FIGS. 3 and 4 for the typical tactile element 18, one end 29 of actuator wire 28 is threaded through three small openings 30, 32 and 34 in the distal end of the cantilever. The opposite end 36 of the wire is raised above the plane of the cantilevers and is attached to an anchor block 38. The anchor block is secured above the top surface of base plate 14 and extends along the proximal ends of the cantilevers. As shown in FIG. 1, a second anchor block 40 is provided on the opposite side of touch plate 12 for securing the actuator wires which are connected to and operate the array of cantilevers on that side of the base plate. A tube 42 is secured as by swaging onto the proximal end of each actuator wire for securing the wire to the anchor block. The swage tubes 42 also provide electrical connections to the control circuit 44, which is shown schematically in FIG. 5. The control circuit pulses current through selected actuator wires under influence of the program control system. Current is separately controlled through each actuator wire, through the BeCu base to which the distal end of the TiNi wire is attached.

When current is supplied through a selected wire by the power circuit, the I^2R heating effect causes the wire's temperature to rise. When the wire temperature is heated through or exceeds the phase change transition temperature of the particular shape-memory alloy material, then the wire contracts to its memory shape. As used herein, the term "heated through the phase change transition temperature" includes both the case of heating the wire to within the relatively narrow range of temperature in which phase change occurs and the case of heating above that temperature. Contraction of the wire applies a moment force to the distal end of the cantilever beam, which is forced to bend upwardly through the angle θ to the position shown in FIG. 4. When current is stopped, the actuator wire is cooled by ambient air to below its transition temperature. The spring force of the cantilever is then sufficient to elongate the wire back to its original length. This allows the cantilever to return to its original unextended position, as shown in FIG. 3.

In operation, the cantilever is brought to the "up" position of FIG. 4 by a pulse of current. The speed with which actuation occurs depends upon the power delivered to the wire and on the rate at which heat is conducted away from the wire. When current density is high, heating is rapid with a low rate of heat dissipation to the surrounding medium, which typically is air. For longer actuation times, a larger fraction of electrical power input is lost, and consequently actuation time is a non-linear function of input power.

For actuation times less than 0.1 second, the energy balance is dominated by Joule heating as follows:

$$E=I^2Rt$$

where

I=current in amperes

R=resistance of the SMA wire in ohms

t=time in seconds

The current I is determined by a constant-current supply, and can range from 0.2 amperes up to 1.0 amperes or more. Resistance R is from 1 to 3 ohms for actuator wires which are typically 0.0075 cm (0.003 inches) in diameter and 1.5 cm long. (Resistivity of the shape-memory alloy is about 80 micro-ohm cm.) A typical actuator weighs 0.0004 grams. Actuation energy E is about 50 watt-sec per gram. From these values the predicted actuation time for a current of 0.5 amp is 0.027 sec. Actual measured time is about 0.035 sec, which is in substantial agreement with theory.

If current in the range of 0.2 to 0.5 amperes is held on continuously, the wire will overheat and be damaged. It has been determined experimentally that a current of 0.2 amperes is sufficient to maintain contraction of a 3-mil shape-memory alloy wire in still air. In the method of the preferred embodiment, the average current is reduced by pulse-width modulation of the signal to prevent damage to the shape-memory wire. Pulse-width will normally have a duty cycle of approximately 50% by controlling current on for approximately the same fraction of time it is off. Therefore the average current to hold the actuator on is approximately one-half the current required to bring it to the "up" position. The frequency of pulse-width modulation is approximately 20 hertz in the preferred embodiment.

Relative strengths of the cantilever and wire are selected such that the strength of the shape-memory alloy element is sufficient to deform the cantilever when the SMA wire is in its austenitic high-temperature state, but is elongated by the cantilever when the SMA wire is in its martensite (room temperature) state. Thus the position of the cantilever is dependent on whether the shape-memory alloy wire is heated or not.

FIG. 5 illustrates the control circuit 44 which provides constant current supply for each of the actuator wires. The control circuit is comprised of a plurality of identical driver circuits. In the drawing one of the driver circuits is shown and is comprised of the components encompassed by the dashed line 46. A separate driver circuit is provided to independently supply current to each SMA actuator wire. Thus, in FIG. 5 the illustrated driver circuit 46 is connected through terminal 48 with an end of one actuator wire 28, the other end of which is connected through line 49 with a switch 50 which is coupled with the +5 V power supply. The remaining actuator wires 28' are connected in parallel with the line 49 leading to switch 50, and the remaining driver circuits (not shown for purposes of clarity) are connected with their respective actuator wires through the remaining terminals 48'. Switch 50 is operated either manually or by other suitable means to provide on/off power to all driver circuits.

Circuit 44 includes an IC control chip 52, preferably of the type sold under the designation Sprague UCN5818, which provides a latching circuit function. Digital control information from a suitable computer microprocessor, not shown, is directed into chip 52 through a serial bit input line 54 and a strobe line 56. A plurality of output control lines 58, 58', 58" etc. lead from chip 52 and each of these output lines is connected into an associated driver circuit for controlling a respective one of the actuator wires. Thus, the output line 58 connects into the illustrated driver circuit 46 for controlling the actuator wire 28, while the output line 58' connects through its associated driver circuit (not shown) for controlling actuator 28'.

Operating under influence of the controls through input line 54 and strobe line 56, the latch circuits within chip 52 set the respective output lines 58 either at five volts (high) representing the latch ON state or at 0 volts (low) representing the latch OFF state. In each driver circuit 46, when the voltage at resistor 60 becomes high, then current is turned on through field effect transistor 62. The current flow is from the +5 V power supply through switch 50, line 49, actuator wire 28, transistor