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Polymer sensorised microgrippers using SMA actuation

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***Abstract*— In this paper a polymer sensorised microgripping tool for micromanipulation is presented. The gripper structure is made by moulding of polyurethane in silicon moulds by the technique of Shape Deposition Manufacturing (SDM), in which the force sensing elements and part of the actuator (in this case, microstrain gauges and SMA (Shape Memory Alloy) wire, respectively) are embedded into the micrgripper in one process step. The actuation principle for the microgripper is an SMA wire. The advantages of the fabrication process are low cost and manufacture cycle time. This paper details the technique for fabrication of the microgripper to produce prototypes. These prototypes were then tested and characterised in terms of force output, hysteresis and repeatability. A further miniaturised unsensorised microgripper based on the same actuation principle and fabrication process (but less than half the size) was fabricated to demonstrate the possibility of further downscaling.**

Keywords: Micromanipulation, Microgripper, SMA, force sensor

1. INTRODUCTION

Nowadays the issues of microassembly and micromanipulation are assuming an ever-growing importance in many fields [1,2]. In areas such as microrobotics there are examples of applications of more and more complex microrobots, devised to accomplish demanding assembly tasks [3]. One can think of the increasing level of miniaturization occurring in many sectors (microelectronics, micromechanics, micro-optics and many others), and of the advantages of miniaturization in terms of savings in building material, space and power. To fulfil the needs of micromanipulation and microrobotics, many research efforts are being devoted to the design and fabrication of microtools and microgrippers, often equipped with position and force sensors, able to perform difficult and precise manipulation tasks, with high levels of accuracy and reliability [4,5].

To realise microgripper devices, two of the most important components of the system are the gripper actuator and the gripper geometry, and several works already detail the various technologies in the state of the art [6,7] and several on unsensorised SMA actuated grippers [8,9]. While the range of microgrippers is quite broad, there exist few microgrippers which are both sensorised and can be produced at very low cost in large numbers and it is for this reason that this work was completed. In the subsequent sections it will be detailed how the SDM process was used to mould sensorised disposable microgrippers which have an operating span of approximately one millimetre, have a high force output and have a high force sensitivity. Fig. 1 shows a design of the gripper with strain gauges indicated.

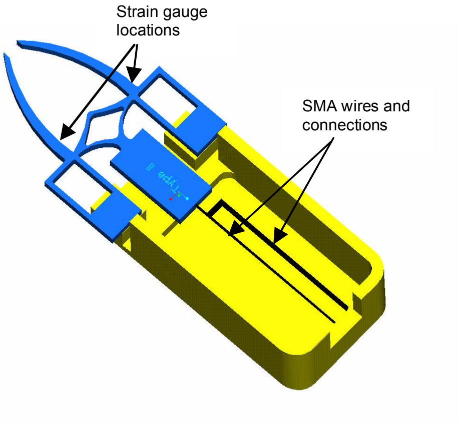

Fig. 1 Drawing of gripper with strain gauges

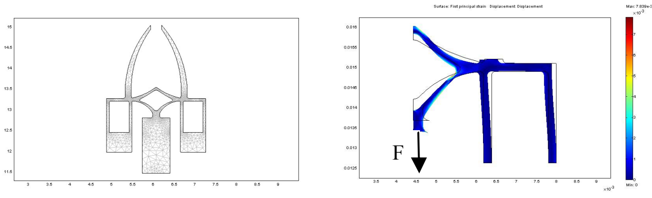

Fig. 2 FEA of microgripper mechanical structure

The SMA actuation principle was based on a simple SMA wire applying a tensile force through the centre of the symmetrical gripper structure, thus causing the gripper tips to move inward. The microgrippers' mechanical structure was optimised so that the maximum force and deflection produced by the SMA wire (Flexinol, 50 micron diameter, 35g max pull) would yield a complete closure of the microgripper tips. This was done by measuring the mechanical properties of the polyurethane (Sintafoam, IT) used and then using FEA software (FEMLAB 3.0, Comsol Inc.) to simulate loading situations. Fig. 2 shows a typical simulation done with the microgripper when a theoretical SMA actuated load was applied-the surface plot is a 2D first

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principal strain plot of the part of the gripper structure which is strained when the SMA wire is actuated.

2. MICROGRIPPERS: DESIGN AND FABRICATION

The SDM process has been implemented and detailed in many previous works with success [7,10]. It was necessary to use this technology so that we could integrate force sensors into the microgripper. The process began by using the 5 axis CNC machine (KERN HSPC) to machine out the shape of the microgripper structure from machineable wax (Freeman Mfg, USA) to give the form in Fig.3a. Moulding silicone (Prochima, IT) was then poured into this part and cured over 24 hours to give the silicone mould in Fig. 3b


Fig. 3a Fig. 3b

Fig. 3(a) Gripper shape in machineable wax Fig. 3(b) Silicone mould

After this step the strain microgauges (VISHAY, EA06015CK120, gauge area 380 x 500 micrometres) were prepared for insertion into the mould. Constantin element gauges were used instead of semiconductor because the available semiconductor gauges were too big to put in the mould-the constantin gauges did not have this problem. In order to have the wires from the strain gauges embedded in the polymer structure, they needed to be very thin, of diameter 50 micrometers. The ends of two of these insulated wires were prepared and then soldered to the strain gauge under microscope. It should be noted at this point that the strain gauge had all excess film material around the gauge cut off under microscope to significantly reduce the size of the strain gauge, thereby further miniaturising the whole microgripper (as shown in Fig. 4).

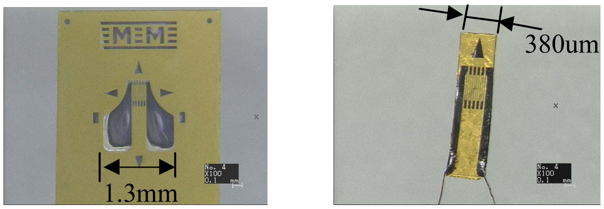

Fig. 4 Micro strain gauge ,before and after trimming

The next step was to place the strain microgauges with attached wires into the open silicone mould in Fig.3b and fitted into place in slots made specifically to fix the strain gauges. A miniscule drop of oil was placed on the outer surface of each of the strain gauges so that it would adhere to the inside surface of the mould and so that when the polymer was poured into the mould, it would not flow around and onto the top surface of the gauge. This situation is not favourable as the strain gauge must be lying flush on the surface of the gripper arms to maximise the strain on the gauge. A further embedding step was to take the SMA wire and insert one end into a slot in the microgripper mould, so that when the polymer was cured, the SMA wire would be mechanically bonded to the microgripper structure-this eliminates the need for post-moulding operations to attach the SMA wire by hand, a tedious and delicate operation. The electrical connections of the SMA wire prepared beforehand by using the conductive paste to attach very light and flexible copper wires to both ends of the SMA wire-these were cured in the oven at 60 degrees Celsius for 15 minutes and the electrical resistances checked to ensure a good electrical bond.

A commercially available polyurethane with a curing time of 20 minutes (Sintafoam, IT) was used in the moulding process, a process similar to previous works [10]. This was poured into the mould by simply using a fine needle to place drops of liquid polymer into specific channels, after which capillary forces would draw the polymer into all parts of the mould. It was important to do this in less than one minute as, after mixing of the two components of this polymer, the polymer viscosity increases exponentially and after one minute the flow of polymer in the channels is negligible. Once the gripper was moulded with the strain microgauges, the next step was to attach this moulded gripper to the actuator housing- it was decided to mould the grippers' strain gauge wires into the actuator housing so that none of the fragile wires would be exposed. Fig. 5 shows the silicone actuator housing mould, along with the mould for making the cover for the actuator housing. The actuator frame mould was filled with polymer and cured as before, and once this was complete, the last step was to bond the microgripper structure to the actuator frame structure by means of a commercially available two part epoxy.

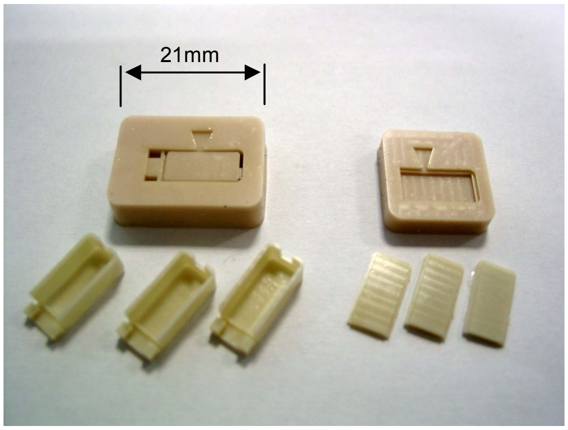

Fig. 5 Silicone mould for SMA actuator housing (left) and housing cover (right)

Now that the most of the physical parts of the microgripper were assembled, it was necessary to finish the electrical connections. Ten wires were embedded in the actuator frame (8 strain gauge wires + 2 SMA actuator wires). These protrude from the back of the actuator frame and for the prototype (and for mechanical reliability), these were soldered to a large block of ten colour coded wires on a ribbon cable. The area between the back of the actuator and the ribbon cable was embedded in a transparent epoxy so that for testing the connections would be robust. The final step in the fabrication process is to attach the covering cap of the actuator housing-the contact edges of this cap are lined with a small amount of epoxy so that once the cap is attached, the cap is sealed and mechanically secure (for the testing of the prototype, this cap was removed). Fig. 6 shows the final fabricated microgippers in the unsensorised form (for fabrication tests), while Fig. 7 shows the sensorised microgripper. Note that in Fig. 6 there is a silicone membrane on the actuator housing which seals and protects the actuator, useful in fluid environments. Although this seal has not been tested, it will be in future work. The fine wires for the strain gauges can be seen protruding from the back of the actuator housing in the left image in Fig. 7. This was taken before they were soldered and mechanically secured as described previously.

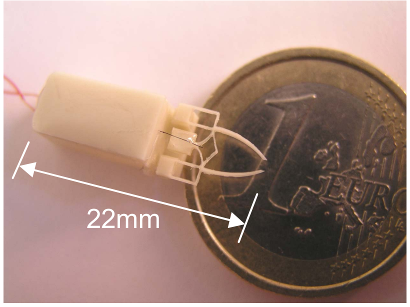

Fig. 6 Unsensorised microgripper with protective silicon membrane

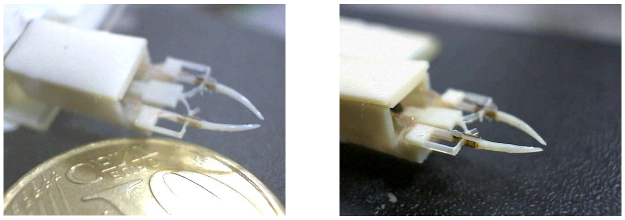

Fig. 7 Sensorised microgripper (left, with 10 Euro cent coin)

As an added part of this work, a further miniaturised SMA actuated gripper shown in Fig. 8 was designed and fabricated using the same techniques. This resulted in a microgripper which is less than half the size of the original prototype, has a tip span of one millimeter and requires a lower operating voltage, to name a few advantages. Unfortunately it is difficult to find a kind of force sensor for a microgripper of this size, as the smallest commercially available strain gauges are too big (their gauge length is nearly half the length of the microgripper arm). Because of this, this smaller gripper has only been tested to demonstrated the successful displacement of the tips and was fabricated mainly to prove that the gripper could in fact be miniaturised-sensorisation of this microgripper is a future challenge.

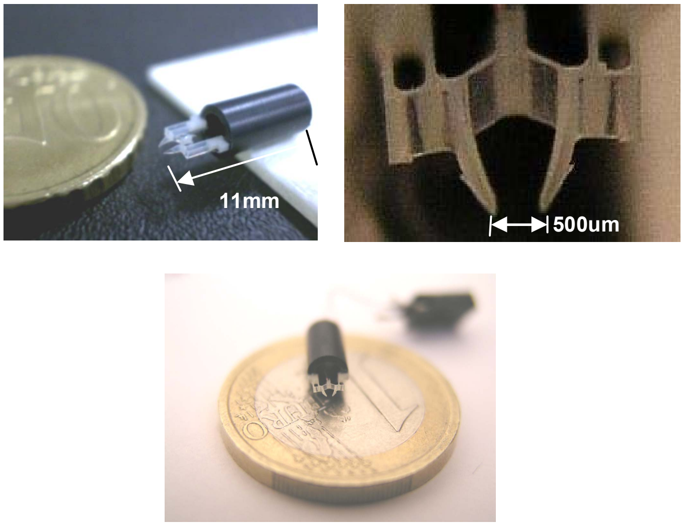

Fig. 8 Further miniaturised SMA actuated microgripper

Following the fabrication of the sensorised microgripper, the electronic circuitry for SMA actuator control and strain gauge output signal processing were designed and implemented.

3. ELECTRONIC DESIGN

The strain gauges from the upper and lower surfaces of the gripper arms (Fig. 8) were connected in a full-bridge configuration. The choice of an optimum bridge excitation voltage presented a problem because the gauges are embedded in a material which is characterized by low thermal conductivity. The supplier of the gauges (Vishay Intertechnology, Inc.) recommended a maximum power of only 0.33mW when operated in a similar environment. The limited power and low resistance of the strain gauges (120Ohm) effectively limited the bridge excitation voltages to only 0.3V to 0.4V, which was not acceptable for sensitive measurements.

We have therefore developed a fully USB-powered microprocessor system that creates a pulsed excitation, synchronous measurement, excitation of the SMA-wire

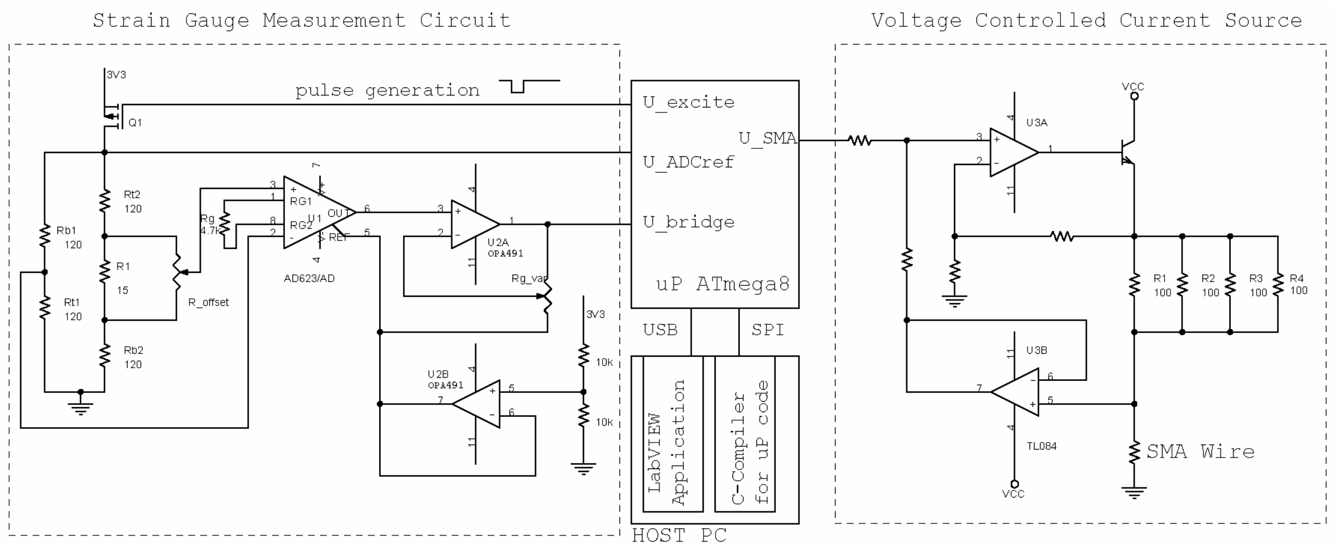

Fig. 9 Simplified schematic of the microprocessor controlled gripper measurement and actuation system. The schematic is greatly simplified. An application on the host PC communicates strain gauge output allows manual adjustment of the SMA current. The system can be easily reprogrammed by an on-board programmer, attached to an SPI interface.

actuated gripper, and communication with a LabVIEW™ (National Instruments) program running on a host PC (Fig. 9, left). A trade-off between achievable sampling rate and bridge excitation level was found by computer simulations of i) dynamic responses of the amplification stage, and ii), the temperature development on the strain gage over time. The short duration of the pulse required a short settling time, suggesting a design of a lower band-width instrumentation amplifier stage with low gain, followed by an operation amplifier with high bandwidth and low offset voltage. The total gain was variable. The 10-bit analog-to-digital conversion was performed inside the processor (ATmega8L, Atmel Corporation) at a rate of 200Hz, and the bridge excitation voltage was used as a reference voltage for AD conversion. The resolution of force was found sufficient for the system to provide set-points for a possible closed-loop force control of the SMA-actuated microgripper (see Discussion). Various control strategies could be feasibly implemented by programming simple arithmetic functions (Fig. 9, middle).

The force of the SMA-wire is a function of temperature, which is proportional to the current through the wire, requiring its accurate adjustment. The voltage controlled current source on the right hand side of Fig. 9 is based on imposing a voltage of up to 2.5V on a resistor network (digital-to-analog converter for the sake of clarity assumed within the microprocessor block). The relatively low control voltage together with the parallel connection of the resistors R1 to R4 greatly reduces the temperature-dependent changes in resistance and allows stable and accurate control of absolute current levels.

4. TESTING AND CHARACTERISATION

It was necessary to test the performance of the microgripper by making the following tests:

1. Testing of strain gauge force sensor outputs
2. Microgripper tip displacement vs Current tests

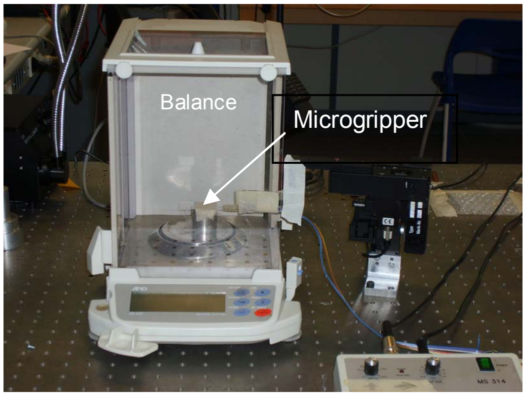

Fig. 10 Micromanipulator and precision balance

4.1 FORCE SENSOR OUTPUTS

Mechanical Setup

A precision balance (AND GR-200, 100μg, repeatability, 200 μg linearity) was used as the independent force sensing element. An aluminium cylinder with a thin small slide (200 micrometers) bonded on top was placed on the precision balance in a setup that can be seen in Fig. 10. The sensorised microgripper was then mounted on a 3 axis micromanipulator of resolution one micrometer (Marzhauser ,DC motor) . This was used to displace the tips of the gripper and press the tip onto the glass slide, transferring the tip force to the weighing scale which can be read out. Furthermore, the repeatability of the force sensor output was investigated by periodically applying a force on the gripper tips. This was achieved by alternating between ascending and descending movement orientation of the micromanipulator's end-effector, after 30 steps with a step-size of 3 micrometers each. To further refine the testing process, the serial output of the weighing scale was used in conjunction with a LabVIEW™ application (National Instruments) to enable the sampling of a large amount of force data for post processing.

Instrumentation

For simplicity only one gripper arm was tested in a half-bridge configuration. The output of the amplification stage (total gain 1267) was connected to an external data acquisition card (NI-DAQ 6062E, 500kSamples/s, 12 bit resolution, National Instruments) and voltage triggered recordings were performed at 500kSample/s. In addition, the bridge excitation voltage was recorded to compensate for its drift. The additional instrumentation was utilized in order to verify the output levels as well as the shape of the conditioned waveform. That way a visual comparison between the settled voltage level as obtained by the data acquisition system and the levels measured by the microprocessor could be performed. In addition, the force that a micromanipulator applied on one arm of the gripper was at the same time recorded by a serial data stream from the balance.

Results

A linear relation between applied force and voltage was found, with a sensitivity of about 90mV/V/mN (Fig. 11). A full bridge configuration would thus lead to twice the sensitivity, about 180mV/V/mN. This is only about 40% less than the sensitivity reported in a related work on super elastic alloys equipped with silicon-based strain gauges, using the same gain [12]. Those strain gauges have about 10 times higher resolution, but a great dependence on temperature [11]. The normalized data for a few cycles is illustrated in Fig. 12. The maximum force applied to the gripper tips was 10 mN.

4.2 TIP DISPLACEMENT CHARACTERISATION

To characterise the displacement of the gripper with actuator current , the tips of the microgripper were viewed under an optical microscope (Hirox, Japan) while the current of the microgripper was controlled by the developed electronics described previously. The current was varied in cycles between 0 and 75mA, to enable full closure of the gripper tips. The distance between the tips was measured graphically between parallel lines that were set by a cursor using the microscope graphical interface. This pixel-counting based method enables accuracies of distance measurements in the micrometer range. A microscopic image with the history of gripper displacement for a closing cycle is illustrated in Fig. 13.

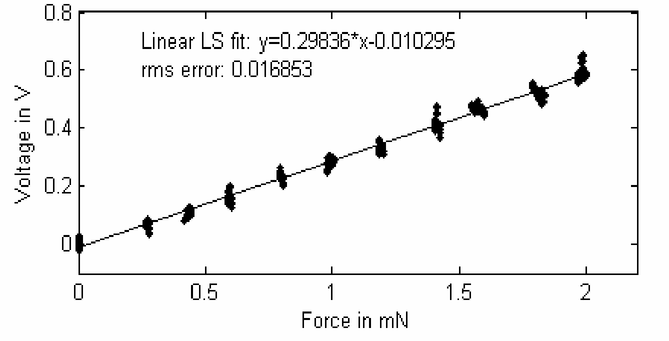

Fig. 11 Measured output voltage samples of the half-bridge vs. force in steps of 0.2mN for a period of several seconds.

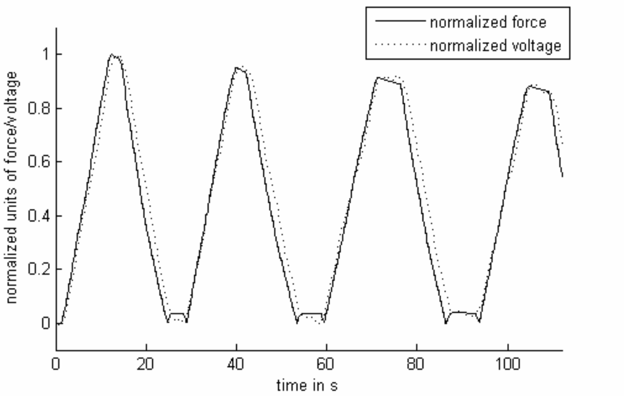

Fig. 12 Repeatability of normalized voltage vs. normalized force, for a periodically applied force by the manipulator.

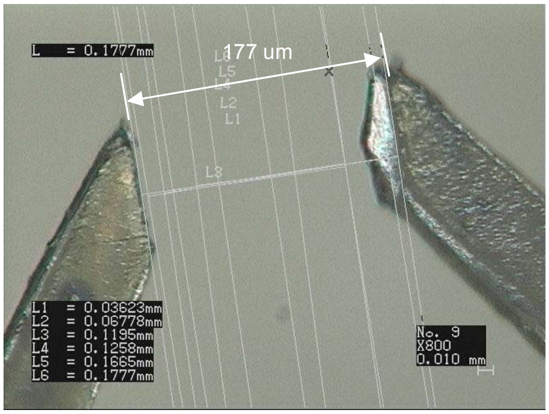

Fig. 13 Image-based measurement of gripper tip displacement vs. current (tip displacement of 177µm in image)

Results

The quantified relation between current and gripper displacement is shown in Fig. 14. A few cycles of opening and closing show a great hysteresis, but a good repeatability of the steep relation between current and tip displacement (about 10 µm/mA), especially for a closing movement, when the current is increased from zero to maximum. The greatest variation of tip displacement for equal currents was about 17um (Fig. 14).

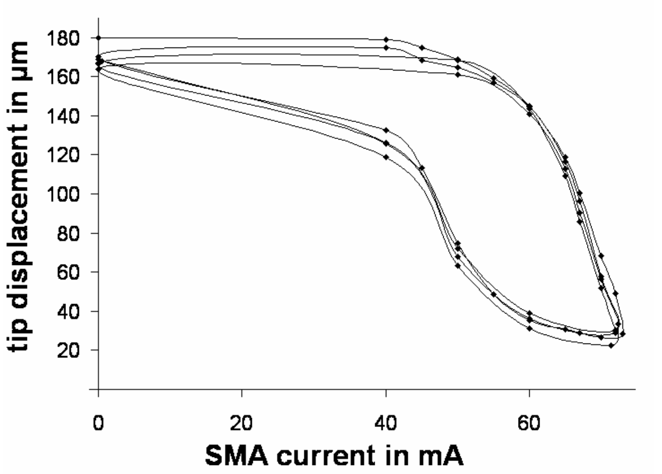

Fig. 14 Gripper tip displacement vs SMA current for four cycles.

CONCLUSIONS AND FUTURE WORK

In this paper the design and fabrication process for a force sensorised polymer microgripper with SMA actuation was detailed. The prototype was then tested and characterised, and these results were presented. A further miniaturised SMA microgripper was produced using the same kind of design and fabrication techniques-this microgripper is half the size of the prototype, however is not force sensorised. This is only due to the limitations of the smallest strain gauges that could be obtained, as the smallest strain gauges available on the market to the authors knowledge are too big for embedding in the further miniaturised gripper. A future plan is to find some other kind of strain/force sensors of very small dimensions which can be embedded into the smaller microgripper-however at this time it is difficult to find such a sensor.

Despite the limited sensitivity of the chosen resistive strain gauge sensors, acceptable accuracy of the overall system could be obtained. This is likely due to the fact that the polyurethane based gripper tips have a high modulus of elasticity, which results into greater strain for the same amount of applied force at the microgripper tip. Another advantage of constantan resistive strain gauges are their excellent linearity, and their low temperature coefficient. In the present design, the bridge excitation current-induced temperature was also minimized by choosing a pulsatile excitation with extremely low duty cycle (in the order of 0.1 percent).

One limitation of the SMA actuation is certainly the considerable hysteresis, for which more advanced control schemes, for instance adaptive controllers as described in [13], might have to be devised. A variety of adaptive control schemes could be implemented in our microprocessor system, provided that certain limits in terms of sampling rate were met. In this work only static loading tests were performed, however the next tests will be to characterise the frequency response of the microgripper, as SMA actuators normally have a low operating frequency.

Regarding the fabrication process, a future task is to develop a setup to crimp the electrical connections to the SMA wire in a reliable and robust way. While there exists crimping kits for connecting wires to SMA on the millimeters range, this is not satisfactory for the connection of very light wires to SMA wires of length 10mm or less. This crimping must allow the light wires (approx. 50 micrometers diameter, Cu, insulated) to be connected without occupying an excessive amount of space, as is the case with the millimeter sized crimps.

Other actuation principles are at present being tested using the same microprocessor system, among them linear stepper motor drives. Some problems like limited torque generation, vibration of gears and limited step size are factors that we are currently addressing in our laboratory and which will hopefully lead to sensorised polymer grippers with exchangeable actuation, depending on the manipulation task being performed.

REFERENCES

[1] R. Hollis and J. Gowdy, “Miniature Factories for Precision Assembly”, *International Workshop on Microfactories*, 1998, pp. 9 - 14

[2] I. Verettas, R. Clavel, A. Codourey, “Microfactory: desktop cleanrooms for the production of Microsystems”, *Proceedings of the IEEE International Symposium on Assembly and Task Planning*, 10-11 July 2003, pp.18 – 23

[3] H. Woern, J. Seyfried, S. Fahlbusch, A. Buerkle, F. Schmoeckel, “Flexible microrobots for micro assembly tasks”, *Proceedings of 2000 International Symposium on Micromechatronics and Human Science, 2000 (MHS 2000)*, 22-25 Oct. 2000, pp. 135 – 143

[4] A. Menciassi, G. Scalari, A. Eisinberg, C. Anticoli, P. Francabandiera, "An instrumented probe for mechanical characterization of soft tissues", *Biomedical Microdevices*, vol. 3, no.2, 2001, pp. 149-156

[5] A. Eisinberg, A. Menciassi, S. Micera, D. Campolo, M.C. Carrozza, P. Dario, "PI force control of a microgripper for assembling biomedical devices”, Circuits, Devices and Systems, Volume 148, Issue 6, Dec. 2001 Page(s):348 - 352

[6] A. Eisinberg, K. Houston, I. Izzo, A. Menciassi, P. Dario, R. Gustaffson, U. Simu, S. Johannson, “Design and fabrication of PZT-actuated tools for micromanipulation”, *Journal of Micromechatronics*, Volume 3, Numbers 3-4, 2006, pp. 329-357(29)

[7] M. Binnard, M.R. Cutkosky, “A Design by Composition Approach for Layered Manufacturing”, *ASME Transactions, J. Mech. Design*, vol. 122, no. 1, March 2000, pp. 91-101

[8] A. P. Lee, D. C. Ciarlo, P. A. Krulevitch, S. Lehew, J. Trevino, M. A. Northrup, “A practical microgripper by fine alignment eutectic bonding and SMA actuation”, *Sensors and Actuators*, A 54, 1996, 755-759

[9] M. Kohl, B. Krevet, E. Just, „SMA microgripper system“, Sensors and Actuators A 97-98, 2002, 646-652

[10] A. Eisinberg, I. Izzo, A. Menciassi, K. Houston, P. Valdastri, P. Dario, R. Gustafsson., U. Simu, S. Johansson , “Design and shape deposition manufacturing (SDM) fabrication of a PZT-actuated tool for micromanipulation”, Computational Intelligence in Robotics and Automation, 2005. CIRA 2005. Proceedings. 2005 IEEE International Symposium on, 27-30 June 2005 Page(s):111 - 116

[11] A. Menciassi, A. Eisinberg , M. C. Carrozza, P. Dario, "Force sensing microinstrument for measuring tissue properties and pulse in microsurgery", *IEEE/ASME Transactions on Mechatronics*, vol. 8, March 2003, pp. 10 -17

[12] U. Tietze, Ch. Schenk, *Halbleiter-Schaltungstechnik*. New York: Springer-Verlag, 1991, ch. 21.

[13] T. Xiaobo, J. S. Baras, “Adaptive identification and control of hysteresis in smart materials”, *IEEE Transactions on Automatic Control”,* vol. 50 , June 2005, pp827-839