Design and development of non-magnetic hierarchical actuator powered by shape memory alloy based bipennate muscle

Kanhaiya Lal Chaurasiya, A. Sri Harsha, Yashaswi Sinha & Bishakh Bhattacharya
Department of Mechanical Engineering, IIT Kanpur

Introduction

- Biological systems, such as the muscle architecture of mammals, can inspire a variety of nuanced actuators. Most of the architecture in the mammalian musculature can be generalized into two vast categories; Parallel and Pennate.
- The muscle fibers in bipennate muscle tissue are present on both sides of the central tendon at an oblique angle, accounting for feather like structure (Fig 1).
- In a given cross-sectional area, a pennate muscle would be stronger and generate higher force compared to parallel fiber muscle architecture.
- This actuator delivers at least five times higher actuation forces compared to the reported SMA-based actuators.[1]
- The system can cater to the need for an alternative for gear-based conventional actuators from the miniature motor industry.
- The use of the proposed product will foster higher utilization rates for a broad-band of gripping force and hence a better cost-benefit ratio.
- As a proof of concept, a SMA-based bipennate actuator is developed (Fig 2) to validate the simulation output of the governing equations with the experimental results.

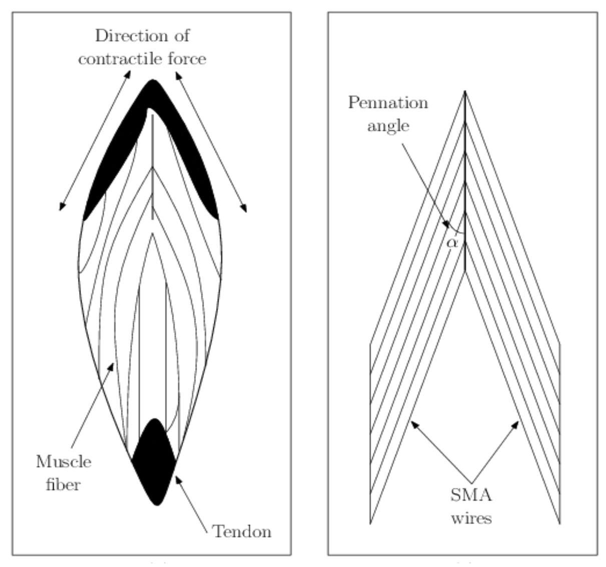


Fig 1 : (left) gastrocnemius pennate muscle tissue (right) arrangement of SMA wires

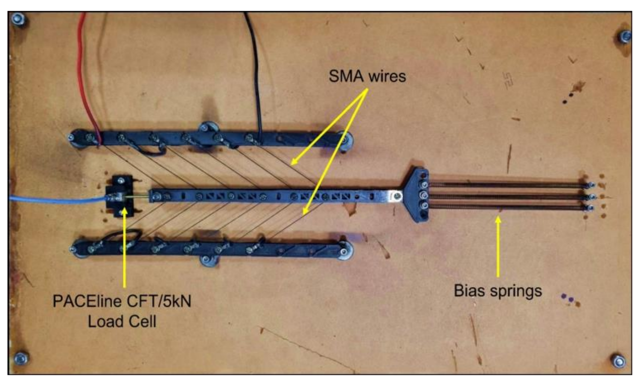


Fig 2 : Top view of the prototype

Results and Discussion

- In the case of the 7 V input voltage condition, the maximum output force obtained from experimental results for the first cycle was 96 N while in the second cycle, the maximum output force was 105 N (Fig 3a).
- For the same input voltage condition, the maximum output force obtained from experimental results for the first cycle was 75℃ while in the second cycle, the maximum output force was 83℃ (Fig 3b).
- The simulation output of the temperature distribution as well as the stress-induced transition temperature of the SMA-based bipennate actuator has been illustrated in Fig 3c.

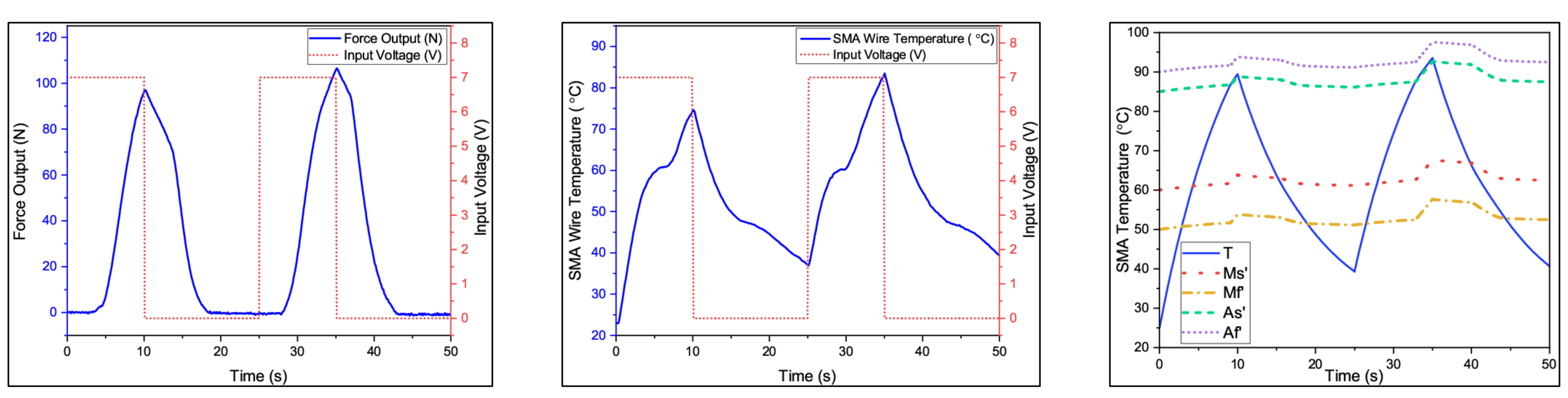
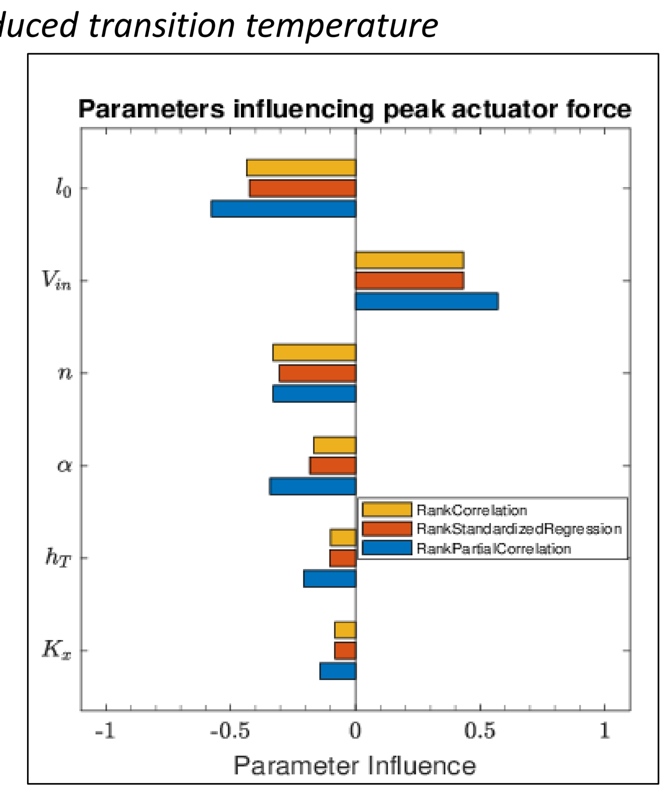


Fig 3 : (a) the experimental force obtained (b) the maximum temperature of the SMA wire (c) simulation output of the temperature as well as the stress-induced transition temperature

- The correlation coefficient values of the model parameters and their influence on the maximum output force for 2500 unique is shown where V_{in} is the sole positively correlated parameter, while l_0 is the most inversely correlated (Fig 4c).
- The influence of (input voltage, length of unipennate) and (number of unipennate, input voltage) parameter sets on the peak muscle force (Fig 4a,4b)



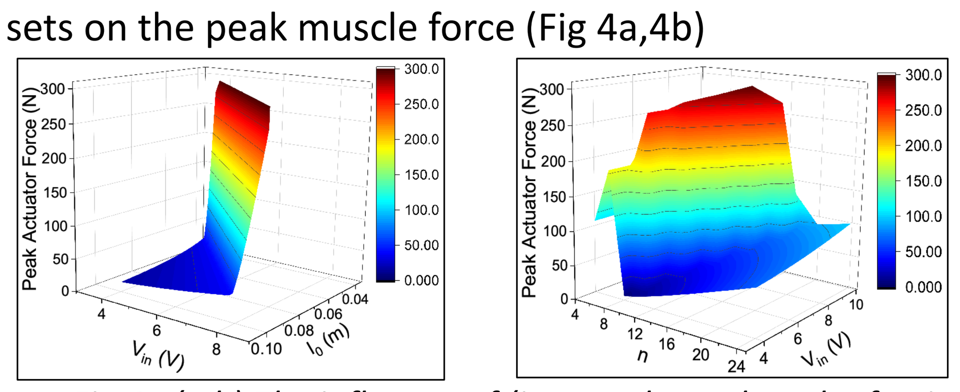


Fig 4 : (a,b) The influence of (input voltage, length of unipennate) and (number of unipennate, input voltage) sets on the peak muscle force (c) correlation coefficient values of the model parameters

Hierarchical Actuator

- In general, the N level actuator is created by substituting the SMA wires of the N − 1 level actuator with the first-level actuator. Each SMA branch mimics the first-level actuator (Fig 5a)
- The peak actuator force was positively linked with hierarchy level (N) in the graph, whereas the stroke has been shown to be inversely correlated with the hierarchy level. For N=5, a peak force of 2.58 kN was observed (Fig 5b).

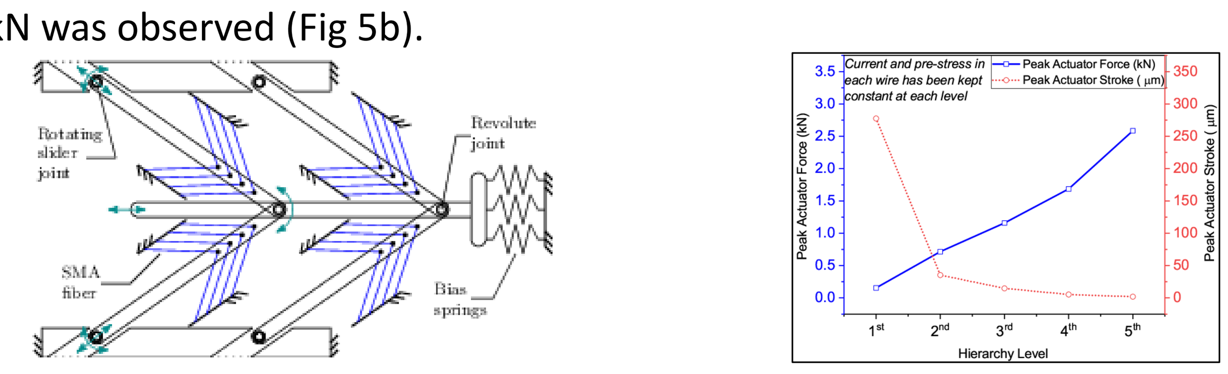


Fig 5 : (a) A shape memory alloy-based two-stage (N = 2) hierarchical linear actuation system (b) distribution of force and displacement as a function of the number of hierarchy levels

Summary

- The proposed SMA-based bipennate actuator design has been found to have a 67% lesser weight of the drive mechanism as compared to stepper motor-driven conventional actuators deployed in the HVAC building automation and controls industry.
- The present invention also caters to the need for actuators in the study involving magnetic resonance imaging as the imaging is very susceptible to electromagnetic noise generated by conventional coil-based motors.
- The current bio-mimic approach can also be used to develop rotary motion for medium to high torque as well as bio-inspired variable force gripper system with potential application in mobile robotics.

Methodology

- **Mathematical Model**

Constitutive Equation

$$\dot{\sigma} = E(\dot{\epsilon} - \epsilon_L\dot{\xi}) + \theta_T\dot{T}$$

Phase Transformation Equation [2]

$$\dot{\xi} = n_\sigma\dot{\sigma} + n_T\dot{T}$$

Heat Transfer Equation

$$m_{wire}C_p\dot{T} = \frac{V^2}{R_{ohm}} - A_C h_T(T - T_\infty) + m_{wire}\Delta H\dot{\xi}$$

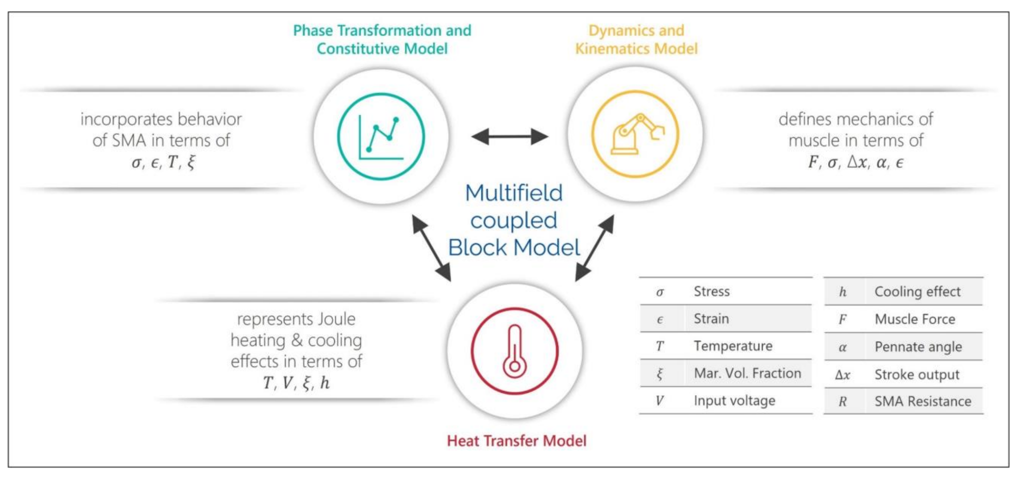


Fig 6: Schematic depicting multi-field coupled block diagram of SMA based bipennate actuation system.

Bipennate Muscle Stiffness Equation :

$$\Delta x_N = \frac{\prod_{i=1}^{n=N}[n_i\sigma A_{cross}\cos\alpha_i] - K_x x_0}{\prod_{i=1}^{n=N} n_i A_{cross}\left[-\frac{E}{l_0}\cos^2\alpha_1 + \sum_{k=2}^{n=N}\left(\frac{\sigma}{l_k}\sin^2\alpha_k\prod_{j=1}^{k-1}\cos\alpha_j\right) + \frac{\sigma}{l_{10}(1-\epsilon)}\sin^2\alpha_j\right]}$$

- **Experimentation**
  - Actuator Force Experiment
    - A piezoelectric load cell (PACEline CFT/5kN) is used to measure the blocked force using a Graphtec GL-2000 data logger (Fig 7a, 7b)
    - The SMA wire temperature increases when a voltage pulse is applied, resulting in the contraction of the SMA wire, as the primary arm collides with the load cell, leading to the force generation of the actuator (Fig 7c)

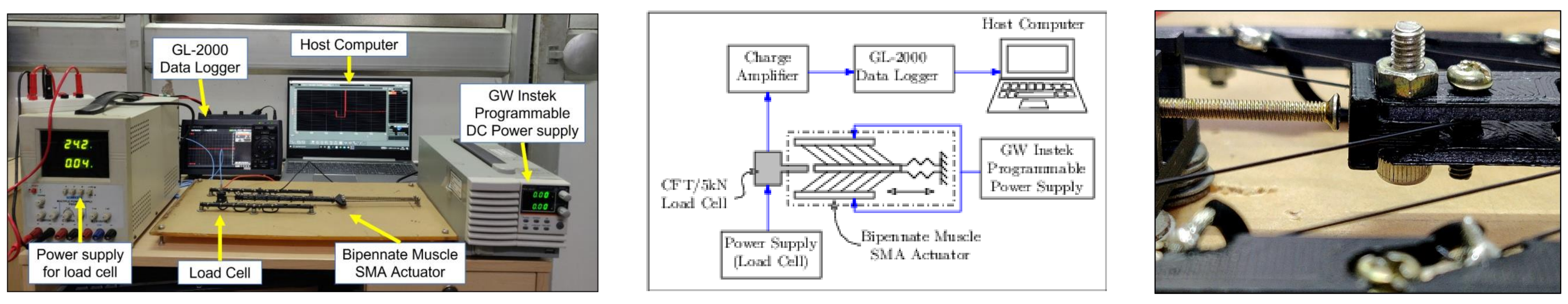


Fig 7 : (a) Experimental Setup (b) schematic showing the circuit of the components of the muscle force measurement experimental setup (c) movable arm striking the piezoelectric force transducer

  - Thermal Imaging Experiment
    - The temperature variation of the SMA wires is measured in real-time using a high-resolution science-grade LWIR camera (Fig 8a, 8b).
    - On the application of voltage pulse, the temperature of the SMA wire rises, causing the SMA wire to contract (Fig 8c).

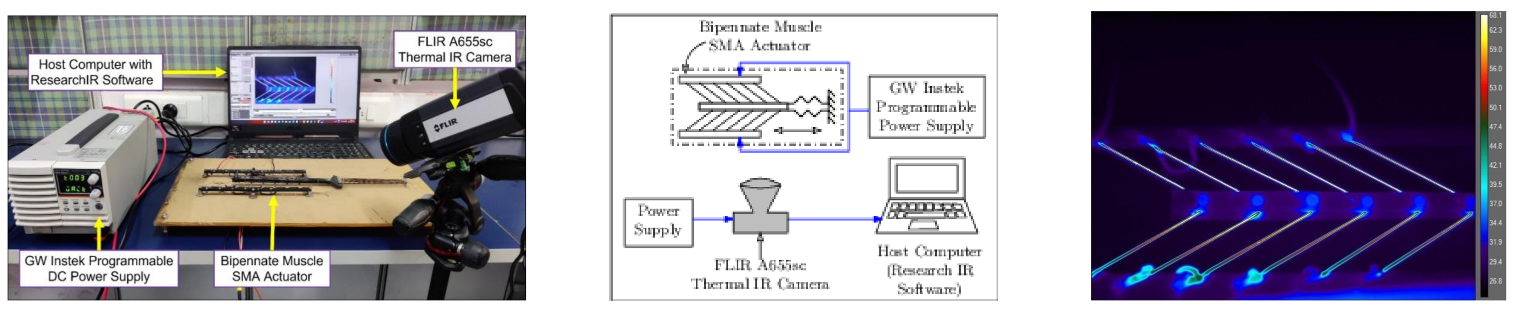


Fig 8 : (a) Experimental Setup (b) schematic showing the circuit of the components of the SMA wire temperature experimental setup (c) snapshot of the temperature across the SMA wires obtained

Validation

- The maximum output force obtained in simulation results and experimental results for the first cycle are 78 N and 96 N, respectively. In the second cycle, the maximum output force was 150 N and 105 N, respectively (Fig 9a).
- The maximum temperature of the SMA wire obtained in simulation and experimental results for the first cycle were 89℃ and 75℃ , respectively, whereas, in the second cycle, the temperature were 94℃ and 83℃ .(Fig 9b)

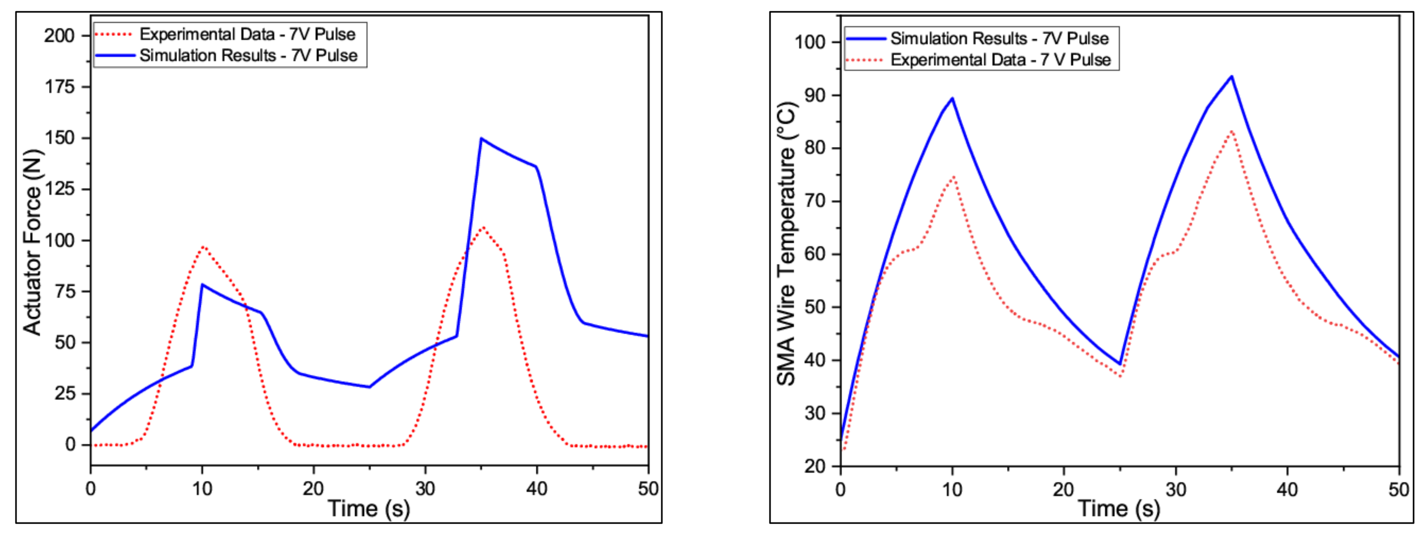


Fig 9 : (a) Comparison of the actuation force using load cell (b) Comparison of SMA wire temperature of the wires using thermal IR camera

References

[1] Lee, J.-H., Chung, Y. S. & Rodrigue, H. Long shape memory alloy tendon-based soft robotic actuators and implementation as a soft gripper. Sci. Rep. 9, 1–12 (2019).
[2] Elahinia, M. H. & Ahmadian, M. An enhanced SMA phenomenological model: II. The experimental study. Smart Mater. Struct.14, 1309 (2005)

Publication

- Chaurasiya, K. L., Harsha, A., Sinha, Y., & Bhattacharya, B. (2022). Design and development of non-magnetic hierarchical actuator powered by shape memory alloy based bipennate muscle. *Scientific Reports*, *12*(1), 1-15.

Acknowledgement

This research work has been partially funded by the **Portescap India Pvt. Ltd**. through a Corporate Social Responsibility (CSR) grant (Project Number: PIPL/DORA/2020022).