Assessment of Shape Memory Alloy Actuators for Steered Parachutes

Final Proposal

16.621

Fall 2002

Author: Brian Wong

Advisor: Dr. Marthinus van Schoor

Partner: Benjamin Brooks

Tuesday, December 10, 2002

Table of Contents

List of Tables

List of Figures

Executive Summary

In recent years, much time and effort has gone into developing controlled parachute systems to improve to accuracy of unmanned airdrops. Most of the research effort has gone into developing the guidance and navigation systems, while ignoring the actuators used to control the airdrop system.

This proposal contains the plans for an experiment to test a new method and type of actuator for autonomous guided parachute systems. The proposed method uses lighter and cheaper actuators made from shape memory alloys, materials that change shape when heated above a certain transition temperature. One such material that is often used and readily available is Nitinol, and alloy of nickel and titanium. The experiment outlined in this proposal will evaluate how well shape memory alloy actuators made of Nitinol wire can steer a parachute.

A scaled-down prototype parachute will be equipped with Nitinol actuators as well as control and sensing circuits housed in a payload container. Simple models were used to determine baseline parameters for the experiment. Three independent variables, each being a different method of changing the amount of power supplied to the actuators will be tested. The system will first be tested in the lab, and then by performing a series of airdrops at a testing facility. Having the collected data meet or exceed defined controllability requirements, would demonstrate the potential use of shape memory alloys as parachute system actuators.

Commercially available equipment will be used to construct the experimental apparatus based on low cost and simplicity. Sources of error have been identified, and the design of the experiment has attempted to minimize or account for these wherever possible. Safety concerns are also addressed, as are the data collection and reduction methods.

The proposal also includes information concerning the testing facility at the US Army Natick Soldier Systems Center, which will be used for the drop tests. A tentative agreement has been reached with Natick, whereby they would provide the facility and support staff free of charge to the project. The proposal also includes information concerning a proposed budget and schedule, and the additional required facilities and staff support.

Introduction

In 1997, the U.S. Air Force Science Advisory Board identified a need to improve the accuracy of unmanned airdrops as one of its recommendations in a report titled "Summary Report: New World Vistas, Air and Space Power for the 21st Century."[1] Unmanned cargo parachutes are used by military and humanitarian organizations to deliver payloads such as food, ammunition and equipment. Unfortunately, without control, cargo parachutes can be knocked off their intended course by wind and other meteorological phenomena, resulting in lost or damaged cargo. Since the New World Vistas report, there has been work on autonomous Guidance, Navigation and Control (GN&C) systems to address the need of improving the accuracy of parachute drops. These efforts have been successful in achieving their goals, but little has been done in the development of actuators for these airdrop systems. In this proposal, an experiment for testing a new type of actuator will be described, which may be a lighter and cheaper alternative to current actuation systems.

The proposed new method involves using shape memory alloys (SMAs) as the actuators for a parachute system. A shape memory alloy is, in simple terms, defined as a material that changes shape when heated above its transition temperature.[2] In this way, the material exhibits memory by "remembering" its original shape. One method of raising the temperature of an SMA is by running a high amount of electric current through the material; a battery can be used to provide the current necessary to effect a change in shape of an SMA. By using this method, a simple actuation system can be built by powering shape memory alloy wires with electric current.

Hypothesis, Objective and Success Criteria

The experiment will assess whether it is possible to control an unmanned parachute by changing the lengths of shape memory alloys woven into its risers. To quantify the amount of control these actuators can provide, the objective of the project will be to assess experimentally what degree of control can be achieved by changing the lengths of the shape-memory alloy wires in the risers of the parachute. Accordingly, the experiment will be deemed a success if it can be determined whether or not using shape memory alloy actuators enables a scaled-down prototype parachute system to meet the following controllability requirements:

1. A horizontal velocity of $0.5\frac{m}{s}$ for every $10\frac{m}{s}$ of vertical drop velocity
2. A change in horizontal path of $1\frac{?}{s}$ for every $10\frac{m}{s}$ of vertical drop velocity

If the scaled-down prototype parachute is in fact able to meet these controllability requirements, it will constitute a strong argument for exploring the use of shape memory alloy wires as the actuators in new and existing parachute guidance systems.

Literature Review

In the late 1990s, the New World Vistas Precision Aerial Delivery (NWV-PAD) research initiative was formed to develop autonomous GN&C systems for unmanned parachutes.[3] The most notable of these efforts are the Affordable Guided Airdrop System (AGAS), developed at the US Army Yuma Proving Ground (YPG),[4] and the Precision Guided Airdrop System (PGAS) developed at the US Army Natick Soldier Systems Center.[5]

A standard G-12 resupply cargo parachute is used by AGAS, a joint development of the Air Force Office of Scientific Research (AFOSR), the US Army Natick Soldier Systems Center, The Boeing Company, and Vertigo Inc. The cargo parachute is modified by extending its risers with four pneumatic muscle actuators (PMAs), which contract in length when pressurized. The AGAS project proved, through extensive Monte Carlo simulations and flight tests, that a controlled, unmanned parachute released at an altitude greater than 5000 *m* can softly land on the ground with an accuracy of within 100 *m* from the target area. For PGAS, the C. S. Draper Laboratory, Inc. developed a government-owned software guidance package that allowed parafoils to reach the same accuracy goals as AGAS. A third system, the Small Autonomous Parafoil Landing Experiment (ALEX) developed at the DLR in Germany is similar to PGAS.[6]

The problem with the AGAS system is that the PMAs that it uses are bulky, expensive and require a tank of compressed nitrogen to function. Likewise, the electromechanical actuators used by the PGAS system are heavy and expensive. In addition, PGAS uses parafoils, which are more expensive than circular parachutes.

Extensive research and development has thus gone into developing autonomous control systems for unmanned parachutes. The main focus, however, has been on the guidance and navigation aspects of the airdrop systems, and not much work has been done to further actuator technology. Using shape memory alloy wires as actuators for a guided parachute system will decrease the overall mass and cost of the system. This alternative actuator option would also not require the additional mass of nitrogen to function, and it is much simpler to construct.

Technical Approach

For this experiment, the type of shape memory alloy that will be used is Nitinol. Nitinol is an alloy of Nickel and Titanium discovered by William Buhler at the U.S. Naval Ordinance Laboratory in 1961.[7] The properties of Nitinol are summarized in Appendix D. It has since then been used in a wide variety of applications ranging from stress sensors to robotic muscles. For our application, Nitinol wires will be woven into the suspension or rigging lines of a scaled-down prototype parachute. A plywood payload container will be constructed to hold the various components of the electronic circuits responsible for control and sensing.

Once these circuits have been constructed and installed, a series of bench tests will be carried out on the ground to determine if the actuators function as anticipated. These tests will include the following:

1. Testing the Nitinol actuators on a stationary parachute to demonstrate that control authority on the length of the rigging lines is within expected bounds.
2. Crashworthy testing of the payload container to ensure that it will not be damaged upon ground impact.
3. Repeated cycles of stationary tests to determine the effects of cyclic loading on the actuators and the electronic system.

A final check of the entire system will be performed before heading out to the test facility for each testing session.

At the first session, a calibration drop test will be performed at an airdrop facility and used as the control of the experiment. Subsequent drops will be performed using the control circuit to apply different perturbations to the actuators, and the sensing circuit to detect the responses of the parachute. A Data Acquisition Unit (DAQ) will store the data collected by the sensing circuit onto a flash memory card for later retrieval.

Finally, in between and after drop tests, data will be uploaded to a personal computer where it can be analyzed using a spreadsheet program such as Microsoft Excel or a numerical analysis program such as MATLAB. The analysis will consist of determining the trends resulting from the different perturbations applied by the control circuit, and evaluating whether or not the prototype system meets the controllability requirements.

Although it may seem that the functionality of the actuators can be determined without actually performing drop tests, this is not the case, as the actuators rely on a combination of ambient air temperature and payload weight to return them to their initial state. Likewise, it is not possible to perform this experiment "horizontally" in a wind tunnel for a number of reasons including:

1. The gravitational force pulling on the payload is not in a direction that will stretch the SMA wires back to their original state during cooling periods.
2. The gravitational force does not allow sideways displacement of the parachute to be tested since there is always a bias to one side.

The experimental setup for the drop tests will be as shown in Figure 1.

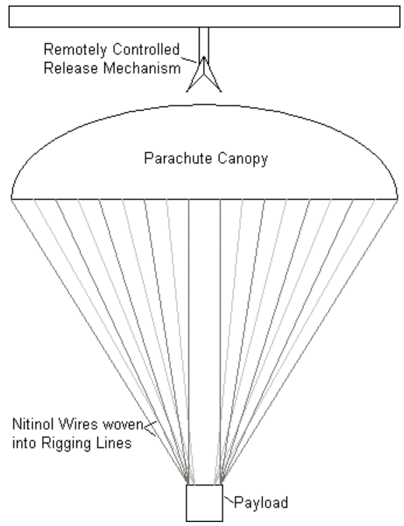

Figure 1: Experimental Setup

Drop tests will be performed at the parachute drop facility at the US Army Natick Soldier Systems Center in Natick, MA. This facility is an enclosed building similar in structure to a warehouse, allowing the parachute actuators to be tested without being affected by wind conditions. The release mechanism is built into the facility at Natick, and consists of a clamp that holds onto the top of the parachute. Using a rope, the release mechanism can be lowered to the ground, whereupon the parachute will be attached. The parachute will then be raised to the ceiling of the facility. Once the parachute is in place, it can be released by remotely controlling the release mechanism from the ground. The height of the ceiling allows the parachute to be dropped from altitudes of up to 35 ft.

Three different ways of changing the signal sent to the actuators will be tested. The first method involves varying the voltage level of the signal, the second varies the width of the pulses of the signal, and the third varies the total time for which the signal is sent to the actuators. All of these independent variables alter the amount of current supplied to the actuators and hence the amount of heat. They will be explained in more detail later.

The data that will be recorded will consist of three orthogonal linear accelerations and one angular acceleration. From these values, the velocity and displacement of the parachute system will be calculated, and used to evaluate the parachute under the defined controllability requirements.

Experiment Design

As noted in the previous section, a scaled-down parachute will be dropped in a series of trials in order to determine the effects of our independent variables. The canopy of the parachute will be circular in shape and made of rip-stop nylon. The canopy will have a diameter of approximately 2.74 *m*, and therefore an effective area of 5.9 m^2. A parachute with a canopy area of 5.9 m^2 will fall at a vertical velocity of approximately 2.7 $\frac{m}{s}$ when its orientation is completely vertical. The following calculations show the origin of the number for vertical velocity.

First, the expression for drag is equated with the gravitational force:

$$\tfrac{1}{2} r v_v{}^2 S C_D \cos q = mg \,, \qquad \text{(Eq. 1)}$$

where r is the air density, v_v is the vertical velocity, *S* is the surface area of the canopy, C_D is the drag coefficient, q is the tilt angle of the parachute from the vertical, *m* is the mass of the parachute, and *g* is the gravitational force. For a dome-shaped parachute, C_D is approximately equal to 1.5.[8] The standard sea level air density is $1.225\,\frac{kg}{m^3}$. The mass estimate for the payload is approximately 4 *kg*. Setting the variables in equation 1 to the following values:

$r = 1.225\,\frac{kg}{m^3}$ $\quad S = 5.9\ m^2$ $\quad C_D = 1.5$ $\quad q = 0°$ $\quad m = 4\ kg$ $\quad g = 9.8\,\frac{m}{s^2}$,

and solving, $v_v = 2.7\,\frac{m}{s}$, a reasonable rate of descent for the purposes of the experiment.

The parachute will have 18 rigging lines mad of para-cord. Each line will be 100 *in* or 2.54 *m* long. The rigging lines are already connected to the canopy of the parachute, but Nitinol wires will need to be woven into the rigging lines of the parachute by hand. The Nitinol wires are strained in the low temperature martensitic phase by the weight of the payload. Heating the material above its transition temperature causes it to undergo a phase change to a more ordered austentic crystal structure. This has the effect of decreasing the length of each wire by about 3%. The thick line in Figure 2 illustrates the path taken by the wires during the transition between the hot and cool states. Note that in reality, the path from the high temperature phase to the low temperature phase and the path from the low temperature phase to the high temperature phase should be slightly different due to hysteresis effects; however this is not shown in Figure 2.

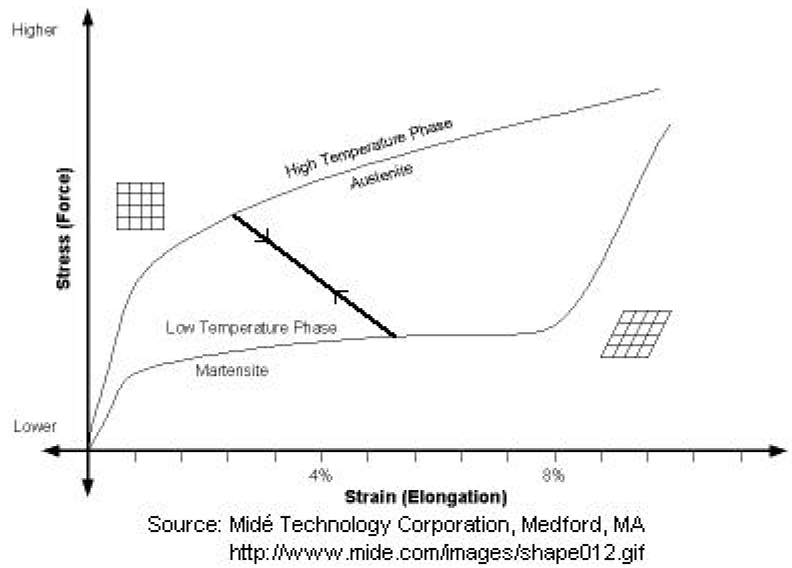

Figure 2: Transition between Martensitic and Austentic States

A thermal model developed at Midé Technology Corp was used to determine the type of Nitinol wire to use. This thermal model predicts the power required to resistively heat Nitinol wires. A set of realistic parameters for the Nitinol wire was determined by trial and error using this model. Based on the lengths of the rigging lines and the amount of current that the batteries could realistically supply, the Nitinol wire for the actuators needs to have a diameter of 1.2 mm, and martensitic and austentic final temperatures of 25 $°C$ and 35 $°C$ respectively. Actuators made from this type of wire should be able to undergo a heating and cooling cycle in about half a second. A copy of a MATLAB implementation of the thermal model showing the chosen parameters is included in Appendix C.

The payload, which consists of the control and sensing circuits as well as the power source, will be housed inside a payload container. This payload container will be constructed using plywood and screws. Holes will be drilled near the top of its sides so that the risers of the parachute can be attached simply by tying knots. The dimensions of the container will be approximately $0.23\ m \times 0.23\ m \times 0.23\ m$. All the components in the payload will be fixed to the container and balanced as well as possible to eliminate changes in mass distribution due to shifting components. To soften the landing, foam padding will be attached to the bottom of the payload container.

The payload will consist of two 12 V motorcycle batteries that will act as a power source for the Nitinol wire actuators and, passed through a voltage regulator, the electronic components in the two main circuits. The motorcycle batteries do not power the cell-phone-sized Data Acquisition Unit, which runs on a separate 9 V Ni-Cd battery. Figure 3 is a block diagram representation of the major components of the payload circuits.

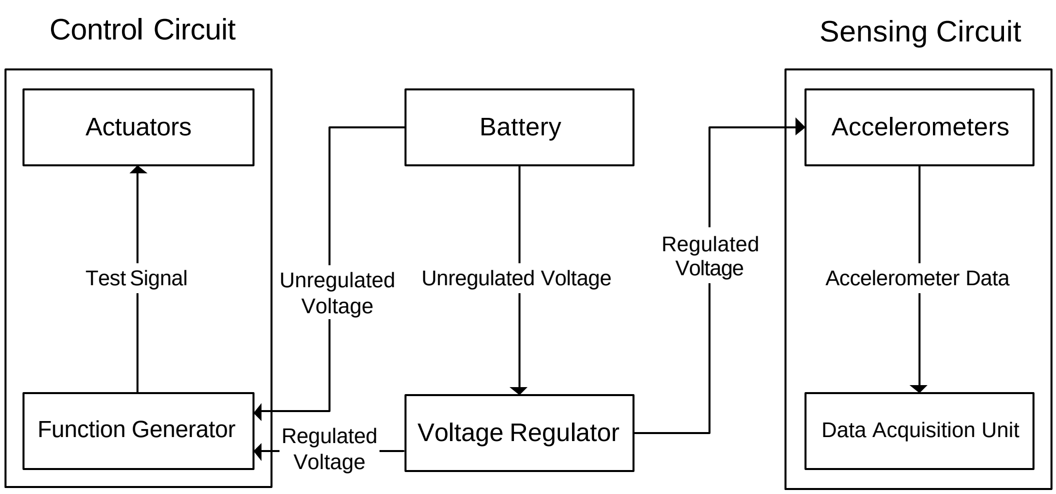

Figure 3: Payload Block Diagram

The Test Function Generator (Figure 4) will be a custom implementation on a Complex Programmable Logic Device (CPLD) chip programmed using Very High Speed Integrated Circuit (VHSIC) Hardware Description Language (VHDL), the Department of Defense standard for hardware description. The function generator will also make use of a potentiometer and relays to switch power among the four different actuators, one for each group of rigging lines. Although similar function generators exist as laboratory equipment, those devices are heavy, bulky and cannot be powered easily using a battery.

Since the experiment only requires square waveforms and a limited number of different voltage and pulse widths, a custom implementation using a CPLD allows the function generator to be scaled down to a simpler and smaller device. Customization also allows the timing delay and choice of length of perturbation to be preset in the source code of the function generator. Two sets of switches will allow the selection of which preset levels to use for a particular trial. The potentiometer in this circuit is used to set the amount of voltage that the actuators receive. The relays indicated in Figure 4 will actually be field effect transistors (FETs).

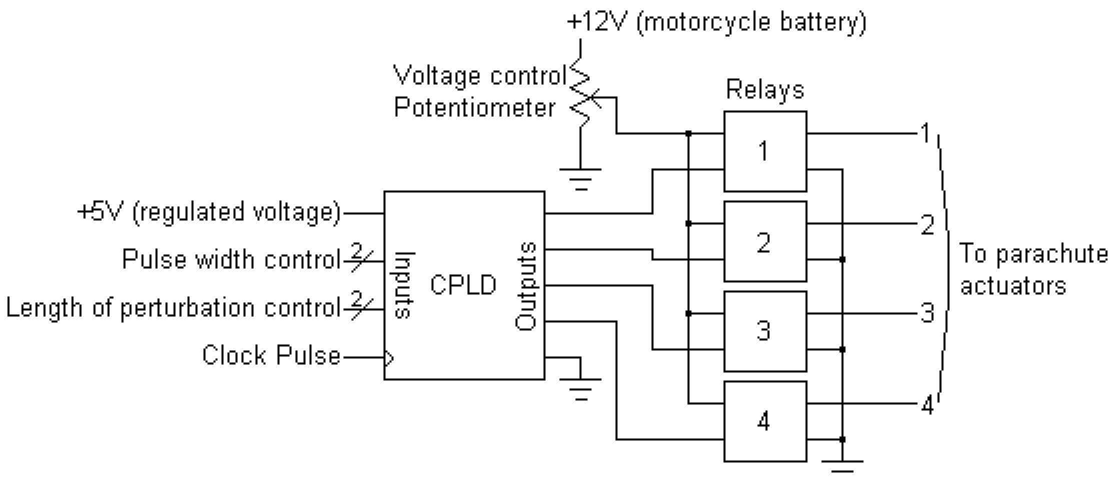

Figure 4: Schematic of Test Function Generator

The sensing circuit is necessary for collecting data. Ideally, a single three-axis accelerometer chip would detect three degrees of linear acceleration, and an angular rate sensor would detect one degree of angular acceleration. However, because of availability and cost, three single-axis linear accelerometers will be used in conjunction with one angular rate sensor. To be compatible with the Data Acquisition Unit described below, the accelerometers must output values between $-5V$ and $+5V$ to represent accelerations. All the integrated circuits in the design are commercially available, and hence are much easier and cheaper to purchase than to construct. In determining whether a certain component should be purchased or constructed, cost and simplicity were the main criteria.

Four channels of an eight-channel Data Acquisition Unit (DAQ) will collect the linear and angular acceleration data, and store it to a flash memory card. The DAQ will be able to store raw data from several trials before reaching full capacity, eliminating the need to transfer data between trials. However, using a laptop computer with a flash memory card reader, data can be analyzed in the field to ensure that the experiment is functioning as planned. The DAQ is approximately the size of a cell phone.

Independent and Dependent Variables

As stated, the goal of this project is to determine if shape memory alloy actuators can be used to control unmanned parachutes. The dependent variables are:

1. The horizontal velocity per $10\frac{m}{s}$ of vertical drop velocity
2. The change in path per $10\frac{m}{s}$ of vertical drop velocity

Velocities and displacements computed from measured accelerations will be used to determine the two dependent variables, which will be compared with the controllability requirements to determine how much of an effect the actuators have on the parachute.

The independent variables are each different methods of applying varying amounts of current to the SMAs to cause them to change shape. In order to achieve control the parachute, varying amounts of current are applied to SMAs in the form of wires to cause them to change shape. They are:

1. Voltage, the potential difference applied to the actuators
2. Pulse width, the length of pulses of current applied to the actuators
3. Length of perturbation, the total length of time that a perturbation is applied

Figure 5 is a sketch of a signal that shows the interrelation of these three independent variables.

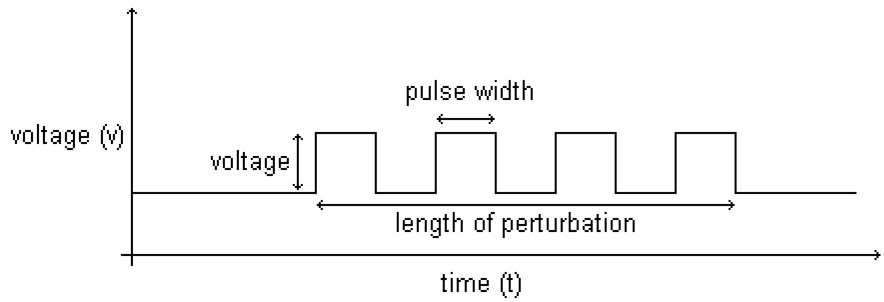

Figure 5: Independent Variables

Test Matrix

In order to test each of these independent variables separately and together, the following test matrix was developed (Figure 6):

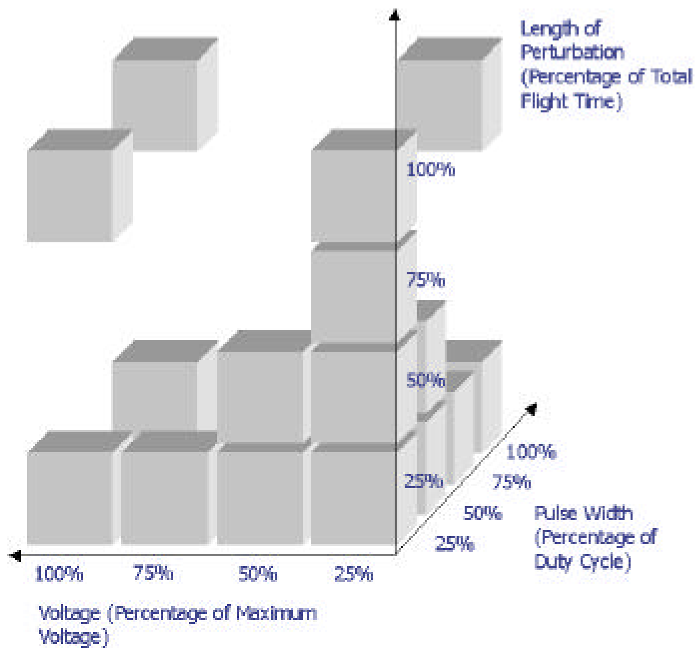

Figure 6: Graphical Representation of Test Matrix

Testing along the axes of the matrix allows the contribution of each independent variable to be evaluated alone. Testing along diagonals will provide insight into the correlation between different independent variables. Note that 25% is used as a minimum value instead of 0%, since, if any one of the three independent variables were set to 0%, the other two would be 0% as well. This can be best visualized using Figure 5.

Data Analysis

The raw accelerometer data will be uploaded onto a personal computer. Then, using Excel, the data relevant to each drop test will be extracted from each data set. Each data set will then be shifted to correct for the bias error of the accelerometers and then rescaled to fit conventional measurement units. Finally data sets from different trials will be compared either graphically, or using a numerical analysis package such as MATLAB to determine trends in the data. If the data shows that the controllability requirements have been met, then the hypothesis of the project will be proven.

Experimental Errors

A number of potential error sources in the experiment have been identified. These are summarized in Table 1 along with a brief description of the problem and how to decrease or eliminate the error.

Table 1: Sources of Error

Source of Error	Description	Method of Mitigation
Hysteresis	Shape memory alloys have a hysteresis effect that could potentially cause the actuators to get “stuck” in a particular state	In order to decrease the effects of hysteresis, ample cooling time will be given between consecutive test runs
Cyclic Loading	Depending upon the frequency and duration of the perturbations, the actuators could experience several thousand cycles of heating and cooling throughout the run of the experiment	A low frequency of perturbations, and periodic checks of a baseline condition will be used to ensure that the actuators have not deformed over time.
Sensors	Commercially available accelerometers will have a certain offset, and will drift with time	These errors will be corrected during data analysis by shifting and rescaling raw data
Inconsistent Release	If the actuators start functioning before the parachute is released or fully inflated, errors resulting from initial conditions could occur.	In order to ensure that the parachute has completely inflated before a test function is sent to the actuators, a time delay will be built into the function generator based on the initial trial run of the experiment.

Source of Error	Description	Method of Mitigation
Ambient Air Temperature	Different ambient temperatures would affect how quickly the actuators cool and return to their low temperature state.	An alloy with a relatively high transition temperature will be used so that changes in ambient temperature will be negligible. Ambient temperature will also be manually recorded by the experimenter and used during analysis to verify that these errors are negligible.
Measuring Current	The power output of the battery is not exact since the amount of current drawn depends on the resistance of the actuators. The resistance of the actuators will change as they change shape.	The actual voltage being sent to the actuators will be recorded by the DAQ as well. If the raw data indicates that there is a significant change in voltage, then the effect will be included in the data analysis.

Safety Concerns

A number of safety concerns were raised during the design of this experiment. Since the experiment deals with high temperatures and high current, care must be taken to ensure that no one and nothing is burned or shocked by the experimental apparatus. To this end, sufficient time will be given between test runs to allow the apparatus to cool down, and all personnel who are handling the equipment will wear protective gloves. The inherent danger of falling objects is also a concern. The safety procedures of the test facility at Natick will be followed. Thus, before each drop test, an auditory warning will be issued to ensure that all personnel and equipment have been evacuated from the immediate testing area. At the start of each drop, all personnel must have their backs against an exterior wall of the facility to ensure that no one will be unexpectedly hit from above. Personnel will also be required to wear hard hats for added protection.

Proposed Budget

Table 2 shows the proposed budget for this project. Since the US Army Natick Soldier Systems Center also has an interest in this research, the Test Facility Rental and Parachute expenses will be covered by Natick. The Data Acquisition Unit and the electronic components for the Function Generator will be borrowed from Midé Technology Corp., in Medford, MA.

Table 2: Proposed Budget

Item	Real World Cost	16.62X Cost
Test Facility Rental (8hrs)	$800	$0
Parachute	$100	$0
Materials		
Nitinol Wire	$240	$240
Payload Container	$50	$50
Data Acquisition Unit	$650	$0
Function Generator	$150	$0
Other Electronic Components	$100	$100
Batteries	$80	$80
Total Cost	$2170	$470

Detailed Schedule for 16.622

The project schedule is displayed in Table 3. A four-week period was reserved for drop tests and data collection since the exact availability of the drop tower at Natick is currently unknown. During the bench-testing period, data analysis procedures will also be developed. Data reduction and analysis will be an ongoing process that occurs as new data becomes available. The month of February is left to install the Nitinol actuators and to construct the payload.

Table 3: Proposed Schedule

ID	622 Schedule	Start	End
1	Install NiTinol Actuators into Parachute	2/5/2003	2/10/2003
2	Build and Integrate Payload	2/5/2003	2/26/2003
3	Perform Bench Tests	2/27/2003	3/12/2003
4	Perform Drop Tests and Collect Data	3/13/2003	4/10/2003
5	Reduce Data and Analyse	3/20/2003	4/29/2003
6	Progress Report Meeting	2/11/2003	2/11/2003
7	Oral Progress Report	3/4/2003	3/4/2003
8	Progress Report Meeting	4/1/2003	4/1/2003
9	Last Day to Take Data	4/18/2003	4/18/2003
10	Final Oral Presentation	4/29/2003	4/29/2003
11	Final Written Report	5/13/2003	5/13/2003

Feb 2003 | Mar 2003 | Apr 2003 | May 2003

2/2 2/9 2/16 2/23 3/2 3/9 3/16 3/23 3/30 4/6 4/13 4/20 4/27 5/4 5/11

Facilities, staff support and space needed

Workspace will be needed to assemble and construct the various components of the payload. Construction of the payload container and installation of the Nitinol actuators should not require any special equipment. Thus, a general laboratory facility such as the Gelb Laboratory should suffice as a workspace. Drop tests will be performed at the US Army Natick Soldier Systems Center, and support staff will be provided by Natick facility to assist in running the trials. The testing facility at Natick was described earlier in the Technical Approach section. Additional equipment that has not been previously mentioned includes a camera to record the progress of the project.

Conclusion

Guided parachute systems are an exciting new application for existing technology that is currently being developed through major research efforts. This proposal outlines an experiment to test a new type of actuator using Nitinol, a shape memory alloy. If it can be shown that shape memory alloys can be effective as actuators for unmanned parachutes, a new generation of lighter and cheaper actuators will become a reality.

Acknowledgements

16.62X Faculty and Staff

Dr. Marthinus van Schoor

List of references

[1] "Summary Report: New World Vistas, Air and Space Power for the 21st Century," USAF Science Advisory Board, 1997. [http://www.fas.org/spp/military/docops/usaf/vistas/vistas.htm. Accessed 11/26/2002.]

[2] "Smart Materials / Motorless Actuators," Midé Technology Corp., Medford, MA, 2000. [http://www.mide.com/expertise/materials.html. Accessed 11/26/2002.]

[3] Hattis, P. D., Fill, T. J., Rubenstein, D. S., Wright, R. P., and Benney, R. J., "An Advanced On-Board Airdrop Planner to Facilitate Precision Payload Delivery," *AIAA Modeling and Simulation Technologies Conference*, Denver, CO, Aug. 14-17, 2000; also AIAA Paper 2000-4307.

[4] Brown, G., Haggard, R., Almassy, R., Benney, R., and Dellicker, S., "The Affordable Guided Airdrop System (AGAS)," *15th CEAS/AIAA Aerodynamic Decelerator Systems Technology Conference*, Toulouse, France, June 8-11 1999, Collection of Technical Papers, American Institute of Aeronautics and Astronautics, 1999, pp. 316-325; also AIAA Paper 99-1742.

[5] Hattis, P. D., Appleby, B. D., Fill, T. J., and Benney, R., "Precision Guided Airdrop System Flight Test Results," *14th AIAA Aerodynamic Decelerator Systems Technology Conference*, San Francisco, CA, June 3-5 1997, Collection of Technical Papers, American Institute of Aeronautics and Astronautics, 1997, pp. 158-168; also AIAA Paper 97-1468.

[6] Thomas, J., "Aerodynamic Model Identification and GNC Design for the Parafoil-Load System ALEX," *16th AIAA Aerodynamic Decelerator Systems Technology Conference*, Boston, MA, May 21-24 2001, Collection of Technical Papers, American Institute of Aeronautics and Astronautics, 2001; also AIAA Paper 2001-2015.

[7] "The History of Nitinol," Images SI Inc., Staten Island, NY. [http://www.imagesco.com/articles/nitinol/02.html. Accessed 10/3/02.]

[8] Anderson, J., "Descent Rate," Washington High Power Rocketry, 2000. [http://www.washingtonhighpower.com/algorithm.htm. Accessed 11/13/02.]

Appendix A: Detailed Parts List

Power Supply and Regulation

2 12-Volt Panasonic LC-R123R4P Motorcycle Batteries
9-Volt Ni-Cd Battery (for Data Acquisition Unit)
LM 7805 5 V Positive Voltage Regulator

Electronic Components and Sensors

Altera MAX 7000S Complex Programmable Logic Device (CPLD)
1.843 MHz Crystal Oscillator
3 Analog Devices ADXL105AQC Single Axis Accelerometers
Analog Devices ADXRS300ABG Angular Rate Sensor
Capacitors, Potentiometers, Resistors, Transistors
Solderless Breadboard

Data Storage Equipment

Eight-Channel Data Acquisition Unit (DAQ)
Flash Memory Card for DAQ
Camera

Data Analysis Equipment

Personal Computer
Laptop Computer with flash memory card reader for quick analysis in the field

Materials

Parachute (Canopy and Rigging Lines: see specifications in Appendix B)
Nitinol Wire
Plywood for payload container
Fasteners and other hardware for payload container
Foam Padding

Manufacturing Facilities

Gelb Laboratory

Development Software

Altera MAX+PLUS® II BASELINE design software

Analysis Software

Microsoft Excel Spreadsheet package
MATLAB Numerical Analysis package

Appendix B: Parachute Specifications

Canopy

Canopy shape: circular
Canopy diameter: 9 ft = 2.74 m
Spill hole diameter: 15 in = 0.38 m
Canopy material: rip-stop nylon

Rigging Lines

Number of rigging or suspension lines: 18
Length of each line: 100 in = 2.54 m
Suspension line material: para-cord

References for Parachute Specifications

Arnott, B., “Rocketry: Useful Stuff: Mil Spec 9’ Chutes,” www.bobarnott.com: Rocketry - The UK's Premier High Power Rocketry Homepage, 2002. [http://www.bobarnott.com/rocketry/stuff/chutes/index.shtml. Accessed 12/10/02.]

“Parachutes,” Federal Army and Navy Surplus, Inc., Seattle, WA, 2002. [http://www.gr8gear.com/?cat=62. Accessed 12/10/02.]

Appendix C: Thermal Model

The following MATLAB file contains the source code for the thermal model from Midé Technology Corp. that was used to determine the power required to resistively heat the Nitinol wires, as well as the number and type of wires.

```
% ACSMART Thermal Model
clear all

Velocity_fluid=1;
freq=0.5;
Npts=100;
T_fluid=20+273;
Number_of_wires=36;

Tmartensite=25+273;  % Martensite final temperature
Taustenite=35+273;   % Austenite final temperature
Tdiff=(Taustenite - Tmartensite)/2;

% Wire Diameter = 1.5, 2.0, 3.0 and 5 (3.81E-05, 5.08E-05, 7.62E-05, 12.7E-05)
Diameter_Wire=12.0E-04;

% Assume conservatively 100 MPa as the maximum allowable stress
Force = Number_of_wires*(pi/4)*Diameter_Wire*Diameter_Wire*100E6;
fprintf('\n\n Number of Wires = %d, Force produced = %5.2f N \n',Number_of_wires,Force)

T_Init_Wire=Tmartensite+10; % Start with wire at martensite temperature

T_film=(T_fluid+T_Init_Wire)/2;
Length_Wire=2.54;
k_wire=1.80E+01;
cp_wire=837;
rho_wire=6450;
rho_air=1.2256;
Area_Wire=(0.25*pi*Diameter_Wire^2);
Vol_Wire=Number_of_wires*(Area_Wire*Length_Wire);
Surface_Area_Wire=Number_of_wires*pi*Diameter_Wire*Length_Wire;

k_air=0.024;
cp_air=1007;

T_lookup=[290.00 328.65    363.15];

% Lookup Tables
Dens_air_lookup=[1.1887 1.0661    0.9624];
Dyn_Vis_air_lookup=[1.817E-05 1.981E-05 2.140E-05];
Spec_Heat_air_lookup=[1006.9 1008.1 1010.3];
Therm_Conduct_air_lookup=[2.583E-02 2.842E-02 3.100E-02];
Therm_Dif_air_lookup=[2.173E-05 2.674E-05 3.211E-05];

rho_air=interp1(T_lookup,Dens_air_lookup,T_fluid);
mhu_air=interp1(T_lookup,Dyn_Vis_air_lookup,T_fluid);
mhu_air_film=interp1(T_lookup,Dyn_Vis_air_lookup,T_film);
k_air=interp1(T_lookup,Therm_Conduct_air_lookup,T_fluid);
k_air_film=interp1(T_lookup,Therm_Conduct_air_lookup,T_film);
cp_air=interp1(T_lookup,Spec_Heat_air_lookup,T_fluid);
cp_air_film=interp1(T_lookup,Spec_Heat_air_lookup,T_film);
a_air_film=interp1(T_lookup,Therm_Dif_air_lookup,T_film);

Rey_lookup=[0.0001   40   41 1000 1001  2E5 (2.E5+1)   1E8];
C_lookup=[    0.75 0.75 0.51 0.51 0.26 0.26    0.076 0.076];
m_lookup=[     0.4  0.4  0.5  0.5  0.6  0.6      0.7   0.7];


Re=rho_air*Velocity_fluid*Diameter_Wire/mhu_air;
Pr=cp_air*mhu_air/k_air;
Prs=cp_air_film*mhu_air_film/k_air_film;
```

```
n=0.37;
if(Pr>=10);n=0.36;end

C = INTERP1(Rey_lookup,C_lookup,Re);
m = INTERP1(Rey_lookup,m_lookup,Re);

NuD=C*(Re^m)*(Pr^n)*(Pr/Prs)^0.25;

% Convection heat transfer coefficient
h_air_film=k_air_film*NuD/Diameter_Wire;

% Thermal diffusivity
alpha_air_film=k_air/(rho_air*cp_air);

% The Biot number
Bi_air_film=h_air_film*(Diameter_Wire/2)/k_wire;

% Now assume that the temperature must be sinusoidally cycled
delt=1/(freq*Npts);
Tmax=10/freq;

Time=[0:delt:Tmax];

[mm,nn]=size(Time);

Tcommand(1) = T_Init_Wire;
T_wire(1)=T_Init_Wire;
Power(1)=0.0;

for i=2:nn
   Tcommand(i)=T_Init_Wire + Tdiff*sin(freq*2*pi*Time(i));
   Tfilm = (T_fluid+T_wire(i-1))/2;

% Calculate convection heat transfer coefficient
k_air_film=interp1(T_lookup,Therm_Conduct_air_lookup,T_film);
cp_air_film=interp1(T_lookup,Spec_Heat_air_lookup,T_film);
mhu_air_film=interp1(T_lookup,Dyn_Vis_air_lookup,T_film);

Prs=cp_air_film*mhu_air_film/k_air_film;

NuD=C*(Re^m)*(Pr^n)*(Pr/Prs)^0.25;

% Convection heat transfer coefficient
h_air_film=k_air_film*NuD/Diameter_Wire;

   dTdt = (Tcommand(i) - Tcommand(i-1))/delt;
%    Power(i)=max(0,h_air_film*Surface_Area_Wire*(T_wire(i-1) - T_fluid) +
rho_wire*cp_wire*Vol_Wire*dTdt);
   Power(i)=max(0,h_air_film*Surface_Area_Wire*(Tcommand(i) - T_fluid) +
rho_wire*cp_wire*Vol_Wire*dTdt);
   if(Tcommand(i) < T_wire(i-1));
      Const = delt*h_air_film*Surface_Area_Wire/(rho_wire*cp_wire*Vol_Wire);
      T_wire(i) = T_wire(i-1) - Const*(T_wire(i-1) - T_fluid);
   else
      if(Power(i) == 0.0)
       Const = delt*h_air_film*Surface_Area_Wire/(rho_wire*cp_wire*Vol_Wire);
       T_wire(i) = T_wire(i-1) - Const*(T_wire(i-1) - T_fluid);
      else
         T_wire(i)=0.5*(Tcommand(i) + T_wire(i-1));
      end
   end
end



Power(1)=Power(2);

tit=sprintf('Flow Velocity=%5.2f m/s, T_a=%5.2f C, N_w=%4.0d, D_w=%5.2f
mils',Velocity_fluid,T_fluid-273,Number_of_wires,Diameter_Wire*1000/.0254);
Velocity_fluid=100;
```

```
freq=100;
Npts=50;
T_fluid=21+273;
Number_of_wires=72;

figure(1)
subplot(211)
plot(Time,T_wire-273,Time,Tcommand-273);xlabel('Time (seconds)');ylabel('T_W & T_C (C)')
title(tit)
subplot(212)
plot(Time,Power);xlabel('Time (seconds)');ylabel('Input Power (W)')
figure(1)
```

Matlab code courtesy of Dr. Marthinus Van Schoor.

Appendix D: Nitinol Properties

Table 4: Properties of Nitinol

Property		Wire Diameter	
		250 µm	375µm
Physical	Minimum Bend Radius [mm] Cross-Sectional Area [mm^2]	12.50 0.049	18.8 0.110
Electrical	Recommended Current [mA] Recommended Power [W/m]	1,000 20.0	2,750 8.00
Strength	Max. Force @ 600 Mpa [N] Rec. Force @ 190 Mpa [N]	28.7 9.11	61.9 19.6
Speed	Max. Contraction Speed [sec] Relaxation Speed (Ambient Air) [sec] Typical Cycle Rate [cycles/min]	0.2 5.5 9	0.5 10.0 5
Thermal / Material	Heat Capacity [cal/g°C] Density[g/cc] Maximum Deformation Ratio [%] Recommended Deformation [%]	0.077 6.45 8 3-5	
		Low Temp	*High Temp*
	Resistivity [mWcm] Young's Modulus [Gpa] Thermal Conductivity [W/cm°C]	76 28 0.08	82 75 0.18

Source: "Shape Memory Alloys," Midé Technology Corp., Medford, MA, 2001. [http://www.mide.com/expertise/matsys/shamemall.html. Accessed 12/10/2002.]