Design and development of a shape memory alloy-powered rotary variable stiffness actuator embedded with an agonist-antagonist mechanism

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ABSTRACT

Advancements in robotic manipulation have led to the development of Variable Stiffness Actuators (VSAs), which have the potential to revolutionize the field by endowing manipulators with high levels of compliant actuation. VSAs are known to provide robustness and flexibility, and hence, they are ideal for tasks requiring variable stiffness, especially in soft robotics and shock-absorbing applications by efficiently harnessing potential energy for repetitive movements. The current research focuses on developing an SMA-based agonist-antagonistic VSA, which follows a non-linear force-displacement relationship. The prototype has been developed with SMA coils in bipenniform configuration with a rotary end effector coupled with an optical encoder to measure the angular displacement. The experiments were conducted on an SMA coil with bias weights, and a regression model was trained for temperature variation with input voltage. ANN (Artificial neural network) was deployed for training the model, achieving an accuracy of 89.12%. Further, an LSTM (Long short-term memory)-based RL (reinforcement learning) model is proposed, that can be integrated with the SMA-based VSA. This architecture defines the change in the state of the current angular displacement depending upon the history of actions. The actions signify the input voltages sampled at regular time intervals during the experiment. Thus, the developed SMA-based VSA system promises to elevate the degree of automation and broaden robotics applications in compliance, adaptability, and efficient energy utilization.

Keywords: Shape-Memory Alloy · Variable Stiffness Actuator. Neural Networks. Reinforcement Learning· LSTM. Agonist-antagonist system

1. INTRODUCTION

1.1 Variable Stiffness Actuators

Actuators can be classified into constant-stiffness-variable-length and variable-stiffness-constant-length actuators of which the latter's stiffness can be varied using passive or active mechanisms. Variable Stiffness Actuators (VSAs) are a class of actuators with the capability of changing their apparent output stiffness independently from the actuator output position.[1]

Adoption of VSAs can prove beneficial due to their multiple properties. Firstly, VSAs are energy efficient and thus, they have the capability to store and release energy.[2] Secondly, these actuators provide higher compliance and this results in a higher workspace. Moreover, these will pave the way for advancements in safe-human-robot interaction field. The integration of biomimicry with robotics becomes fairly simple as the use of VSAs for bio-inspired antagonism is easy. Also, these make the robot robust against external disturbances.

The above-mentioned advantages of VSAs can be exploited for their use in various applications. Cyclic movement is one such application where the energy efficiency of these actuators is used to reduce the redundant

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movements while carrying out periodic motions.[2] Further, VSAs seem an ideal fit for those robots that are desired to perform tasks requiring shock absorption.[3] VSAs can also provide explosive movements by storing energy over a period of time and releasing it instantaneously. Such actuators also find their use in applications that require stiffness variation with a constant load.

1.2 Shape-Memory Alloy(SMA)-based VSAs

The current research work focuses on developing a solution that tackles four primary challenges. The first of which was to build an actuator having the characteristics of a Mechanically Adjustable Compliance and Controllable Equilibrium Position Actuator(MACCEPA)-concept.[4] The second challenge was to develop an actuator with minimal use of rigid links to enhance safety during human-robot interaction. The third challenge entailed incorporating a robust control structure for the antagonist movement of the actuators. Lastly, the aim was to build an actuator that would reduce the overall weight of a robot's body. Thus, an SMA-based VSA embedded with an LSTM-based VSA can prove to be a boon in the field of robotics by solving the above challenges (see fig 1).

SMA are alloys that have the ability to recover their original shape after being deformed, as long as they are heated, even if the deformation occurs at a temperature lower than a certain threshold.[5] Nitinol (Ni-Ti)-based SMAs have a high Power-to-Weight ratio[6] . It is observed that SMAs have shown superior mechanical properties including improved wear resistance compared to their conventional counterparts of the same surface hardness.[7] The intrinsic compliance of SMA provides for a safe human-robot interaction. Furthermore, Velázquez et al present an in-depth analysis of how the shape of SMA can be controlled using temperature.[8] Moreover, the advancements in the SMA-based actuators can lead to a whole new domain of research in the MedTech industry since these alloys are found to be biocompatible.[3]

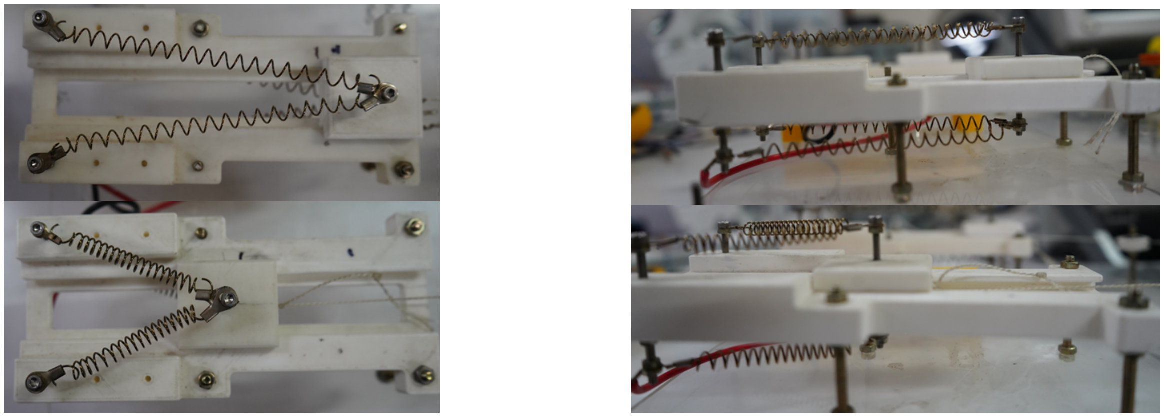

(a) (b)

Figure 1: The figure shows the SMA-bipenniform's cooled and heated states in (a) Top-view and (b) Side-view

1.3 Design review and prototype design

A variety of design approaches have been adopted by researchers to develop VSAs. Some VSAs are based on the principle of adaptable pivot point and variable lever ratio.[9] The peak torque attained was 117Nm by CompACT VSA while the highest resolution of stiffness adjustment was 189 Nm/rad^2. Work has also been done on the development of an electromechanical motor-powered VSA.[10] An antagonist tendon-driven VSA integrated with cascade control is also on of the approaches[11] to design a VSA. One category of such actuators is an SMA-based-continuous-stiffness-adjustment torsional elastic component for variable stiffness actuators.[12] Different designs have different advantages depending on their mechanisms. Some include beam-based Compliant Transmission Elements (CTEs),[13] allowing for larger deflections and thus extending the VSA stiffness variability range. In fact, the adjustable equilibrium position of the actuator may also be used[4] . Work has also been done to develop a high-compliance spring robot with soft-joints which enables the control of structural deformation of the actuator.[14] Furthermore, in one of the approaches a leveraged arrangement for the development of VSAs is used.[13]

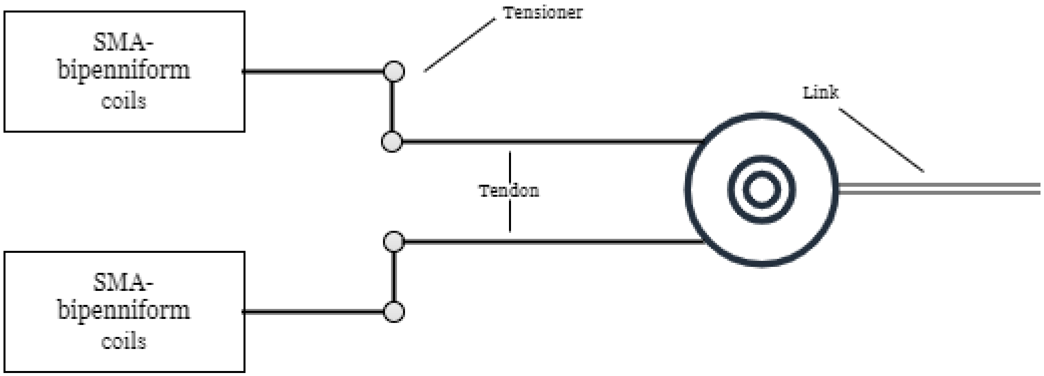


Figure 2: The figure depicts the agonist-antagonist actuation mechanism of the VSA. The tensioners ensure that the tendon coil remains taut and the rotary encoder is attached to the end-effector link.

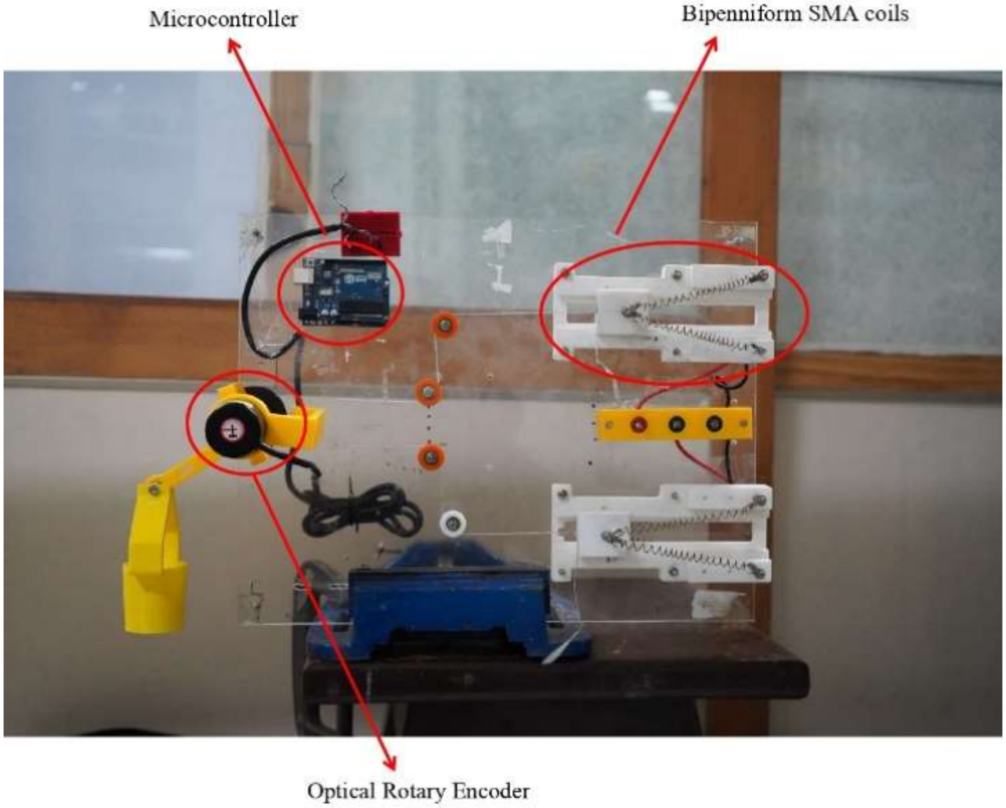


Figure 3: SMA-based Variable Stiffness Actuator equipped with an optical rotary encoder and a microcontroller.

The current research focuses on integrating SMA coils to develop a rotary VSA. Chaurasiya et al have developed a bipenniform structure that can generate a maximum force of 150 N when applied linearly.[15] Thus, two of these SMA-coil driven actuators are used to power the rotary end-effector and are attached to each other through a string (see fig 2). To tighten the grip of the attachment string, tensioners are used. The link is mounted on an optical rotary encoder which in turn is connected to a microcontroller. The entire set up is mounted on a plexiglass to ensure robustness. A common ground is set up for the actuator SMA coils and this is integrated through a compact-circuit plug-and-play mount. Figure 3 shows the prototype setup. The microcontroller used here is Arduino Uno which connects the rotary encoder to the computer. Thus, the dynamic link angle reading is fed into the control algorithm. The incremental encoder gauges the clockwise or counter-clockwise movement of the link depending on the light channels' interruption order.

$$f(a,b) = \begin{cases} clockwise & \text{if } a < b \\ counter - clockwise & \text{if } a > b \end{cases} \tag{1}$$

Let an incremental encoder have two light channels 'A' and 'B', then assuming 'a' and 'b' to be the timestamps of light interruptions respectively, we can determine the motion sensing mechanism of the encoder as given by equation (1). Whereas, an absolute encoder indicates the position and not merely the change. Here we have used an absolute rotary encoder and the result from such encoders usually appears in binary form, employing Gray Code to reduce reading errors. Gray Code guarantees that consecutive numbers vary by just one bit, thereby averting errors during transitions. Decoding the code is achievable using the XOR operation in the following manner:

$$G_i = B_(i) \oplus B_(i+1) \tag{2}$$

Where B_i is the binary digit and G_i is the Gray digit.

2. PREDICTIVE MODELING OF AN SMA COIL

Predictive modeling was performed on SMA coils to gauge the strain rate variation. For this, an ANN was trained because, in the context of SMA coils, where the thermomechanical behavior is influenced by various factors such as temperature, stress, and material properties, ANNs can effectively recognize patterns and correlations that may be challenging to model using traditional analytical or numerical techniques.

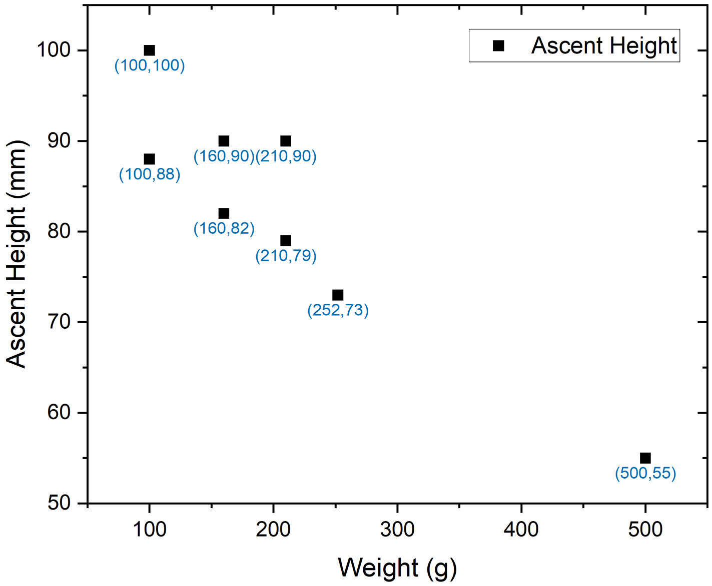


Figure 4: The figure shows the ascent height data points captured for linear actuation of the SMA-coils

As shown in figure 4, the maximum height of 100mm achieved was for a 100 gram payload. To measure the ascent height, a laser displacement sensor was used and the weights ranged from 100 grams to 500 grams. These experiments were carried out to gauge the payloads that our prototype actuator would be able to tolerate. The maximum height achieved was 100mm for a payload of 100 grams while the least ascent height was 55mm for a payload of 500 grams.

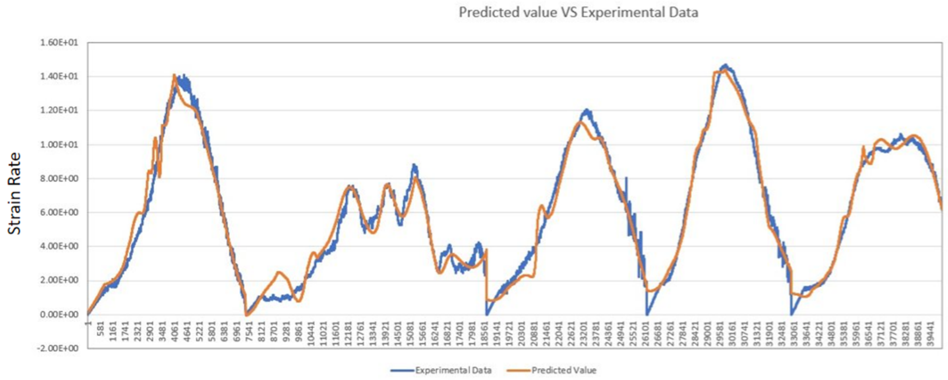


Figure 5: The figure shows the predicted strain rate vs experimental strain rate for the linear displacement of SMA-coils. The accuracy of the predictive model achieved was 89.12%

The experiments were conducted with biased weights on an SMA coil. Data pre-processing was done, followed by implementing optimization techniques for data cleaning. The pre-processed experimental data was split into 70% training data and 30% testing data. Initially, the raw data underwent a cleaning process using Python's data frame. This involved initializing the data in the Time and Distance columns appropriately and conducting interpolation to fill in any missing data. Following this, the regression model was trained using ANN taking 'Average Strain Rate' as the Target Variable and 'Current, Weight and Time' as Predictors. The neural network consisted of one input layer with three input features, one hidden layer with 32 neurons, and one output layer with a single neuron for regression. The maximum ANN accuracy achieved was 89.12% (see fig 5).

3. EXPERIMENTAL ANALYSIS ON THE ROTARY SMA-BASED VSA

The experiments with the straight SMA coils helped us in choosing the upper limit of weights for our VSA prototype. We conducted experiments with 8 payloads of which were as follows: 29 grams, 78 grams, 100 grams, 129 grams, 158 grams, 178 grams, 207 grams, and 237 grams. The variation of the end effector's link angle with different voltages was measured. The experiments were conducted by varying the input current from 5A to 8A with a sampling rate of 0.1A.

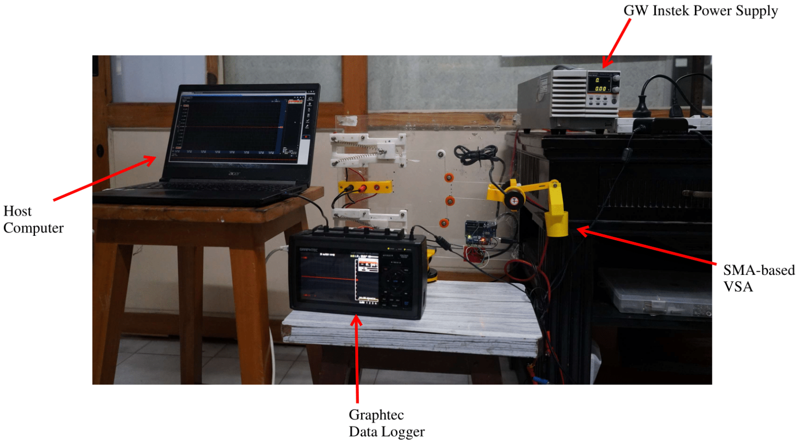
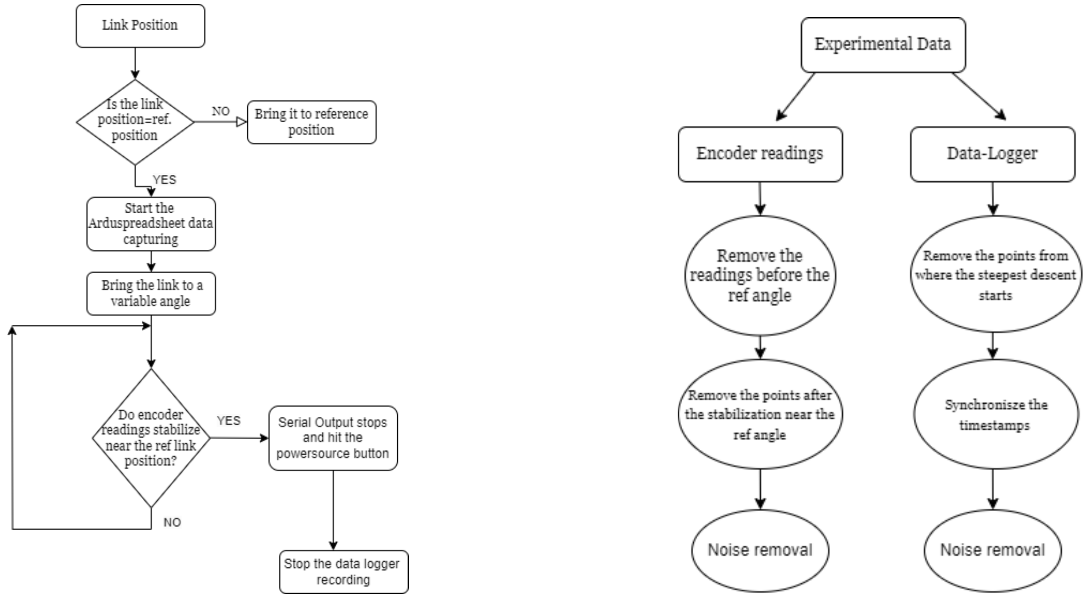


Figure 6: The figure depicts the experimental setup used during the voltage history capturing experiments

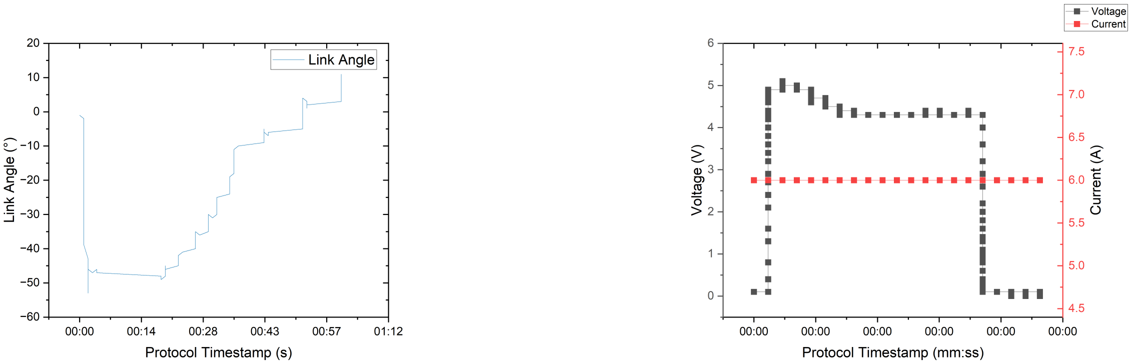
The experimental setup for capturing the voltage history consisted of a host computer, GW Instek Power Supply, Data Logger, SMA-based VSA prototype, and variable payloads (see fig 6). In each iteration, the link



(a) (b)

Figure 7: (a) Depicts the decision tree for the voltage history capturing experiments (b) The figure shows the pre-processing steps followed for data-cleaning and synchronization

position was checked initially, if this did not match the reference link position then, it was brought to the link position else the Arduspreadsheet data capturing was triggered (see fig 7). Following this, the actuator was subjected to sudden payloads and the SMA-bipenniform performed the actuation until the encoder readings stabilized (see fig 8)



(a) (b)

Figure 8: The figure depicts (a) The end-effector's link-angle variation with time captured using the absolute rotary encoder. The initial spike is due to the encoder noise. (b) Voltage variation captured using the Graphtec data logger for the constant current mode of the GW Instek power supply

The entire dataset consists of around 200,000 data points captured over 80 sets of experiments. Initially, the data was pre-processed and then sensor fusion was performed. Firstly, the encoder readings before bringing the link to the reference position were removed and then those after the stabilization were removed. Similarly, for the data logger data points were removed from where the steepest descent starts. Following this, the data from the data logger and the absolute rotary encoder were synchronized. Lastly, noise removal was done for both data sets.

4. PROPOSED CONTROL ARCHITECTURE

A neural network utilizing Long Short-Term Memory (LSTM) is proposed to be incorporated, determining changes in the current angular displacement based on a history of actions. These actions would correspond to input voltages sampled at regular intervals during the experiment. The actuator would employ an LSTM-based Reinforcement Learning (RL) control architecture, leveraging LSTM for handling temporal dependencies and RL for maximizing reward. This innovative control framework would allow the Shape Memory Alloy (SMA) actuator to dynamically adjust its stiffness, effectively maintaining a constant reference end effector position even under sudden 250-gram loads. The system demonstrates a rapid repositioning time, and the LSTM memory cell's input comprises the voltage history.

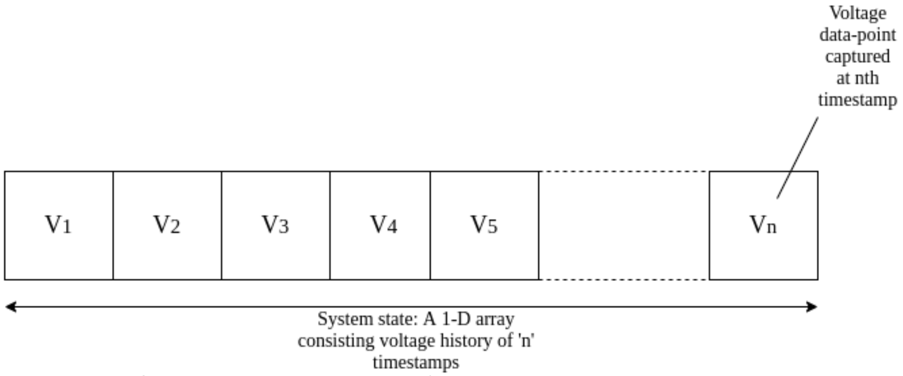


Figure 9: The figure depicts the state of the system being used in the memory cell

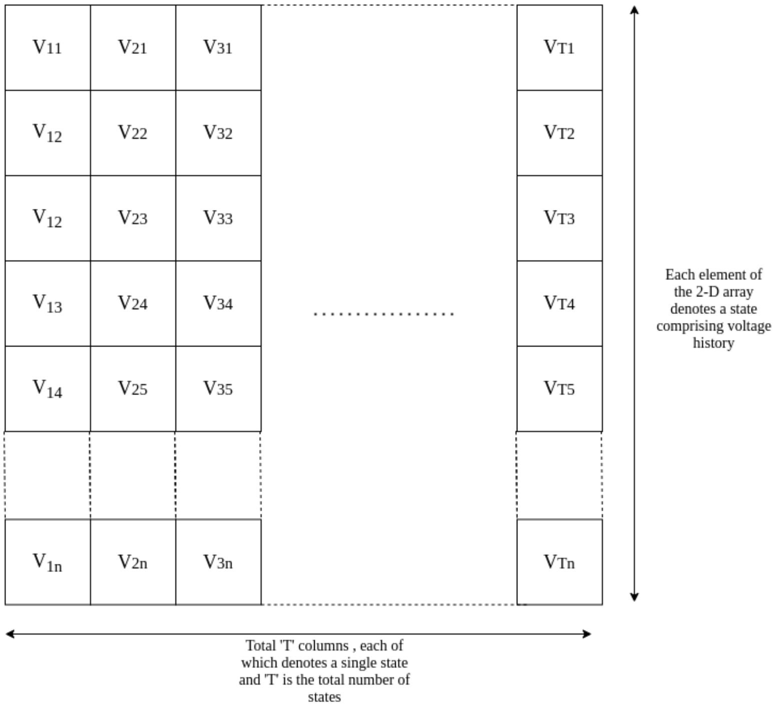


Figure 10: The figure shows the Markov state space of the system, here T denotes the total number of possible states and $T = J^n$ where J is the total number of possible voltage values. Further, in the above 2-D array V_{ij} denotes the voltage data point in i^{th} state and at the j^{th} timestamp

As shown in figure 9, the state of the system would be a one-dimensional array containing the voltage history for the previous n timestamps. The Markov state-space would consist of a 2-D array containing all the possible states of the system. Further, the action-space would be the set of all possible actions in the form of a one-dimensional array in which each action has been assigned a tag.The representation of a populated state space is shown in figure 10. The LSTM-based RL architecture that we propose is shown in figure 11. The environment here would consist of four parameters which are Observation Space, Action Space, Maximum Angle Deviation, and the Control Logic. The Q-Learning Agent would derive 'actions' and 'rewards' from the environment and this would be followed by a training loop. The updated Q-values from the training loop would be fed into the testing loop. The control logic is shown in figure 12.

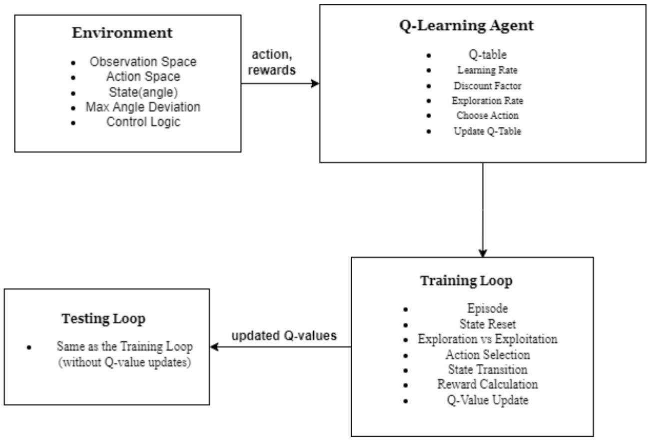


Figure 11: The figure depicts the proposed LSTM-based RL control architecture

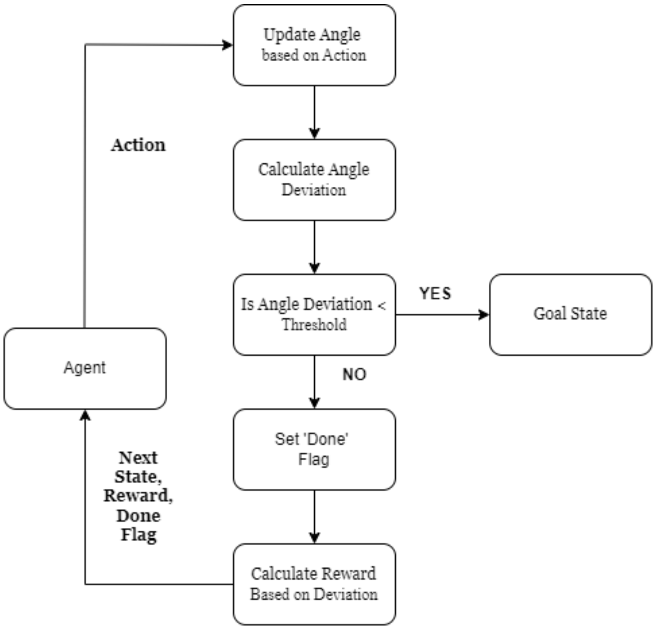


Figure 12: The figure depicts the proposed control logic to be incorporated in the control framework

5. CONCLUSION

In the rapidly advancing field of robotics, researchers are increasingly focusing on Variable Stiffness Actuators (VSAs), particularly those leveraging Shape Memory Alloy (SMA) technology, for their potential to enhance compliance and adaptability. The SMA-based VSAs, designed in an agonist-antagonistic configuration with SMA coils arranged in a bipenniform configuration, offer a non-linear force-displacement relationship, enabling greater flexibility and responsiveness. Through the utilization of artificial neural networks (ANNs), the system achieves high accuracy in modeling and predicting actuator behavior. Further, an integrated LSTM-based neural network, in tandem with RL, would enhance adaptability by enabling efficient stiffness modulation in response to varying loads and environmental conditions, ensuring constant positioning even under sudden changes. LSTMs are designed to address the vanishing gradient problem that plagues traditional RNNs, making them more capable of learning and remembering long-term dependencies in sequential data.Moreover, LSTMs have gating mechanisms such as input gates, forget gates, and output gates that regulate the flow of information within the network.This sophisticated control framework would not only improve adaptability but also enhance repositioning capabilities, promising heightened levels of automation and expanded robotics applications. The current research is being carried out with the aim of building an actuator having the characteristics of a MACCEPA which would involve minimal use of rigid links to enhance safety during human-robot interaction while reducing the weights of robots. Thus the developed SMA-based VSA integrated with a robust control framework to elevate automation and broaden robotics applications, with a focus on compliance, adaptability, and efficient energy utilization.

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REFERENCES

[1] Visser, L. C., S. S. and Bicchi, A., "Embodying desired behavior in variable stiffness actuators," *IFAC Proceedings Volumes* (2011).

[2] Exley, T. and Jafari, A., "Maximizing energy efficiency of variable stiffness actuators through an interval-based optimization framework," *Sensors and Actuators A: Physical* **332**, 113123 (09 2021).

[3] Jugulkar, L., Singh, S., and Sawant, S., "Analysis of suspension with variable stiffness and variable damping force for automotive applications," *Advances in Mechanical Engineering* **8** (05 2016).

[4] Van Ham, R., Vanderborght, B., Damme, M., Verrelst, B., and Lefeber, D., "Maccepa: The mechanically adjustable compliance and controllable equilibrium position actuator for 'controlled passive walking'," **2006**, 2195 – 2200 (06 2006).

[5] Mohd Jani, J., Leary, M., Subic, A., and Gibson, M., "A review of shape memory alloy research, applications and opportunities," *Materials Design* **56**, 1078–1113 (04 2014).

[6] Nath, T., . S. S. K. . (2021, month = 09, pages = 446-453, title = Nitinol shape memory alloy spring.Indian Journal of Engineering and Materials Sciences (IJEMS), volume = 28, journal = Indian Journal of Engineering and Materials Sciences (IJEMS), doi = http://op.niscair.res.in/index.php/IJEMS/article/view/42812).

[7] "Wear in superelastic shape memory alloys: A thermomechanical analysis," *Wear* **488-489**, 204139 (2022).

[8] Velázquez, R. and Pissaloux, E., "Modelling and temperature control of shape memory alloys with fast electrical heating," *International Journal of Mechanics and Control* **13**, 3–10 (01 2012).

[9] Jafari, A., Tsagarakis, N., and Caldwell, D., "Energy efficient actuators with adjustable stiffness: A review on awas, awas-ii and compact vsa changing stiffness based on lever mechanism," *Industrial Robot: An International Journal* **42**, 242–251 (05 2015).

[10] Tonietti, G., Schiavi, R., and Bicchi, A., "Design and control of a variable stiffness actuator for safe and fast physical human/robot interaction," *Design and Control of a Variable Stiffness Actuator For Safe and Fast Physical Human/ Robot Interaction* , 526 – 531 (05 2005).

[11] Lukic, B., Jovanovic, K., and Šekara, T., "Cascade control of antagonistic vsa—an engineering control approach to a bioinspired robot actuator," *Frontiers in Neurorobotics* **13** (09 2019).

[12] Xiong, J., Sun, Y., Zheng, J., Dong, D., and Bai, L., "Design and experiment of a sma-based continuous-stiffness-adjustment torsional elastic component for variable stiffness actuators," *Smart Materials and Structures* **30** (08 2021).

[13] Bilancia, P., Berselli, G., and Palli, G., "Virtual and physical prototyping of a beam-based variable stiffness actuator for safe human-machine interaction," *Robotics and Computer-Integrated Manufacturing* **65** (03 2020).

[14] Negrello, F., G., C., Garabini, M., Poggiani, M., G., C., Tsagarakis, N., and Bicchi, A., "Design and characterization of a novel high-compliance spring for robots with soft joints," (07 2017).

[15] Chaurasiya, K., Harsha, A., Sinha, Y., and Bhattacharya, B., "Design and development of non-magnetic hierarchical actuator powered by shape memory alloy based bipennate muscle," *Scientific Reports* **12**, 10758 (06 2022).