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TECHNICAL PAPER

Modelling the steady state response of CuAlNi/polyimide bimorph actuator

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Abstract

Microactuators developed from shape memory alloy (SMA) thin films on flexible substrates find good applications in MEMS design. This article presents the models of the actuation behaviour of a thin film SMA bimorph, developed by depositing CuAlNi SMA on a curved Kapton polyimide sheet substrate through a physical evaporation technique. The thermo-mechanical behaviour of the bimorph is analyzed by actuating it through Joule heating, for various inputs. During heating, the CuAlNi SMA film produces a forward displacement and in the cooling cycle, the curved flexible substrate substantiates for a bias force to recover the bimorph to its original shape, thus revealing the shape memory effect. Modelling and simulation are essential for decision making and control to involve the SMA bimorph in applications since the model help to understand the input–output performances. The article briefs about the models developed from mathematical analysis and simulation based on the physics involved in the bimorph SMA structures; analytical models of the bimorph are developed for the thermal and mechanical responses and, a simulation model is developed to obtain its actuation. The results of the models developed coincide with the experimental outputs in the actuation voltage range of 1–2.5 V.

Keywords Shape memory alloy · CuAlNi · Joule heating · Curved Kapton polyimide · Bimorph actuator · Steady state model

1 Introduction

Microactuators are now becoming the essential blocks of MEMS devices that are equally capable of performing the functions of conventional actuators. Though several micro actuation mechanisms based on electrical, magnetic, mechanical, thermal are known, the primary focus is on the microactuators that have electrical input like voltage or current, so that they can be easily compatible with the power supply of the electronic devices (Li and Chew 2014; Fu et al. 2004). In this way, the electrothermal, piezoelectric, and electrostatic microactuators gain momentum. Among these, the electro-mechanical actuation mechanism using thin film shape memory alloy (SMA) exceeds the performance of the other actuation mechanisms owing to its advantages like a small amount of thermal mass required to heat or cool, reduced response time, good work output per volume and flexibility of design. Since these alloys can recover large strains, they are suitable for applications like micropumps and micro-grippers (Fu et al. 2004, 2005; Shin et al. 2005). Many actuators are being developed with SMA thin films in the forms of cantilevers, diaphragms, etc. Thin film SMAs developed on flexible substrates have exceptional thermo-mechanical properties and are also used to overcome problems with training (Ishida 2013; Kotnur et al. 2014).

The shape memory effect (SME) was first observed in samples of Au–Cd by Olander (1932). Later there were many other SMAs discovered like NiTi also known as Nitinol by William Buehler and Frederick. Among these, copper-based SMAs can be used in high temperature

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applications as their transformation temperatures lie beyond 200 °C and also exhibit minimum hysteresis (Lovey et al. 2008). CuAlNi and CuZnAl are excellent actuators with exceptional properties of shape memory effect at lower manufacturing cost and have the potential to replace the conventionally used NiTi (San Juan et al. 2014; Juan et al. 2010). CuAlNi SMA has been proved to show 18 percent of recoverable strain which is much higher when compared to the conventional NiTi SMA (Yin et al. 2013; Fu et al. 2009). Their properties such as good machinability, ease in the forming process, high thermal stability, rapid heating and cooling rate, less hysteresis, and higher Young's modulus play a vital role in accomplishing micro actuation (Araujo et al. 2015; Huang 2002).

Thin film SMAs can be actuated using different sources like a laser, hot fluid, Joule heating, etc., among which actuation through Joule heating provides simplicity and convenience. The elastic substrates can be prestrained in different shapes according to the constraint; it acts as a bias force during the cooling cycle by returning the bimorph to its original shape and inducing stress required for cyclic actuation (Choudhary and Kaur 2016).

The technology of assimilating SMA structures in the form of composites has opened up a new arena for the improvement of micro and macro devices. Such technology is the use of flexible polyimide substrate along with the SMA, together called the shape memory alloy bimorph. Bimorph actuators are suitable for deflection type micromirrors; this work is intended to be a subsection of such a design (Potekhina 2019). Deflection type micromirrors are broadly used in various types of applications such as bar code scanning, projection displays, object recognition, communication, and sensors applications. In comparing other actuators for MEMS mirrors, the electro-thermal actuators perform the best in both out-of-plane motion and rotational motions. Due to its small size, lightweight, low energy consumption, and minimum cost it is also inevitable in medical applications namely medical endoscopy, optical scanning microscopy, confocal microscopy/OCT, and laparoscopy (Pengwang et al. 2016).

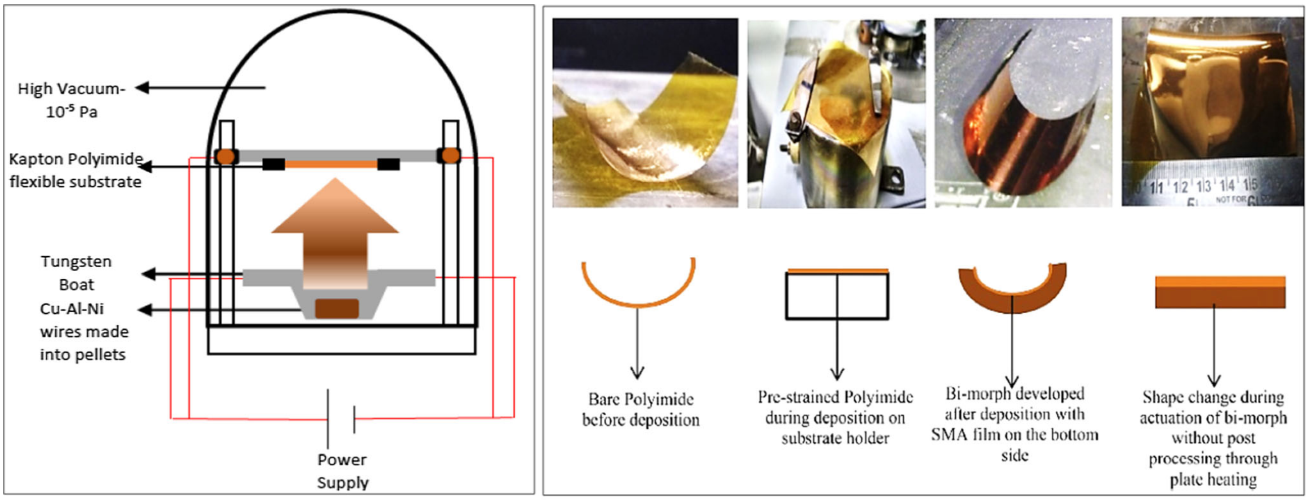
The research group (Akash et al. 2017a, b; Jayachandran et al. 2019) has developed a bimorph by deposition of composite material over a passive flexible substrate, which provides two way shape memory effect without any bias mechanism and investigated for different substrate thickness and different substrate temperatures. These investigations stated that the Cu–Al–Ni/Polyimide bimorph (bimorph SMA actuator) developed through direct thermal evaporation method at 150 °C growth substrate temperature on flexible pre-strained 75 µm thick Kapton polyimide sheets displayed two-way shape memory effect without any post processing and training with higher displacement, lower fatigue and better applicability in microdevices.

While designing bimorph actuators the dynamic and steady state behaviour is important because the deformation is nonlinear. To identify the performance of these bimorph actuators, important actuation properties to be considered are displacement, temperature and electrical resistance. A lot of research has been carried out in the modelling of bimorph (Ezzat and El-Bary 2012; Velazquez and Pissaloux 2012) with respect to the size dependency for microscale and nanoscale employing non-classical continuum theories (Ghobadi et al. 2019; Mehralian and Beni 2018). The current study concentrates on a mesoscale bimorph actuator of dimension 3 cm × 2 cm × 76.75 µm and the model is derived from the basic analytical equations of mechanics. Some of the researchers have also carried out the finite element simulation and validation of the deflection of SMA Bimorph (Abu Zaiter et al. 2015; Pal and Xie 2010). All the SMA models conventionally contribute to characterizing the properties of NiTi wires and embedded SMA structures, but the model of bimorph SMA actuators is not found in the literature until now.

The objective of this paper is to develop analytical and simulation models of the mechanical and electrical properties of thin film CuAlNi/polyimide SMA bimorph actuator and validate them experimentally. It presents the studies of the effects on temperature and the displacement of the thin film SMA bimorph when it is subjected to Joule heating. A structure-based finite element (FE) model of a thin film of Kapton HN material deposited with a thin film SMA is developed in COMSOL Multiphysics®. The experimental results are compared with the analytical and simulation results performed for different voltage inputs. The paper is organized as follows: Sect. 2 explains the design and working of CuAlNi/polyimide bimorph actuator followed by Sect. 3—analytical model, Sect. 4—simulation model, Sect. 5—physical model, Sect. 6—results and discussion, and Sect. 7—conclusion.

2 CuAlNi/polyimide bimorph actuator

CuAlNi/polyimide SMA bimorph exhibits shape memory effect without any training or post-processing. These bimorphs are developed through the direct thermal evaporation method. The facility for the thermal evaporation method is shown in Fig. 1a, in which CuAlNi SMA is of composition Cu–14Al–4Ni wt%. Deposition of (small pellets of 100 mg) SMA is allowed on a flexible pre-strained (curved) 75 µm thick Kapton polyimide HN sheets shown in the first part of Fig. 1b of required dimension at appropriate substrate temperature (150 °C) under the system chamber of high vacuum. During this thermal evapouration process, the 75 µm thick Kapton polyimide HN



(a) Schematic of the fabrication facility [17]   **(b)** Development stages of the bimorph [18]

Fig. 1 Development of bi-morph and its shape memory effect. **a** Schematic of the fabrication facility (Akash et al. 2017a). **b** Development stages of the bimorph (Akash et al. 2017b)

sheet is held to the substrate lamp as shown in the second part of Fig. 1b.

After deposition, upon removal from the holder the CuAlNi/Polyimide SMA bimorphs folded into a curved shape due to the trained polyimide substrate and it resembles the third part of Fig. 1b. And during actuation, the SMA bimorph flattens as shown in the fourth part of Fig. 1b. The detailed fabrication process adopted for developing SMA/polyimide bimorph may be referred from Akash et al. (2017a). The bimorphs display a two-way shape memory effect without any post-processing and training.

2.1 Structure of bimorph SMA

Electro-thermal bimorph actuators consist of two layers sandwiched together along their longitudinal axis serving as a single composite film; one layer consists of an alloy having a lower coefficient of expansion while the other layer is polyimide with a higher coefficient of expansion. This composite has the same length and width with different thicknesses of the substrate and the deposited film. The bimorph film is bent downwards due to the cup like shape of the polyimide sheet. The structure of a CuAlNi/Polyimide SMA bimorph actuator is illustrated in Fig. 2a, b.

2.2 Actuation principle of bimorph SMA

The actuation principle of a CuAlNi/Polyimide SMA bimorph actuator is illustrated in Fig. 2c. This actuator is heated by an electrical current passing through the conductive SMA layer due to an applied DC voltage. The heated bimorph actuator moves upward with a force due to a change in phase (martensite to austenite) of the SMA layer. When the DC voltage is removed the bimorph actuator returns to its normal state due to the bias force of the trained polyimide sheet.

3 Analytical model

The analytical model of a CuAlNi/polyimide SMA bimorph actuator is shown in Fig. 3. In the analytical model, to describe the system, the changing parameters are expressed as a mathematical function. The analytical model of the SMA bimorph actuator is grouped into three sections of models namely, the thermal model, mechanical model and temperature-based resistance model. The thermal model describes the temperature variation in the SMA bimorph actuator when subjected to Joule heating. The mechanical model describes the change in displacement effected in the SMA bimorph actuator for a change in the temperature. The resistance model describes the resistance variation of the SMA bimorph actuator corresponding to the temperature change.

3.1 Thermal model

The block diagram of thermal model for CuAlNi/Polyimide SMA bimorph actuator is demonstrated in Fig. 4. The thermal model is arrived based on the principle that the change in the internal heat energy of the CuAlNi/polyimide SMA bimorph actuator is equivalent to the energy supplied to it by the voltage source, minus the energy dissipated to the air by normal convection. The thermal balance equation

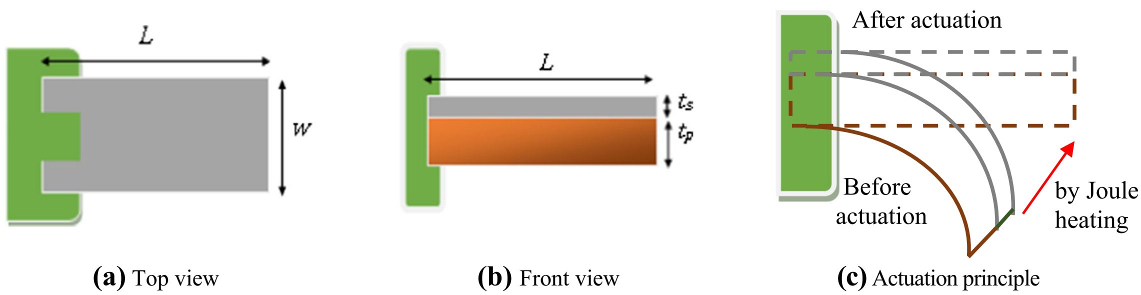


Fig. 2 CuAlNi/polyimide SMA bimorph actuator

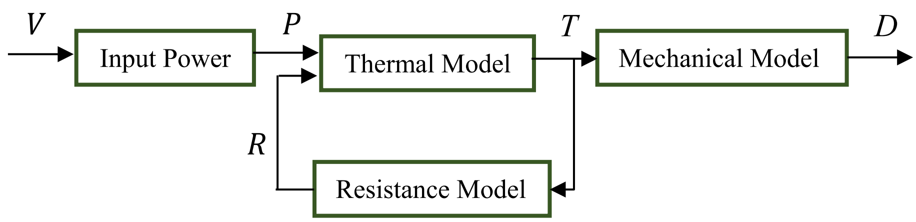


Fig. 3 Block diagram of the analytical representation of CuAlNi/polyimide bimorph actuator

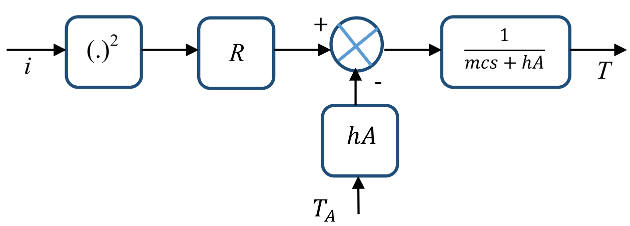


Fig. 4 Pictorial representation for the thermal model of CuAlNi/polyimide bimorph actuator

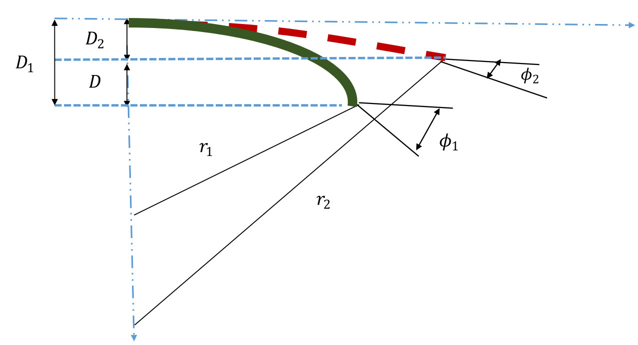


Fig. 5 Conceptual illustration to calculate the vertical displacement of curved SMA bimorph

of the SMA bimorph when a voltage applied to the SMA is given by,

$$Q_b = Q_{in} - Q_{loss} \tag{1}$$

The heat input is given by,

$$Q_{in} = i^2.R \tag{2}$$

The heat absorbed by the bimorph actuator is,

$$Q_b = mc\frac{dT}{dt} \tag{3}$$

The heat loss due to convection

$$Q_{loss} = hA(T - T_A) \tag{4}$$

Equations 2, 3 and 4 substitute in Eq. 1,

$$mc\frac{dT}{dt} = i^2.R - hA(T - T_A) \tag{5}$$

The temperature of the bimorph is

$$T = \frac{1}{mc}\int (i^2.R - hA(T - T_A))dt \tag{6}$$

where, m is the mass in kg, c is the specific heat capacitance in J/°C. kg, h is the heat transfer coefficient in W/m^2 °C, A is the cross sectional area in m^2, T is the temperature in °C, T_A is the ambient temperature in °C, $R(T_A)$ is the resistance at ambient temperature in ohm, i is the current in mA.

3.2 Mechanical model

In Fig. 5, r_1, D_1, ϕ_1 are radius distance and bending angle of the CuAlNi/polyimide SMA bimorph actuator due to the prestraining of the Kapton polyimide and r_2, D_2, ϕ_2 are radius, distance and bending angle after thermal actuation of the CuAlNi/polyimide bimorph SMA actuator.

From Fig. 5, the free end displacement of bimorph SMA due to Joule heating is given by,

$$D = D_1 - D_2 \tag{7}$$

where, D_1 is the free end distance of the bimorph SMA from its reference axis due to the prestraining of the Kapton polyimide and D_2 is the free end distance of the bimorph SMA from its reference axis after the thermal actuation.

In general, the trained SMA bimorph is considered to have the shape of a circular arc of length L, radius r and angle ϕ. From Fig. 6, the tip displacement D of the SMA bimorph from the reference axis (blue dotted line) is found using the radius of curvature of SMA bimorph r (green bolded line) and, the angle between reference axis and curved bimorph SMA axis ϕ (violet line).

The tip displacement of the bimorph from the reference axis is given by

$$D = r - rcos\phi \quad (8)$$

ssuming a small bending ($\phi = 0, cos\phi = 1$ and $sin\phi = 0$), the vertical tip displacement can be approximately calculated from the first two terms of a Taylor series expansion. Equation 8 can be approximated as,

$$D = r - rcos\phi = r - r\left(1 - \frac{1}{2}\phi^2\right) = \frac{1}{2}r\phi^2 \quad (9)$$

The value of ϕ is determined using the values of length of the bimorph and the radius of curvature is determined as

$$\phi = \frac{L}{r} \quad (10)$$

Therefore, the vertical tip displacement from its reference axis due to the prestraining of the Kapton polyimide is

$$D_1 = \frac{L^2}{2.r_1} \quad (11)$$

where, r_1 is the initial radius of curvature in mm.

Vertical tip displacement from its reference axis due to the thermal actuation is given by

$$D_2 = \frac{L^2}{2.r_2} \quad (12)$$

where, r_2 is the final radius of curvature in mm.

Since the heated bimorph is unfolded, the resultant curvature, r_{th} is considered to be negative and therefore the final curvature of the SMA bimorph is as referred from Lammel et al. (2002).

$$\frac{1}{r_2} = \frac{1}{r_1} - \frac{1}{r_{th}} \quad (13)$$

where, r_{th} is the radius of curvature due to thermal deflection in mm. The detailed

$$\frac{1}{r_{th}} = \frac{6.t.(\alpha_p - \alpha_s).(T - T_A)}{\frac{E_s^{'}.t_s^3}{E_p^{'}.t_p} + \frac{E_p^{'}.t_p^3}{E_s^{'}.t_s} + 6.t_s.t_p + 4.t_s^2 + 4.t_p^2} \quad (14)$$

E' is the biaxial elastic modulus

$$E^{'} = \frac{E}{1 - \vartheta} \quad (15)$$

where, ϑ is the Poisson's ratio, E is the elastic modulus in Pa, t is the thickness in mm, α is the thermal coefficient of expansion in K^{-1}, Index p for polyimide, s for SMA.

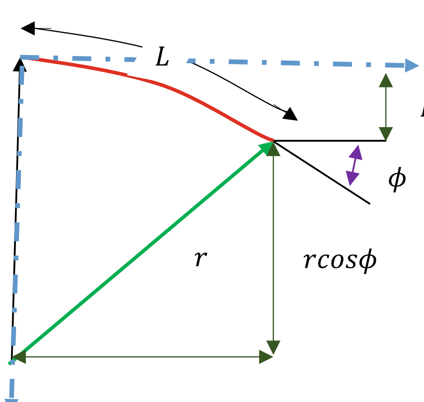


Fig. 6 Free end distance calculation of the bimorph SMA from its reference axis

3.3 Temperature dependent resistance model

In general, the variation of electrical resistance of metals shows a linear relationship with the temperature change. The temperature coefficient of resistance is initially calculated from the linearized resistance formula from Eq. 16 using the experimentally measured resistance and temperature.

$$R(T) = R(T_A).(1 + \beta.(T - T_A)) \quad (16)$$

where, T is the temperature, °C, T_A is the ambient temperature, °C, $R(T_A)$ is the resistance at ambient temperature, ohm, β is the temperature coefficient of resistance, K^{-1}. The Fig. 7 shows resistance vatiation of SMA bimorph with respect to temeparture.

CuAlNi/polyimide SMA bimorph actuator has negative temperature coefficient of resistance and it is found that its average value is 0.348 K^{-1}. The analytical resistance is evaluated by substituting the temperature calculated in Sect. 3.1 and temperature coefficient of resistance using Eq. 16.

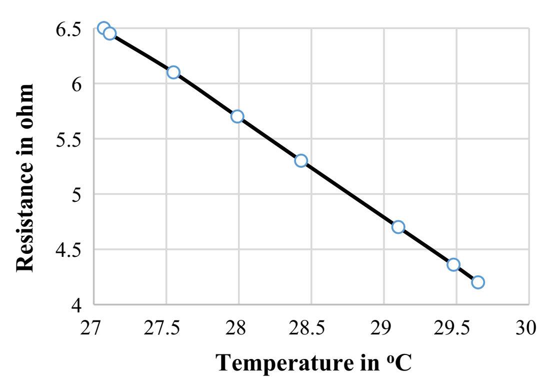


Fig. 7 Change in resistance with respect to temeparture

The dimensions of the Polyimide substrate and thin film CuAlNi which are used for the analysis and numerical simulation are presented in Table 1.

The thermo-mechanical properties of Polyimide substrate and thin film CuAlNi are defined in Tables 2 and 3 respectively. The same are used for the analysis and numerical simulation.

Figure 8 illustrates the variation of temperature with respect to change in voltage based on the Eqs. (1–5) and the variation of displacement with respect to temperature change based on Eqs. (6–15). The figure also depicts the variation of resistance with respect to temperature change. The temperature and displacement have a nonlinear increase with linear increase of voltage whereas resistance decreases nonlinearly with linear increase in voltage.

4 Simulation of CuAlNi/polyimide bimorph

The displacement characterization of bimorph SMA is performed using structure based Finite Element Analysis (FEA) in COMSOL Multiphysics® software. The SMA bimorph is curved when unactuated due to the prestraining of the polyimide; the bimorph flattens i.e.; the radius of curvature increases during actuation. Analytically, the expression of the radius of curvature for both straight and curved geometries is the same after and before actuation respectively. In numerical simulation, it is complicated to model a structure with an initial bend. The analysis is possible by considering the SMA bimorph with a straight polyimide substrate that curves during actuation, since both the options offer the same curvature.

For the purpose of the analysis, a SMA bimorph sheet of dimension 3 cm × 2 cm × 76.75 µm is considered. A cut of 1 cm × 1 cm dimension is made at the middle of one end to realise the shape of a bilegged cantilever and it is fixed to a support to provide the supply voltage. The voltage is provided at the fixed end and the displacement is measured at the free end as shown in Fig. 9.

Simulations are carried out in COMSOL Multiphysics® to determine the displacement profile of the structural model of the CuAlNi SMA bimorph actuator for the voltage range of 1–3.5 V. Figure 10 shows the meshing of the designed structure. Table 4 lists the number of mesh elements for each geometry of CuAlNi SMA bimorph actuator. Figure 11 shows the simulated displacement of CuAlNi SMA bimorph. Table 5 gives the X, Y, Z

Table 1 Dimensions of the SMA bimorph actuator

Property	Value	
	polyimide	SMA
Thickness (µm)	75	1.75
Length (mm)	30	30
Width (mm)	20	20

Table 2 Thermo mechanical properties of polyimide substrate (http://www.lookpolymers.com/polymer_DuPont-Kapton-300HN-Polyimide-Film-75-Micron-Thickness.php)

Property	Value
Coefficient of thermal expansion (1/K)	$20–40 \times 10^{-6}$
Density (kg/m^3)	1420
Young's modulus (Pa)	165×10^6
Poisson's ratio	0.34
Specific heat (J/kg °C)	1090
Electrical resistivity (Ω m)	1×10^{-8}

Table 3 Thermo mechanical properties of CuAlNi SMA (Juan et al. 2010)

Property	Value
Coefficient of thermal expansion (1/K)	17×10^{-6}
Density (kg/m^3)	7100–7200
Young's modulus (Pa)	$80–100 \times 10^9$
Poisson's ratio	0.34

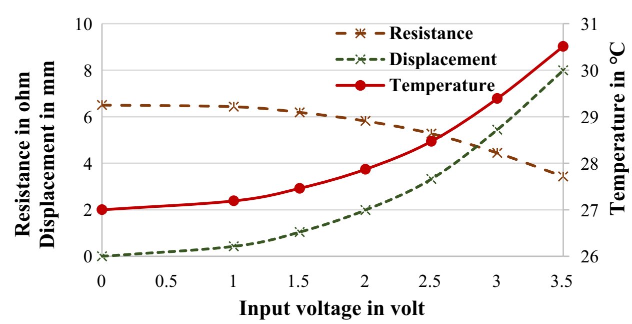


Fig. 8 Variation of temperature, displacement and resistance with respect to voltage change (analytical results)

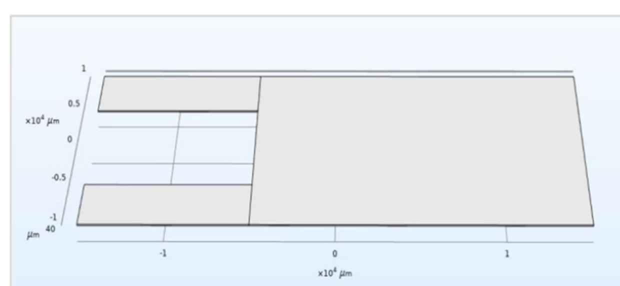


Fig. 9 Simulation model of CuAlNi/polyimide bimorph actuator

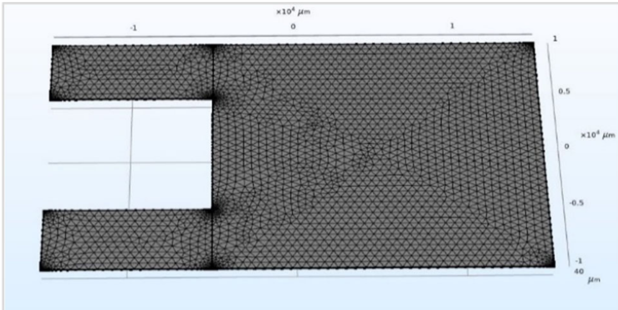


Fig. 10 Mesh model of CuAlNi/polyimide bimorph actuator

Table 4 Finalized geometry for the numerical simulation

Type of element	Number of mesh elements
Domain	6
Boundary	33
Edge	56
Vertices	30

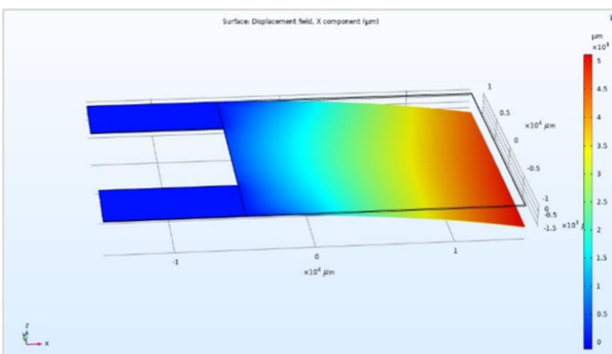


Fig. 11 Simulated displacement of CuAlNi/polyimide bimorph actuator

Table 5 X, Y, Z coordinates and values of simulated model of SMA response

X	Y	Z	value
14,753	− 9857.7	− 1539.2	5048.9
14,876	− 7682.1	− 1504.7	5013.9
14,941	− 8350.3	− 1530.1	5048.4

coordinates of the simulated model of CuAlNi SMA bimorph. Based on these coordinate values the tip displacement of the model is obtained through numerical simulation.

Based on the simulation results, the displacement variation of the SMA bimorph actuator for various voltages are as shown in Fig. 12. When the voltage increases, the displacement is also found to increase with the maximum value of 6 mm for the input voltage of 3.5 V.

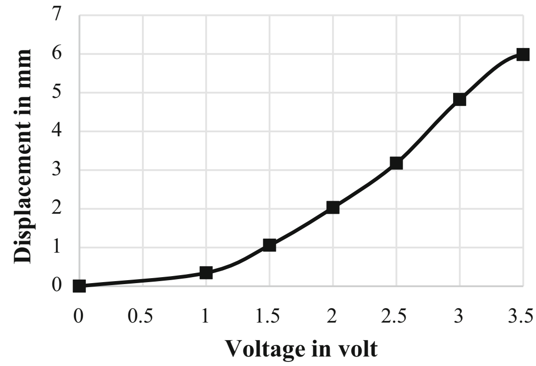


Fig. 12 Variation of displacement with respect to voltage change

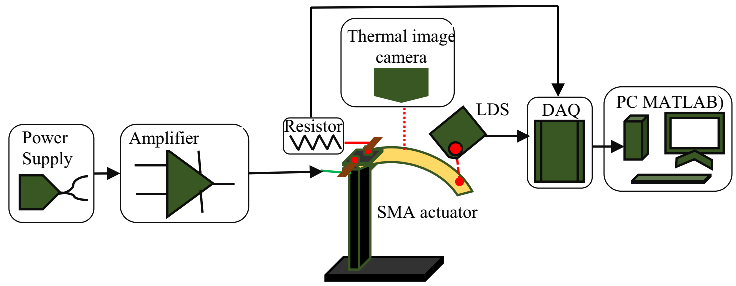
5 The physical model of CuAlNi/polyimide bimorph

To facilitate the Joule heating procedure, a mechanical arrangement is made of acrylic sheets with a provision to hold the bimorph sample. The SMA bimorph is cut in the shape of a bi-legged cantilever and copper leads are provided at both the legs of the cantilever to minimize the contact resistance and help in the flow of current to the sample. The schematic block diagram and photograph of the experimental setup to provide Joule heating to the SMA bimorph actuator and obtain its displacement characteristics is as shown in Fig. 13a, b. When an input voltage is given to the SMA bimorph using amplifier circuit, the current flowing through the SMA layer of the bimorph increases its temperature and moves it upward due to thermal actuation. A non-contact type laser displacement sensor (LDS) is used to measure the displacement of the SMA bimorph. A thermal imaging camera is used to capture the temperature of bimorph SMA sample. An external resistor R_0 is connected in series to the SMA bimorph. The voltage across the bimorph V_{SMA} and the external resistance V_{Ro} are used to evaluate R_{SMA} the resistance variation of SMA bimorph using Eq. (17).

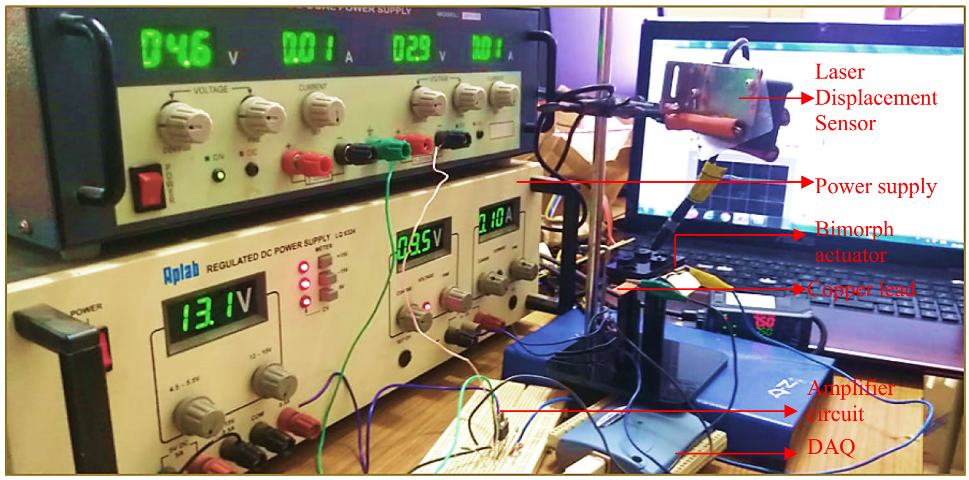
$$R_{SMA} = \frac{V_{SMA}}{V_{R_0}} * R_0 \qquad (17)$$

When actuating the CuAlNi/Kapton SMA bimorph actuator by Joule heating using the experimental setup shown in Fig. 13b, the actuator moves upward due to temperature variation of the SMA layer. The position/tip of the bimorph due to the displacement before and after actuation is as shown in Fig. 14a, b. The temperature distribution of the bimorph actuator is obtained using the FLIR thermal imaging camera and the image is as shown in

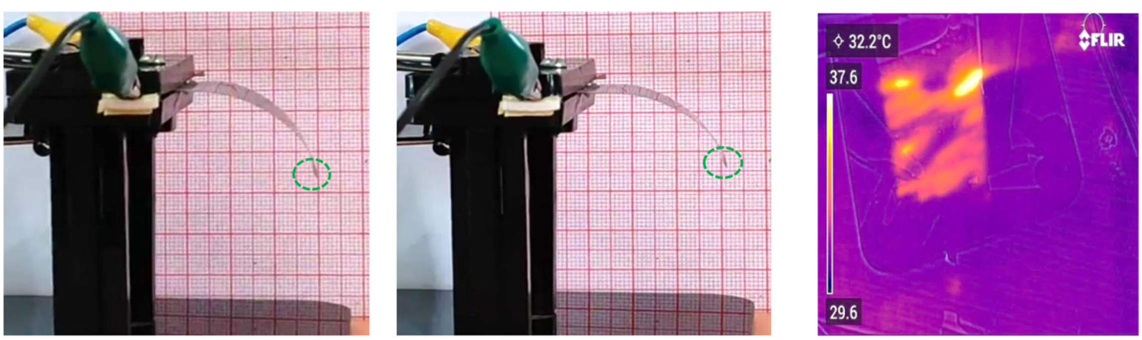
Fig. 13 Experimental set up to obtain the vertical displacement of curved SMA bimorph



(a) Schematic representation



(b) Photograph



(a) Before actuation (b) After actuation (c) Thermal image

Fig. 14 Experimental resposes of the bimorph SMA actuator

Fig. 14c. The maximum temperature of 37.6 °C is observed at the legs of the bilegged cantilever where the supply is connected and minimum of 29.6 °C is observed at the tip of the cantilever. The values of the surface temperature of the thin film SMA by Joule heating are substantiated by the (surface temperature of the thin film SMA by plate heating) results of the earlier literature (Jayachandran et al. 2019), which confirms that although the difference in the surface temperature between the unactuated and actuated state is lesser, the displacement of the bimorph during the heating cycle is due to the shape memory effect of the coated material. The variation of temperature, displacement and resistance with respect to variation of the input voltage are acquired and are plotted in Fig. 15. For the voltage below 1 V the system responds with negligible changing parameters; hence the voltage below 1 V is the inactive range. For the voltage from 1 to 3 V the system parameters displacement, temperature and resistance vary considerably and hence this portion between 1 and 3 V is considered as the active region. When the voltage is increased from 3 to 3.5 V, the system is saturated to the maximum displacement value of

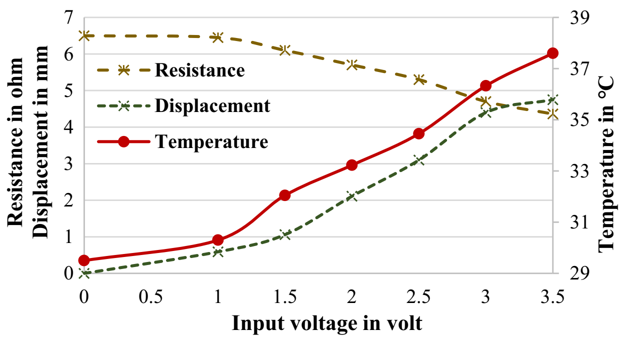


Fig. 15 Variation of temperature, displacement and resistance with respect to voltage change (simulation results)

4.5 mm; hence the voltage range beyond 3–3.5 V is considered as the saturated region. When the voltage is increased beyond 3.5 V, the bimorph burns out. The SMA deposition withers out as shown in Fig. 14d and the sample becomes unfit for further use. Hence the safe operating voltage range of SMA bimorph actuator is 1–3.5 V and the system shows the following responses in the operating voltage of 1–3.5 V: temperature increases from 30.3 to 37.6 °C, displacement increases from 0.5 to 4.79 mm and resistance decreases from 6.5 to 4.2 Ω.

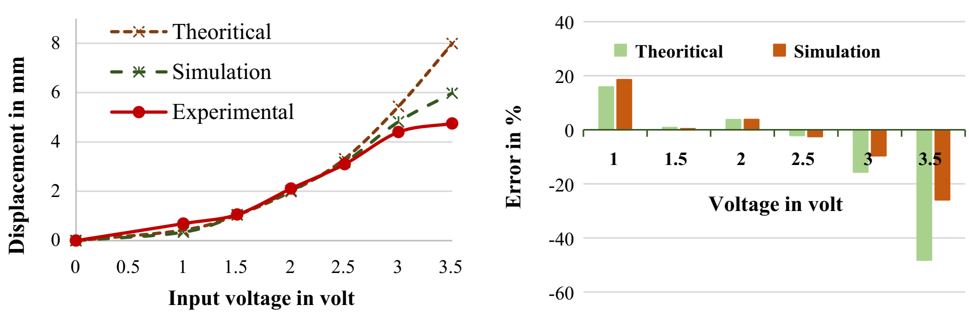
6 Results and discussion

Figure 16a shows the theoretical, simulated and experimental responses for the given input voltages and Fig. 16b shows the percentage of error in displacement of theoretical and simulation results corresponding to the experimental results.

For the active region of voltage ranging from 1.5 to 2.5 V, the displacement change of the theoretical model and simulation model are approximately equal to the experimental model. In this active region, the displacement changes with respect to changing voltage are approximately linear with a slope of 2.5. After analyzing Fig. 15, it is found that the response of the analytical model and simulated model capture the majority of the input output behaviour of the system in the active range of 1.5–2.5 V.

The response time of the CuAlNi/polyimide SMA bimorph actuator is observed when actuated for 1 V, 2 V and 3 V. Corresponding plots are represented in Fig. 17a; it is observed that the bimorph takes 0.3 s to respond for an applied voltage of 3 V. Further, the repeatability of actuation of the CuAlNi/polyimide SMA bimorph actuator is observed by Joule heating with pulse input of 0.05 Hz frequency corresponding to input voltages of values 1 V,

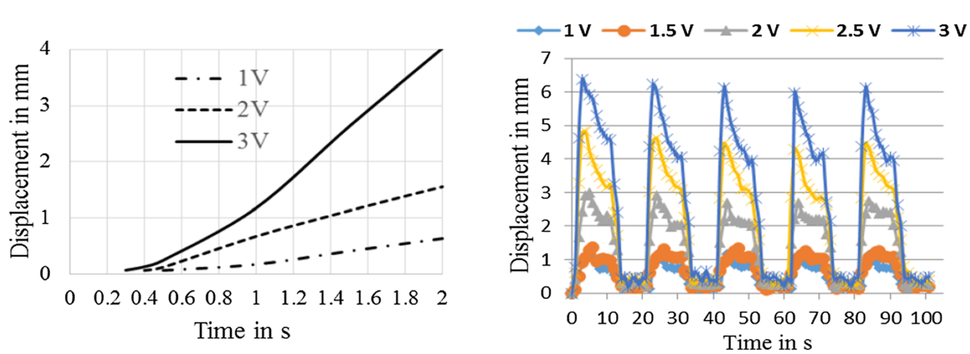
Fig. 16 **a** Variation of displacement with respect to voltage change **b** percentage of error



(a) Variation of Displacement with respect to voltage change

(b) Percentage of Error

Fig. 17 Response of the SMA bimorph



(a) Response time of actuation

(b) Repeatability of actuation cycles

1.5 V, 2 V, 2.5 V, and 3 V, measured the displacement using laser displacement sensor and plotted in Fig. 17b.

Having understood the potential of the bimorph, a micro manipulator is proposed to be designed and implemented using a couple of SMA bimorph actuators to be suitable for micro mirror applications. The proposed micro manipulator will be able to move the micro mirror in vertical direction (Y-manipulation) and angular direction (θ-Manipulation), by using 2 bimorph actuators. One end of each actuator is fixed to the base and the other end is attached to the mirror plate which undergoes micro manipulation. By activation of both the actuators, the mirror moves in vertical direction along Y axis. By activation of any one of the actuators, the mirror moves in angular direction along θ axis. Detailed investigations on micro manipulation and control of the proposed SMA bimorph based micro mirror applications are the future scope.

7 Conclusion

Models of wire and spring forms or thin film SMA actuator likewise other bimorphs though it involves numerous parameters have been extensively developed by many researchers. The main issue involved in modeling the integrated SMA composites lies in the identification of the associated thermo-mechanical parameters. To overcome this, an analytical model and simulation model of thin film CuAlNi/Kapton SMA bimorph actuator is presented using simple equations with limited known parameters of the SMA composite and polyimide; further, the thermo-mechanical behaviour is analyzed. The structural and thermal models are analyzed to elucidate the displacement, temperature and resistance characteristics by Joule heating actuation. A structure based FEA simulation is carried out in COMSOL Multiphysics. The analytical and simulation results are compared with the experimental results for validation. It is observed that the analytical model and simulation model parameters (displacement, temperature and resistance) varies linearly with respect to input voltage for the active region corresponding to the voltage range of 1–2.5 V.

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Data availability Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

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