Shape memory alloy resistance behaviour at high altitude for feedback control

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Abstract. Many recent aerospace technologies are using smart actuators to reduce the system's complexity and increase its reliability. One such actuator is shape memory alloy (SMA) actuator, which is lightweight, produces high force and large deflection. However, some disadvantages in using SMA actuators have been identified and they include nonlinear response of the strain to input current, hysteresis characteristic that results in inaccurate control and less than optimum system performance, high operating temperatures, slow response and also high requirement of electrical power to obtain the desired actuation forces. It is still unknown if the SMA actuators can perform effectively at high altitude with low surrounding temperature. The work presented here covers the preliminary process of verifying the feasibility of using resistance as feedback control at high altitude for aerospace applications. Temperature and resistance of SMA actuator at high altitude is investigated by conducting an experiment onboard a high altitude balloon. The results from the high altitude experiment indicate that the resistance or voltage drop of the SMA wire is not significantly affected by the low surrounding temperature at high altitude as compared to the temperature of SMA. Resistance feedback control for SMA actuators may be suitable for aerospace applications.

1. Introduction
The shape memory alloy (SMA) actuators have been proposed for numerous commercial applications such as automotive, aerospace, robotic and biomedical [1]. In the aerospace research, SMA actuator has found its way in many systems including aircraft, helicopters and satellites [2]. SMA actuator can also be considered as the enabling technology for morphing wing concept, which allows the lift coefficient to be varied accordingly to produce more efficient flight [3-6]. Furthermore, engine nozzle sections can also be varied with application of SMA to reduce noise during take-off [7], and SMA wires have been used in the release mechanisms in small satellites and vibration counter mechanisms [2]. Moreover, the helicopter blades can be folded or retracted using SMAs to ease storage in the designated bay [8], which is an innovation as most helicopters utilize manual folding that requires more manpower and significant amount of time to accomplish it.

In a recent development, it is highlighted that limitations have been found in using SMA actuators for a morphing wing on a real aircraft. These include high operating temperatures, slow response and high need in electrical power to obtain the desired actuation forces [3]. This present study is carried out to understand the behaviour of SMA and its feasibility to be utilized as an actuator at high altitude for aerospace application. Resistance of SMA is chosen as an alternative to a few common feedback control variables such as position and temperature feedback control. Resistance feedback control is expected to
be less affected by the significant changes in temperature as compared to other variables like temperature and strain feedback control. High altitude experiments are conducted to verify this notion.

2. SMA Actuator

SMA wires are able to change their length when a change in temperature occurs. Two types of heating that can introduce temperature changes are conventional and Joule heating. The conventional heating involves placing the SMA wire near a heat source. On the other hand, Joule heating can be achieved by connecting the two ends of the SMA material to an electrical power source. Many works that are carried out by researchers used Joule heating over conventional heating [9-12]. SMA undergoes phase transformation in two types of conditional change: temperature and loading. The phases are austenite, twinned martensite and de-twinned martensite [13]. The common initial phase is twinned martensite. Upon loading, the SMA changes into de-twinned martensite phase. If the de-twinned martensite SMA is heated, it changes into austenite. Allowing the SMA to cool down will return it to the initial phase of twinned martensite. SMA has been labelled as high energy density, large energy storage and high force produced-to-weight ratio material. Force is produced by means of strain, particularly when the SMA undergoes a change in its dimension, most commonly, length. The small size of SMAs enables them to replace the conventional actuators that are mostly much larger in size and to be used in small workspaces or areas.

The shape memory effect in SMA can be divided into two categories: one-way and two-way [14-15]. SMA with one-way shape memory effect operates in a way that it can return to its original state after deformation. For example, after a load is applied to deform the SMA, heat can be used to revert it to its original state. On the other hand, SMA with two-way shape memory effect can remember two states: one at high temperature and another at low temperature. SMAs require training for this purpose or effect. Several types of variables can be used to control the SMA actuator that include temperature, resistance, strain and position. Temperature and resistance are associated with the SMA actuator itself whereas strain and position are usually related to the system that is being actuated. Using temperature as a feedback control requires some compensations to be carried out. As the current is allowed to flow through the SMA wire, the temperature of the wire increases. However, when the current is stopped or removed, the temperature curve does not go back down through the same line. In general, two types of approaches can be taken to remove the hysteresis effects. The first one is the open loop compensation, which can be done by applying the inverse of the generalized Prandtl-Ishlinksii model that is used to model the hysteresis [16]. On the other hand, the second one is the closed loop feedback, whereby a corrective heat input is generated based on the error [17].

Furthermore, resistance is studied as an option to overcome hysteresis. Resistance of a material can be measured using a two-wire or four-wire configuration [18]. Both concepts require the presence of a small power supply to the device under test (DUT). The voltage drop across the DUT and the current in the circuit are used to compute the resistance. For a four-wire setup, additional resistors are placed in the circuit to reduce the measurement error. This setup is recommended for resistance measurement under 100 ohms. In previous work by Dhanalakshmi (2014), differential resistance feedback control is applied to control two antagonistic SMA actuators [12]. The values of resistance are computed from voltage drop measurements of both SMA wires and the difference between them is used to determine rotational movement of the shaft-disc. The angular change of shaft-disc is also shown in a manipulator arm. Moreover, the capability of resistance feedback control to control the position of a slider has also been demonstrated [19]. A Linear Variable Differential Transformer (LVDT) position sensor is placed against the slider to measure the displacement.

In certain applications of SMA actuators, the actuation is indirectly controlled. For example, strain feedback uses strain gauges to monitor the strain of the system being actuated. For the morphing wing, the change in strain experienced by the wing structure due to the SMA wire exerting a force is used as a feedback signal to obtain the desired shape. A certain shape of the wing corresponds to a specific lift coefficient [5]. In another work, the strain is measured and controlled to study the performance of the proportional-integral (PI) controller on a flexible aluminium beam [20]. To track position or deflection
of an actuated system, a laser range sensor is required for the position feedback. The tip position of the composite beam with embedded SMA wires can be controlled accurately by position feedback using a laser range sensor, with the aid of feed-forward action, PD controller and a robust compensator. In this work, the feasibility of using resistance as feedback control at high altitude for aerospace applications is explored. A composite plate, actuated by a Ni-Ti shape memory alloy wire, is used for this study.

3. Methodology
Prior to this experimental work, finite element method is used to gauge the structural response of the composite plate actuated by SMA actuators. Different configurations have been analyzed by changing the properties of the composite material, position of SMA actuators within the structure and the forces exerted on the structure by the actuators. The placement of the actuators is critical in obtaining the desired plate displacement. The design objective that has been set then is to produce a plate that can be displaced at least 10mm along the z-axis at the tip. A different combination of applied forces by the SMA actuators is analyzed. The analysis is repeated for different configurations of the SMA actuators. It has been found that the number of SMA actuators used and their orientation will produce significant variation in plate displacement [21].

Figure 1 illustrates the schematic diagram of the SMA actuators on the composite plate used in this study. The dimension of the composite plate is 52cm in length and 20cm in width. Three SMA wires with a length of 35.5cm are instilled on the surface of the plate at a distance of 2.5cm between each other. One strain gauge is placed on the surface of the plate and a thermocouple has been attached to the SMA actuator. The experiments are conducted using single cantilever plate, where one end is fixed while another is free to move. The laminated woven composite model is composed of six fiberglass/epoxy layers with equal 0° layup. The SMA actuator selected is Ni-Ti wires provided by Dynalloy, in which sold under the trade name FLEXINOL.

![Figure 1: Schematic diagram of composite plate with SMA actuators](image)

An experimental test bench has been designed to analyze the performance of strain feedback smart structure system composed of the composite laminate plate with SMA actuators placed on the surface of the plate. A proportional-integral-derivative (PID) controller has been designed using mathematical model of the SMA actuator and its performance has been verified to be effective through a hardware-in-the-loop experiment [22]. However, using the strain of the composite plate as feedback can be quite complicated as the input parameter to the control system does not come directly from SMA actuator. Hence the objective of this current work is to determine the feasibility of using resistance of the SMA actuator as input variable to the control system. It is believed that this will produce accurate response for the deflection of the composite plate in order to reduce overshoot and steady state error.

For the preliminary stages, basic experiments are carried out to determine the relationship between several variables. The manipulated variable is voltage of power supply and the responding variables are temperature of SMA, voltage drop of SMA, force produced by SMA and also resistance of SMA as shown in Figure 2. Meanwhile, the measurement process for the experiments is depicted in Figure 3. For the temperature of SMA, a voltage is supplied from 0V up to 2.5V to activate the SMA, and the temperature readings are recorded using thermocouple. As for the voltage drop, similar voltage supply is used and the voltage drop is recorded using two wires. Both responding variables are measured by
their respective measurement device, alongside data acquisition cards from NI and LabView. As for the force produced, a digital hanging scale is aligned horizontally and hooked on to the SMA wire to measure the pulling force. The resistance of the SMA is computed by dividing the voltage drop by the current. The conducted measurement process for this is depicted in Figure 4 and Figure 5.

Figure 2: Graphs of outputs against voltage

Figure 3: Measurement process of temperature and voltage drop

Figure 4: DAQ to acquire and generate signals

Figure 5: Digital hanging scale to measure force produced by SMA

For the high altitude testing, resistance of the SMA wire is measured with a different power source. The adjustable power supply is replaced with a battery, which will introduce a constant power supply. This alternative is suggested since there was very limited onboard space when the high altitude testing was carried out. A composite plate comprising of fiberglass and epoxy hardener is drilled at both of its ends, with the diameter of a small screw’s thread. One end of the plate is screwed onto a small wooden block glued in the glider while the other end is left to remain a free end. The fixed end has two screws, diagonal to each other, to prevent the plate from rotating. The free end of the composite plate has been supported by another piece of wooden block. Figure 6 shows the composite plate with SMA placed in the High Altitude Testing platform. The sensor onboard is a thermocouple as shown in Figure 7, where the SMA temperature and the ambient temperature in the glider are measured. A 3.7V rating battery is connected to the SMA wire to complete the circuit. Figure 8 shows the Arduino Uno board that is used to control the actuation that sent signals to connect or disconnect the circuit. The board measured the voltage drop of the SMA during actuation. The SMA is actuated at five different altitudes during the ascent of the balloon: 4km, 8km, 12km, 16km and 20km.

The High Altitude Fixed Wing Experimental Platform is flown with a 1600g balloon and 2.5kg payload (fixed wing). It is launched from the paddy field in Langkap, Perak, Malaysia (4°2’31.62”N 101°10’4.45”E) at 12:00 pm, carrying the experimental test bed onboard. The flight is fully controlled by the control module system. When the balloon reached 108268ft, it burst and the fixed wing payload
began its free fall, which is then slowed down by a parachute at 88582.7 ft. During descent, the release mechanism is activated to release the parachute and the fixed wing began its autonomous mission back to the desired landing site, which has been designated to be at Seberang Perak, Malaysia (4°3'31.51"N 100°51'54.00"E). After arriving at the landing coordinate, the fixed wing began to loiter autonomously to descend slowly before the ground station controller took over control from the autopilot to make a smooth landing. Figure 9 shows the flight path profile of the glider and Figure 10 shows the change in altitude of the balloon. After 2 hours 48 minutes, the fixed wing safely landed by manual control at 50m from the ground station. All experiments and system hardware are recovered with very minimal damage to the fixed wing body.

For the next stage, resistance is used as a variable for feedback control to actuate a composite plate. Three SMA wires are arranged in a series electrical connection on the surface of a composite plate as shown in previous Figure 1. For the feedback control process, the voltage drop is measured across the SMA wires that are arranged in series. This value is obtained on the LabView interface using NI 9201 and then compared to a user input value. The input is keyed in numerically in the visual interface. The PID controller ensured appropriate amount of current is supplied to allow the measured voltage drop to match the input value. Figure 11 shows the schematic diagram of the feedback control system.

4. Results and Discussion
The graphs of voltage drop and temperature against voltage supply indicates that the SMA temperature contains more hysteresis compared to the voltage drop when it is being heated and cooled as shown in Figure 12 and Figure 13. Therefore, based on the results, the option of using voltage drop in feedback control reduces the need for compensation to be applied. The voltage drop response is more linear than
temperature response, which can be contributed to the independence of voltage drop towards external factors. On contrary, temperature is easily affected by the ventilation or the external heat source. The electrical resistivity of SMA is dependent on the temperature of the SMA that causes the modification of electronic structure of the material [23]. Figure 14 shows the force produced by the SMA wire with the change in voltage, where the force increases with the voltage supply but underwent a sudden spike after approximately 2.25V. This could be due to the phase transformation of the SMA wire. The large magnitude of force can be applied to do some heavier work whereas the linear part of the relationship is useful for controlling a range of force.

Figure 11: Schematic diagram of feedback control system

The SMA actuator is activated by providing PWM at different altitudes as shown in Figure 15. A few parameters have been observed including voltage drop, resistance, SMA temperature and ambient temperature in the fixed wing glider. The battery of 3.7V has managed to supply voltage above 3.5V consistently as shown in Figure 16. From Figure 17, it can be seen that both the ambient temperature and SMA temperature decreases when the altitude increases. The power supply is activated at altitudes of 4km, 8km, 12km, 16km and 20km, and it is deactivated after 2km in all occasions. The ambient temperature reading in the fixed wing glider can be observed before each SMA peak temperature, with the first phase recording was 30°C, second was 26°C, third was 17°C, fourth was 8°C and the fifth was 0°C. From the readings for the temperature and resistance measurement, it can be clearly seen that the temperature of SMA is highly affected by the change in altitude and ambient temperature. However, the resistance of SMA is only slightly affected by the change in the altitude and ambient temperature as shown in Figure 18. This shows that resistance feedback control of SMA actuator is more suitable for aerospace applications. For the resistance feedback control at ambient or room temperature, a step input of 8V has been selected. The result in Figure 19 shows that the system is able to provide the desired response. However, the steady state error is large, which is approximately 22.5%. In view of this, further improvement on the controller design may improve the transient and steady state response of the resistance feedback system for the SMA actuated composite plate.
5. Conclusion

The experimental data obtained in this study has indicated that temperature contains a higher level of hysteresis than voltage drop. This comparison results suggest that voltage drop provides better control without requiring further compensation. The results from the high altitude experiment also have shown that the resistance of SMA wire is not notably affected by low surrounding temperature. Independence
towards surrounding temperature makes resistance a good option as the variable for feedback control. Feedback control has been successfully carried out using voltage drop as the feedback variable for the SMA actuated composite plate. An output voltage supply response to actuate the composite plate is also achieved. The composite plate represents a simple simulation or portrayal of a morphing structure for aerospace application. The results have demonstrated the feasibility of using resistance feedback control for SMA actuating system. By employing this method, the external sensor can be eliminated since SMA actuator itself acts as the sensor. This will help to further reduce the complexity of the system.

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