Development and Validation of an Instrument for Measuring Actuation Behaviour of Non-freestanding Conducting Polymer Films

Ameya Nijasure[1], Priam V. Pillai[2]
[1,2]*Department of Mechanical Engineering, Pillai College of Engineering, New Panvel, India*

***Abstract*—Conducting Polymer as actuators have gained attentions due to their low operating voltage, lightweight structure and high strain generation. Conducting Polymer to be used as an actuator, Characterization of actuation in terms of force generated in essential for practical application. However, conventional force measurement techniques require freestanding films, which complicates early-stage material characterization. This work introduces novel instrument designed for the in situ measurement of actuation force in non-freestanding films directly deposited in electrodes. The system integrates load cell with probe designed to measure force generated due to electrochemically induced swelling in the thickness direction. The instrument is validated using electrochemically synthesized polypyrrole films of varying thicknesses. The results demonstrate stable and repeatable force in the direction of thickness, measured in the range of the milli-Newtons (mN). The instrument was validated using polypyrrole (PPy) films of varying thicknesses, demonstrating stable and repeatable force measurements in the milli-Newton (mN) range under a step function of +2V to -2V. This system eliminates the need for time-consuming freestanding film preparation, offering a scalable and efficient tool for rapid material screening and actuator development during the early synthesis phase.**

***Index Terms*—Electromechanical Force Generation, In Situ Measurement, Polypyrrole (PPy) Actuators, Propylene Carbonate Electrolytes, Non-Freestanding Films,**

I. INTRODUCTION

Conducting Polymers are a promising category of smart materials emerging as actuators for soft robotics, artificial muscles, biomedical devices, and micro-electromechanical systems (MEMS) [1, 2, 6]. They have the ability to generate significant strain under low operating voltages with lightweight and flexible structures [4]. The actuation mechanism in conducting polymers is primarily governed by ion movement in an electrically conducting liquid environment when subjected to an external electrical stimulus [3, 11]. This electrochemical coupling leads to measurable deformation, which can be characterized in terms of displacement or generated force [5]. Accurate measurement of these parameters is essential for understanding material behavior, optimizing synthesis conditions, and enabling their integration into practical engineering systems [7,12].

A wide range of experimental setups and instruments have been developed to characterize the actuation performance of conducting polymers. These include dynamic mechanical analyzers, laser displacement-based systems, and force measurement setups integrated with electrochemical testing environments [3, 10]. While these systems provide valuable insights into actuator performance, they are predominantly designed for freestanding films that possess sufficient mechanical integrity to be handled, clamped, and tested independently [4, 11]. However, in the early stages of material development, conducting polymers are typically synthesized as thin films deposited directly onto electrode substrates. These non-freestanding films lack the structural robustness required for conventional testing, making it challenging to evaluate their actuation behavior without additional processing [9]. The fabrication of freestanding films is often time-consuming, material-intensive, and may alter intrinsic properties, thereby limiting rapid screening and iterative development of new materials and composites [2, 6, 13].

This limitation highlights a critical gap in existing characterization techniques: the lack of a measurement system that can quantify actuation force behavior in non-freestanding conducting polymer films [9, 10]. Considering novel material development cycles and performance assessment at an early stage, addressing this gap is essential [8]. In this work, a novel instrument is developed for the measurement of actuation force in non-freestanding conducting polymer films deposited on electrode substrates. The proposed system is designed to capture actuation-induced force in the thickness direction using a sensitive load cell coupled with a probe mechanism under electrochemical excitation [10]. The instrument integrates a potentiostat for controlled voltage input and a data acquisition system for synchronized measurement of electrical and mechanical responses. To validate the proposed instrument, polypyrrole films are synthesized via electrochemical deposition with controlled thickness variations and tested under different excitation conditions. The system demonstrates the ability to measure force responses in the milliNewton range with consistent repeatability and sensitivity. The developed approach enables direct characterization of electrode-supported films, eliminating the need for freestanding sample preparation.

II. WORKING PRINCIPLE AND SYSTEM ARCHITECTURE

The primary objectives of the proposed instrument are as follows

- To enable direct measurement of actuation behavior in non-freestanding conducting polymer films deposited on electrode.
- To provide a controlled electrochemical environment for high-sensitivity force measurement.
- To capture actuation data at high sampling rates to accurately record rapid responses occurring under low-voltage inputs.

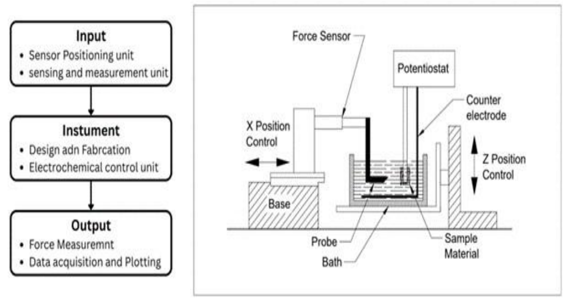

Figure 1: 3D CAD model of an instrument Setup

II.1 Working Principle and force measurement

The operation of the instrument is based on the electro-chemical actuation of conducting polymer films. When an electrical potential is applied between the working and counter electrodes, ions from the electrolyte migrate into or out of the polymer matrix, resulting in volumetric expansion or contraction of the film. In non-freestanding configurations, this deformation is swelling of sheet. To capture this behavior, the sensing probe is brought into contact with the surface of the polymer film under a preload condition. Upon application of the electrical stimulus, the polymer undergoes swelling due to ion insertion, exerting a force on the probe in the normal (thickness) direction. This force is transmitted to the load cell, which converts the mechanical input into an electrical signal proportional to the applied force.

The force measurement approach is based on indirect sensing through calibrated load cell output. The sensor signal, obtained in millivolts, is amplified and converted into force values using a predefined calibration factor. The sensor is capable of capturing low-magnitude forces with high sensitivity and resolution, making it suitable for studying both static and dynamic actuation behavior.

II.2 Selection of Components

The selection of key components for the proposed instrument was carried out based on requirements of sensitivity, precision, and compatibility with electrochemical testing conditions, as summarized in Table 1. All selected components were verified for compatibility with the National Instruments (NI) DAQ system to ensure seamless integration and reliable data acquisition.

Table 1: Selection of Key Components and Justification

Component	Selected Component	Key Specifications	Selection Criteria
Glassy Carbon Electrode	Glassy Carbon Flat Electrode – Conducting Material	• High conductivity • Chemically inert; • Stable surface interface	Suitable for conducting polymer deposition; corro- sion resistant and electro- chemically stable
Force Sensor	Futek Jr. Miniature S-Beam Load Cell (5 lbs) with Amplifier	• Capacity: ~22 N (5 lbs) • High sensitivity (mV output)	High sensitivity for low-force (mN) measurement; compact and DAQ-compatible
Actuation Mechanism	NEMA 18 Stepper Motor	Precise step control, Repeatable positioning, Moderate torque	Precise and repeatable probe positioning; enables controlled preload
Potentiostat	PalmSens 3	• Wide voltage range and cycle options Low current capability (~mA), Portable, PC interfacing	Accurate low-voltage electrochemical control; real-time measurement capability

II.3 System Architecture and Design

The system architecture integrates mechanical positioning, force sensing, and electrochemical control to measure actuation in conducting polymer films. As shown in Figure 1, a probe coupled with a force sensor is precisely positioned to interact with the polymer-coated electrode within an electrolyte bath, while a potentiostat provides controlled electrical excitation. The resulting actuation is captured as force signals and recorded through a data acquisition system for analysis. This modular design enables controlled, reliable, and real-time measurement of actuation behavior in non-freestanding films.

III. DESIGN AND FABRICATION OF INSTRUMENT

SolidWorks 2021 is used to model a full-scale 3D Model of an experimental setup derived from proposed instrument layout as shown in figure 1. Complete 3D model of an instrument setup is shown in figure 2. Base of an instrument is fabricated in acrylic which provides stability. Nylon is selected as material for Bath. CNC milling machine is used to fabricate a cylindrical bath of 100 mm diameter. Bath is designed to hold electrolyte and electrodes in position while instrument is in operation. Two electrode configuration is selected for depending on experimental requirements. Flat carbon electrode is used as working electrode with polymer deposited on it and thin copper sheet is used as counter electrode. To ensure a defined active area for polymer deposition and subsequent force testing, the carbon electrode was covered using paper adhesive tape. Futek Jr. Miniature S-Beam Load Sensor is mounted on steeper motor assembly which is free to move laterally as illustrated in schematic. Sensor mount is fabricated using a FDM 3D printer and PLA material and nylon probe is attached to a sensor which comes in contact with deposited film on electrode while testing. PalmSens 3 is used as potentiostat to apply a constant voltage to the working electrode. National Instruments (NI) DAQ system is used to control experimental setup and data acquisition. The DAQ system is interfaced with LabVIEW 2024 software, where front and back-end interfaces are developed to enable tracking of data. Voltage signal is acquired using NI 9205 C series module. Two channels are used one for recoding load cell output and other is connected between working and counter electrode monitoring input voltage provided to system. Raw data is logged and collected in excel sheet column arrays enabling post experiment analysis of data. Figure 3 shows fabricated setup of an instrument with all hardware components.

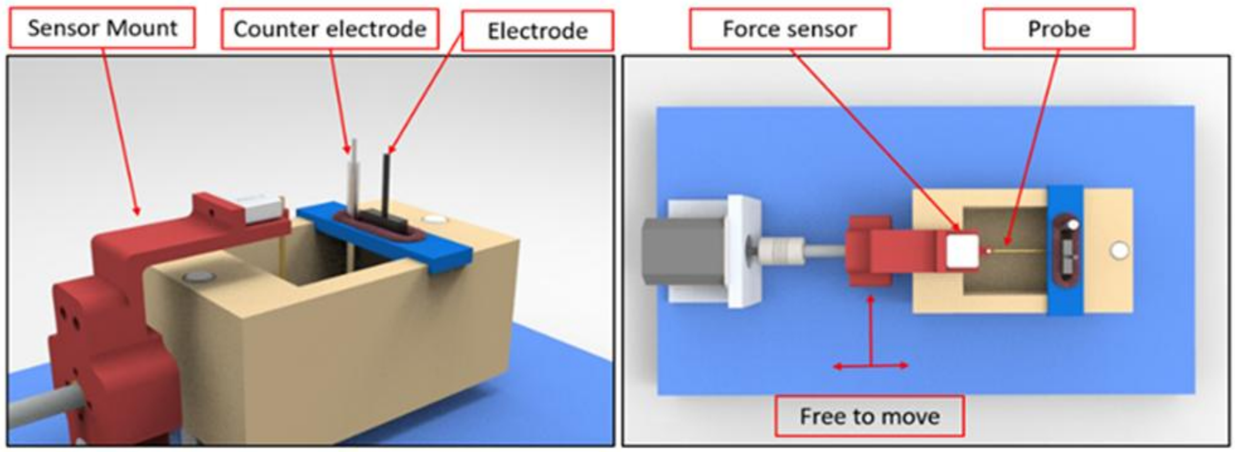

Figure 2: 3D CAD model of an instrument Setup

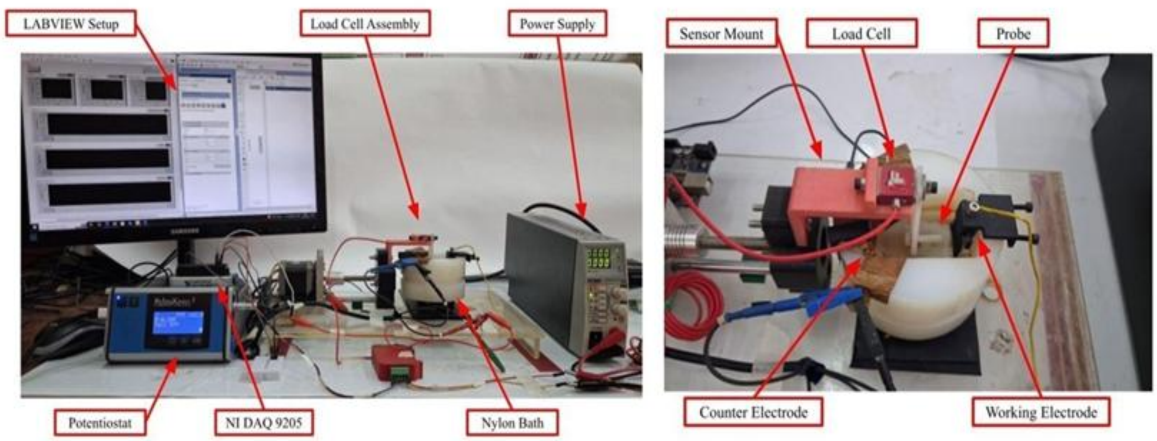

Figure 3: Labelled Instrument setup – Including Nylon Bath, Power Supply, Electrode arrangement, Potentiostat Setup, Motor Assembly, NI-DAQ system connected to PC.

IV. VALIDATION AND TESTING

To evaluate the performance and reliability of the developed instrument, a series of tests were conducted using polypyrrole (PPy) film synthesized via electrochemical deposition. Thin films of polypyrrole (Ppy) were synthesized by electrochemical polymerization using nylon bath. The solution for polymerization process was prepared by mixing 1 ml of pyrrole with 30 ml of Propylene Carbonate as organic solvent and 3 grams of Organic salt Tetramethylammonium hexafluorophosphate (TMEP) (C4H12F6NP). Sample is kept for 3Hrs at content voltage of 4V in a system. A black polypyrrole coating of approximately 150 micron formed on the working electrode, which was subsequently used for actuation testing in developed instrument discussed in previous section. The PPy/ C4H12F6NP sample films were tested on instrument at different scan rates between +2.0 and −2.0V step cycles using Palmsense 3 as potentiostat. Figure 4 shows force generated by film when sample is tested for different cycles. Sample is tested for different cycle frequencies ranged from 0.05 Hz to 0.0083 Hz. After testing PPy/ C4H12F6NP film in experimental setup polymer film can be observed in lifted from surface. That provides confirmation on film actuation in experimental setup. Samples tested at higher frequencies provide better actuation compared to small frequencies. Also drift is observed in sample while testing which results into accumulation of force in each cycle. This also confirms ion movement in to the film which is a reason for actuation force in electrochemical testing.

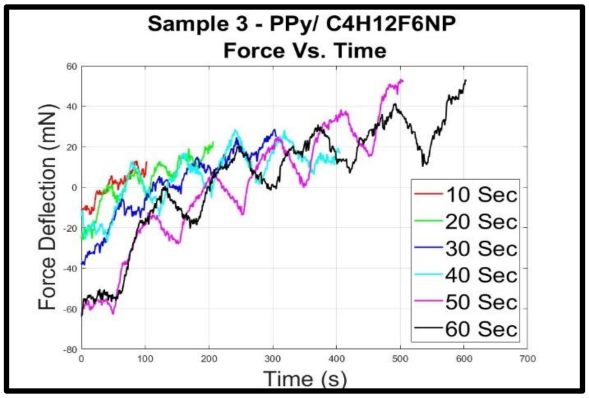

Figure 4: Force generated by PPy/ $C_4H_{12}F_6NP$ samples for testing duration from 0.05 Hz to 0.0083 Hz

V. RESULTS AND DISSCUSSION

The developed instrument provides solution for characterizing electrochemical behaviour of conduction polymer films. It incorporates several key features that distinguish it from conventional measurement systems:

- Direct measurement of actuation in non-freestanding films without sample modification
- Capability to measure force in the thickness direction with high sensitivity.
- Integration of electrochemical control and mechanical sensing in a single platform.
- By offering a modular and efficient platform, the instrument enables rapid screening and iterative development of new polymer composites

These features collectively enable accurate and repeatable characterization of conducting polymer actuation behaviour, particularly in early-stage material development where conventional testing approaches are not feasible.

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