed by using gear reduction at the expense of introducing friction, noise, backlash and torque ripple [2]. Compliant motion and fine torque control on each joint are required to tackle these challenges. Consequently, intrinsically elastic joints have been adopted for a variety of robotic applications over the last years. With elastic components working as a low-pass

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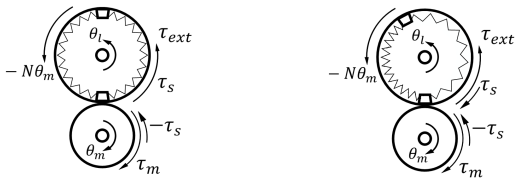


Fig. 1: *Serpens*, a low-cost snake robot with series elastic actuator (SEA), precision torque control and a screw-less assembly mechanism (top); the proposed design of the elastic gears for *Serpens* (bottom).

shock filter, shock tolerance is improved in unstructured environments. Furthermore, energy storage capability, power output and force sensing are also enhanced [3]. If the elastic component in an elastic actuator is a linear spring, the Hook’s law ( $F = K\Delta x$ ) can be utilised, and the force/torque control problem becomes as a position control problem. Despite having numerous advantages in force control, controlling position and velocity of elastic actuators is more challenge than conventional stiff actuators due to the fluctuation caused by elastic components. In addition, external forces/torques can cause the elastic actuator to deviate from its original position.

In this article, a two-feedback loops position control algorithm is proposed to deal with the influence from external disturbance: an adaptive control is designed in the inner loop to stabilise the system and deal with uncertainties, while a fuzzy controller is considered for the outer loop to eliminate the influence of external force/torque. As shown in Fig. 1, the considered elastic actuator was recently designed by our research group for *Serpens*, a low-cost, open-source and highly-compliant multi-purpose modular snake robot [4], [5]. A mathematical model of the considered elastic actuator is also presented to validate the proposed controller through simulations.

The paper is organised as follows. A review of the related research work is given in Section II. In Section III, we



(a) Without external force/ torque. (b) Compressed/ Tensed by external action.

Fig. 2: Elastic actuator system.

focus on the description of the proposed control algorithm. In Section IV, related simulation results are outlined. Finally, conclusions and future works are discussed in Section V.

## II. RELATED RESEARCH WORK

The advantages of elastic actuators are first outlined by Pratt and Williamson's research [2], where a proportional-integral-derivative (PID) control scheme was proposed. Similarly, proportional-derivative (PD) controllers with on-line gravity compensation are considered in [6], [7]. The global asymptotic stability of these control laws is demonstrated via Lyapunov's argument and La Salle's theorem. Another alternative approach is based on robust controllers with a disturbance observer (DOB) [8]. In [9], a combination of a feedback linearisation-based controller for the trajectory tracking problem and an extended state observer for uncertainty and states estimation is considered. Feedback linearisation and robust integral of sign of error (RISE) methods for controlling position are proposed in [10]. Specifically, the dynamics of the actuator is first feedback linearised, then a RISE method is applied to adapt the system model to uncertainties. A model reference adaptive control approach is implemented in [11] to adapt to uncertainties in system parameters, while the adoption law is demonstrated using Lyapunov's theory. To the best of our knowledge, an adaptive control aiming at both stabilising the system as well as dealing with uncertainties to eliminate the influence of external force/torque has not been released yet.

## III. CONTROL ALGORITHM

In this section, a mathematical model of the considered elastic actuator system is introduced. Then, the proposed control algorithm is discussed.

### A. Mathematical model

By considering *Serpens'* elastic actuator [4], [5], the corresponding schematic diagrams are illustrated in Fig. 2. There are two gears with gear ratio  $N = N_l/N_m$ , where  $N_l$  and  $N_m$  are the number of teeth for the load and the motor gear, respectively. The torques shown in these diagrams are motor torque ( $\tau_m$ ), spring reaction torque ( $\tau_s$ ) and external torque ( $\tau_{ext}$ ). Fig. 2a illustrates the system when there is no external force/torque, while Fig. 2b illustrates the system affected by an external action.

The whole system is affected by external disturbances from the motor ( $d_m$ ) as well as from the load ( $d_l$ ). By denoting the motor angular position as  $\theta_m$ , the load angular position as  $\theta_l$ , the rotor inertia as  $J_m$ , the motor damping

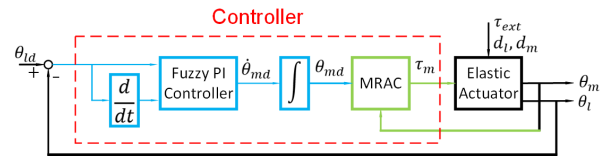


Fig. 3: The proposed nested system controller.

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:

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

$$\tau_s = K_s(-N^{-1}\theta_m - \theta_l) + D_s(-N^{-1}\dot{\theta}_m - \dot{\theta}_l), \quad (2)$$

$$d_l + \tau_s + \tau_{ext} = J_l\ddot{\theta}_l + D_l\dot{\theta}_l. \quad (3)$$

Equation 1 shows the relationship on the motor-side between the motor torque, the spring torque and the motor angular position. The spring torque,  $\tau_s$ , is obtained by equation 2. The interaction between the spring torque, the external torque and the load angular position is illustrated by equation 3.

### B. Controller Design

The objective of this work is to develop a controller that can track the desired load angular position when considering external disturbances on the load and uncertainties in system parameters. To achieve this objective, two separate types of controllers are utilised for the motor-side and the load-side, respectively. For the load-side, we propose using a Fuzzy PI Controller (FPIC) to reduce the effect of external disturbances on the load. The considered external disturbances are the forces/torques caused by undesired collisions when operating in unknown environments. The output of the FPIC is used as the desired angular position of the motor. For the motor-side, a Model Reference Adaptive Controller (MRAC) is used to cope with uncertainties in system parameters. The uncertain system parameters could be the inertia of the load or the stiffness of the spring. The idea comes from a previous research of Losey et al. [11]. The advantage of combining the FPIC and the MRAC controllers is the possibility of achieving independence with respect to imprecise system parameters. In previous works, the motor angular position is prioritised more than the load position because the target is force control. The contribution of the paper is that a robust position control algorithm for the load position is proposed. In addition, a better spring model is given with the damping coefficient added. The proposed control algorithm diagram is presented in Fig. 3.

1) *Fuzzy PI Controller*: an FPIC is applied to the load-side to cope with the effect of external disturbances on the elastic actuator system. A fuzzy controller is not based on a mathematical model and is widely used to solve problems under uncertain and vague environments, with high nonlinearities [12]. A fuzzy algorithm is a control method based on fuzzy logic, which uses "fuzzy inference rules" instead of "equations". These fuzzy inference rules may come from

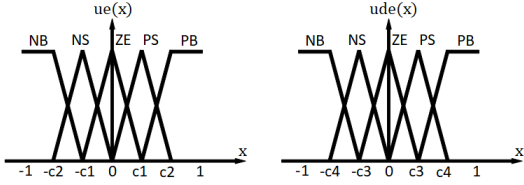


Fig. 4: Input membership functions.

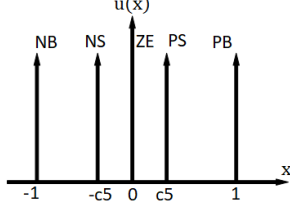


Fig. 5: Output membership functions

experience of a human expert in controlling a specific object, or in other cases, from the understanding of dynamics and behaviour of the target plant. A fuzzy controller can be combined with a conventional PID controller to obtain a fuzzy PI, a fuzzy PD or a fuzzy PID controller. The fuzzy PI type controller is known to be more practical than fuzzy PD types because it is difficult for the fuzzy PD to remove steady state errors [13]. The relationship between the input and the output in a conventional PI controller is:

$$u(t) = K_p e(t) + K_i \int_0^t e(t) dt, \quad (4)$$

where,  $K_p$ ,  $K_d$  and  $K_u$  are scaling the coefficient of the feedback error, the change of feedback error and the change of control signal, respectively. By differentiating equation 4, we obtain:

$$\dot{u}(t) = K_p \dot{e}(t) + K_i e(t). \quad (5)$$

A fuzzy PI controller can be obtained by combining equation 5 with the fuzzy controller. Inputs of the FPIC are the feedback error ( $e$ ) and the change of this error ( $\dot{e}$ ), while the output of the FPIC is the change of control signal ( $\dot{u}$ ).

The membership functions for the input and the output are shown in Fig. 4 and Fig. 5, in which  $c1 - c5$  are parameters to be adjusted. The membership functions for the error and the change of error are similar, including the rules base of the fuzzy model: Negative Big (NB), Negative Small (NS), Zero (ZE), Positive Small (PS), and Positive Big (PB). The membership functions for the change of the control signal are in singleton over the output, given NB, NS, ZE, PS, and PB. On the basis of the input and output membership functions, 25 fuzzy inference rules are established as shown in table I.

2) *Model Reference Adaptive Controller.*: although there are various control algorithms, uncertainties in system parameters can lead to instability in many cases. Adaptive controllers are developed to overcome this problem. An MRAC is an important adaptive controller typology in which the desired response is expressed by a reference model. The adaptation law modifies the system parameters based on the difference between the output of the real system and the

TABLE I: Fuzzy inference rules.

$\dot{e} \backslash e$	NB	NS	ZE	PS	PB
NB	PB	PB	PB	PS	ZE
NS	PB	PB	PS	ZE	NS
ZE	PB	PS	ZE	NS	NB
PS	PS	ZE	NS	NB	NB
PB	ZE	NS	NB	NB	NB

output of the reference model. In this article, Lyapunov's stability theory is applied to design the adaptation law. Lyapunov's stability criterion states that a system,  $\dot{x} = f(x)$ , with equilibrium point at  $x = 0$ , is stable if there is a function,  $V(x)$ , that satisfies the following conditions:

$$V(x) = 0 \text{ if } x = 0, \quad (6)$$

$$V(x) > 0 \text{ if } x \neq 0, \quad (7)$$

$$\dot{V}(x) \leq 0 \text{ for all } x \neq 0. \quad (8)$$

Firstly, the control law is derived. The motor-side system equations can be rewritten by using equations 1 and 2 (ignoring the motor-side external disturbance  $d_m$ ) as:

$$\begin{aligned} \dot{\theta} &= \begin{bmatrix} \dot{\theta}_m \\ \ddot{\theta}_m \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ \frac{K_s N^{-2}}{J_m} & \frac{D_s N^{-2} - D_m}{J_m} \end{bmatrix} \begin{bmatrix} \theta_m \\ \dot{\theta}_m \end{bmatrix} + \\ & \begin{bmatrix} 0 \\ \frac{1}{J_m} \end{bmatrix} (\tau_m + K_s N^{-1} \theta_l + D_s N^{-1} \dot{\theta}_l) \\ & = A\theta + B(\tau_m + K_s N^{-1} \theta_l + D_s N^{-1} \dot{\theta}_l). \end{aligned} \quad (9)$$

In equation 9, the state matrix  $A$ , input matrix  $B$  and state vector  $\theta$  of the system can be obtained as:

$$A = \begin{bmatrix} 0 & 1 \\ \frac{K_s N^{-2}}{J_m} & \frac{D_s N^{-2} - D_m}{J_m} \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ \frac{1}{J_m} \end{bmatrix}, \quad \theta = \begin{bmatrix} \theta_m \\ \dot{\theta}_m \end{bmatrix}. \quad (10)$$

The motor-side system equations have the form of a second-order system, so the reference model is a second-order system model with the desired signal  $\theta_{md}$ , natural frequency  $\omega_n$ , and damping coefficient  $\xi$ :

$$\begin{aligned} \dot{\theta}_{ref} &= \begin{bmatrix} \dot{\theta}_r \\ \ddot{\theta}_r \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\omega_n^2 & -2\xi\omega_n \end{bmatrix} \begin{bmatrix} \theta_r \\ \dot{\theta}_r \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_n^2 \end{bmatrix} \theta_{md} \\ & = A_r \theta_{ref} + B_r \theta_{md}. \end{aligned} \quad (11)$$

In equation 11, the state matrix  $A_r$ , input matrix  $B_r$  and state vector  $\theta_{ref}$  of the reference model can be obtained as:

$$A_r = \begin{bmatrix} 0 & 1 \\ -\omega_n^2 & -2\xi\omega_n \end{bmatrix}, \quad B_r = \begin{bmatrix} 0 \\ \omega_n^2 \end{bmatrix}, \quad \theta_{ref} = \begin{bmatrix} \theta_r \\ \dot{\theta}_r \end{bmatrix}. \quad (12)$$

A general control law for the system with state equations 9 is:

$$\tau_m = M\theta_{md} - L\theta - \hat{K}_s N^{-1} \theta_l - \hat{D}_s N^{-1} \dot{\theta}_l. \quad (13)$$

Parameters with hats ( $\hat{D}_m$ ,  $\hat{J}_m$ ,  $\hat{K}_s$ ,  $\hat{D}_s$ ,  $\hat{D}_l$ ,  $\hat{J}_l$ ) are estimated parameters, while matrices  $M$  and  $L$  need to be

determined. By substituting  $\tau_m$  to system equation 9, we have:

$$\begin{aligned} \dot{\theta} &= (A - BL)\theta + BM\theta_{md} \\ &+ B((K_s - \hat{K}_s)N^{-1}\theta_l + (D_s - \hat{D}_s)N^{-1}\dot{\theta}_l). \end{aligned} \quad (14)$$

If perfect estimation of parameters is obtained, we have  $\hat{K}_s = K_s$  and  $\hat{D}_s = D_s$ . As the columns of matrices  $A - A_r$  and  $B_r$  are linear combinations of the vector  $B$ , there exists optimal matrices  $M^*$  and  $L^*$  of matrices  $M$  and  $L$  such that:

$$A - A_r = BL^*, \quad (15)$$

$$B_r = BM^*. \quad (16)$$

Equations 15 and 16 are called compatible conditions. If these conditions are satisfied and we have perfect estimation of parameters, then the controller 13 can yield perfect tracking of the reference model. From these equations, the controller optimal matrices  $M^*$  and  $L^*$  can be obtained as below:

$$M^* = (B^T B)^{-1} B^T B_r = \omega_n^2 J_m, \quad (17)$$

$$\begin{aligned} L^* &= (B^T B)^{-1} B^T (A - A_r) \\ &= [(K_s N^{-2} + J_m \omega_n^2) \quad (D_s N^{-2} - D_m + 2J_m \xi \omega_n)]. \end{aligned} \quad (18)$$

Based on the above formulas 17 and 18 for the controller optimal matrices, the matrices  $M$  and  $L$  can be approximated as:

$$M = (B^T B)^{-1} B^T B_r = \omega_n^2 \hat{J}_m, \quad (19)$$

$$\begin{aligned} L &= (B^T B)^{-1} B^T (A - A_r) \\ &= [(\hat{K}_s N^{-2} + \hat{J}_m \omega_n^2) \quad (\hat{D}_s N^{-2} - \hat{D}_m + 2\hat{J}_m \xi \omega_n)]. \end{aligned} \quad (20)$$

Secondly, the error equation is determined. The feedback error, which is the difference between the output of the real system and the output of the reference model, is determined as:

$$e = \theta - \theta_{ref}. \quad (21)$$

The derivative of error is determined as:

$$\begin{aligned} \dot{e} &= \dot{\theta} - \dot{\theta}_{ref} \\ &= (A - BL)\theta + BM\theta_{md} + B((K_s - \hat{K}_s)N^{-1}\theta_l \\ &+ (D_s - \hat{D}_s)N^{-1}\dot{\theta}_l) - (A_r\theta_{ref} + B_r\theta_{md}) \\ &= A_r e - A_r \theta + (A - BL)\theta + BM\theta_{md} \\ &+ B((K_s - \hat{K}_s)N^{-1}\theta_l + (D_s - \hat{D}_s)N^{-1}\dot{\theta}_l) - B_r\theta_{md} \\ &= A_r e + \Psi(\Phi - \Phi^*), \end{aligned} \quad (22)$$

where, it should be noted that:

$$\begin{aligned} \Psi &= B \begin{bmatrix} -\theta^T & \theta_{md} & (-N^{-1}\theta_l) & (-N^{-1}\dot{\theta}_l) \end{bmatrix}, \\ \Phi &= \begin{bmatrix} L^T \\ M \\ \hat{K}_s \\ \hat{D}_s \end{bmatrix}, \quad \Phi^* = \begin{bmatrix} L^{*T} \\ M^* \\ K_s \\ D_s \end{bmatrix}. \end{aligned} \quad (23)$$

Thirdly, the adaption law can be obtained by applying Lyapunov's stability theory. A Lyapunov function is introduced as:

$$V = \frac{1}{2}\gamma e^T P e + \frac{1}{2}(\Phi - \Phi^*)^T (\Phi - \Phi^*), \quad (24)$$

where,  $P$  is a symmetric positive definite matrix and  $\gamma$  is a learning rate. The function  $V$  is positive definite. The derivative of  $V$  is obtained as:

$$\begin{aligned} \dot{V} &= \frac{1}{2}\gamma \dot{e}^T P e + \frac{1}{2}\gamma e^T P \dot{e} + (\Phi - \Phi^*)^T \dot{\Phi} \\ &= -\frac{1}{2}\gamma e^T Q e + (\Phi - \Phi^*)^T (\dot{\Phi} + \gamma \Psi^T P e), \end{aligned} \quad (25)$$

where,  $A_r^T P + P A_r = -Q$  and  $Q$  is a symmetric positive definite matrix. The existence of matrix  $Q$  is demonstrated by using the Kalman-Yakubovich lemma [14]. If the adaption law is chosen to be:

$$\dot{\Phi} = -\gamma \Psi^T P e, \quad (26)$$

then the derivative of Lyapunov function  $\dot{V}$  is negative definite with all  $e \neq 0$ , which means that the feedback error between the output of the real system and the reference model will go to zero when time goes to infinity.

In this article, matrices  $P$  and  $Q$  are chosen as:

$$P = \begin{bmatrix} p_1 & p_2 \\ p_2 & p_3 \end{bmatrix}, \quad Q = \begin{bmatrix} q_1 & 0 \\ 0 & q_2 \end{bmatrix}, \quad (27)$$

where,  $q_1$  and  $q_2$  will be tuned appropriately. From equation  $A_r^T P + P A_r = -Q$ ,  $p_1$ ,  $p_2$  and  $p_3$  can be obtained by using the following formulas:

$$p_2 = \frac{q_1}{2\omega_n^2}, p_3 = \frac{2p_2 + q_2}{4\xi\omega_n}, p_1 = 2\xi\omega_n p_2 + \omega_n^2 p_3. \quad (28)$$

In real applications, discrete system equations are utilized instead of continuous ones. By approximately discretising the reference system equation 9, we obtain:

$$\begin{bmatrix} \theta_r(k+1) \\ \dot{\theta}_r(k+1) \end{bmatrix} = \begin{bmatrix} 1 & T \\ -T\omega_n^2 & 1 - 2T\xi\omega_n \end{bmatrix} \begin{bmatrix} \theta_r(k) \\ \dot{\theta}_r(k) \end{bmatrix} + \begin{bmatrix} 0 \\ T\omega_n^2 \end{bmatrix} \theta_{md}. \quad (29)$$

#### IV. SIMULATION AND EXPERIMENTAL RESULTS ON MATLAB SIMULINK

In this section, simulations are outlined with the aim of validating the proposed control algorithm for modelling and control of the considered highly compliant low-cost SEA [4], [5]. The responses of the considered elastic actuator with step and sinusoidal wave inputs are presented. The influence of an external torque and disturbances on the whole elastic system is also illustrated. In this article, the system parameters are shown in table II.

TABLE II: System parameters.

Parameter	Value	Parameter	Value
Gear ratio(N)	1	Spring stiffness ( $K_s$ )	3
Load damping coefficient( $D_l$ )	0.006	Motor damping coefficient( $D_m$ )	0.06
Load inertia ( $J_l$ )	0.065	Motor inertia ( $J_m$ )	0.1
Spring damping coefficient( $D_s$ )	0.6	Sampling rate (T)	0.001

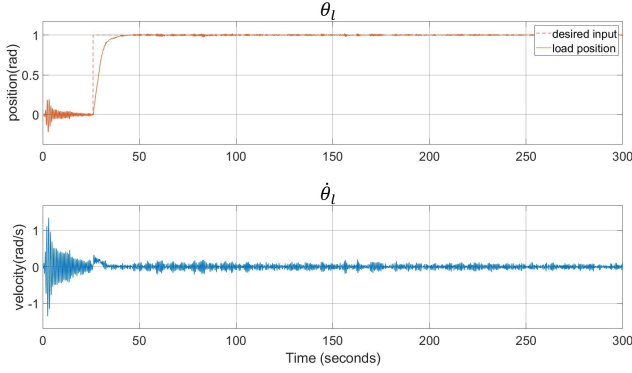


Fig. 6: Load-side step response.

#### A. Response of the load-side system with step and sine desired signals without external torque

This section demonstrates the response of the load-side system without external torque. Step and sine responses are shown in Fig. 6 and Fig. 7, respectively, in which red dashed lines are desired inputs, red solid lines are load angular positions, blue solid lines are load angular velocities. There is an unstable stage at the beginning of the simulation, in which the MRAC is in a learning phase. As shown in Fig. 6, the response on the load-side of the elastic actuator depends on the motor-side system, which has second order system form. Disturbances on the load-side  $d_l$  cause some slight fluctuation on the load-side response, but the FPIC can keep the system successfully stable.

#### B. Response of the motor-side system with step and sine desired signals without external torque

The response of the motor-side system without external torque is presented in this section. Step and sine responses

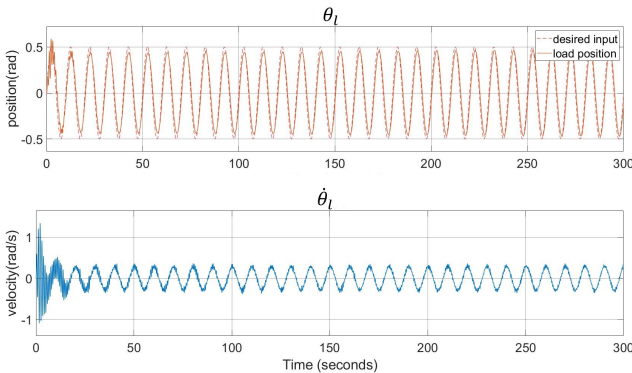


Fig. 7: Load-side sine response.

TABLE III: Reference model and MRAC parameters.

Parameter	Value	Parameter	Value
Damping coefficient ( $\xi$ )	1	$p_1$	1.26
Natural Frequency ( $\omega_n$ )	1.4	$p_2$	0.26
$q_1$	1	$p_3$	0.27
$q_2$	1	Learning rate coefficient ( $\gamma$ )	0.98

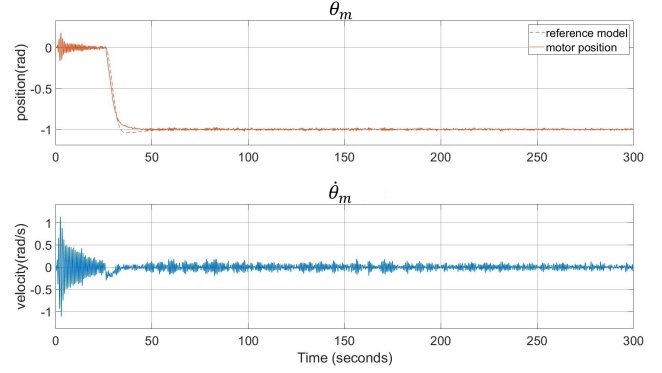


Fig. 8: Motor-side step response.

are shown in Fig. 8 and Fig. 9, respectively. The reference model and the MRAC parameters are shown in table III. During the learning phase, the system parameters are modified corresponding to the adaption law 26 to reduce the error between reference model and real motor response. The Lyapunov's approach in designing the adaption law has an advantage: arbitrary large values of the learning rate coefficient  $\gamma$  can be used [14].

The damping coefficient  $\xi$  of the reference model is chosen to be critically damped ( $\xi = 1$ ) because there are no oscillations or overshoots in this configuration and the system returns to equilibrium in minimum time. However, Fig. 8 shows that there is a small overshoot in the reference model graph. This is caused by the integrator in the FPIC, not by the reference model in the MRAC, and could be reduced by appropriately adjusting the  $K_p$  coefficient. The rising time of the reference model is calculated by using the approximation formula:  $\frac{5.83392}{\omega_n}$ .

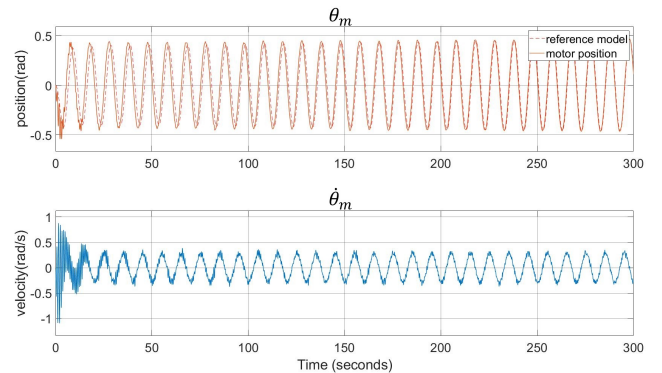


Fig. 9: Motor-side sine response.

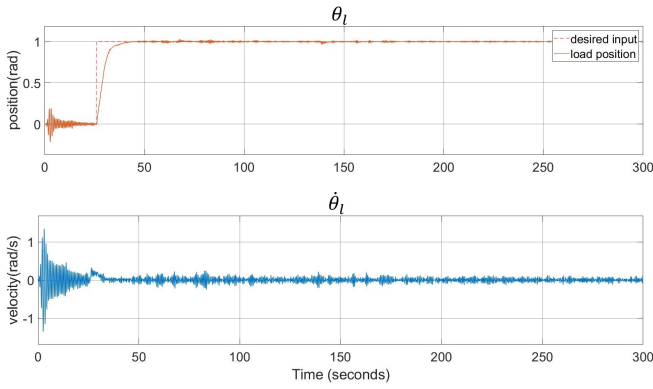


Fig. 10: Load-side response with external disturbance.

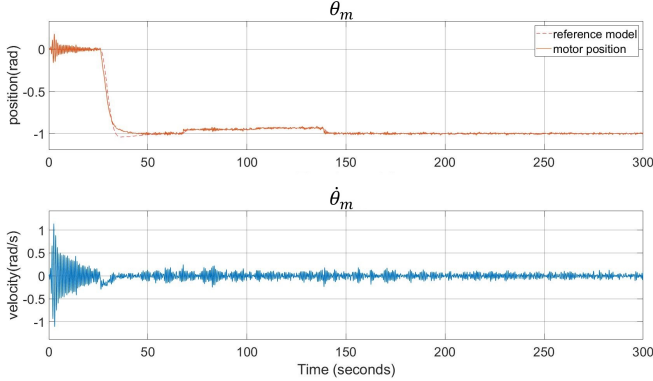


Fig. 11: Motor-side response with external disturbance.

### C. Response of the load and motor-side system with external torque to the step desired signal

The influence of the external torque on the elastic actuator and the effectiveness of the proposed algorithm is illustrated in this section. The step response of the load-side system and the motor-side system is shown in Fig. 10 and Fig. 11, respectively. The motor torque and external torque are shown in Fig. 12. In the proposed control algorithm, the FPIC is applied to reduce the effect of external disturbances from the load-side and the MRAC is utilised to deal with uncertainties in the motor-side system. When there is an external torque, the FPIC adjusts its fuzzy output signal, which is the derivative of the motor angular position, so that the error between the desired load angular position and the real load angular position goes to zero. As shown in Fig. 11, the motor angular position changes when the external torque appears and the influence of this external torque is eliminated.

## V. CONCLUSIONS

In this paper, a two-loop control algorithm for controlling an elastic actuator was presented. The considered elastic actuator was recently designed by our research group for *Serpens*, a low-cost, open-source and highly-compliant multi-purpose modular snake robot [4], [5]. The proposed novel controller has two loops: the inner loop is implemented as a model reference adaptive controller (MRAC), while the outer loop adopts a fuzzy proportional-integral controller (FPIC). The FPIC is applied from the load-side to reduce the effect of

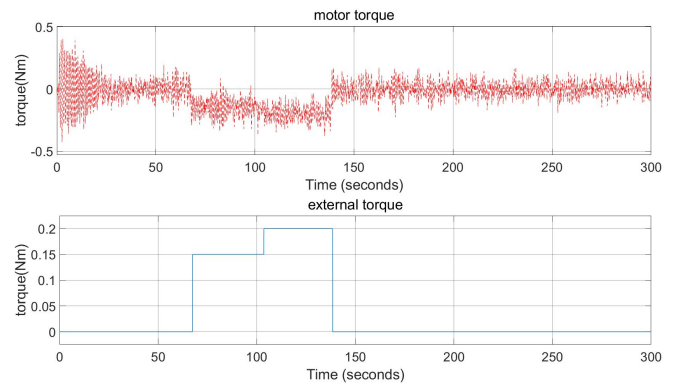


Fig. 12: Motor torque and external torque.

external disturbances on the load. The output of the FPIC is used as the motor desired angular position. From the motor-side, the MRAC is used to cope with uncertainties in the system parameters. The advantage of combining the FPIC and the MRAC controllers is the possibility of achieving independence with respect to imprecise system parameters. Experimental simulation highlighted the effectiveness of the proposed algorithm with respect to the influence of external torque on the considered elastic actuator.

As future work, the design of reliable low-level control algorithms for the proposed elastic joints will be integrated into *Serpens*. This is essential to enable the achievement of *perception-driven obstacle-aided locomotion (POAL)* [15]–[17]. To accomplish this, the current low-level control algorithm must be complemented with a hierarchical organisation by considering the standard functions and capabilities of guidance, navigation, and control (GNC). Furthermore, the proposed hybrid controller will be compared with other recent methods and a novel machine learning based controller that our research group is currently designing [18].

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