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13. ABSTRACT (Maximum 200 words) In this work, a compact fuel-powered (FPC) SMA actuator and a compact thermoelectric (TEC) SMA actuator has been designed, fabricated and tested. An FPC-SMA actuator system has been developed utilizing high energy density of fuels. The final FPC-SMA actuator system is composed of an SMA strip, two pumps, valves, two bellows, a multi-channel combustor/heat exchanger, a micro-tube heat exchanger (radiator) and a control unit. The SMA strip is embedded in a rectangular channel. This channel also contains a rectangular piston with a slot, such that the piston can move along the SMA strip and prevent mixing between the hot and cold fluids. The final FPC-SMA system can generate 250 N force of 2.0 % strain at 1.0 Hz actuation frequency under closed-loop test conditions. The second actuator is a solid-state, compact, TEC-SMA actuator utilizing the thermoelectric effect. The TEC-SMA system is currently able to produce 100MPa stress with 1.5% strain under 0.5Hz actuation frequency. Work on the TEC-SMA actuator includes development of a basic experimental setup to characterize and optimize actuator bandwidth, stroke, output power and energy density. Design and development of a fixture for improved contact between the SMA and the thermoelectric elements and a test matrix for evaluation of actuator bandwidth, stroke, power and energy densities with respect to commercially available TE modules. This feasibility study shows that to further optimize both the power density and efficiency of the TEC-SMA actuator, SMA surface area to volume ratio needs to be increased while maintaining heat sinks at low temperatures and minimizing contact resistances.				
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1. Objective

The main goal of this project is to perform a feasibility study on Fuel-Powered and Thermoelectric Shape Memory Alloy (SMA) actuators to develop highly-compact SMA actuators. The specific objectives for the Fuel-Powered Compact (FPC) SMA actuator are given below:

- Design, fabricate and test highly compact Shape-Memory-Alloy (SMA)-based actuators that utilize the high energy density of fuels.
- Optimization of FPC-SMA energy density, compactness and volumetric efficiency. Comparison with conventional actuator systems.
- Implement modular design to allow for alternative energy sources including parasitic heat and electric systems.

The objectives for the Thermoelectric Compact SMA Actuator (TEC-SMA) are given as:

- Develop a Solid State TEC-SMA utilizing the Peltier effect.
- Optimization of TEC-SMA output energy density, output power density and compactness.
- Increase the bandwidth of SMA based actuators.

2. Significance

The prototype design-fabrication-testing process will result in detailed feasibility assessment and quantification of the operational specification ranges for both actuators. The actuators' potential for compactness and miniaturization will be assessed and quantified. The proposed actuator design will merge the advantages of SMAs, fuels and thermoelectric elements, i.e., the high actuation forces, the large power densities and the silent actuation characteristics of SMAs, the large energy densities of fuels and the compactness and operation simplicity of thermoelectric elements.

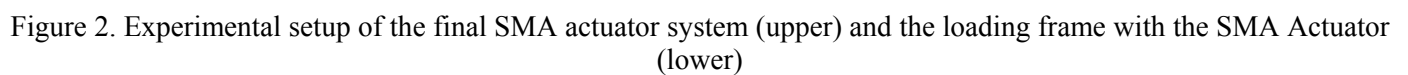
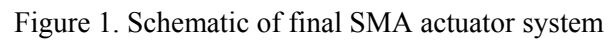
3. Methodology and results

The approach followed for the development along with the results for two compact SMA actuators are discussed in the following two subsections.

3.1. Fuel-Powered Compact (FPC)-SMA Actuator

Final FPC-SMA Actuator System

Figure 1 and Figure 2 show schematic and experimental setup of the final actuator system, which is based on the second-generation actuator system (Phase II) focusing on decreasing the mixing between the hot and cold water streams in order to increase the energy and power densities at the expense of simplicity of the system, as compared to the first-generation actuator system. A small size of SMA strip (2.5 mm x 0.9 mm in cross section) was used as the SMA element in order to increase the heat transfer rate compared to an SMA wire having the same cross section area. The SMA element is embedded in a rectangular channel with a rectangular piston, such as the second-generation actuator system.



The final actuator system is focused on miniaturization, compactness and lightness, thus the strip size is decreased compared to the second-generation actuator system. Micro/minature technology was adopted in designing and fabricating its components such as the combustor and the heat exchanger in order to increase efficiency and compactness. The final actuator systems was made up of two gear pumps, four check valves, four solenoid valves, two bellows, a micro-tube heat exchanger (radiator), and a multi-channel combustor/heat exchanger. A loading frame simulates the actuation load and measures the force and displacement of the SMA actuator. This loading frame was composed of a load cell, a LVDT, a compression spring and linear bearings.

FPC-SMA Actuator

A K-alloy type SMA strip, which is a Ni, Ti and Cu alloy, is used as the SMA element. Its cross section is 2.5 mm x 0.9 mm (0.1 inch x 0.034 inch) and it is cut by EDM (Electrical Discharge Machining) to a dog-bone shape, after being annealed to prevent stress concentration at the two ends of the SMA strip. The channel design of the final SMA actuator is based on the second-generation SMA actuator (phase II), which was designed to decrease the mixing between the hot and cold fluid in the system. Figure 3 shows the SMA element and the rectangular channel. The main function of the rectangular piston is to separate the hot and cold fluids in the channel during the actuation thus decreasing the mixing in the system. The piston has a magnet on top of it in order to turn the solenoid valves on and off according to the heating and cooling cycles.

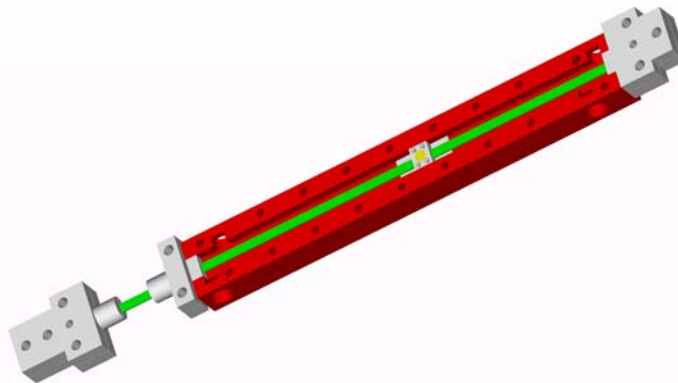


Figure 3. SMA actuator

Multi-Channel Combustor/Heat Exchanger

The size of the combustor/heat exchanger was 76.2 mm x 71.1 mm (3.0 inch x 2.8 inch), which was about $\frac{1}{4}$ of the first-generation combustor/heat exchanger. The channel size of the heat exchanger side was 76.2 mm x 0.81 mm (spacing: 0.032 inch=0.81 mm). The channel size of the combustor side was 2.5 mm x 0.81 mm (spacing: 0.032 inch=0.81 mm) and was fabricated by aluminum. The total number of channels of each side is 39. Screws and RTV sealed the combustor/heat exchanger. The actuator power output ranged up to 800 Watts. The efficiency of the combustor/heat exchanger was estimated at around 70%. Figure 4 shows the multi-channel combustor/heat exchanger utilized in the final SMA actuator system.

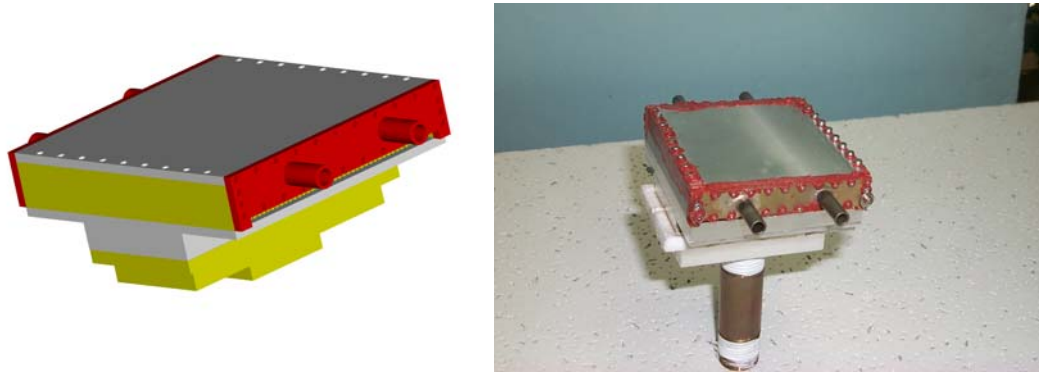


Figure 4. Multi-channel combustor/heat exchanger

Micro-tube Heat Exchanger

The micro-tube heat exchanger disposes of the energy obtained from the SMA strip to the surroundings, by forced air convection cooling. The micro-tube heat exchanger operated under laminar flow conditions. A 59.2 l/min (125.5 CFM) fan was used to generate the force air convection. 561 copper micro tubes (having 0.95 mm outside diameter, 0.7 mm inside diameter and 140 mm length) were used to increase the heat transfer rate and decrease the volume size of the heat exchanger. The micro-tube heat exchanger, as shown in Figure 5, measures 114.3 mm x 177.8 mm x 28 mm (core size=100 mm x 130 mm x 20 mm) and has high heat transfer rate. It dissipates around 380 Watts under a 24 °C inlet temperature difference between the two working fluids (air and water).



Figure 5. Micro-tube combustor/heat exchanger

Brass Gear Pump

A brass gear pump was designed and fabricated in our CNC machine, in order to run at high operating temperatures. The pump operation was based on two brass gears with following parameters: 24 pitch, 9 teeth, pitch diameter = 9.5 mm (0.375 inch), outside diameter = 11.6 mm (0.458 inch) and height = 9.5 mm (0.375 inch). The pump circulates the hot medium and is run by a DC motor. These pumps run alternatively according to the heating and cooling cycles. O-rings and screws were used to seal the brass gear pump. The brass gear pump has the following dimensions; 26.7 mm x 38.1 mm x 35.6 mm (1.05 inch x 1.5 inch x 1.4 inch). Figure 6 shows the designed brass gear pump with two brass gears. It has 1430 ml/min flow rate at 6 psi pressure loss.

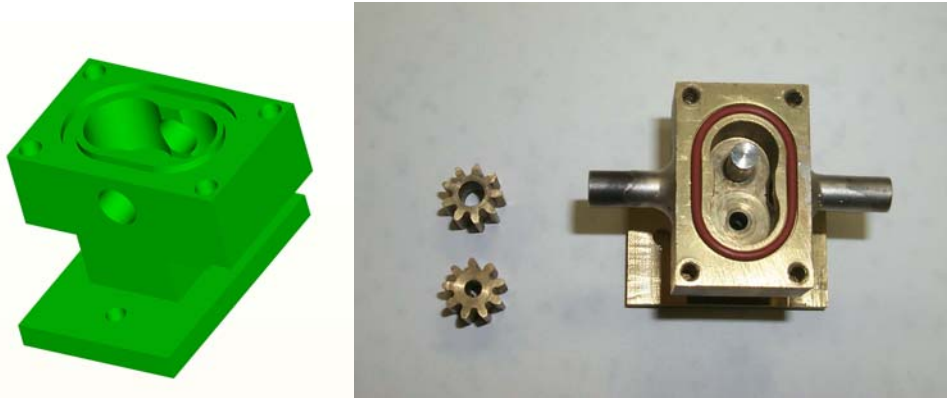


Figure 6. Brass gear pump

Experimental Results

Figure 7 shows closed-loop test results at 1.0 Hz actuation frequency. The heating and the cooling periods of the SMA strip were 0.5 second each. These plots also show that the combustor/heat exchanger and radiator have enough power at the given conditions. The mass of each circuit is balanced after 150 sec. The displacement was around 2 mm and the maximum stress was 114 M Pa. The actuation frequency of the final SMA actuator system was 1.0 Hz in closed-loop configuration at the given conditions.

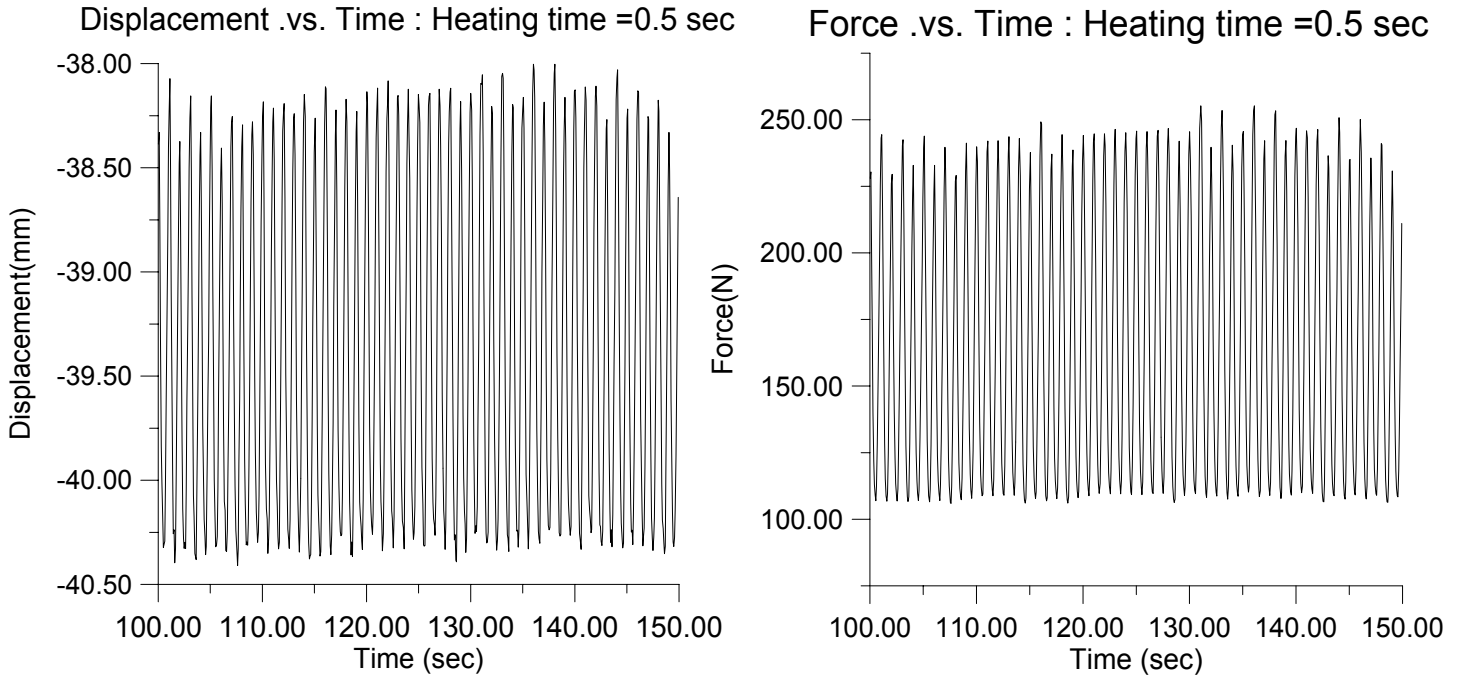


Figure 7. 1 Hz actuation frequency

Energy Densities of FPC- SMA Actuator System

Table 1 shows the mass of each component and mass of the system. The total mass of the system is 4.138 Kg including fuel and battery mass required to run 3600 cycles at 1.0 Hz actuation frequency. The energy density of propane is assumed as 50.4 MJ/Kg and the energy density of a battery (lithium-ion battery) is assumed as 540 KJ/Kg. The work and power generated during actuation were 0.5 J and 0.5 W with 2 mm displacement and 250 N at 1.0 Hz actuation frequency, respectively. Thus the energy density of the system is obtained as,

$$Energy_density_system = \frac{Total_mechanical_work}{Mass_system} = \frac{1800J}{4.138Kg} = 435J / Kg$$

Where the total mechanical work, 1800 J, is given by 1 cycle work (0.5 J) x 3600 cycle.

If the energy source of SMA actuator is the parasitic energy from a plant or a vehicle, an SMA actuator system would be just an SMA actuator and the energy density would increase significantly according as the number of actuation cycle increases. The parasitic actuator system will not need any additional devices and power by using the existing devices. The following calculation of energy density is based on 3600 cycles at 1.0 Hz actuation frequency.

$$Energy_density = \frac{Total_mechanical_work}{Mass_SMA_actuator} = \frac{1800J}{0.2Kg} = 9000J / Kg$$

Also the energy density of SMA material at 3600 cycles becomes tremendous in parasitic energy system, as the number of cycles increases.

Table 1. Energy density of the SMA actuator system

Component	Unit mass (g)	Number	Total (g)
Solenoid valve	132	4	538
Brass pump	356	1	356
Plastic pump	234	1	234
SMA actuator with connectors	197.05	1	197.05
SMA strip	2.95	1	2.95
Combustor/heat exchanger	400	1	400
Water + bellows	130	2	260
Tube + tube connectors+ check valves	300	1	300
Fuel with tank (3600 cycle)	80	1	80
Battery with cables (3600 cycle)	400	1	400
Total mass of the system			4138

Results of FPC-SMA Actuator System

- Combustor can generate actual output power up to 800 watts
- Micro-tube heat exchange can dissipate 380 watts at 24 °C temperature difference between air and fluid
- The SMA strip (2.5 mm x 0.9 mm x 114 mm) produced 250 N (110 MPa) at 1.0 Hz and 2.0 mm displacement (2 % strain) in closed-loop operation
- Small amount of electrical power (43 Watts) required to operate pumps, valves and fan.--Very small compared to electrical power needed for resistive heating and forced convection cooling of SMA actuator
- The mixing between hot and cold water decreased significantly

Conclusions of FPC-SMA Actuator System

- The fuel-powered SMA actuator system was successfully designed and tested---use the high energy density of fuel, such as propane, as the main energy source.
- First SMA actuator adopting forced convection heating and cooling heat transfer mechanism --- has relatively high actuation frequency and does not overheat the SMA element
- SMA actuator system approach --focus on the energy and power densities of the system and development of the actuator system.
- Heating of the SMA by utilizing existing parasitic heat in the vehicle/plant, This will yield a relatively high energy density actuator

3.2. Thermoelectric Compact (TEC)-SMA Actuator

3.2.1. TEC-SMA Actuator

The TEC-SMA approach was based on finding optimal power and energy densities for the actuator system. As a first step, commercially available thermoelectric modules (TEM)s were tested for optimal heating and cooling capabilities under no-thermal load. Figures 8-10 shows the TEM evaluation setup along with the stacked TEM configuration temperature vs. time and minimum temperature vs. voltage and current results

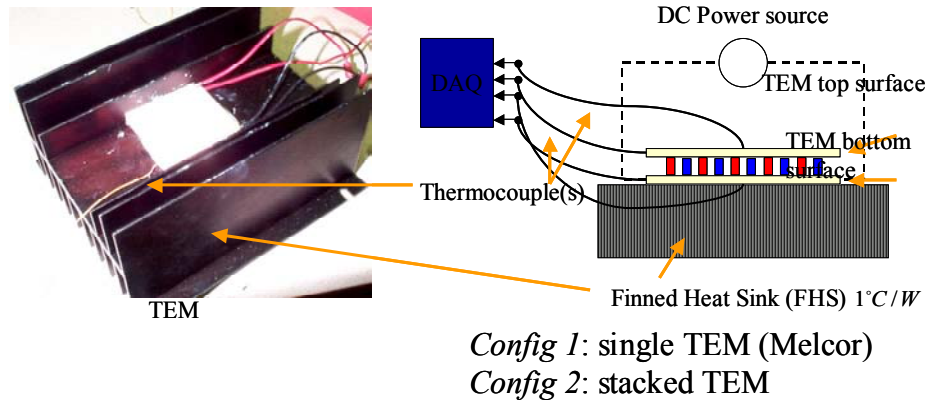


Figure 8. TEM evaluation setup.

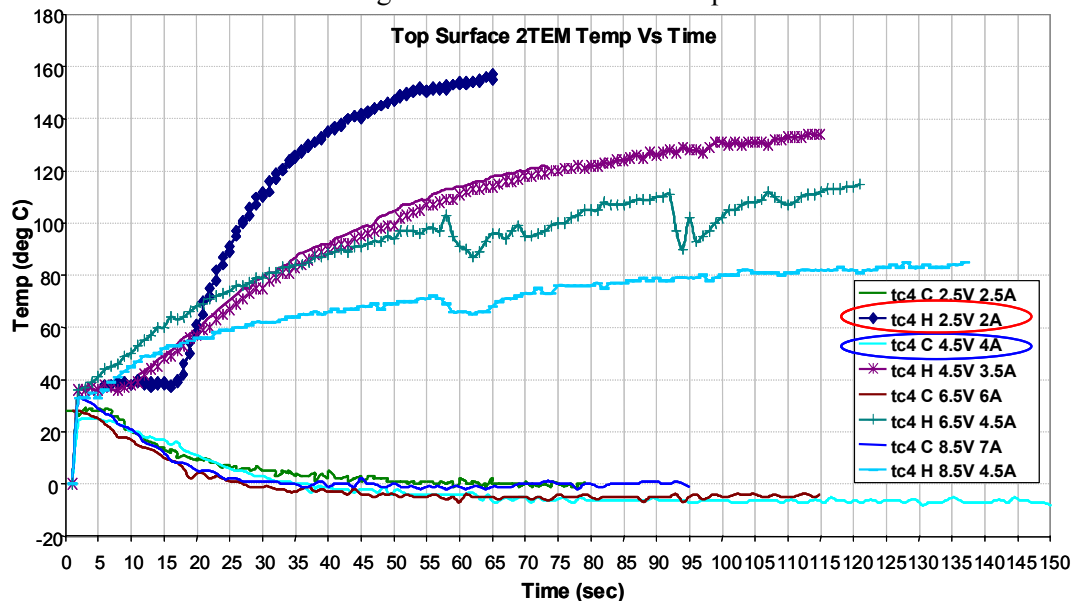


Figure 9. Stacked TEM maximum and minimum temperature curves

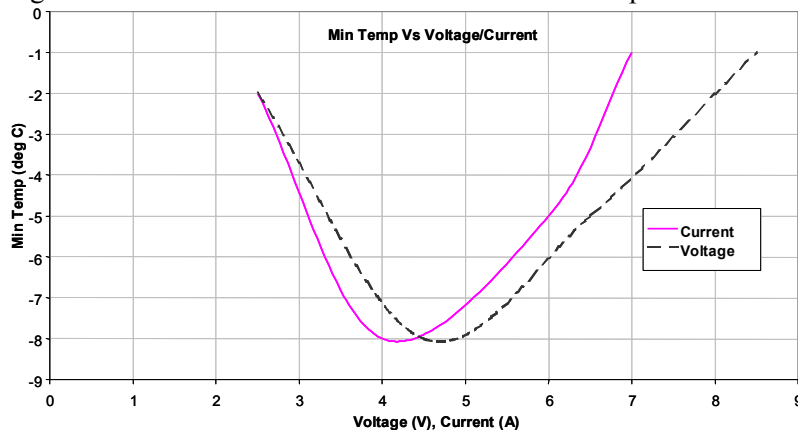


Figure 10. Stacked TEM minimum temperature versus voltage and current

Based on the optimal TEM heating and cooling conditions under no-load, a TEC-SMA test setup was assembled. Figure 11 shows the schematic of the experimental setup. The SMA actuator used in this setup was acquired from SMA Inc., and it had the following specifications; length 43mm (1.7”), thickness 0.384mm (0.01”), width 2.54mm(0.1”). The SMA actuator was pre-strained to 3% before testing. A PWM based actuation control scheme was used to resistively heat the SMA actuator. TEMs were acquired from Melcor and were used under an On/Off type control setting.

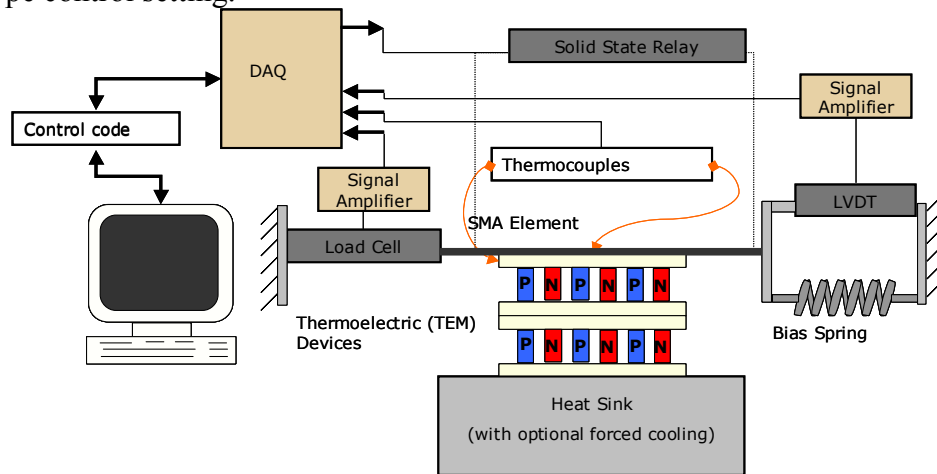


Figure 11. TEC-SMA experimental setup schematic.

The completed tasks for the TEC-SMA actuator are as follows

Design and Construction of Experimental Setup:

- SMA strips (Nitinol).
- Thermoelectric element based on commercially available Peltier modules.
- Optimize TEC-SMA bandwidth and stroke length based on both full and partial SMA transformation cycles.
- Parametric study of force, stroke and frequency
- Determination of Force vs. Displacement for actuator system at a range of actuation frequencies.
- Determination of TEC-SMA output power density and output energy density.

Instrumentation:

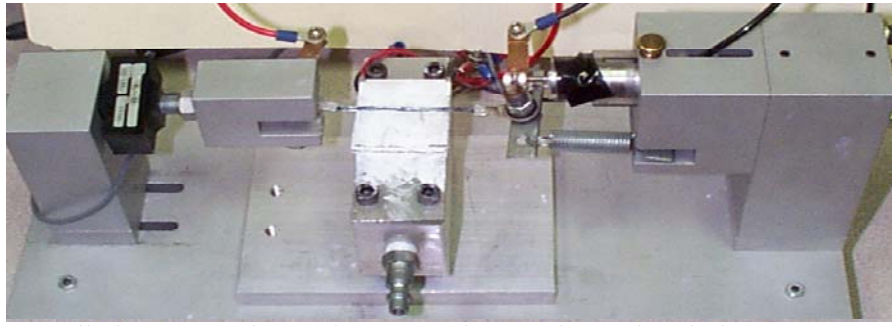
- Stroke measured with LVDT (Res. 0.01 mm).
- Load cell for output force measurements.
- Thermocouples for SMA temperature measurements.
- Supply voltage and current measurements to determine thermoelectric element power consumption.
- Continuous measurements allow for closed loop actuation control.

Actuator Performance Modeling:

- SMA constitutive model integrated with heat transfer capabilities

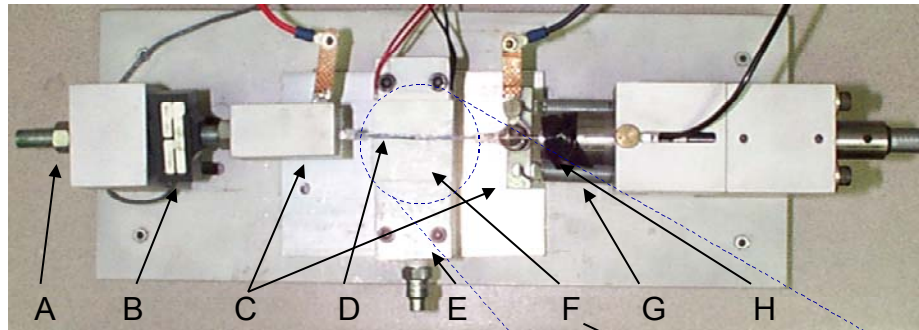
Results

Figure 12 shows the existing experimental setup involving an SMA strip as an actuator and two Peltier devices. The SMA strip is free to move on the cold surface of the Peltier device using silicon based thermal paste to ensure thermal connection. The NiTi SMA strip has cross sectional dimensions of 0.1 x 0.015 inches (2.54 x 0.384 mm), and a length of 1.702 inches (43.3 mm). The SMA strip is electrically heated using 30-60A current. Results of a preliminary test case are presented in Figures 10, 11 and 12. The results are for a time period of 0.5Hz and 1Hz, with SMA actuation of 0.1 seconds with a constant SMA current-on to current-off ratio ($\tau = t_{ON}/t_{OFF}$, $\tau = 0.05$).



Preliminary experimental setup to characterize and optimize

- Actuator bandwidth
- Stroke
- Dimensions
- Output power and energy density



- | | |
|--------------------|---------------------|
| A. Tightening Bolt | E. Heat Sink |
| B. Load Cell | F. Peltier Elements |
| C. SMA Connectors | G. Bias Spring |
| D. SMA Strip | H. LVDT |

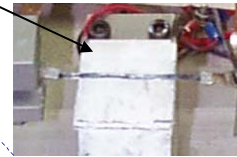
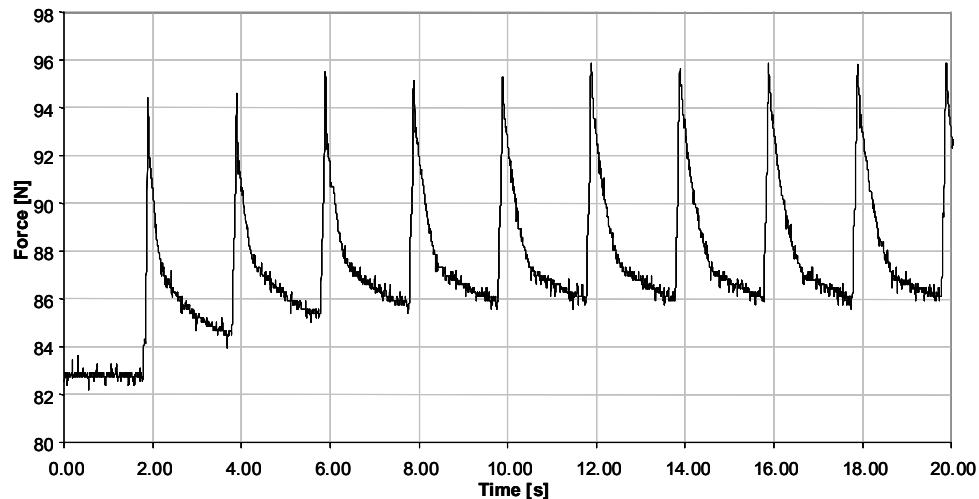


Figure 12. TEC-SMA experimental setup.

Figures 13 and 14 show the variation of SMA actuator force and displacement with time for 0.5Hz actuation frequency. Figures 15 and 16 the variation of SMA actuator force and displacement with time for 1.0Hz actuation frequency.

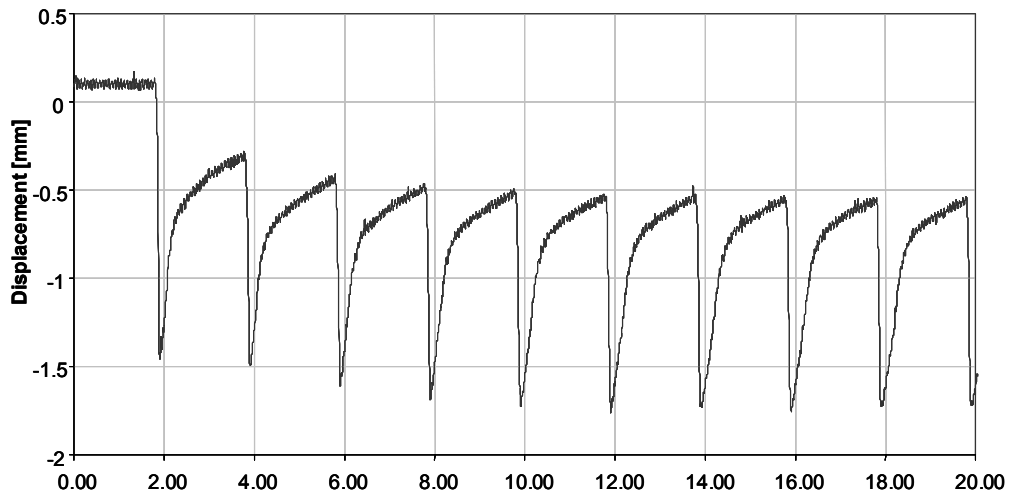
SMA strip:

CS = 2.54mm x 0.384mm (0.1" x 0.015"), Length = 43.3mm (1.702")



SMA strip generated force for $f = 0.5\text{Hz}$ and $\tau = 0.05$

Figure 13. SMA force for 0.5Hz.

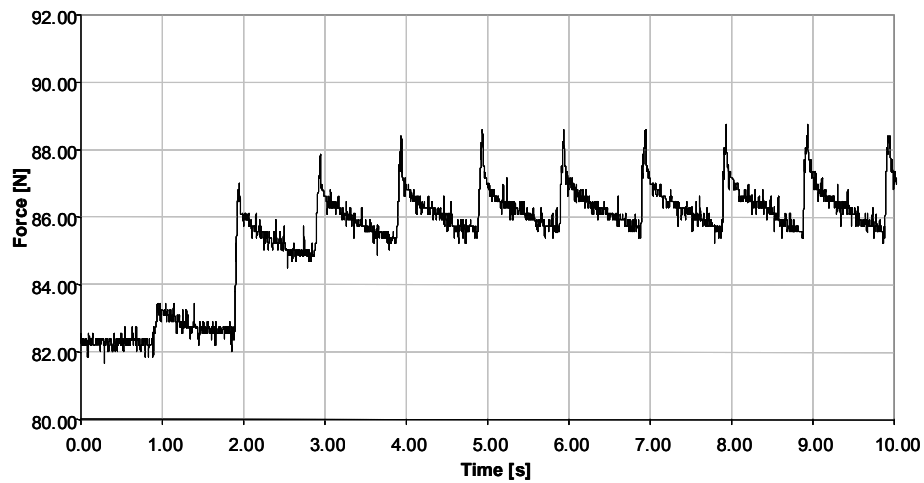


SMA strip displacement for $f = 0.5\text{Hz}$ and $\tau = 0.05$, and average recoverable strain of 2.5%

Figure 14. SMA displacement for 0.5Hz.

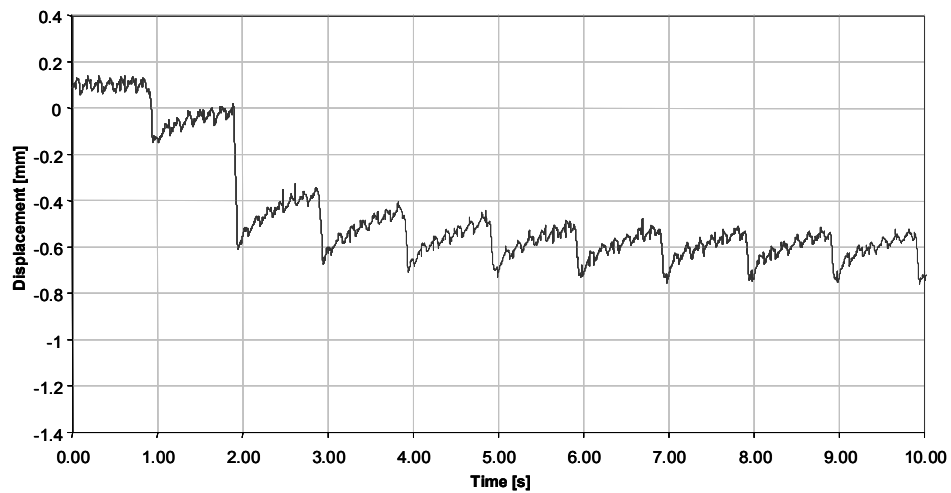
SMA strip:

CS = 2.54mm x 0.384mm (0.1" x 0.015"), Length = 43.3mm (1.702")



SMA strip generated force for $f = 1.0\text{Hz}$ and $\tau = 0.05$

Figure 15. SMA force for 1.0Hz.



SMA strip displacement for $f = 1.0\text{Hz}$ and $\tau = 0.05$, and average recoverable strain of 1.3%

Figure 16. SMA displacement for 1.0Hz.

Table 2 shows the TEC-SMA system energy and power densities along with the efficiencies. The data presented in Table 2 shows that for the tested cases a 21% increase in power density resulted in 39% decrease in energy density, due to 45% decrease in actuator displacement. Figure 17 further illustrates these results. Based on the results presented the following steps can be considered to maximize TEC-SMA efficiency

- For a fixed volume - increasing SMA surface area to volume ratio to maximize heat transfer by reducing thickness
- Ensuring ΔT of TEMs is as high as possible by maintaining heat sinks at a constant low temperature
- Minimizing contact resistance b/w SMA actuator and power leads to reduce losses

Table 2. TEC-SMA test results

SMA Actuator		SMA Actuator + Stacked TEM System (for a fixed duty cycle)		
Length	43 mm	Frequency	0.5Hz	1.0Hz
Width	2.54mm	Avg. Force	88.2N	86.7N
Thickness	0.384mm	Avg. Stroke	0.5mm/s	0.56mm/s
Mass	243.83mg (2.4x10 ⁻⁴ Kg)	Avg. Displacement	1.0mm	0.56mm
		Avg. Recovered Strain	2.5%	1.3%
		Avg. Power Output	1.70W	2.06W
		Avg. Energy Output	0.17J	0.103J
		Energy Input	72J	36J
Stacked (2) TEMs		Power Input	501.6W	501.6W
Power Input	1.6W	Avg. System Power Density	698.36W/Kg	845.9/Kg
Weight	2.2gr (2.2x10 ⁻³ Kg)	Avg. System Energy Density	69.83J/Kg	42.3J/Kg
		Avg. SMA Power Density	3041.7W/Kg	4750W/Kg
		Avg. SMA Energy Density	308.33J/Kg	237.5J/Kg
		Carnot SMA Efficiency	8.5%	~8%
		TEM Efficiency	13%	~13%
		Actual System Efficiency	0.34%	0.41%

Under given conditions an SMA strip of 2.5x10⁻³in³ weighing 5.2x10⁻⁴lbs can lift a weight of 20lbs to a distance of 0.04" at a frequency of 1Hz .

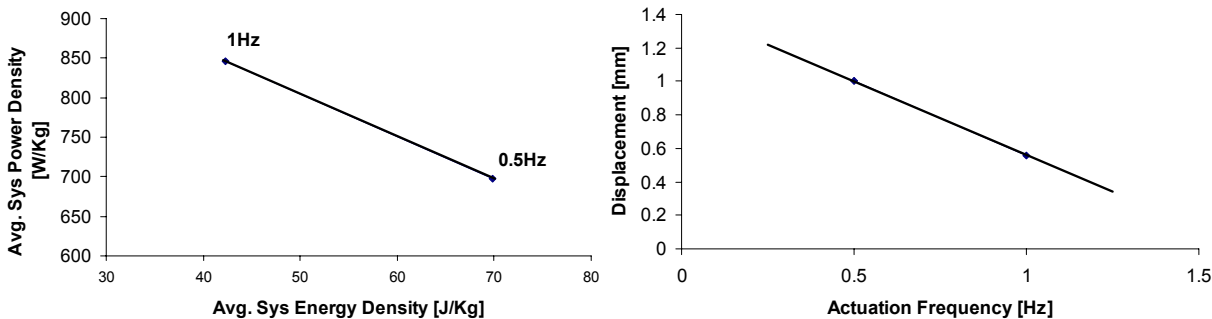


Figure 17. TEC-SMA results

3.2.2.TEC-SMA Key Achievements

Experimental Setup:

- SMA strips (Nitinol).
- Thermoelectric element based on commercially available Peltier modules.

Instrumentation and testing:

- Stroke measured with LVDT (Res. 0.01 mm).
- Load cell for output force measurements.
- Thermocouples for SMA temperature measurements.
- Supply voltage and current measurements to determine thermoelectric element power consumption.
- Continuous measurements allow for closed loop actuation control.
- PWM based actuation control

This feasibility study shows the need for maximizing SMA surface area to volume ratio while maintaining heat sinks at low temperatures and minimizing contact resistances to achieve optimal TEC SMA performance.

4. Publications

Lagoudas, D. C., Rediniotis O. K. Jun, H. Y., and Allen, R. D, “Fuel-powered compact SMA actuator”, In proceedings of SPIE Smart Materials and Structures Conference, March 2002, San Diego, CA.

Khan, M. M., Lagoudas, D. C. and Rediniotis O. K., “Thermoelectric SMA actuator: prototype testing”, In proceedings of SPIE Smart Materials and Structures Conference, March 2003, San Diego, CA.

Jun, H. Y., Allen, R. D., Lagoudas, D. C., and Rediniotis O. K., “Fuel-powered compact SMA actuator: second-generation”, In proceedings of SPIE Smart Materials and Structures Conference, March 2003, San Diego, CA.