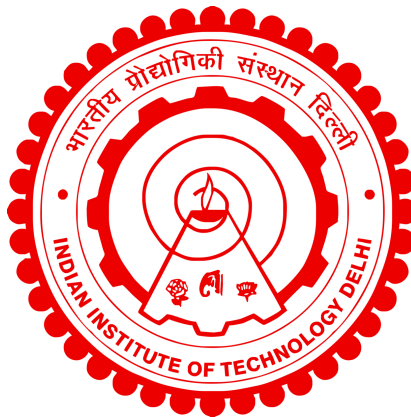


**COMPUTATIONAL DESIGN AND ANALYSIS
OF SKELETAL MUSCLE-LIKE SOFT
ACTUATORS**

SASWATH GHOSH



**DEPARTMENT OF APPLIED MECHANICS
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

JULY 2025

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by

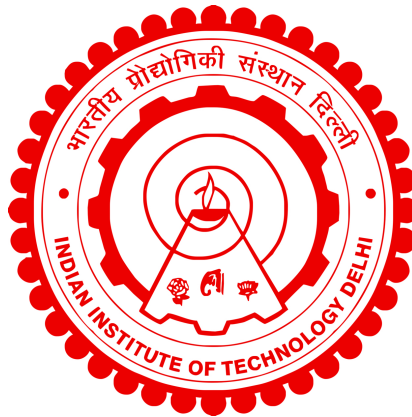
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Submitted

in fulfillment of requirements of the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

JULY 2025

*Dedicated to my dear parents, whose love and support
have been my greatest source of strength and inspiration.*

Certificate

This is to certify that the thesis entitled "**Computational Design and Analysis of Skeletal Muscle-like Soft Actuators**", submitted by **Mr. Saswath Ghosh** to the **Indian Institute of Technology Delhi** for the award of the degree of **Doctor of Philosophy** is a record of the original, bonafide research work carried out by him under my supervision. The thesis works meets the requisite standards and the candidate is worthy of consideration for the degree of Doctor of Philosophy in accordance with the regulations of the institute.

The results contained in this thesis have not been submitted in part or in full to any other university or institute for the award of any degree or diploma.

Date: 15 July 2025

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Abstract

Soft actuators drive the motion in soft robots. The design and development of these actuators depend on the intended application. In this work, the design and analysis of skeletal muscle-like soft actuators is carried out, which have the potential to be utilized in the domain of soft wearable technology. Notably, the work focused on designing and modeling pneumatically and electrically-driven fiber-reinforced tubular soft actuators.

The initial phase of this research involves the detailed modeling, fabrication, and experimental characterization of pneumatic-based soft actuators, specifically Pneumatic Braided Muscle (PBM) actuators. A nonlinear physics-based model incorporating friction loss factors is developed, which characterizes the quasi-static behavior of PBM actuators. In addition, the model is validated with the experimental results. In order to characterize these actuators, a set of three PBM actuators is fabricated in-house. Moreover, it is observed that the geometrical parameters of the actuators affect the actuation. Consequently, it motivates the development of a parametric computational design framework to generalize the design of soft actuators. The computational design framework uses a generative machine learning model to generate new designs. The qualitative and quantitative methods are used to evaluate the generative model, and the performance of the novel designs is evaluated using Finite Element (FE) analysis. The complete process is automated using an in-house Python code. The developed algorithm is applied to generate new designs of soft Pneumatic Network (Pneu-net) actuators that could perform a multimodal actuation. Moreover, the algorithm could be applied to PBM actuators as well to obtain new designs. Further, a natural muscle-like dynamic model is developed to study the nonlinear dynamic response of PBM actuators. The nonlinear frequency response provides essential guidance for selecting parameters of PBM actuators in dynamic applications.

In the following part of the study, Electroactive Polymer (EAP)-based soft actuators are focused on, particularly the Dielectric Elastomer Actuators (DEAs) and Conducting Polymers (CPs). First, an Electro-PBM (EPBM) actuator is modeled by substituting the silicone bladder with DE. The constitutive relations change for EPBM actuators. However, the actuator requires input voltage in the range of

a few kilo Volts to operate and does not deliver a high free contraction. Subsequently, low voltage-driven EAPs, specifically Fiber-reinforced Tubular Conducting Polymer (FTCP) actuators, were investigated as a viable solution. An electro-chemo-mechanical model of FTCP actuators is developed. The nonlinear deformation model is linearly coupled with an electrical circuit-based electrochemical model. The model predicts the response of FTCP actuators for an applied voltage (< 5 V). Moreover, the alteration in the fiber properties results in dual-mode actuation for the same applied voltage.

Overall, this thesis contributes to the design and analysis of skeletal muscle-like soft actuators. The findings underscore the importance of design parametrization of pneumatic and electrically-driven soft actuators, thus paving the way for future advancements in soft wearable robotics.

Keywords: Soft Robotics, Soft Actuators, Artificial Muscle, Soft Pneumatic Actuators, Conducting Polymer Actuators, Generative Design

सार

सॉफ्ट एक्ट्यूएटर्स सॉफ्ट रोबोट में गति को संचालित करते हैं। इन एक्ट्यूएटर्स का डिज़ाइन और विकास इच्छित अनुप्रयोग पर निर्भर करता है। इस कार्य में, कंकाल पेशियों जैसे सॉफ्ट एक्ट्यूएटर्स का डिज़ाइन और विश्लेषण किया गया है, जिनका उपयोग सॉफ्ट वियरेबल तकनीक के क्षेत्र में किया जाना है। उल्लेखनीय रूप से, यह कार्य वायवीय और विद्युत-चालित फाइबर-प्रबलित ट्यूबलर सॉफ्ट एक्ट्यूएटर्स के डिज़ाइन और मॉडलिंग पर केंद्रित है।

इस शोध के प्रारंभिक चरण में वायवीय-आधारित सॉफ्ट एक्ट्यूएटर्स, विशेष रूप से वायवीय ब्रेडेड मसल (PBM) एक्ट्यूएटर्स का विस्तृत मॉडलिंग, निर्माण और प्रयोगात्मक लक्षण वर्णन शामिल हैं। घर्षण हानि कारकों को शामिल करते हुए एक गैर-रैखिक भौतिकी-आधारित मॉडल विकसित किया गया है, जो PBM एक्ट्यूएटर्स के अर्ध-स्थैतिक व्यवहार की विशेषता बताता है। इसके अलावा, इन एक्ट्यूएटर्स की विशेषता को परखने हेतु तीन सैंपल्स का प्रयोगशाला में निर्माण किया गया और मॉडल को प्रयोगात्मक परिणामों के साथ मान्य किया गया है। इसके अतिरिक्त, यह देखा गया है कि एक्ट्यूएटर्स के ज्यामितीय पैरामीटर्स एक्चुएशन को प्रभावित करते हैं। परिणामस्वरूप, यह सॉफ्ट एक्ट्यूएटर्स के डिज़ाइन को बनाने के लिए पैरामीट्रिक कम्प्यूटेशनल डिज़ाइन फ्रेमवर्क के विकास को प्रेरित करता है। कम्प्यूटेशनल डिज़ाइन फ्रेमवर्क नए डिज़ाइन बनाने के लिए एक जनरेटिव मशीन लर्निंग मॉडल का उपयोग करता है। नए जेनेरेटेड डिज़ाइन का मूल्यांकन करने के लिए गुणात्मक और मात्रात्मक तरीकों का उपयोग किया गया है, और नए डिज़ाइनों के प्रदर्शन का मूल्यांकन फिनाइट एलिमेंट (FE) विश्लेषण का उपयोग करके किया गया है। पूरी प्रक्रिया को पायथन कोड का उपयोग करके स्वचालित किया गया है। विकसित एल्गोरिथ्म का उपयोग सॉफ्ट न्यूमेटिक नेटवर्क (Pneunet) एक्ट्यूएटर्स के नए डिज़ाइन बनाने के लिए किया गया है जो मल्टीमॉडल एक्ट्यूएशन कर सकते हैं। इसके अलावा, एल्गोरिथ्म को नए डिज़ाइन प्राप्त करने के लिए PBM एक्ट्यूएटर्स पर भी लागू किया जा सकता है। आगे, PBM एक्ट्यूएटर्स की अरेखीय गतिशील प्रतिक्रिया का अध्ययन करने के लिए एक प्राकृतिक मांसपेशी जैसा गतिशील मॉडल विकसित किया गया है। अरेखीय आवृत्ति प्रतिक्रिया गतिशील अनुप्रयोगों में PBM एक्ट्यूएटर्स के मापदंडों के चयन के लिए आवश्यक मार्गदर्शन प्रदान करती है।

अध्ययन के अगले भाग में, इलेक्ट्रोएक्टिव पॉलीमर (EAP)-आधारित सॉफ्ट एक्ट्यूएटर्स पर ध्यान केंद्रित किया गया है, विशेष रूप से डाइइलेक्ट्रिक इलास्टोमर एक्ट्यूएटर्स (DEA) और कंडक्टिंग

पॉलीमर्स (CP)। सबसे पहले, सिलिकॉन ब्लैडर को DE से प्रतिस्थापित करके एक इलेक्ट्रो-पीबीएम (EPBM) एक्ट्यूएटर का मॉडल बनाया गया है। EPBM एक्ट्यूएटर्स के लिए संरचनात्मक संबंध बदल जाते हैं। हालांकि, एक्ट्यूएटर को संचालित करने के लिए कुछ किलो वोल्ट की सीमा में इनपुट वोल्टेज की आवश्यकता होती है और यह उच्च मुक्त संकुचन भी प्रदान नहीं करता है। इसके बाद, कम वोल्टेज से चलने वाले EAP, विशेष रूप से फाइबर-प्रबलित ट्यूबलर कंडक्टिंग पॉलीमर (FTCP) एक्ट्यूएटर्स की जांच एक व्यवहार्य समाधान के रूप में की गई। FTCP एक्ट्यूएटर्स का एक इलेक्ट्रो-केमो-मैकेनिकल मॉडल विकसित किया गया है। अरेखीय विरूपण मॉडल को विद्युत सर्किट-आधारित इलेक्ट्रोकेमिकल मॉडल के साथ रैखिक रूप से जोड़ा गया है। मॉडल लागू वोल्टेज ($<5\text{ V}$) के लिए एफटीसीपी एक्ट्यूएटर्स की प्रतिक्रिया बताता है। इसके अलावा, फाइबर गुणों में परिवर्तन के परिणामस्वरूप समान लागू वोल्टेज के लिए दोहरे मोड की प्रतिक्रिया प्रदर्शित करता है।

सारांशतः, यह थीसिस कंकाल पेशियों जैसे सॉफ्ट एक्ट्यूएटर्स के डिजाइन और विश्लेषण में योगदान देती है। खोज वायवीय और विद्युत चालित सॉफ्ट एक्ट्यूएटर्स के डिजाइन पैरामीट्रिजेशन के महत्व को रेखांकित करते हैं और इस प्रकार सॉफ्ट वियरेबल रोबोटिक्स में भविष्य की प्रगति का मार्ग प्रशस्त करते हैं।

संकेतशब्द: सॉफ्ट रोबोटिक्स, सॉफ्ट एक्ट्यूएटर्स, कृत्रिम मांसपेशी, सॉफ्ट वायवीय एक्ट्यूएटर्स, कंडक्टिंग पॉलीमर एक्ट्यूएटर्स, जनरेटिव डिज़ाइन

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Symbols

\mathcal{B}_0	Undeformed configuration
\mathcal{B}	Deformed configuration
\mathbf{F}	Deformation gradient tensor
\mathbf{B}	Left Cauchy-Green tensor
σ^{iso}	Cauchy stress tensor for an isotropic material
μ	Friction coefficient
P	Applied pneumatic pressure
R	Radial coordinate in undeformed configuration
Θ	Circumferential coordinate in undeformed configuration
Z	Longitudinal coordinate in undeformed configuration
r	Radial coordinate in deformed configuration
θ	Circumferential coordinate in deformed configuration
z	Longitudinal coordinate in deformed configuration
F_{act}	Total actuation force of PBM actuators
\mathbf{x}_d	Training design dataset
\mathbf{x}_{gen}	Generated design dataset
ω_0	Natural frequency
ω	Excitation frequency
P_s	Static pressure
P_d	Dynamic pressure
β	Non-dimensional damping coefficient
ϵ	Scaling parameter
t	Time
τ	Non-dimensional time
σ	Electro-mechanical stress

s	Laplace variable
$v_{in}(t) [V_{in}(s)]$	Applied step voltage in time [Laplace] domain
$i(t) [I(s)]$	Total circuit current in time [Laplace] domain
R_e	Equivalent circuit resistance
C_{dl}	Double layer capacitance
$i_c(t) [I_c(s)]$	Double layer charging current in time [Laplace] domain
$i_d(t) [I_d(s)]$	Diffusion current in time [Laplace] domain
$Q'(s)$	Total ionic charge in double layer
$c(R, t) [C(R, s)]$	Mobile ion concentration inside conducting polymer along radial direction in time domain
A	Surface area of the double layer capacitor
δ	Double layer thickness
D	Diffusion coefficient of mobile ions
\mathbf{j}	Ionic flux vector
$Y(s)$	Circuit admittance
ν	Volume ratio of FTCP actuator
V_f	Deformed volume of FTCP actuator
V_0	Undeformed volume of FTCP actuator
Q	Total steady-state charge stored in FTCP per unit its undeformed volume
κ	Shear modulus of FTCP actuators
ζ	Anisotropic factor representing the fiber strength
$\sigma_{\mathbf{aniso}}$	Cauchy stress for an anisotropic material
F_{axial}	Axial force of FTCP actuators
λ_3	Axial stretch of FTCP actuators

Abbreviations

PBM	Pneumatic Braided Muscle
EPBM	Electro-Pneumatic Braided Muscle
EAP	Electroactive Polymer
CP	Conducting Polymer
FE	Finite Element
DE	Dielectric Elastomer
LCE	Liquid Crystal Elastomer
FTCP	Fiber-reinforced Tubular Conducting Polymer
Pneu-net	Pneumatic Network
CAD	Computer Aided Design
UTM	Universal Testing Machine
PSA	Pneumatic Soft Actuators
t-SNE	t-distributed Stochastic Neighbor Embedding
GMM	Gaussian Mixture Model
PaGD	Performance-augmented Generative Design
MSM	Multiple Scales Method
EC	Electrochemical
DL	Double Layer

Physical Constants

Faraday constant	$F = 9.648533 \times 10^4 \text{ C mol}^{-1}$
Electrical permittivity in vacuum	$\epsilon_0 = 8.854 \times 10^{-12} \text{ F m}^{-1}$