Computer Vision-based Fluid-Structure Interaction Tracking using an Electroactive Polymer (EAP) Sensor

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ABSTRACT

Ionic polymer-metal composites (IPMCs) are a type of soft robotic electroactive polymer (EAP). The unique two-way transduction property of IPMCs allow for both actuation and sensing, which, in conjunction with its ability to be used in aqueous environments, can be used for various underwater applications[1,2,3]. In this study, we aim to use several imaging and image processing techniques by developing a computer vision-based code within Wolfram Mathematica for the purpose of tracking sensor deflection and travel velocity of an IPMC sensor.

Presently, experimental validation of IPMCs as an active real-time flow sensor is limited due to lack of current fluid-structure flow visualization studies for measuring the flow field of a surrounding environment. This lack of visualization disallows a means for validation and calibration of current research on the subject. By developing and implementing computer vision, the accuracy of the IPMC flow sensor can be improved and can provide verification and understanding of sensor measurements.

The scientific impact of this research effort is directly related to the increasing surge of smart materials and artificial muscles within the scientific community. Continuous effort in understanding and applying smart material-based technology is a significant step in the advancement future technology that will ultimately benefit humanity.

INTRODUCTION

Ionic polymer-metal composites are unique electroactive polymers that are constructed from flexible polymers that can sustain large deformations and strains. IPMCs are formed by compositing an electrode material, typically a noble metal, onto the surface of an ionomer membrane[4]. The mechano-electric transduction abilities of IPMCs allow them to function as sensor devices, producing signals within the mV range. The work presented herein will be focused on this aspect of IPMC physics.

The usage of IPMCs as active sensor devices have been discussed in various literature on the topic and show great potential to be further investigated and integrated into a real-time sensor feedback system[3,5]. By studying and classifying the sensor response, detailed spatial-temporal information can be acquired in real-time fluid flow environments and hence can be utilized in various feedback configurations to improve performance of an underwater structure.

To study IPMCs as a sensor, it is imperative to calibrate and classify the acquired voltage response during stimulus. External imaging equipment and image processing can be used as a validation method and can provide a means to future understand the open circuit voltage of an IPMC sensor within an active fluid environment.

Wolfram Mathematica has been proven to be a user-friendly and robust tool for image processing and was used as the primary program in this study. Herein, we developed a user interactive notebook within Wolfram Mathematica with two major goals:

1. Capture and track the relative velocity of IPMC sensor using imaging and image process techniques. Confirm this value with our known value.
2. Capture and measure the tip displacement of the IPMC sensor during travel using imaging and image process techniques and compare to acquired voltage data from the sensor.

Through computer vision, gathered sensor response data can be compared to captured physical fluid-structure interaction, and can be used in future studies to anticipate environmental flow dynamics.

METHOD

Experiments were conducted within an 85-gal tank with the IPMC sensor mounted to an inverted linear belt slide system (MacronDynamics MSA-M6S) driven by a stepper motor (Applied Motion Products SSM23IP-4EG). The motor software was programmed to run at 200 rps, traveling at 150 mm/rev (300 mm/s). Voltage readings were acquired directly using a Keithley 6510 DAQ. Two cameras were primarily used for capture for two individual applications: velocity, and tip deflection (**Fig. 1, 2**).

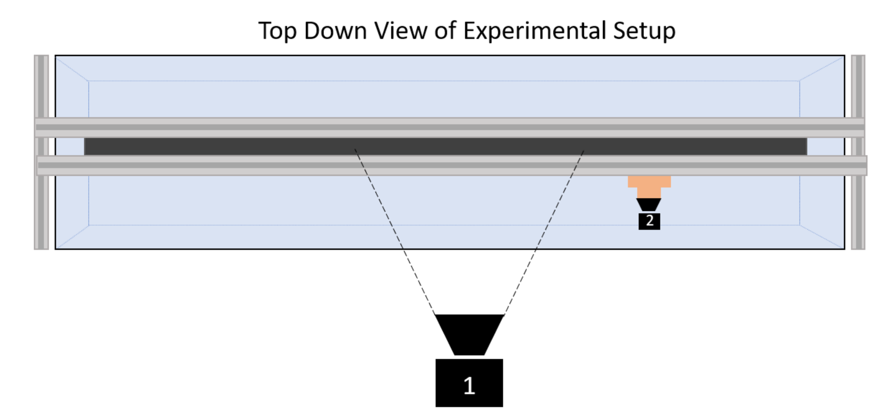

Fig. 1 Illustration demonstrating the experimental setup and positions of both cameras relative to the aquarium and sensor carriage (in orange).

- **Camera 1 (Canon EOS Rebel SL1)**
  - Used to capture the travel speed of the sensor mount
    - Fixed directly facing the side wall of the aquarium
  - Fitted with a stock 18-55mm Canon lens
  - Video was captured at 1080p, 30 fps

The far-side of the aquarium is fitted with a 1-inch grid poster that was used to determine the calibration factor of the footage. Various light-sources were set behind the background image in order to produce backlit footage of the sensor mount traveling.

- **Camera 2 (DJI OSMO Action)**
  - Used to for observing sensor deformation from an above view and to relate the dynamic tip displacement of the IPMC to the acquired voltage response
    - Mounted directly to the carriage to travel alongside the sensor
  - Captured high speed footage at 1080p, 240 fps
    - Ideally to capture the nuance in the deformation

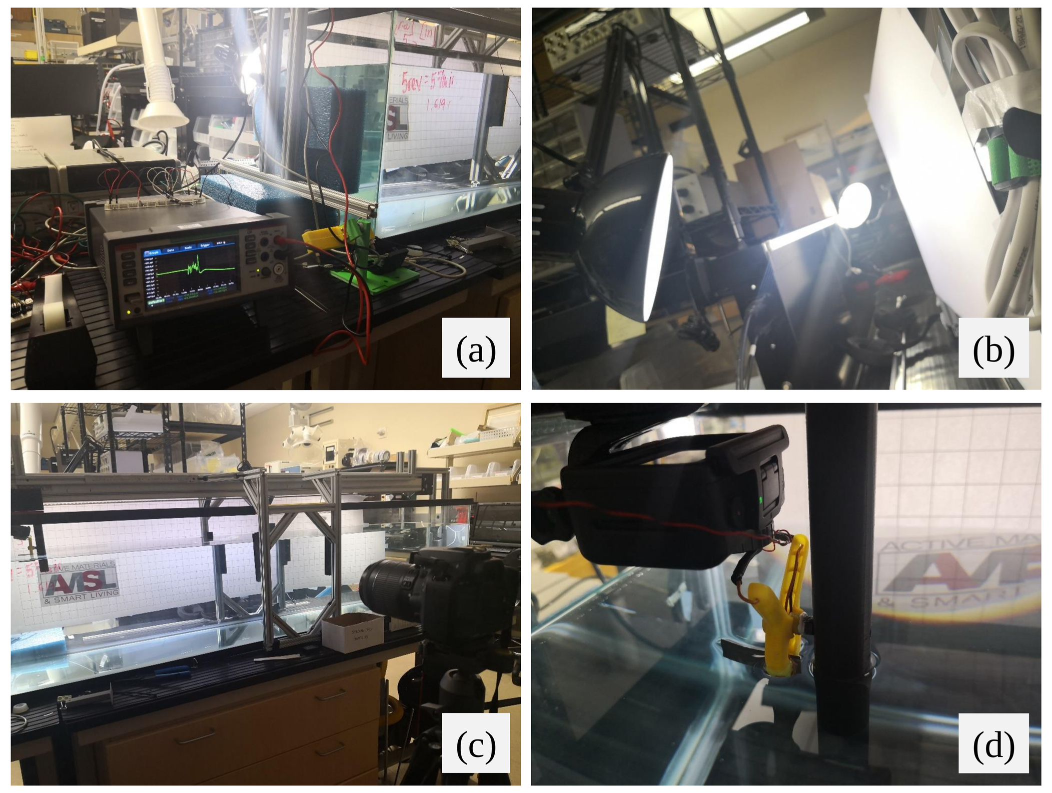

Fig. 2 (a) Keithley 6510 DAQ pictured alongside 85-gal aquarium slide apparatus (b) Lighting setup providing backlit imaging (c) Camera 1 positioned directly to face the side wall of the aquarium (d) Camera 2 positioned to capture directly above the IPMC sensor

Velocity Tracking

Wolfram Mathematica was implemented to detect the velocity of a discrete binarized section of the sensor carriage mount. The found velocity was then verified by the programable velocity from the provided linear belt slide software. An assumption is made that the carriage, clamp, and IPMC sensor are traveling as a single body, and thus share the same velocity.

Prior to analysis, the captured experimental video was exported as a series of .png formatted images through an external video editing software, which was then imported and resized for data management.

Velocity Tracking Steps Followed:

1) Apply a mask to isolate a specific region of capture that will be used for simplifying the binarization of the moving carriage.
2) Color separate into CMYK color channels.
   - The yellow channel, which best isolated the color of the clamp, was used identify the moving carriage using a threshold binarization.
3) Identify the centroid of each binarized component within each frame and store into an array.
4) Calculate velocities by determining travel distance in successive frames and then by subsequently dividing the time step and multiplying by the calibration factor.
5) Calculate mean velocity by partitioning a stable region of velocities.

Displacement Tracking

Wolfram Mathematica was also used to track IPMC deformation during travel.

Displacement Tracking Steps Followed:

1) Apply a mask to each frame to isolate the region of interest.
2) During binarization, apply a Sobel edge detection kernel
   - This will increase the accuracy of binarization by detecting the edge of the rectangular IPMC.
3) Apply a second mask to segment the IPMC into four sections for tracking curvature through the component centroids.
4) Calculate displacement by determining the distance traveled by the centroid of successive frames.

RESULTS

Velocity Tracking

The resulting calculated velocity was plotted as shown in **Fig. 3**. The determined average velocity was comparable to the motor programmed speed (V_{avg} = 330 mm/s, V_{real} = 300 mm/s). Possible sources of error include the fact that the measurement plane used for determining the calibration factor was not in the same plane as the moving carriage, which would induce some parallax error. Refraction through the water from the calibrated grid lines could have also affected this value.

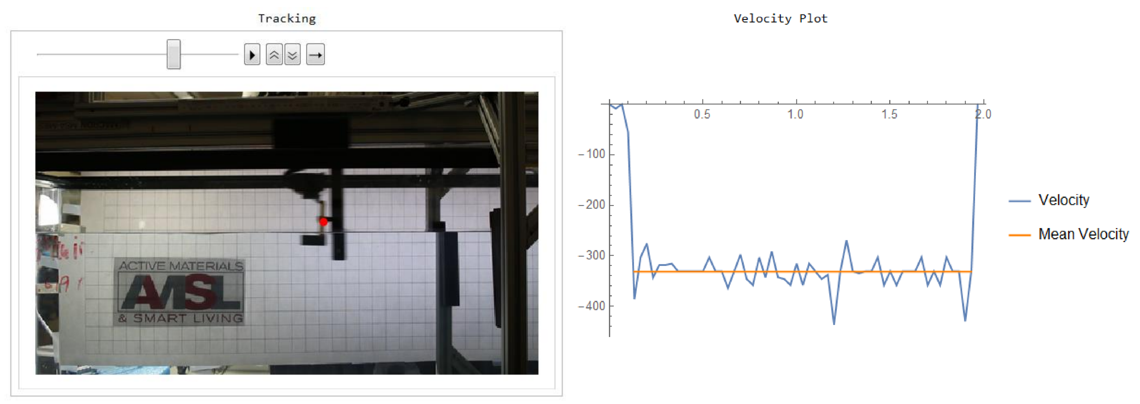

Fig. 3 (Left) Still-frame of velocity tracking footage with centroid of the clamp highlighted by the red dot. (Right) Plotted velocity data along with calculated mean velocity (330 mm/s).

Displacement Tracking

The centroid of each component segmented along the IPMC edge was plotted to visualize curvature through time (**Fig. 4**). The farthest component (Point 1) from the clamped end of the IPMC was shown to have the largest displacement (max 2.5 mm) which was expected.

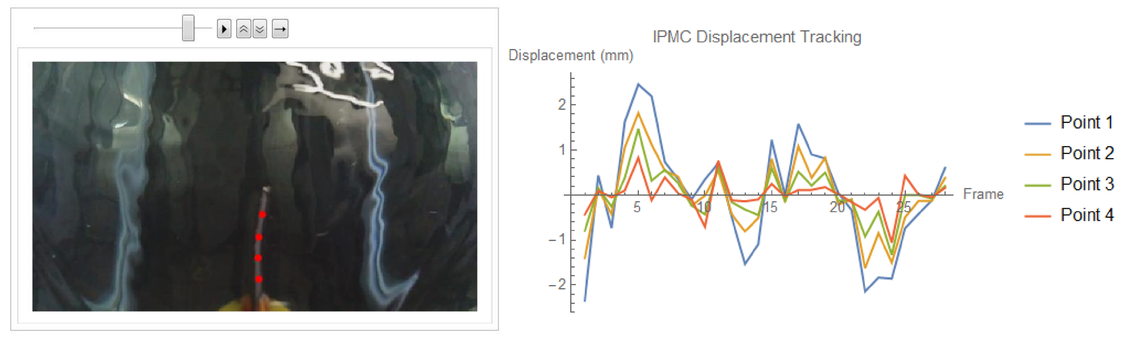

Fig. 4 (Left) Still-frame of velocity tracking footage with centroid of the clamp highlighted by the red dot. (Right) Plotted velocity data along with calculated mean velocity (330 mm/s).

The max displacement data was also compared to the voltage response acquired from the IPMC directly using a data acquisition device (**Fig. 5**). These two plots demonstrate similarity in trends supports the hypothesis that tracking the displacement of an IPMC can correlate to the sensor's open-circuit voltage response.

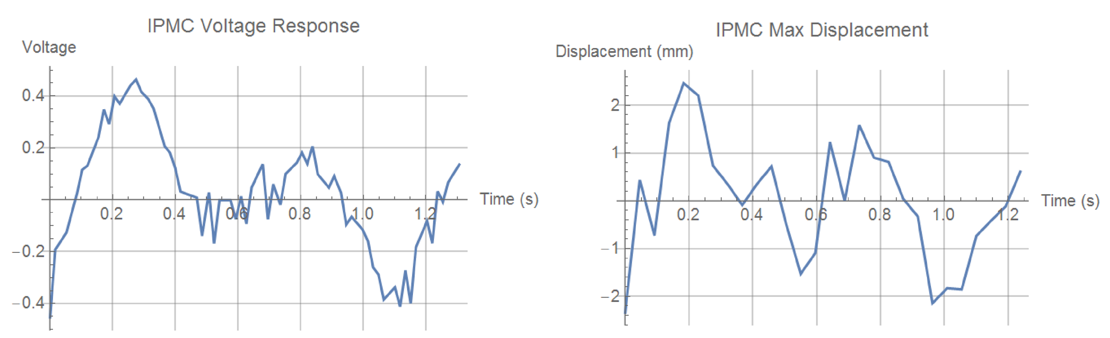

Fig. 5 IPMC open circuit voltage response data (in mV) juxtaposed to computer vision displacement data.

CONCLUSION

The work presented herein demonstrates an initial step in using computer vision to study fluid-structure interaction and the unique phenomenon of IPMC sensing. By first developing a displacement and velocity tracker, future analysis can be performed on additional fluid and structural occurrences such as local vortex shedding and structural stress. Correlating and confirming displacement and voltage data is essential in the future study of IPMCs as flow sensor devices and in turn, future technology.

Some improvements to the work presented herein include increasing the quality of imaging during the experimental process. This includes:

- Establishing a better lighting system to decrease reflectivity
- Applying more prominent tracking points for better clarity and accuracy during binarization
- Providing an in-plane measurement tool for more precise distance calibration
- Applying a Hough transform as an alternative method for IPMC deformation tracking
  - This method will highlight changes along straight edges

Future efforts on this program will be transferred to Python, specifically utilizing the acclaimed computer vision library, OpenCV.

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ACKNOWLEDGEMENTS

This material is based upon work supported in part by the National Aeronautics and Space Administration under Grant No. NNX15AIO2H. Also, KJK thanks the partial financial support from Office of Naval Research (N00014-16-1-2356).