Data Driven Modeling of Shape Recovery Behavior in SMP Laminates

Ritaban Dutta[1], David Renshaw[1], Hong Yin[1], Daniel Liang[1], David Howard[1], Tirthankar Bandyopadhyay[1]

I. INTRODUCTION

Newly discovered and experimented Shape Memory Polymers (SMPs) are increasingly being used for application solutions in automotive, aerospace, construction and commercial field. However, being a nascent field there is little knowledge on the shape recovery behaviour of laminates with an SMP film and there are only methods reported in the literature for quantifying the material behaviour. Through various experimental data gathering and analysis, influences of different variables that affect the recovery behaviour of thermoplastic shape memory polyurethanes based laminates including ambient temperature (45 °C and 65 °C), material modulus, and adhesive strength have been investigated to develop a physical model to formulate the recovery behaviour of the material. It has been identified that a fundamental optimisation problem that needs to be solved is to maximize the final angle recovery ratios and recovery rates of a material to increase the overall efficiency of a targeted SMP material.

In this study, we present early results on using data-driven machine learning to learn and predict deformation characteristics of such SMP laminates without explicit knowledge of the internal constitution of the laminar SMP material. Such data-driven approaches can be rapidly applied as a characterization tool for novel SMP material and shapes without having to perform complex physical modeling of material properties and structural influences to the foil deformation. Figure 1 shows the overview of the approach taken in this paper.

II. APPROACH

In manufacturing the SMP sample, a thin SMP was formed by hot-compressing the SMP powders at elevated temperature. Then it was trained to bending at the middle of the foil, and, after the SMP training, a thin layer of conductive polymer materials was applied onto the surface the SMP foil. The thickness and shape of the conductive polymer layer were optimised to provide the sufficient thermal stimulus at the adequate actuation speed.

To capture the movement of the SMP foil and quantification of bending angles (defined by two angles, e.g. angle to pivot and angle to tip), video-processing techniques were used to automatically extract key features from the captured video both in visual and thermal ranges. Speeded-Up Robust Features (SURF) technique was used to detect up to 400 key features from each of the video frames. Based on the SURF detected features, positions of the two key points along the length of the foil, namely, tip and bending points were detected dynamically, and angles were derived against a horizontal line representing the original pre-heating position of the SMP foil. Figure 2 shows three examples to describe the overall feature extraction process and angle estimation dynamically. The blue dots in Figure 2 were the features extracted using SURF. Derived angles were used to model the bending behavioural change of the SMP foil and its associated material.

Similarly, for the thermal video, SURF based features were used in the thermodynamic modeling of the SMP foil. SURF feature points based multi-point temperature detection was applied to capture the thermodynamic nature of the SMP while heated by a constant current Figure 2(b). This was an unconventional approach to derive thermodynamics of such a material by using data-driven approaches instead of physical experiment and characterisation of a material. The rationale behind this approach was to make the modelling of SMP as generic as possible, hence flexibility and variation of material could be substantial.

Based on the multiple point SURF feature points, dynamically a polynomial was fitted through the feature points to represent behavioural changes and bending of the SMP foil (as shown in Figure 2(b)). On the other hand temperature readings of those SURF key feature points were used as distributed thermodynamic profile across the foil structure to be used for training a model. For this phase of modeling, a simple Bayesian Ridge Regression algorithm (BRR) was used. Training input of this model was the multi-point temperature profile of the SMP foil, whereas training target was the set of polynomials that were captured during the video analysis.

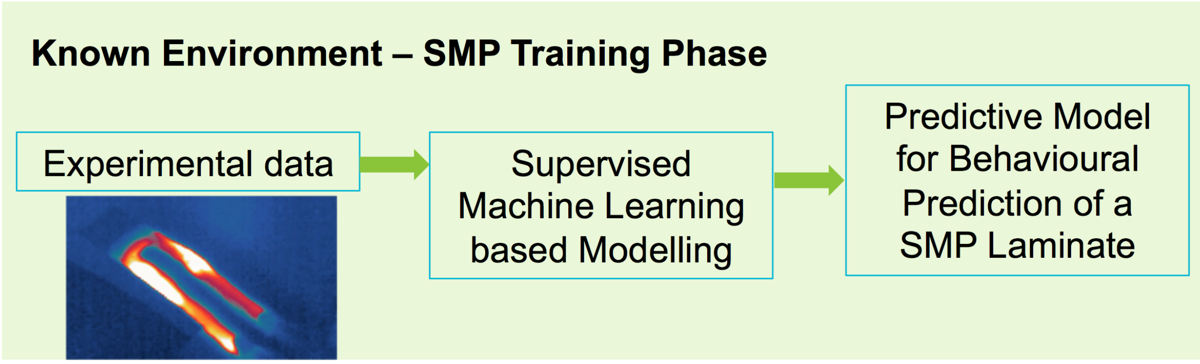
III. EXPERIMENTS

An SMP laminate was heated by a constant current of 5A through the body of the foil structure to initiate bending of the SMP material. As shown in the figure2, SMP foil structure changed its shape due to heating while temperature increased from 23 °C to 52 °C at the connection. In terms of data gathering, a thermal camera and a normal digital camera were used to capture the bending SMP foil as a video file to be analysed in the modeling phase. Figure 2(a) shows some snap-shots from the captured visual video during the experimentation with SMP foil, whereas Figure 2(b) shows the same movement captured on a thermal camera.

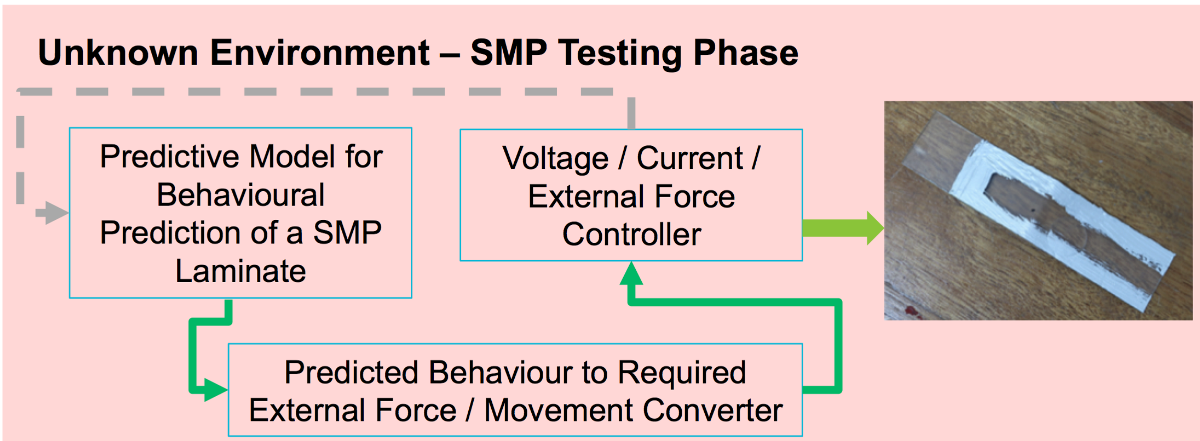
Actual temperatures were measured and logged as a time series by a separate temperature sensor during the experiments along with the thermal readings by a thermal video

This work was supported by Active Integrated Matter, a Future Science Platform at the CSIRO.

[1]All the authors are with the Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia

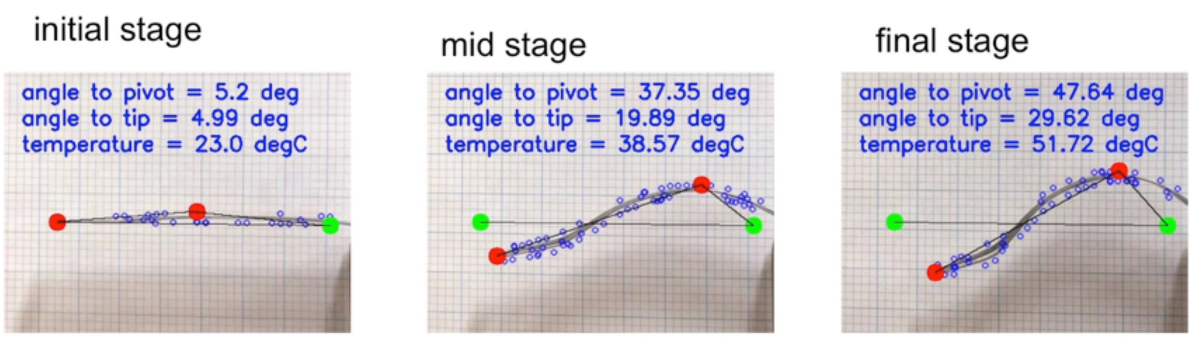


(a)

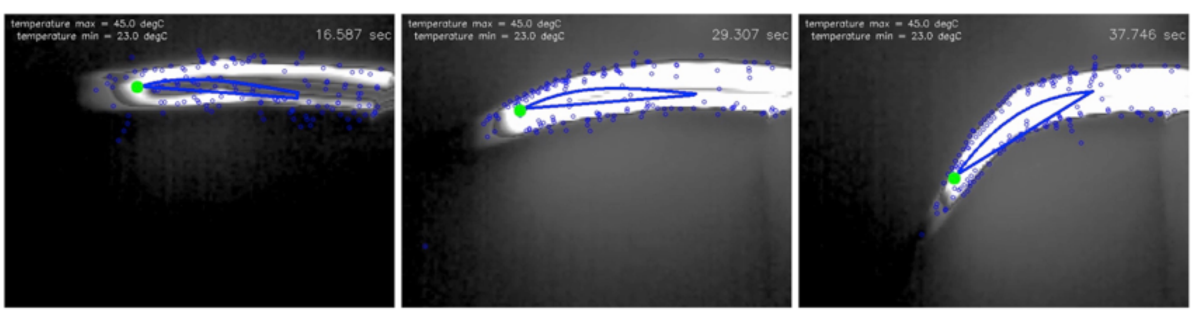


(b)

Fig. 1. General overview of the data driven learning pipeline used. The behavior of the SMP laminate is learnt from experimental data and applied to predict the motion of the laminate in an unknown environment.



(a) Visual images



(b) Thermal images

Fig. 2. (a) SURF features extracted from the visual images and a simplified shape representation learned from the image stream at various temperature. The red points indicate identified bending points and the derived angle from the original horizontal profile is depicted at various temperature levels. (b) The intensity of the image is calibrated using a temperature sensor to generate a thermal profile at various deformation stages.

camera. Temperature time series data was used to derive a temperature variation across the structure based on thermal colour variations recorded by the thermal video camera.

The variations in bending angles were automatically derived from the thermal videos. This was used as Training Targets for developing a data-driven model. Although this training target was generated from the actual experiment, for the modeling, it was treated as unknown targeted output, hence during the model training this was used as ground truth information (as verified visually) to develop a trained model capable of mimicking the same outcome while tested with similar thermal inputs.

IV. RESULTS

An Isotonic Regression Model was developed to predict bending angle of the SMP foil while heated with a constant current flow. Aim of this phase was to achieve a model to take current as input and predict a potential bending angle to mimic the bending behaviour of the physically trained SMP. In the training phase of the data driven experiment, recorded changing profile of the increasing temperature was used to formulate a thermodynamic input to SMP foil structure, whereas measured angles from the video were used as training targets. Figure 3 shows the model prediction performance of such a model with good accuracy.

As shown in the Figure 4, BRR based model was able to predict a suitable polynomial independently, purely based on thermodynamic variation across the foil structure due to constant current flow. The red line indicates the predicted polynomial from a trained model, which could be used as an independent predictor for an SMP foils behavioural changes while used in conjunction with a controller. This work could be expanded further for refinement of such a predictive model in regards to accurate control of an SMP based foil structure for a Soft-Robotic movement.

REFERENCES

[1] Behl M, Razzaq M Y and Lendlein A 2010 Multifunctional shape-memory polymers Adv. Mater. 22 3388410.

[2] Lendlein A and Kelch S 2002 Shape-memory polymers Angew. Chem., Int. Ed. 41 203457.

[3] Pieczyska E A, Staszczak M, Maj M, Kowalczyk-Gajewska K, Golasinski K, Cristea M, Tobushi H and Hayashi S 2016 Investigation of thermomechanical couplings, strain localization and shape memory properties in a shape memory polymer subjected to loading at various strain rates Smart Mater. Struct. 25 085002.

[4] Zhang R, Guo X, Liu Y and Leng J 2014 Theoretical analysis and experiments of a space deployable truss structure Compos. Struct. 112 22630.

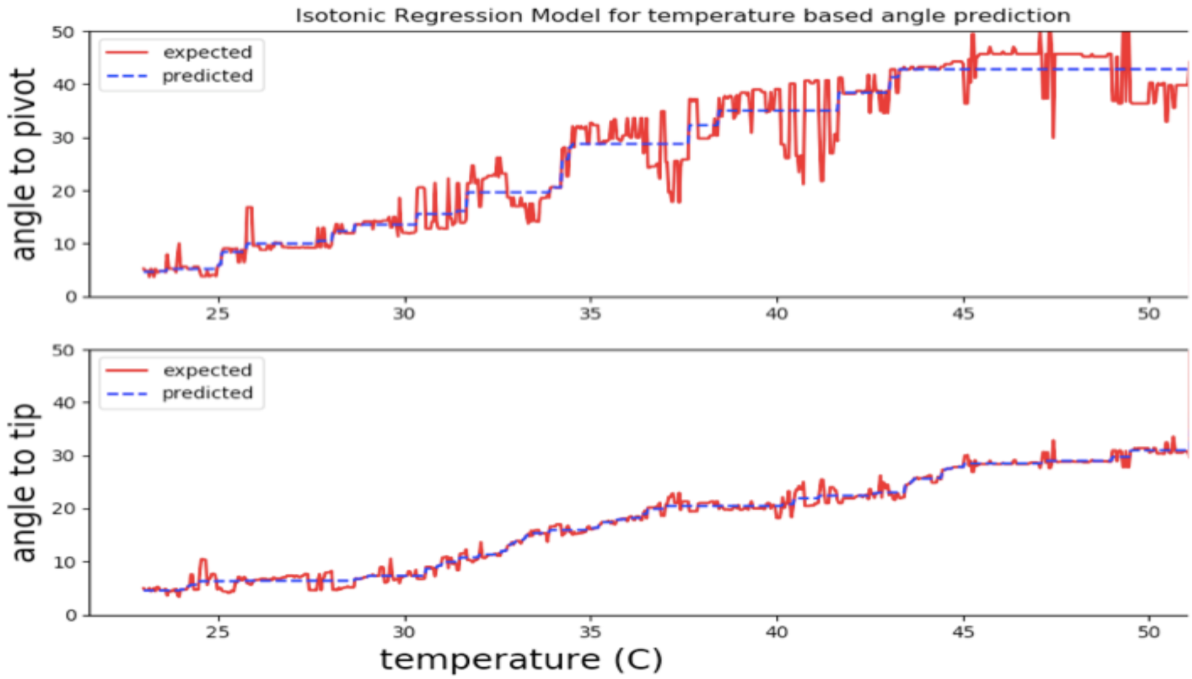


Fig. 3. Isotonic regression applied to the data as measured from the experiments done at 2(a).

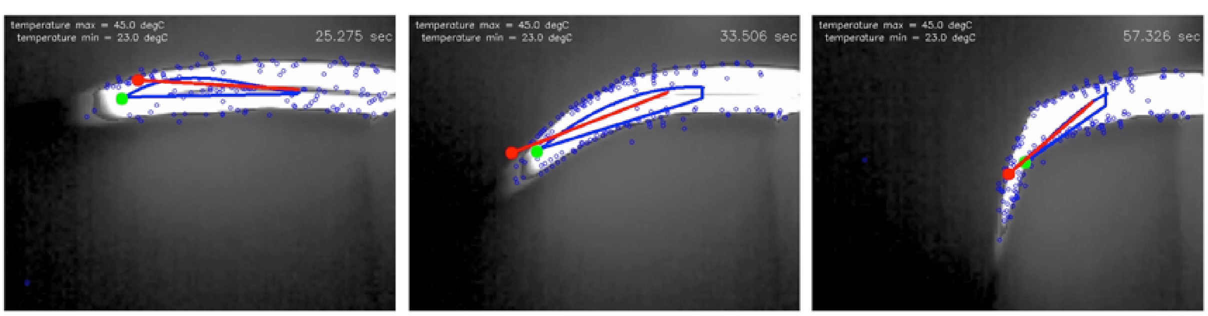


Fig. 4. The predictive bending shown by the red line matches closely with the bending represented by the SURF point based polygon representation of the SMP foil. This shows thermodynamic input as a good indicator of foil deformation prediction even in laminar SMPs.