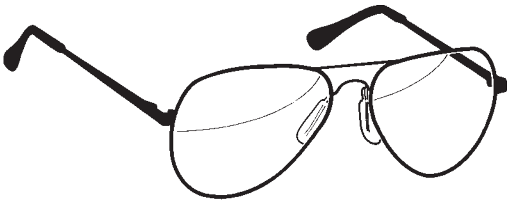
SECTION 3

SHAPE MEMORY ALLOY (OR "SMART WIRE") ACTUATORS

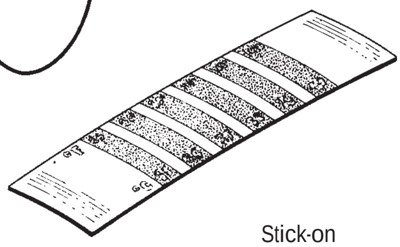
A relatively new type of electromechanical actuator uses shape memory alloy (SMA).

Smart Materials
Most materials that we use in products have properties which remain more or less constant in use. 'Smart' materials are different; they respond to external factors such as differences in light or temperature levels and change in some way. They are described as 'smart' because they seem to be intelligent or have a mind of their own.

Smart materials are now being applied in everyday products. Examples include sunglass lenses (and spectacle lenses) which darken as light intensity increases and stick-on thermometers whose colour changes to indicate temperature. Smart materials are now even used in clothing!

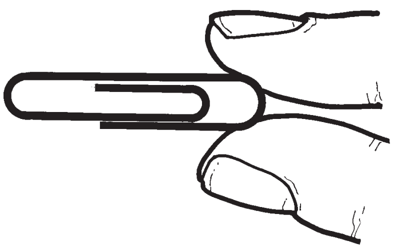


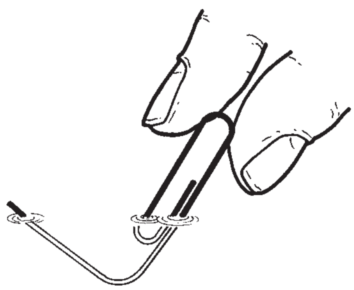
Reactolight glasses



Stick-on thermometer

Shape Memory Alloy (SMA)
SMA is a smart material which, as its name suggests, has a memory. The most common SMA is an alloy (mixture of metals) of nickel and titanium - called **nitinol**. By means of special heat treatment, a piece of SMA can be made to 'remember' a shape. For example, a length of wire can be made to remember that it should be straight at temperatures above 70°C. If you bend this wire at normal room temperature into the shape of a paper clip, it stays bent and will continue acting as a paper clip. However, if you place it in a glass of water whose temperature is above 70°C, it immediately straightens out! When cool, it remains straight until it is bent again.



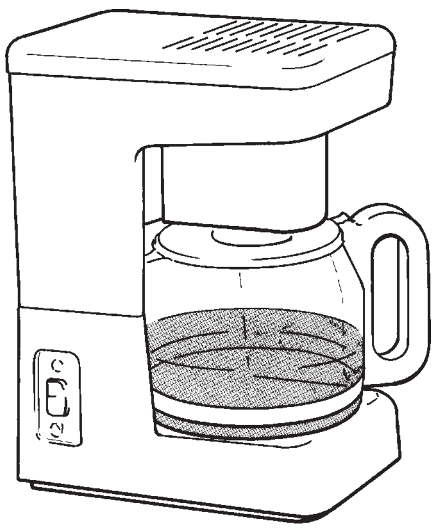


This cycle of bending and then straightening when heated can be continued millions of times. The temperature at which SMA 'remembers' its original form is called the *transition* temperature and when this point is reached, it changes shape.

SMA has a relatively high electrical resistance and can be heated to its transition temperature by passing an electrical current through it.

Applications of SMA
SMA can be used to give a mechanical movement when a set temperature is reached. For example, current applications include:

- seals for hydraulic tubing (which shrink into position)
- electrical connectors
- fire alarm systems - to trigger a sprinkler
- waste bins - to trigger a falling lid if fire occurs
- coffee machines - to open a valve so that hot water falls on the coffee

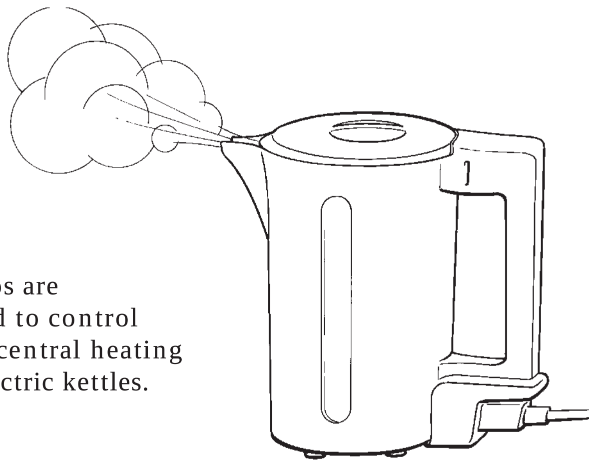


- air conditioning units - to move louvres or flaps to direct air movement
- shower units - to control hot water control valves

The advantage of SMA in these and many other applications is the fact that it provides large forces and movement at a precise temperature. It is also possible to pre-shape the SMA in different ways - for example as a spring or a flat plate.

Smart wire has a relatively high electrical resistance and can be heated to its transition temperature by passing an electrical current through it. Before SMA was available, bi-metallic strips were really the only simple way of causing mechanical movement by change of temperature. A bi-metallic strip consists of two metal ribbons bonded together. One metal has a high rate of expansion when heated; the other has a low rate of expansion. When the strip is heated, it curls because one side expands more rapidly than the other.

Bi-metallic strip

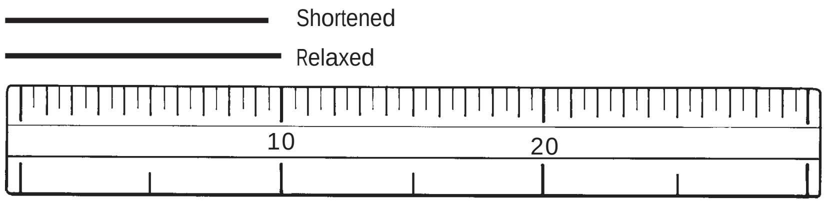


Bi-metallic strips are commonly used to control thermostats in central heating systems and electric kettles.

Unlike SMA, bi-metallic strips change shape gradually when heated - not all at once. Also, in practice, they cannot be made to change shape when current is passed through them.

Smart Wire
A common form of SMA is wire available in different diameters. This ranges, for example, from 5 mm diameter down to 50 microns (1 micron = 1/1000 millimetre). The SMA wire sample provided with this book is Nitol with a diameter of 100 microns. It is heat treated to 'remember' that it has a shorter length when heated above its transition temperature (70°-80°C) than below it.

If the sample length of wire is held between two points it has a length of approximately 10 cm. When heated to between 70° and 80°C, it shortens by about 5% or 1/20 and exerts a useful pulling force. (The wire becomes shorter and it gets slightly fatter.) When the wire cools down, it relaxes to its longer length of 10 cm.

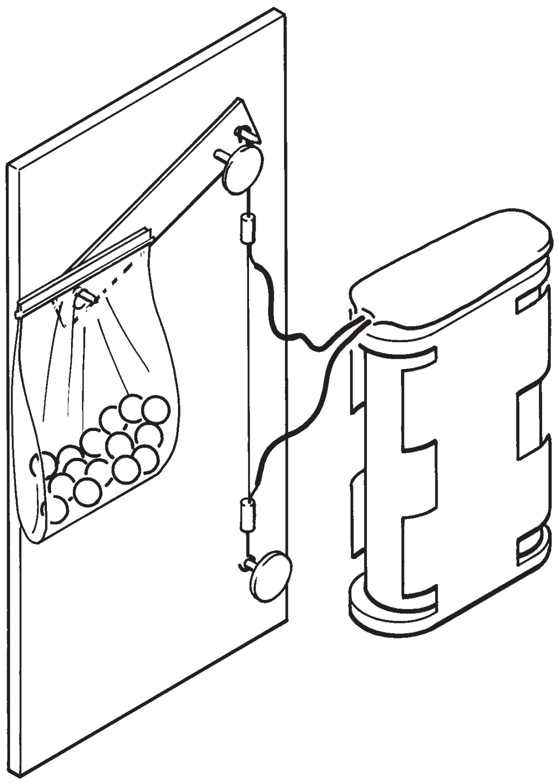


The 5% change in length is constant for any length or diameter of SMA wire. This results in quite small movements for shorter lengths of wire. However, the movement can be increased by increasing the length of wire. To work out the amount of movement for a given piece of wire, you simply multiply its length by 5%.

For example, for a wire 150 mm in length, the shortening is:

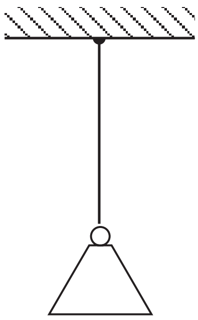
$150/1 \times 1/20 = 150/20 = 7.5$ mm

The 5% shortening of SMA can also be turned into a much larger movement using simple lever systems.

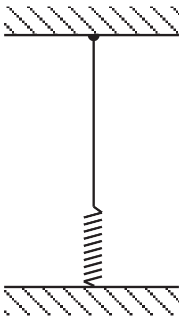


SMA wire has to be stretched or biased to return to its longer length. The force required to do this is much smaller than the pulling force that the wire exerts when it shortens. There are two main ways of biasing:

- Using a weight
- Using a spring

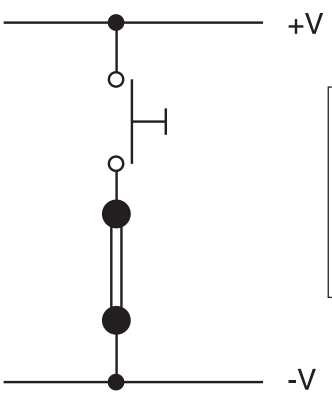


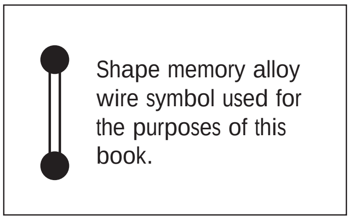
Using a weight



Using a spring

Because SMA has a relatively high electrical resistance, it can be heated to its transition temperature simply by passing current through it. This opens up many possibilities for providing mechanical actuation (movement) without any moving parts other than those the SMA is attached to! Also, for smaller diameter wires, the currents needed are quite small and can be provided from smaller batteries.





Shape memory alloy wire symbol used for the purposes of this book.

In a practical design using SMA wire, you need to know what force to use to bias it, and what force it will exert when it shortens. If you are heating it with electric current, you also need to know how much current to pass without overheating and damaging it.

All these figures (for 100 micron wire) are provided in the table below:

Bias force	0.3 N
Pulling force	1.5 N
Resistance	150 ohms per metre
Max. current	180 milliamps
Max. power	5 Watts per metre
Shortening time	0.1 second
Relaxation time	1.0 second
Recommended extension	5%
Minimum bend radius	5 mm
Effective transition temperature	70°Centigrade
Pulling starts at	68°C.
Pulling finishes at	78°C.
Relaxation starts at	52°C.
Relaxation finishes at	42°C.

Explanation of the Table

The table tells us that at normal room temperature the wire needs to be stretched with a bias force of 0.3 newtons - which is roughly equivalent to hanging a weight of approximately 30 grams on the end. When heated to the transition temperature of between 70° to 80°C, the wire shortens about 5% in length and will exert a pulling force of 1.5 newtons - roughly equivalent to lifting a weight of 150 grams.

The speed at which the wire shortens when it reaches the transition temperature is about 0.1 seconds. It takes longer to relax or stretch back to its longer length - about 1 second. The table also tells us that when heated, the wire actually starts changing length at 68°C and finishes at 78°C. When it cools, however, the stretching or relaxation does not take place until it has reached 52°C.

The figures given in the table are the recommended ones for 100 micron nitol; if they are exceeded, the useful life of the wire will be reduced.

The supply needed to heat the wire can be determined using Ohm's Law. This states the relationship between voltage (V), current (I) and resistance (R), as follows:

$V = I \times R$
$I = V/R$
$R = V/I$

The table gives us the resistance of the wire and also states the maximum current. Using Ohm's Law, we can therefore work out the voltage needed.

For example, what is the voltage needed to pass the maximum safe current through the 10 cm length of 100 micron sample wire provided with this book?

Step 1
The resistance of the wire is 150Ω per metre.
Divide by 100 = 1.5Ω per cm.
The resistance of 10 cm of wire = 1.5Ω × 10 = 15Ω.

Step 2
The maximum current is 180 mA or 0.18 A.
(1 milliamp = 1/1000 Amp.)

Step 3
V = I × R. Substituting the figures above gives:
V = 0.18 A. × 15Ω = 2.7 volts.

A 3 volt battery (two AA cells in series) can be used to power this length of wire because as current is drawn, its voltage will reduce slightly.

To check that the power rating (the rate of doing work) is not exceeded, we can use the power equation W = I × V.

If we substitute the above figures W = 0.18 × 2.7 = 0.49 Watts for a 10 cm length of wire and 10 × 0.49 = 4.9 for a metre length. This is the maximum figure given in the table.

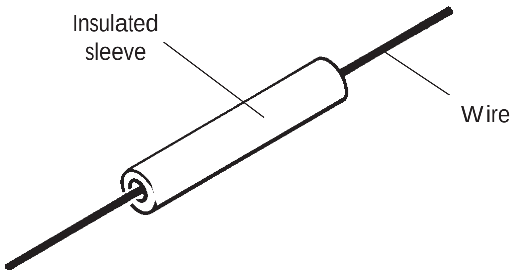
What voltage would be needed to supply a 15 cm length of 100 micron SMA wire?

How many times per minute could a length of 100 micron SMA wire go through a complete shortening and relaxation cycle?

Using SMA Wire

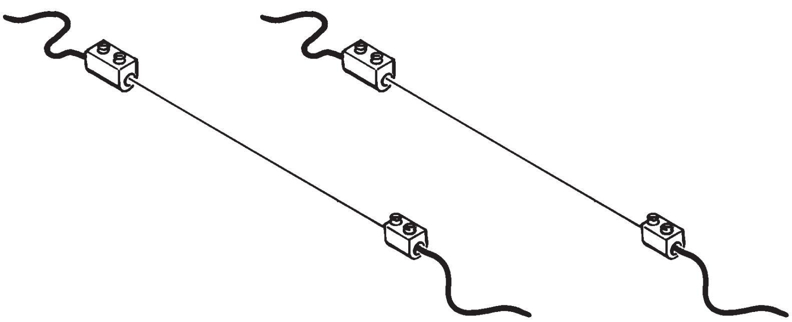
It is important to make good electrical and mechanical connections to the ends of SMA wire. The wire cannot be soldered and must be joined to other conductors by mechanical means. It is also important to remember that where the wire is in contact with a metal component or surface, some heat will be conducted away and that the whole length of wire may not exhibit the memory effect.

The response times given in the table are for SMA in a normal room environment. If the wire is enclosed in an insulated sleeve, for example, it will take longer to cool down and relax to its longer length. If air is blown over it, it will cool more rapidly.



Increasing Pulling Force

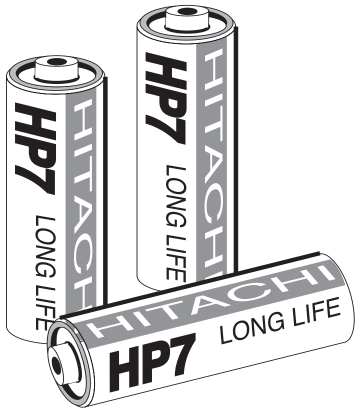
The pulling force of SMA wire cannot be increased by supplying current beyond the recommended limit; this will damage it. However, two or more wires can be run in parallel. Two wires will give double the pulling force and so on. You must remember, though, that if the wires are connected in parallel, you also double the current needed to heat them up.



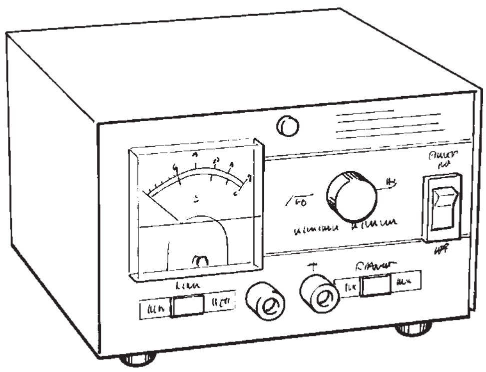
Power Supplies

Current supplied to the SMA wire must be within the recommended limit to avoid any damage. There are several ways of doing this including:

- use of an appropriate number of 1.5 V batteries connected in series.

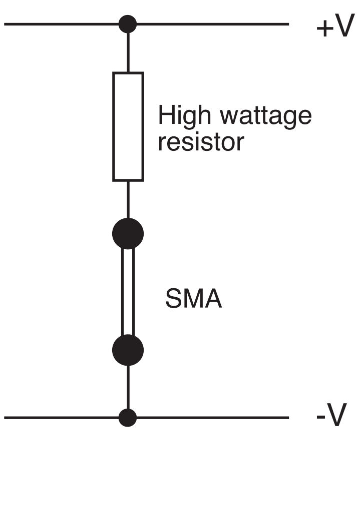


- use of an adjustable power supply unit (PSU).

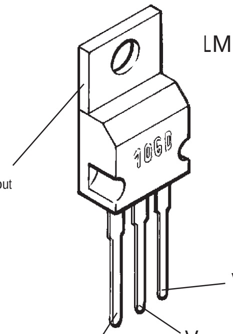


- use of a series resistor to regulate the supply. It may not be possible to 'fine tune' a number of batteries accurately enough or you may have an unsuitable supply. In either case, current can be regulated by using a series resistor in the circuit. Ohm’s law can be used to work out the value of this resistor.

  [Note: the resistor should be a higher wattage type. The power in the circuit can be worked out using W (watts) = I (current) × V (volts). If a variable resistor is used, it should be a wire-wound higher wattage type.]



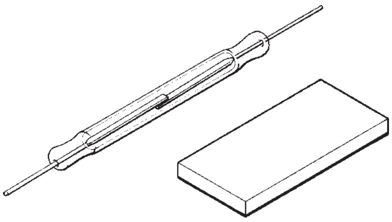
• use of a voltage regulator



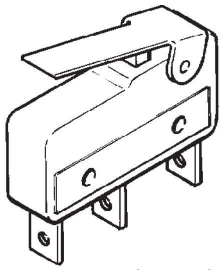
Control Circuits

1. Open loop control

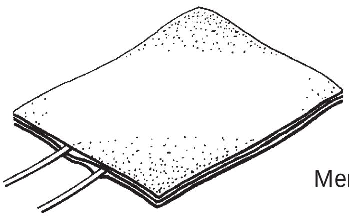
In open loop control, there is no feedback. The supply is simply switched on or off - for example, using a press switch or a timer circuit. Switches that can be used include: reed switches operated by a magnet, micro switches, membrane panels.



Reed switch and magnet

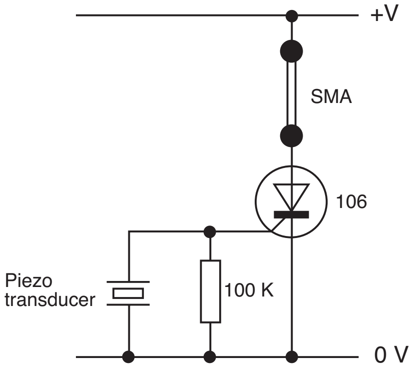


Micro switch

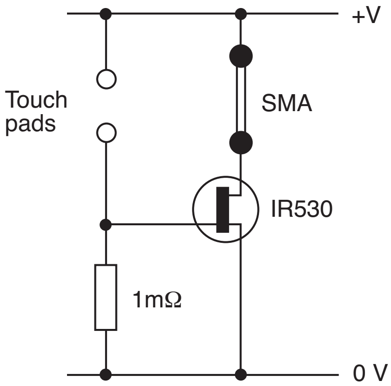


Membrane panel

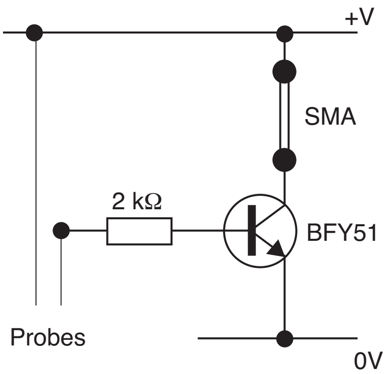
Supply current can be 'switched' by a thyristor, bipolar transistor or FET (field effect transistor). The example circuits show how sensors can control the supply switching.



Thyristor triggered by shock

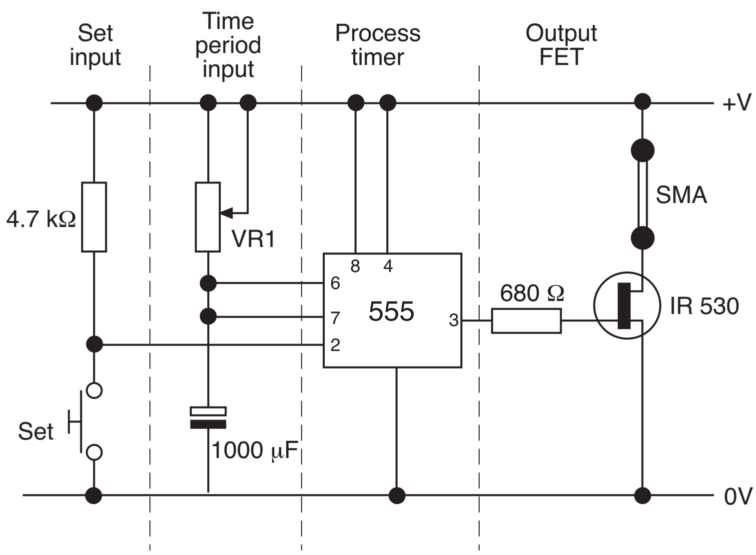


FET switched on by placing finger across touch pads

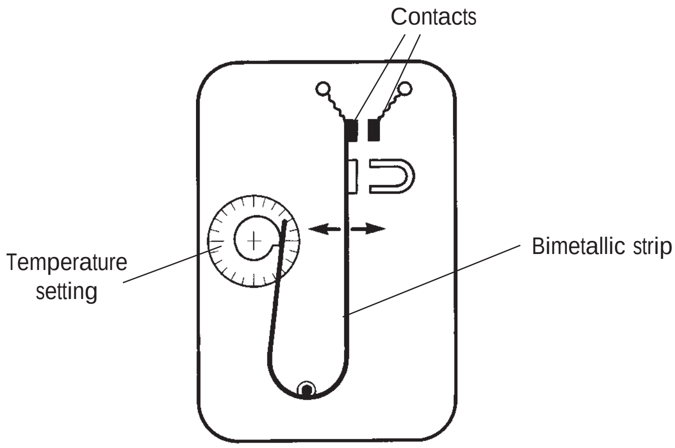


Transistor switched on by water bridging across probes

Bipolar transistors and FETs can also be used as the output stage of microelectronic control circuits - e.g. a 555 timer.

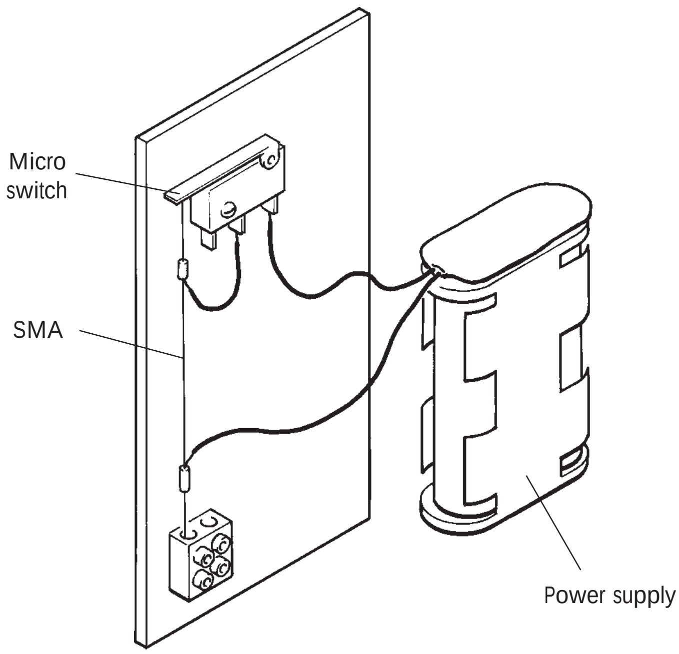


2. Closed loop control
Closed loop control involves something feeding back (feedback) from the output to the input of a system. A central heating system turns on and off at a temperature set by a thermostat. A bi-metallic strip in the thermostat heats up and moves to switch off the heating boiler when an appropriate temperature has been reached.



Thermostat

Because SMA wire changes length when it is heated, the movement can be used as feedback - for example, to switch the supply on and off. A very simple example involves connecting a length of SMA to a microswitch. When the wire is relaxed the switch is 'on' and current flows through the wire. The wire then shortens, depresses the switch contact and turns off the supply. The wire then relaxes and the whole cycle begins again.

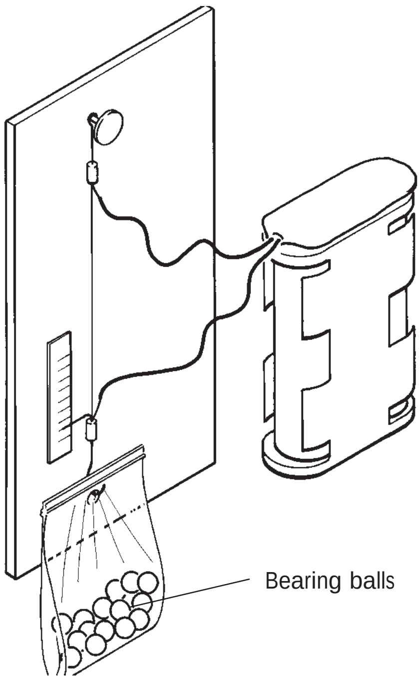


[Note: Ingenious heat engines have been built from SMA materials using a closed loop system. In one example, a wire relaxes and dips into hot water. This causes it to change shape and move out of the water to cool down and relax again. The same cycle repeats over and over again and turns a small flywheel.]

Experiments With SMA Wire

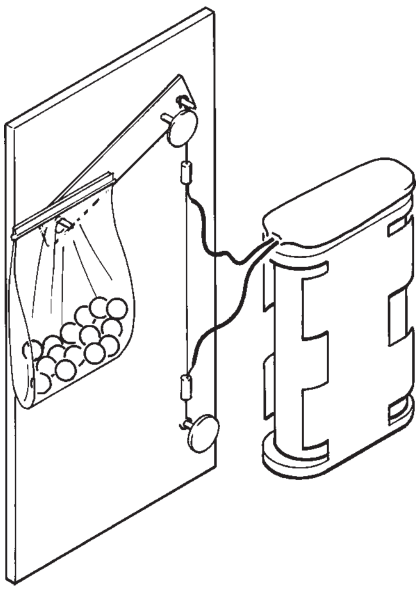
- Lifting weights

This experiment simply involves attaching a length of SMA wire to a weight (e.g. ball bearings in a bag) and observing the contraction when the wire is heated by current. The bias force is automatically supplied by the weight.

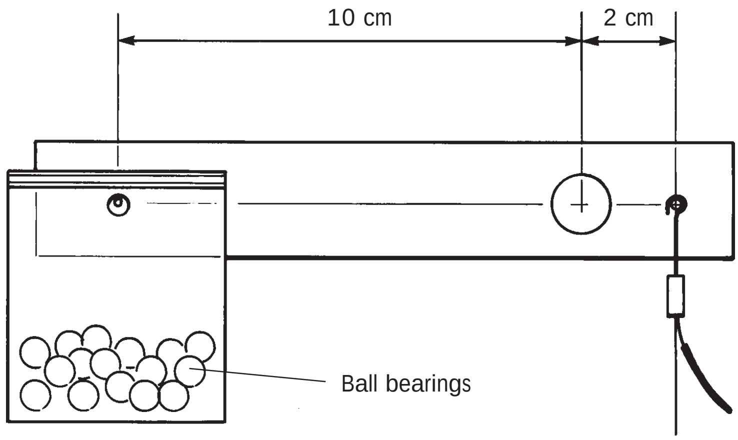


- Amplifying movement with levers

A simple two dimensional lever system can be assembled on a baseboard using polystyrene or card strip for the lever and a drawing pin pivot. The 'load' on the lever can be supplied by weights or a spring (e.g. elastic band).

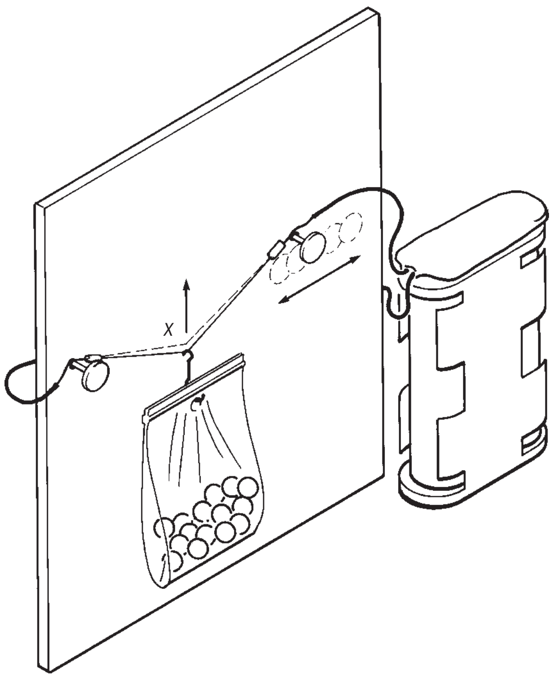


The distances from the pivot to (a) the wire attachment and (b) the weights can be expressed as a ratio. In the example shown the ratio is 5:1. For every millimetre moved by the wire end the weighted end will move through 5 millimetres.



- Amplifying movement using geometry

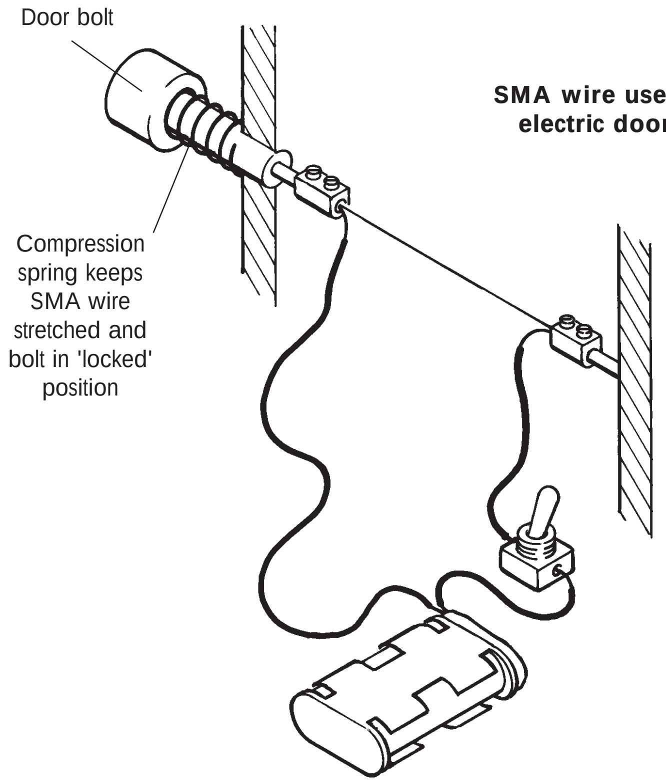
A weight is attached to the centre of a length of SMA wire so that it forms two sides of an inverted triangle. Over a range of angles the vertical movement of the weight will be greater than the linear movement of the wire. This effect increases as the angle at *x* increases (i.e. as the wire becomes closer to horizontal). However, the forces required also increase. Try experimenting with SMA wire at an angle at x of 140° and plot the movements of the weight on a piece of paper.



Practical Applications of SMA Wire

Linear actuation

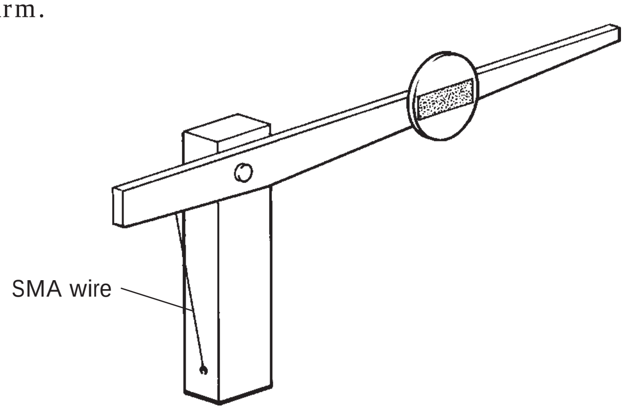
SMA wire is most easily used to provide linear or straight line movement. The example shown uses SMA wire to pull a bolt in a simple lock. In this application very little linear movement is needed. If its length can be accommodated, SMA wire can often be used in place of a more expensive solenoid. A free-standing actuator can be made by containing the wire in a plastic tube.



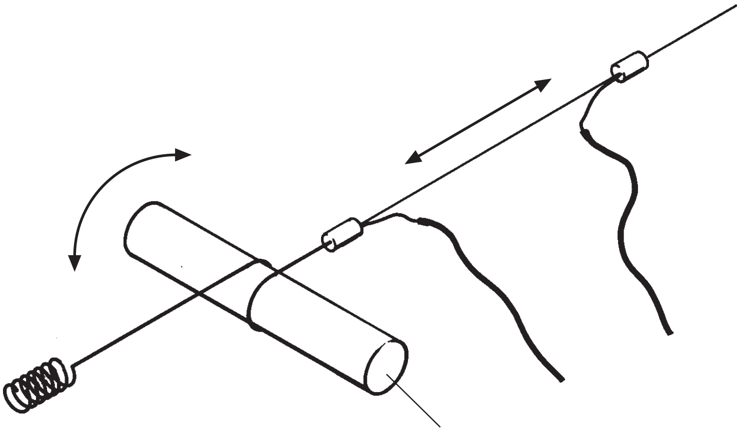
SMA wire used in an electric door lock

• **Angular actuation**

In many practical applications of SMA wire, a mechanical system is used to amplify movement. The barrier prototype model illustrated uses the lever principle to move and lift up the arm. The same principle can be used to provide the movements of a robot arm.

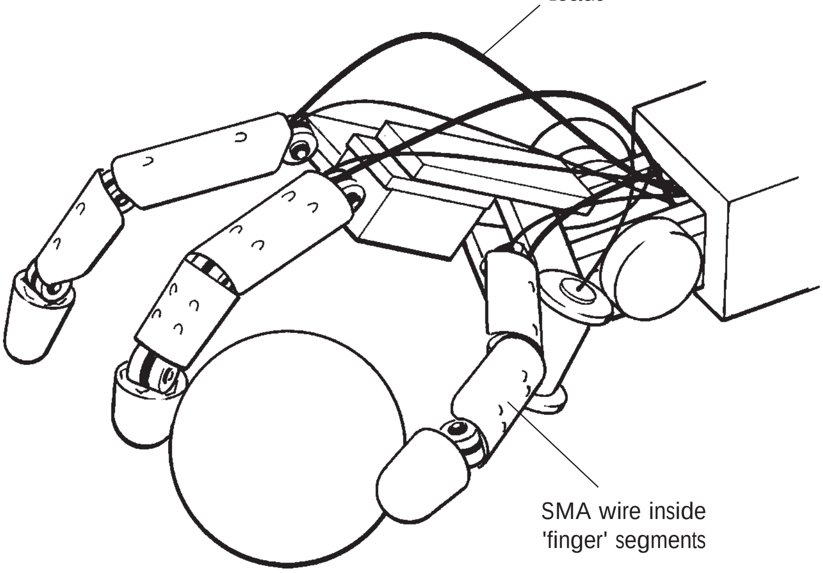


Rotary actuation
SMA wire (or a cord extension from it) can be wound around a shaft, drum, pulley, or cam to produce rotary movement. For a given length of wire, the larger the diameter of the shaft etc., the smaller the rotation - and vice versa. If the shaft etc., is very small and expected to rotate through several revolutions, particular attention has to be given to biasing - either with a weight or a spring.

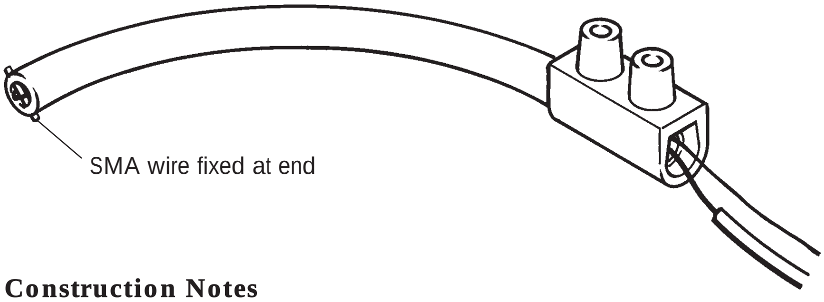


Anthropomorphic actuation
'Anthropomorphic' describes something which has human characteristics. A lot of robotics research is currently directed at making robotic movements - especially hand movements - imitate human ones. This is because of their potential as artificial arms and limbs for disabled people and as precision manipulators for industrial robots. Many of these experimental devices use SMA wire to provide mechanical movement.

It is surprisingly easy to make an actuator that imitates - say - a finger movement. One method is to stretch the SMA wire inside a 'springy' plastic tube. This will cause the tube to curl slightly. When the SMA wire is heated by current, it exerts a stronger pulling force inside the tube and this causes it to curl around even further - closing the 'finger'. When the wire relaxes, the 'finger' opens again.



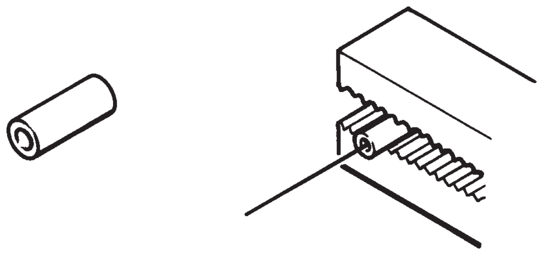
In many commercial prototype hands the robotic fingers are made up from hinged segments with small springs to keep them straight. When SMA wire running through the segments contracts, the 'finger' curls just like the tube.



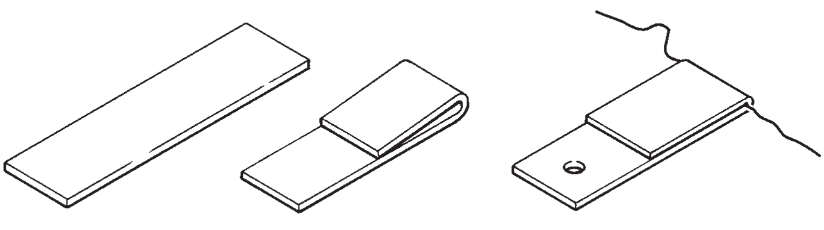
Construction Notes
The most difficult aspect of using small diameter SMA wire is holding it securely and making good electrical contact. These are some of the methods employed:

• **Wire Crimps**. These are small fastenings pressed flat around wires to be joined; they are available commercially in many different shapes and sizes. The most useful ones for SMA wire are miniature tubes which are closed with special crimping pliers or ordinary pliers. The crimps can be placed at the very end of an SMA wire or somewhere along its length.

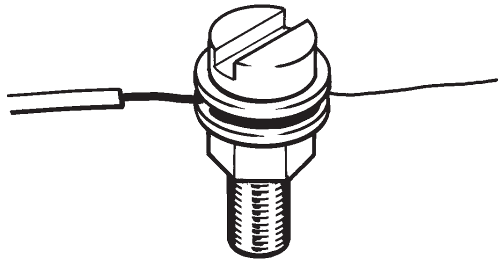
Note: The most common miniature crimps available are 'bootlace' types - a small tube but with one end closed. These will work for all the applications shown in this book.



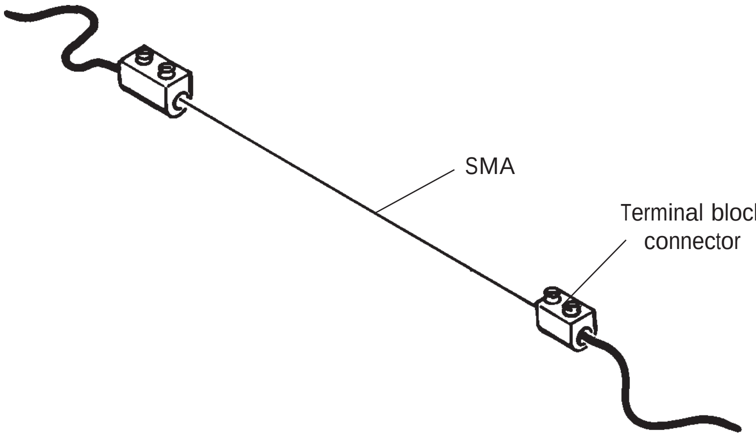
• **Edge and corner crimping**. This is a technique for making wire crimps on the corner or edge of a metal tab - e.g. copper. An edge or corner is folded over using a pair of pliers. Because the metal at the bend hardens as it deforms it does not close over completely and leaves a small opening. The wires can be inserted in this opening which is then finally closed by ‘nipping’ with the pliers. One or more holes punched in the tab can be used to fasten it.



• **Screw, nut and washers**. SMA wire and connecting wire can be fastened to a small screw using two washers and a nut. The free end of the screw can also be used to provide a mechanical anchorage to something else.



• **Terminal block**. Commercial terminal blocks contain twin-screw brass fastenings in a polythene strip. Individual fastenings can be removed from the plastic strip as necessary. Note: It is an advantage to attach a crimp to the SMA wire before securing it in the terminal block.



Further Reading

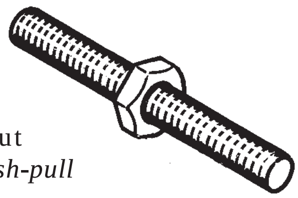
Bowyer, M.J. Design and Applications of Ni-Ti Shape Memory Alloy Springs, **Engineering Design**, November 1988.

Gilbertson, R.G. **Muscle Wires**, Mondo-tronics, 1992.

Cave, J.F. (Ed.) **TEP Electronics 14-16**, The Engineering Council, 1994

SECTION 4

LINEAR ACTUATORS



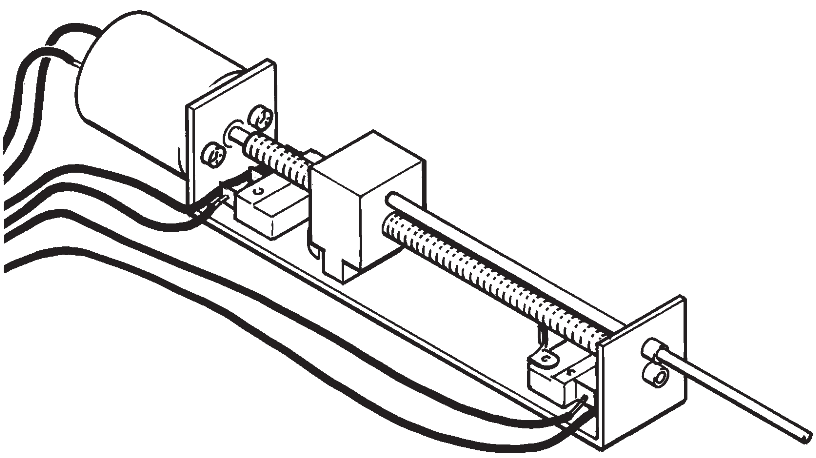
A *linear actuator* is a motorised unit which often resembles a hydraulic or pneumatic cylinder. It contains a motor, gearbox and a means of converting the rotary output from the gearbox into a powerful *push-pull* linear movement. This movement is normally obtained by a *nut* moving along a rotating screw thread - the same means used to move the carriage on a manual lathe.

Most larger commercial linear actuators use a *ball screw*. This works on the same principle as a basic nut and screw but the nut is separated from the screw by ball bearings to minimise friction.

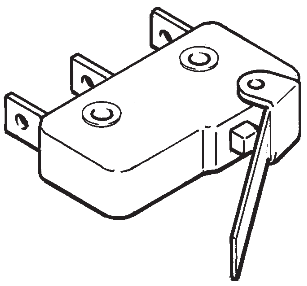
Linear actuators are normally used to provide *intermittent* rather than continuous push-pull movements. They are self-contained units, and very easy to build into systems such as window opening mechanisms. However, because the motor is totally enclosed, they have a limited *duty cycle*. This means that they can be energised for only a certain percentage of the time. For example, an actuator with a duty cycle of 50% means that it should only be running for only - say - 2 minutes within a 4 minute period. Manufacturers state the precise duty cycle conditions in their literature.

TEP linear actuator

The TEP linear actuator is an *open-frame* type that comes almost completely assembled. It uses a 5mm diameter screw driven directly by a miniature DC motor. The screw engages a brass nut set into a plastic block which also accommodates a push rod. The end of the screw is supported in a nylon bearing at one end of the frame and above this an identical bearing providing support for the push rod.



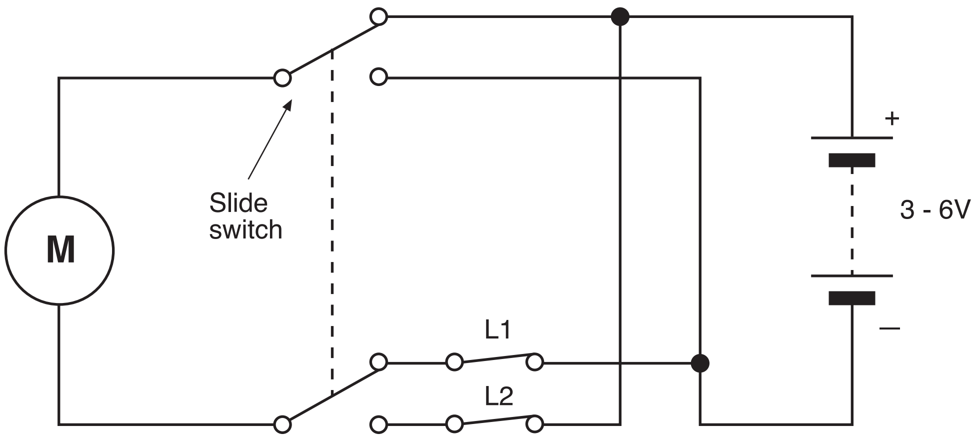
If the motor is connected to a 3v - 6v battery supply, the nut will run rapidly to one end of the frame. Reversing the motor supply will cause it to run in the opposite direction. If you do this simple experiment, however, you will find that at the end of its travel, the nut will lock onto the screw and simply reversing the motor will not be enough to free it. To prevent the nut reaching the extremity of the thread and to provide proper control, it is necessary to add two *limit switches* to the frame. These switch off the motor when the nut is almost at the end of its travel. They also enable manual or automatic reversing of the nut.



Setting up the limit switches
The actuator is supplied with two limit switches and small self-tapping screws for fixing. Two leads should be soldered to each switch as shown, and the switches fastened to the frame. **The lever of each switch should be bent outwards so that the supply is switched off well before the end of the nut's travel.** This needs to be done because the motor continues to spin after the supply is switched off, and the nut travelling beyond its limit will jam.

As a guide, use only a 3 volt supply either to trial the actuator or run it with a light load. With a heavier load, you can use a 4.5v - 6v supply.

For manual operation of the actuator, the limit switches are connected to a DPDT (double pole, double throw) switch as shown. When the slide switch, provided with the actuator, is in the centre position, it is 'off'. In either of the other two positions it supplies current to the motor until one of the limit switches breaks the circuit. The slide switch can then be thrown to the other 'on' position to reverse the nut. Manual switching might be used, for example, to cause the actuator to throw a lock bolt.



L1 and L2 are the limit switches. Use connections marked 'con' and 'NC"

The actuator can be controlled electronically by using an appropriate circuit and a DPDT relay (or two SPST relays). For example, a "Bit by bit" controller can be programmed to switch a pair of SPST relays on and off.

There are many variations on the control theme. For example, a sensor might be used so that the actuator opens:

- a vent when a set temperature is reached
- a vent above a set light level
- a valve when water (or moisture) falls below a fixed level