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Shape memory alloys and its applications: reviews

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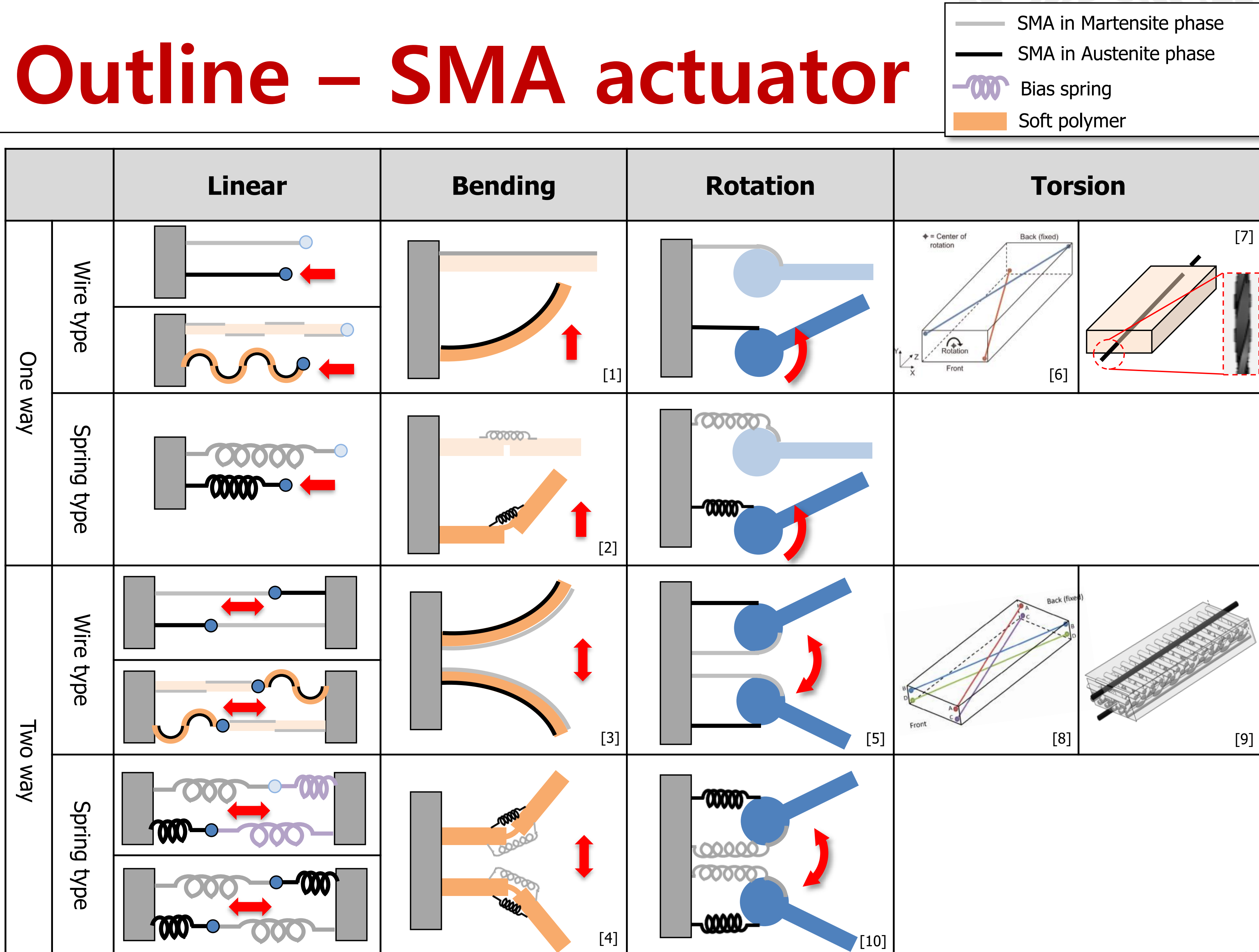
Outline

Paper review - Shape memory alloy

1. **Critical review of current trends in shape memory alloy actuators for intelligent robots**

2. **TiNi-based thin films in MEMS applications: a review**

Outline – SMA actuator



Outline – SMA actuator

[1] A. Villanueva, K. Joshi, J. Blottman, and S. Priya, 2010, "A bio-inspired shape memory alloy composite (BISMAC) actuator," Smart Materials and Structures, vol. 19, p. 025013.

[2] J.-S. Koh and K.-J. Cho, 2009, "Omegabot: Biomimetic inchworm robot using SMA coil actuator and smart composite microstructures (SCM)," in Robotics and Biomimetics (ROBIO), IEEE International Conference on, 2009, pp. 1154-1159.

[3] Wang, Z., Wang, Y., Li, J., and Hang, G., 2009, "A micro biomimetic manta ray robot fish actuated by SMA," 2009 IEEE International Conference on Robotics and Biomimetics (ROBIO), pp. 1809-1813.

[4] J.-S. Koh and K.-J. Cho, 2013, "Omega-shaped inchworm-inspired crawling robot with large-index-and-pitch (LIP) SMA spring actuators," Mechatronics, IEEE/ASME Transactions on, vol. 18, pp. 419-429.

[5] K. Kuribayashi, 1991, "Improvement of the response of an SMA actuator using a temperature sensor," The International Journal of Robotics Research, vol. 10, pp. 13-20.

[6] Rodrigue, H., Wang, W., Bhandari, B., Han, M.W. and Ahn, S.H., 2014, "Cross-Shaped Twisting Structure using SMA-Based Smart Soft Composite," International Journal of Precision Engineering and Manufacturing-Green Technology, The Korean Society for Precision Engineering (Korea), in co-publication with Springer Verlag GmbH, Vol. 1, No. 2, pp. 153-156 (SCI(E), ISSN: 2288-6206, DOI 10.1007/s40684-014-0020-5).

[7] Shim, J.E., Quan, Y.J., Wang, W., Rodrigue, H., Song, S.H. and Ahn, S.H., 2015 "Development of a twisting actuator using a single SMA wire".

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[9] Kim, H.J., Song, S.H. and Ahn, S.H.*, 2013, "A Turtle-like Swimming Robot using a Smart Soft Composite (SSC) Structure," Smart Materials and Structures, IOP Publishing, Vol. 22, 014007, January (SCI, IF 2.089, DOI: 10.1088/0964-1726/22/1/014007, ISSN 1552-3098.

[10] Han, M.W. and Ahn, S.H., 2017, "Blooming Knit Flowers: Loop-linked Soft Morphing Structures for Soft Robotics," Advanced Materials, Wiley-VCH (Germany), Vol. 29, No. 13, 1606580

[11] Wang, W., Li, C.Z., Rodrigue, H., Yuan, F.P., Han, M.W., Cho, M.H. and Ahn, S.H., 2017, "Kirigami/Origami-based Soft Deployable Reflector for Optical Beam Steering," Advanced Functional Materials, Volume 27, Issue 7, No.: 1604214, February 17, 2017

[12] M. Bergamasco, F. Salsedo, and P. Dario, 1989, "A linear SMA motor as direct-drive robotic actuator," in Robotics and Automation, 1989. Proceedings., 1989 IEEE International Conference on, pp. 618-623.

SMA Paper review

1. M. Sreekumar, T. Nagarajan and M. Singaperumal, Critical review of current trends in shape memory alloy actuators for intelligent robots, *Industrial Robot: An International Journal*, Vol. 34, No. 4, 2007 , 285–294

   - Review of current application areas of shape memory alloy (SMA) actuators in intelligent robotic systems.
   - Design/methodology/approach

2. Yongqing Fua, Hejun Dua, Weimin Huanga, Sam Zhang, Min Hua, TiNi-based thin films in MEMS applications: a review, *Sensors and Actuators A* 112, 2004,395–408

   - Review of critical issues and problems in the development of TiNi thin film
   - Introducing different types of TiNi thin film based micro devices

Other references

[1] Simaan, N., Taylor, R. and Flint, P. (2004), "A dexterous system for laryngeal surgery (multi-backbone bending snake-like slaves for teleoperated dexterous surgical tool manipulation)", *Proceedings of the 2004 IEEE International Conference on Robotics & Automation, New Orleans, LA,* April, pp. 351-7.

[2] Mineta, T., Mitsui, T., Watanabe, Y., Kobayashi, S., Haga, Y. and Esashi, M. (2001), "Batch fabricated flat meandering shape memory alloy actuator for active catheter", *Journal of Sensors and Actuators A*, Vol. 88, pp. 112-20.

[3] Kim, B., Lee, S., Park, J.H. and Park, J.O. (2005a), "Design and fabrication of a locomotive mechanism for capsule-type endoscopes using shape memory alloys (SMAs)", *IEEE/ASME Transactions on Mechatronics*, Vol. 10 No. 1, pp. 77-86.

[4] Kohl, M., Krevet, B. and Just, E. (2002), "SMA microgripper system", *Journal of Sensors and Actuators A*, Vol. 97/98, pp. 646-52.

[5] Shinjo, N. and Swain, G.W. (2004), "Use of a shape memory alloy for the design of an oscillatory propulsion system", *IEEE Journal of Oceanic Engineering*, Vol. 29 No. 3, pp. 750-5.

[6] Hikiji, R. and Hashimoto, R (2000), "Hand-shaped force interface for human-cooperative mobile robot", *Proceedings of the First International Workshop on Haptic Human-Computer Interaction*, Vol. 2058, pp. 76-87.

[7] Hino, T. and Maeno, T. (2004), "Development of a miniature robot finger with a variable stiffness mechanism using shape memory alloy", *Proceedings of International Symposium on Robotics and Automation, Mexico.*

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[10] Yao, Q., Jin, S. and Ma, P.N. (2004), "The micro trolley based on SMA and its control system", *Journal of Intelligent and Robotic Systems*, Vol. 39, pp. 199-208.

[11] E. Hawkesa, B. Anb, N. M. Benbernoub, H. Tanakaa, S. Kimc, E. D. Demaineb, D. Rusb, and R. J. Wooda, Programmable matter by folding, *Proceedings of the National Academy of Sciences USA*, June, 2010

SHAPE MEMORY ALLOY FOR ROBOTIC APPLICATIONS

REVIEW 1 : CRITICAL REVIEW OF CURRENT TRENDS IN SHAPE MEMORY ALLOY ACTUATORS FOR INTELLIGENT ROBOTS

Robotic applications of shape memory alloys

- **Advantages of shape memory alloys in robotic applications**
  - One-way and two-way shape memory effect
  - Pseudoelasticity
  - High damping capacity
  - Good chemical resistance
  - Biocompatibility

- **Important factors of SMAs to be considered in robotic applications**
  - Shape (wire/spring/strip/diaphragm) of the actuator
  - Force required for deforming the actuator
  - Heating and cooling technique adopted
  - Sensors incorporated to measure the position, temperature, force and resistance
  - Type of control scheme implemented.

Issues

- **Issues to be covered**
  - Number of actuators
  - Degree of freedom (DOF)
  - Overall size of the robot
  - Mechatronic devices integrated
    - For obtaining fast actuation response
  - Type of heating and cooling strategies
    - For improving the time response, positioning accuracy, frequency
  - Software and hardware components used
- **Application areas of SMA actuated robotic devices**
  - Minimal invasive surgery (최소침습수술)
  - Colonoscopy (대장경검사)
  - Micro-actuators and grippers
  - Underwater robots
  - Artificial limbs
  - Self-reconfigurable robots
  - Autonomous/walking/in-pipe robots
  - Parallel manipulators.

Minimally invasive surgery (MIS)

- **Minimally invasive surgery (MIS) (or keyhole) operations are performed using specialized instruments like catheters and endoscopes**
  - To simplify the procedures for minimum patient trauma with localized surgical intervention
  - Robots are used to amplify the surgeon's capabilities in the form of complex instruments

- **Major problem associated with keyhole surgery**
  - Reduced degree of freedom (DOF) for manipulation compared to open surgery
  - the lacks of surgeon's direct feeling of the operation

  - Most of the existing instruments have 2-3 DOF only
  - More agile instruments with 4 or more DOF have been proposed and actuated by SMA

A dexterous system for laryngeal surgery

- **A dexterous system for laryngeal surgery**
  - An SMA actuated and tele-operated 35 DOF snake robot prototype
  - For MIS (minimally invasive surgery) of throat
  - 28mm long, 4.2mm diameter
  - ±90° bending in any direction

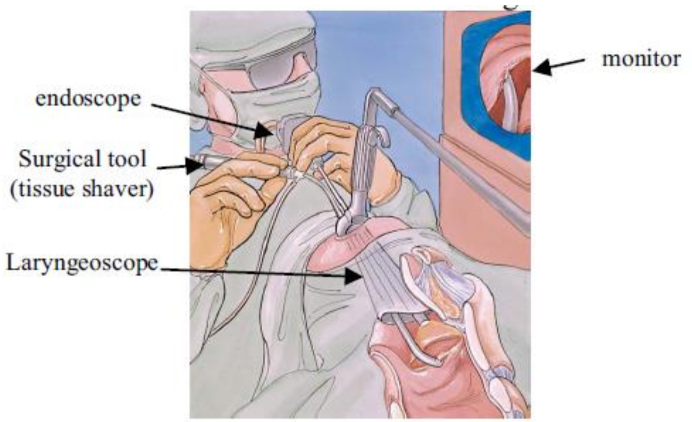


Fig. 1 A typical surgical setup of minimally invasive laryngeal surgery.

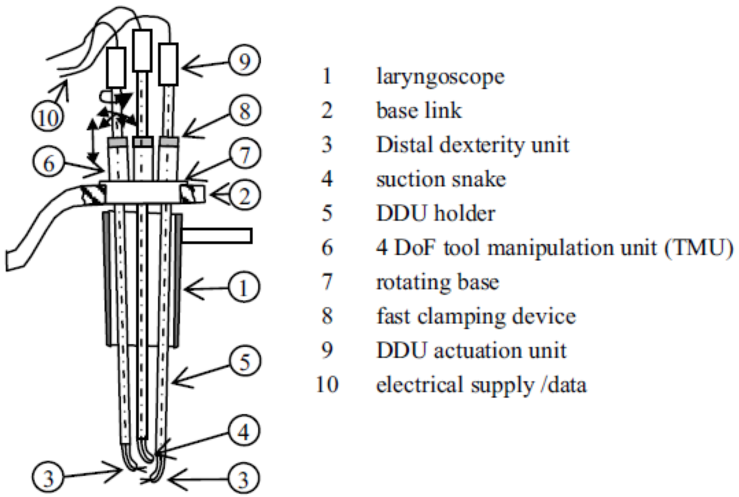
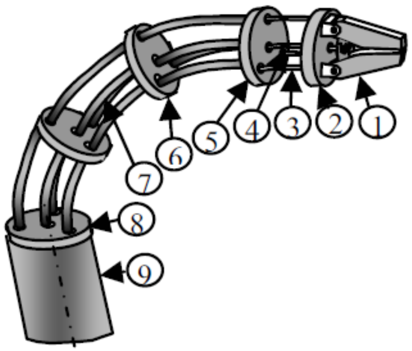


Fig. 2 Overview of the throat surgical assistance slave.

[1] Simaan, N., Taylor, R. and Flint, P. (2004), "A dexterous system for laryngeal surgery (multi-backbone bending snake-like slaves for teleoperated dexterous surgical tool manipulation)", Proceedings of the 2004 IEEE International Conference on Robotics & Automation, New Orleans, LA, April, pp. 351-7.

A dexterous system for laryngeal surgery



1 gripper
2 moving platform
3 parallel stage wires
4 gripper wire
5 end disk
6 spacer disk
7 central backbone tube
8 base disk
9 DDU holder

Fig. 3 The DDU (Distal Dexterity Unit) using a multi-backbone snake-like robot with detachable parallel tip.

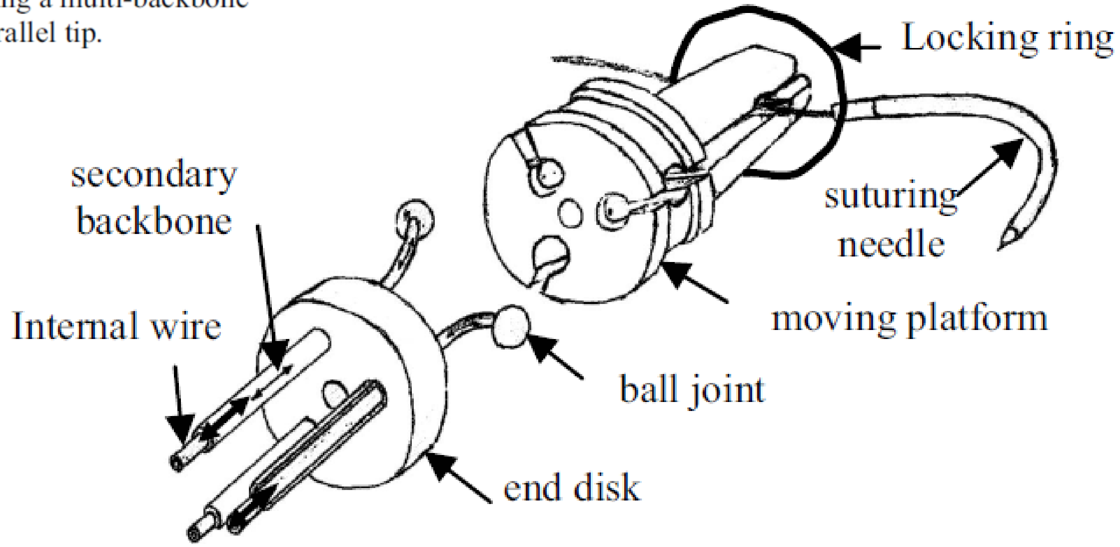


Fig. 4 The detachable parallel tip.

A dexterous system for laryngeal surgery

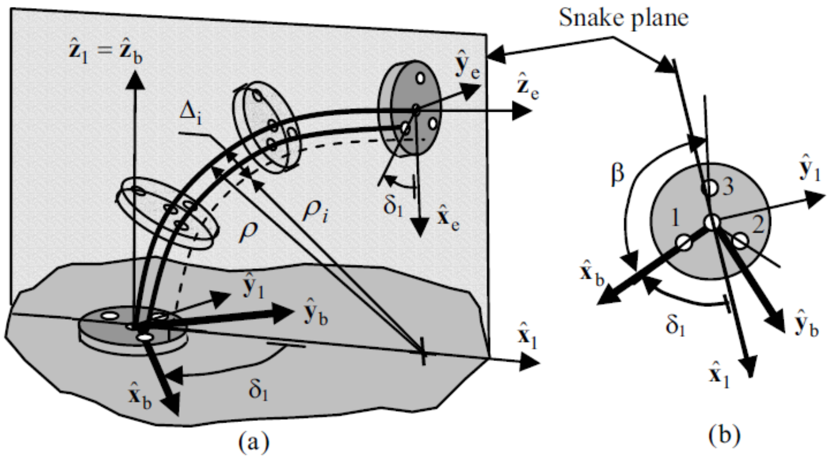


Fig. 5 The snake-like unit in a bent configuration (a) top v iew of the base disk (b)

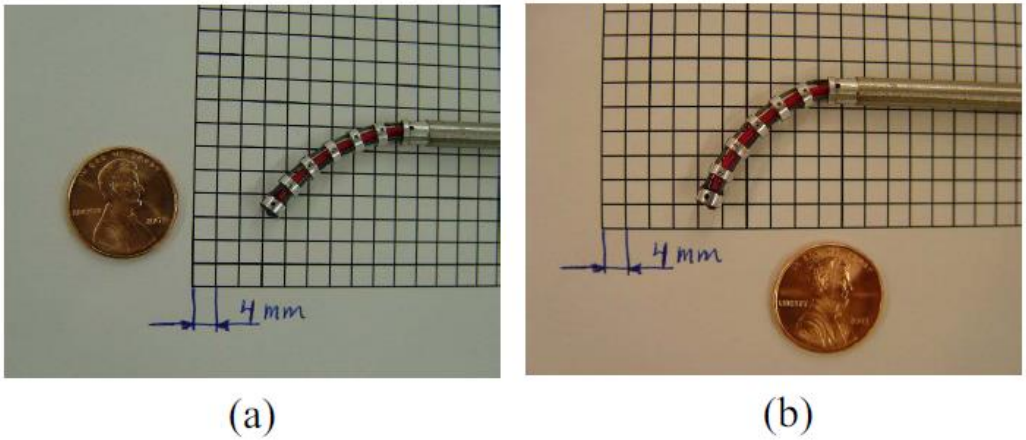


Fig. 6 The 4.2 mm diameter prototype in two bent configurations with only two of the available three secondary backbones actuated manually.

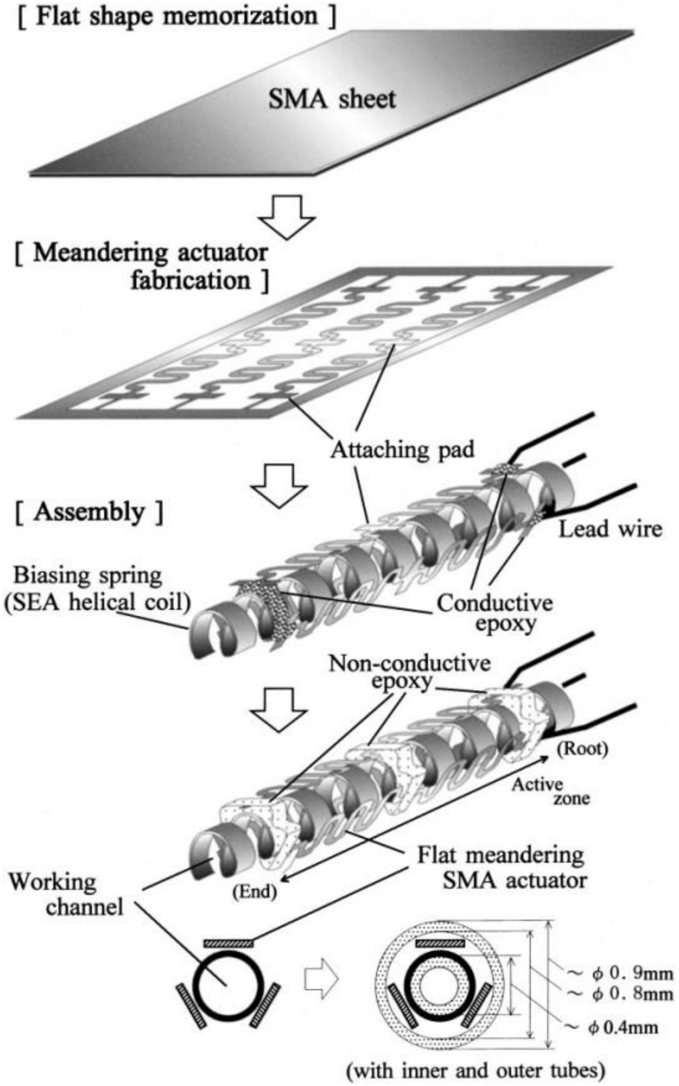
Active catheter

- **Batch fabricated flat meandering shape memory alloy actuator for active catheter**

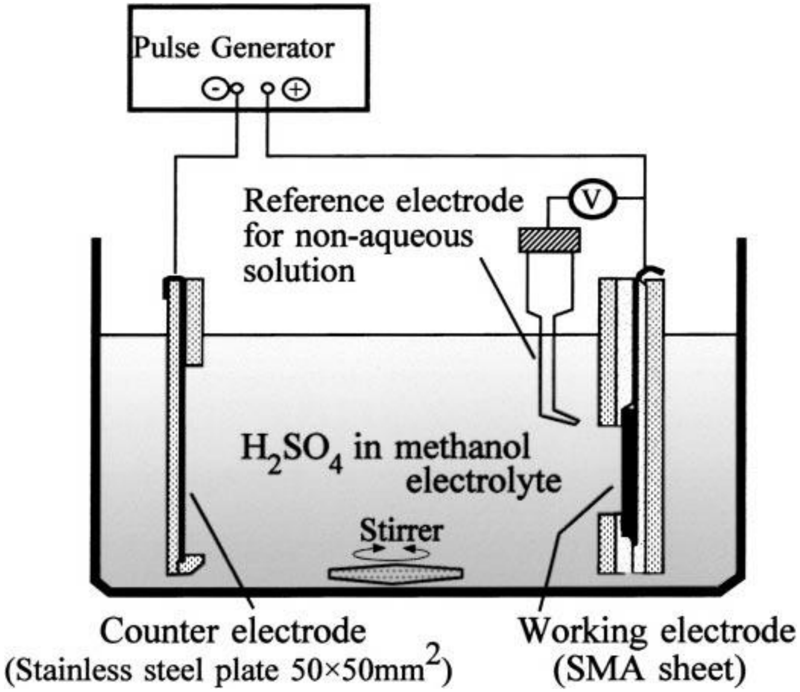
  - Outer diameter is less than 0.8mm
  - Batch fabrication process of SMA sheet based on electrochemical etching
  - Flat SMA sheet and NiTi super elastic alloy (SEA) helical coil were used
  - Maximum bending angle: 50° (without cover), 35° (with Si cover)
  - Time response: 0.5 s
  - Heating current: 60 mA

[2] Mineta, T., Mitsui, T., Watanabe, Y., Kobayashi, S., Haga, Y. and Esashi, M. (2001), "Batch fabricated flat meandering shape memory alloy actuator for active catheter", Journal of Sensors and Actuators A, Vol. 88, pp. 112-20.

Active catheter

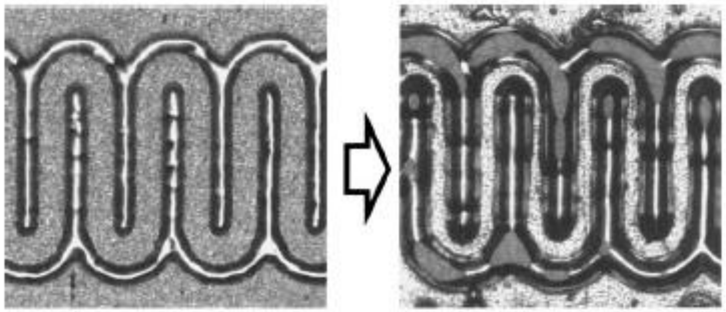


Concept of the flat meandering SMA actuator and application to an active catheter.



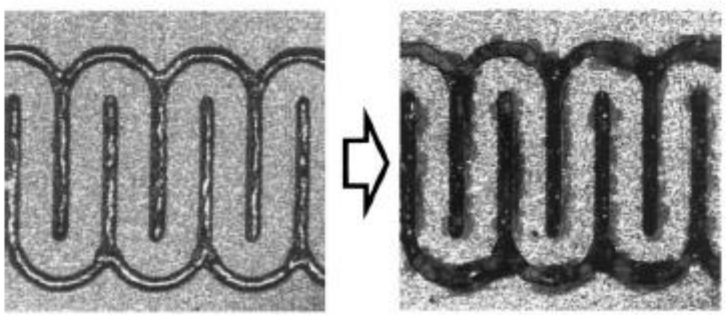
Set-up for electrochemical etching of SMA sheet.

Active catheter



(Half etching) (Throughout etching)

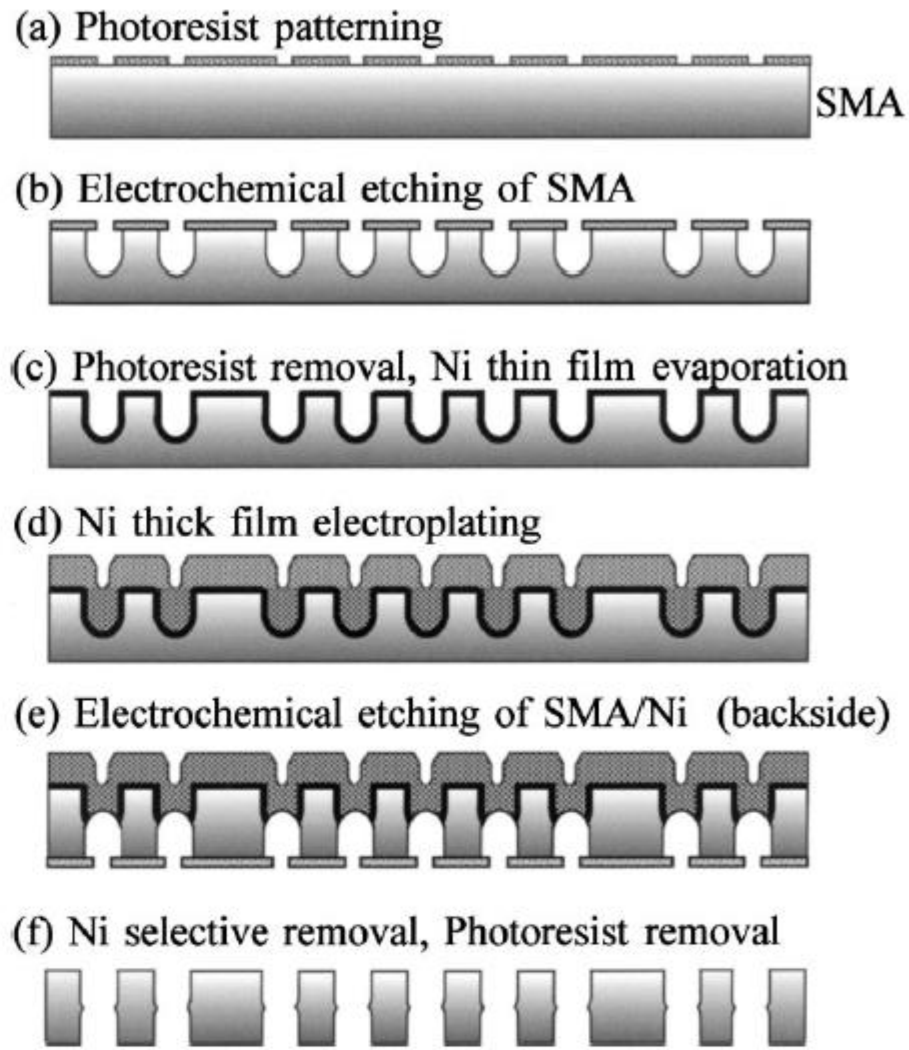
(a) DC etching (+8V)



(Half etching) (Throughout etching)

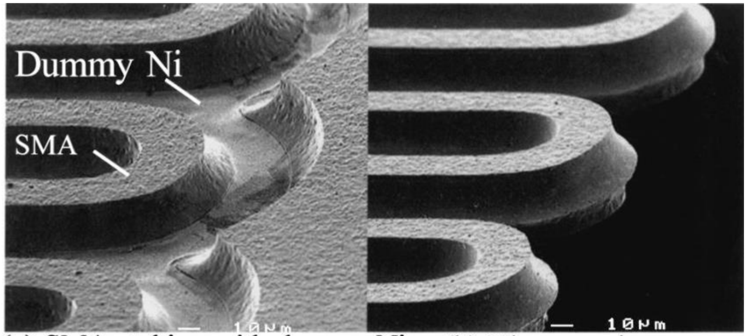
(b) Pulse etching (+8V, 50/50ms)

Worm-eaten patterns caused by throughout etching (backside: photoresist coating).



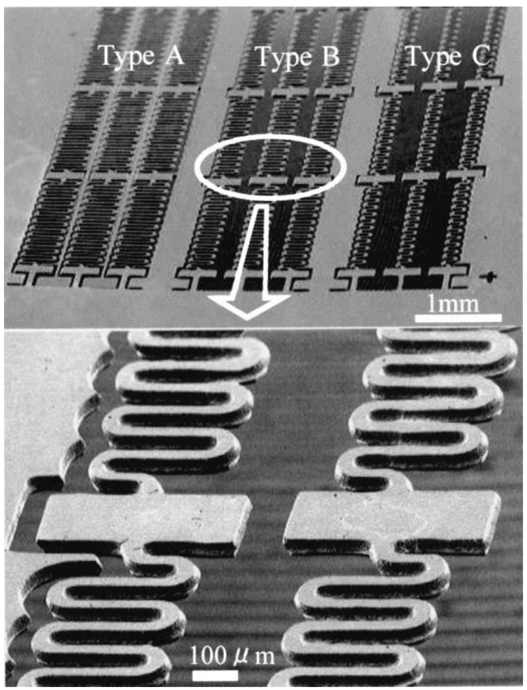
Process flow of dual-face SMA etching with a dummy metal layer.

Active catheter

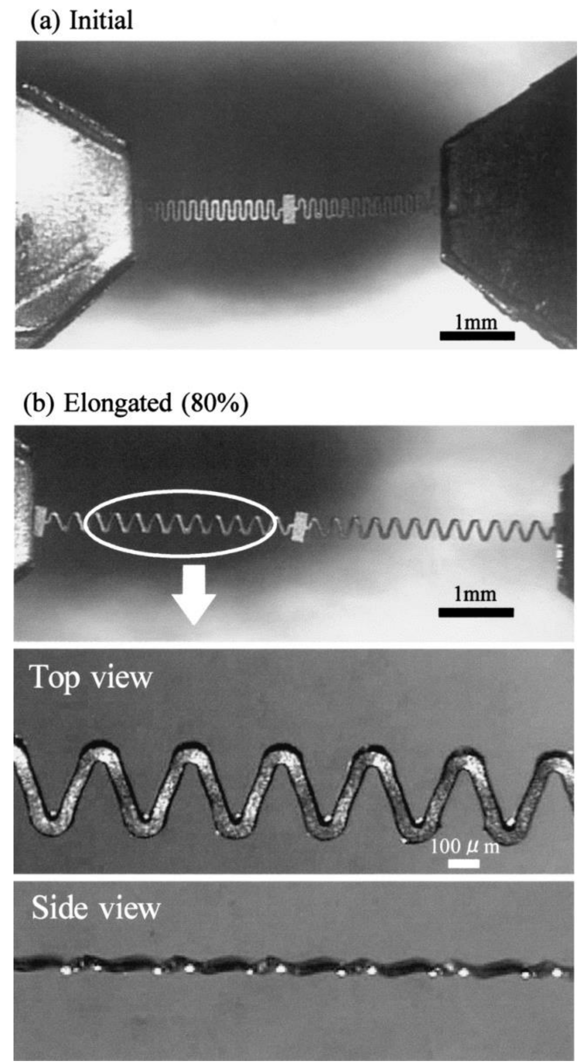


(a) SMA etching with dummy Ni (b) Ni removal

SEM photographs of meandering SMA actuator fabricated with Ni dummy layer.

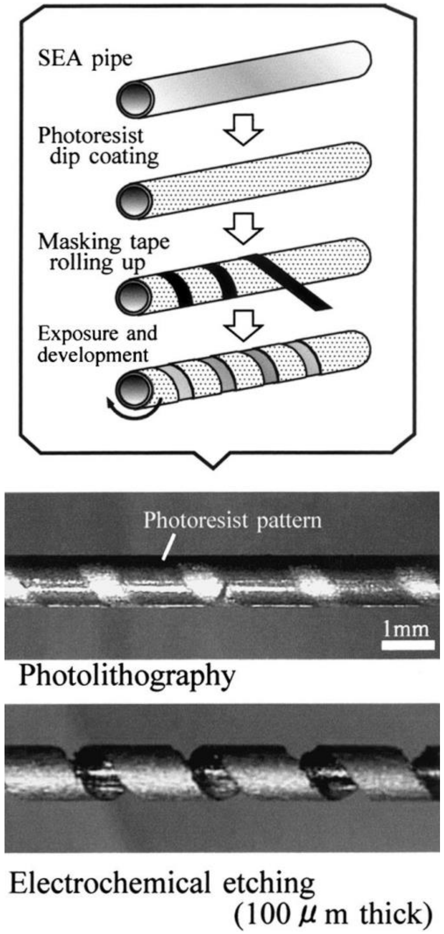


SEM photographs of the fabricated SMA actuators

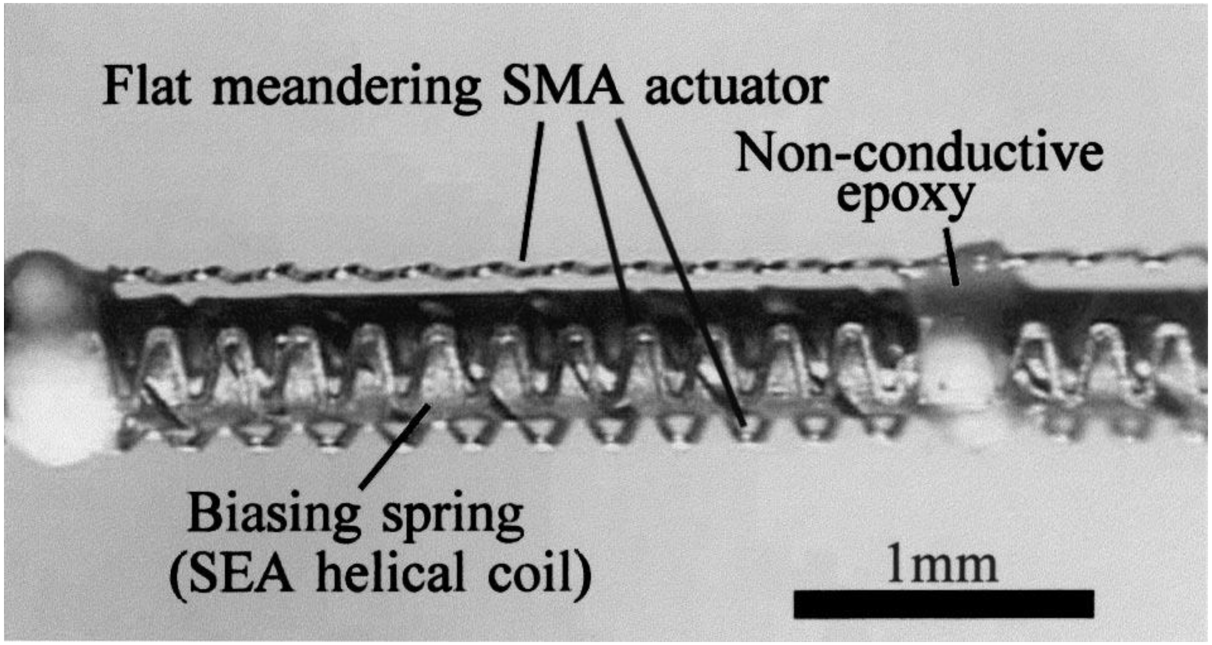


Photographs of the elongated SMA actuator

Active catheter

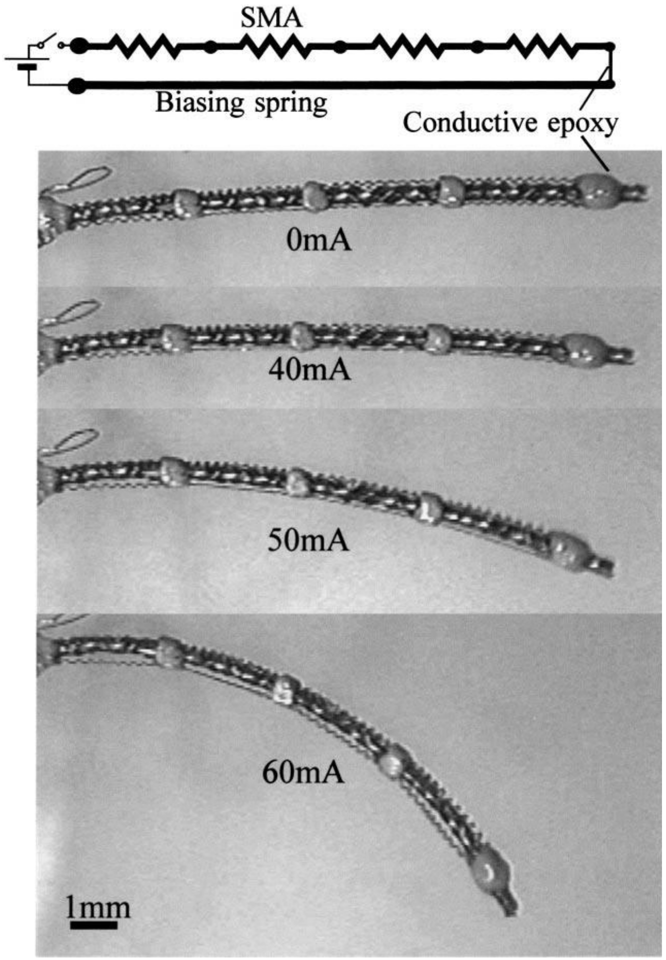


Helical coil made of etched SEA pipe

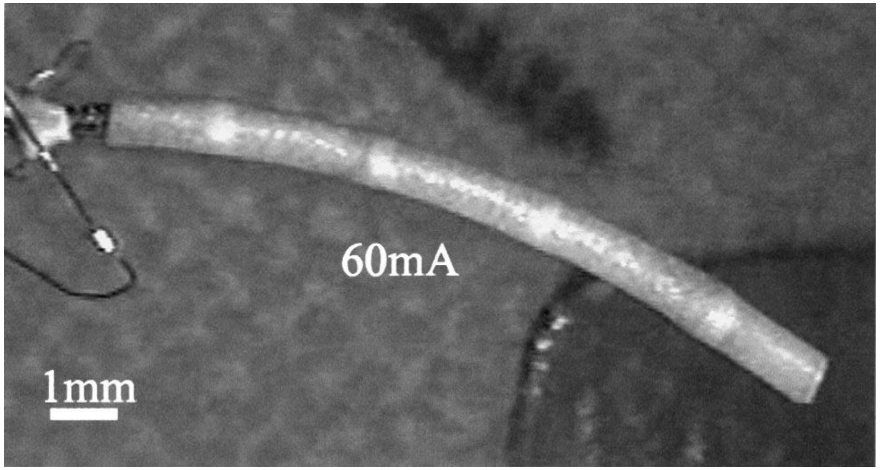


Active catheter bending mechanism consists of the SMA actuators and the SEA biasing spring

Active catheter



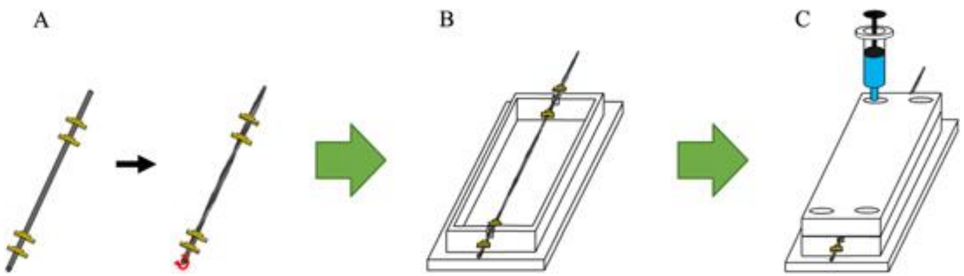
Bending characteristics of the active catheter without the outer tube



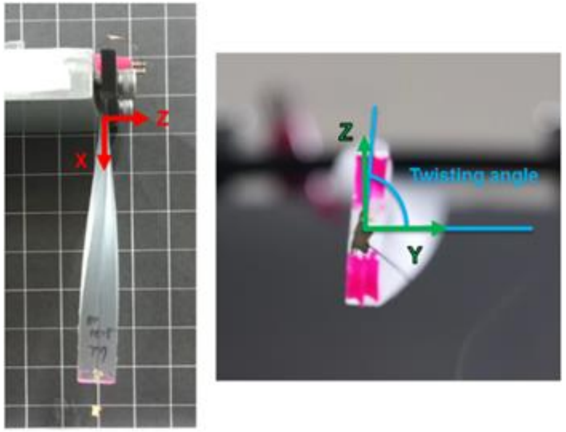
The active catheter with outer tube

Active catheter using a single SMA wire

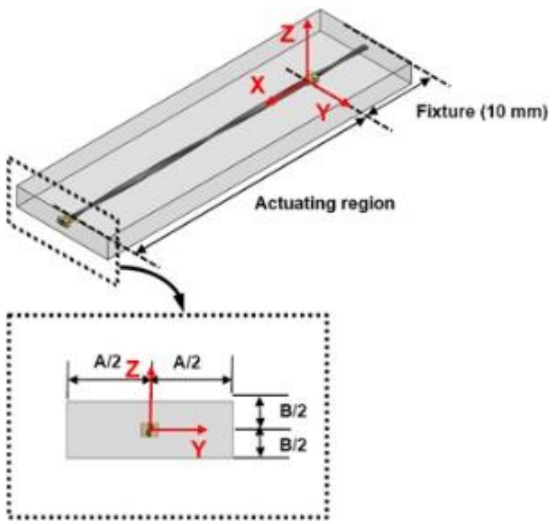
- **Actuator design**



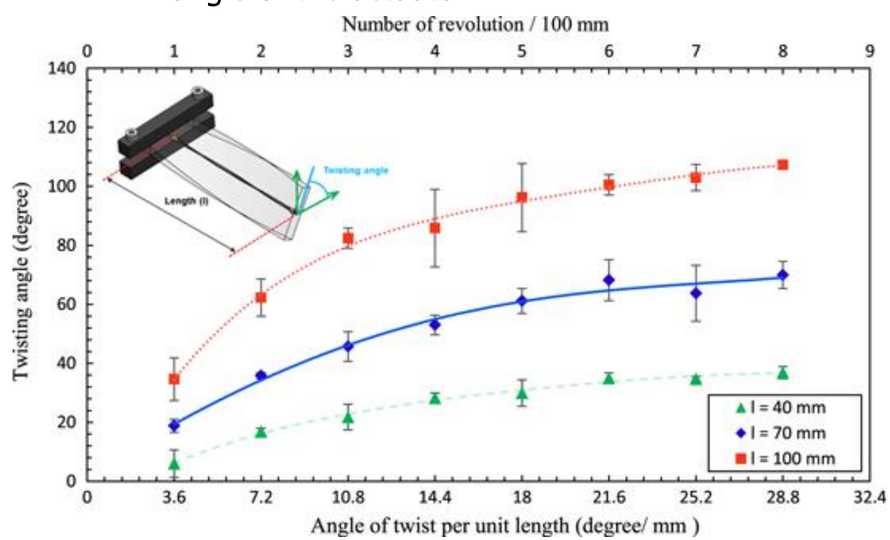
Fabrication method of a twisting actuator



Setup for the measurement of the twisting angle of the actuator



Isometric view of a twisting actuator

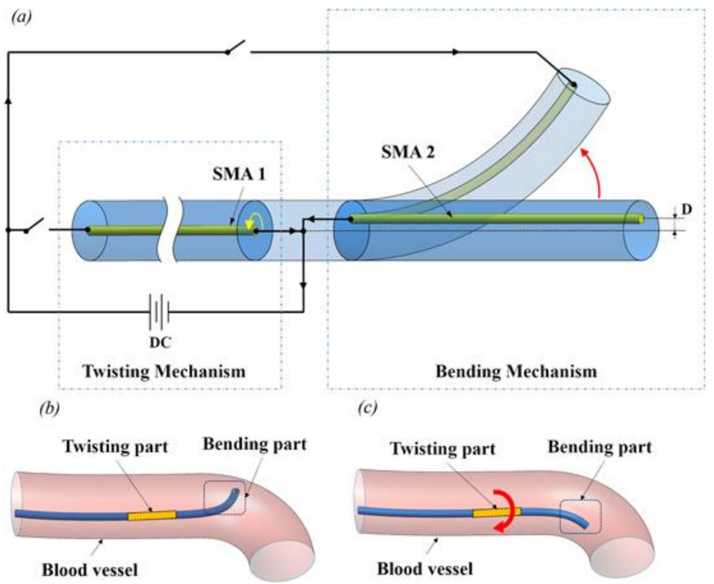


Effect of angle of twist per unit length of the SMA wire and length of the twisting angle of the actuator

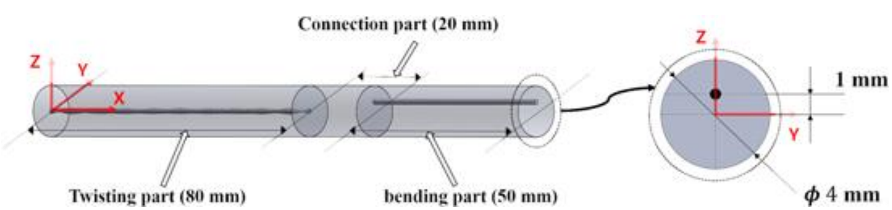
Shim J E, et al. A smart soft actuator using a single shape memory alloy for twisting actuation. Smart Materials and Structures, 2015, 24(12): 125033.

Active catheter using a single SMA wire

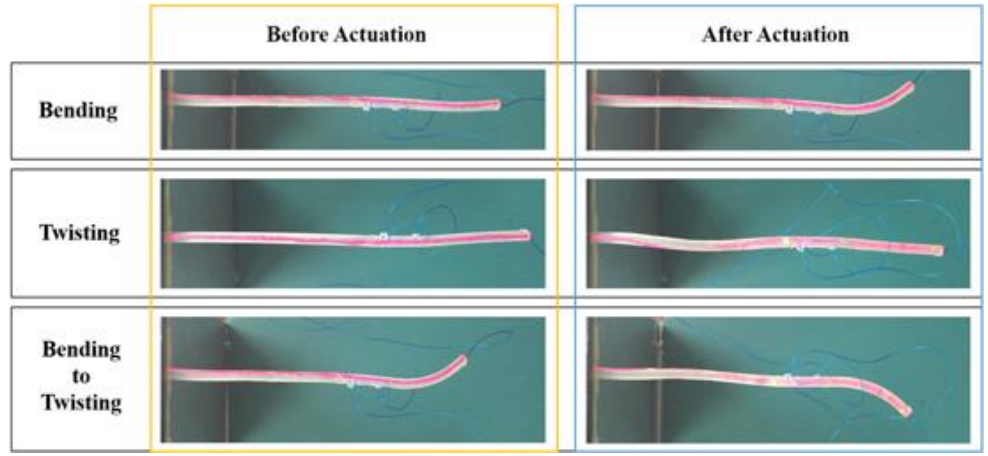
- **Catheter design**



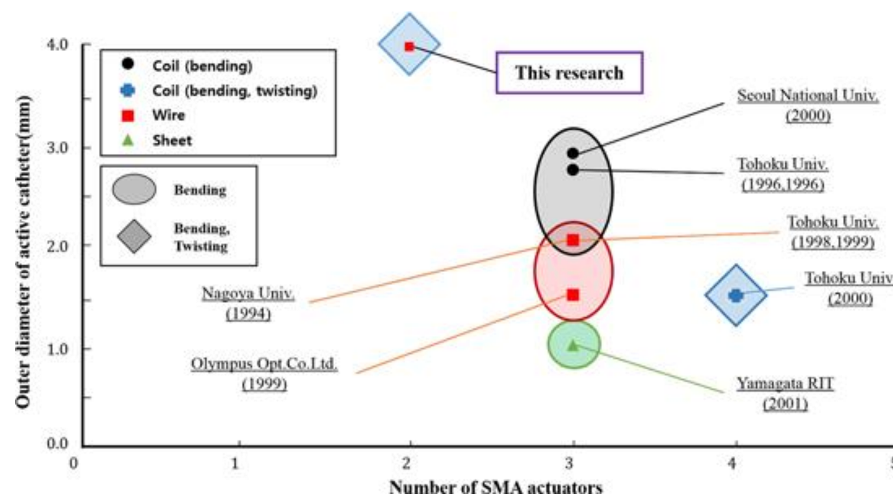
A new mechanism for an active catheter



Concept design of an active catheter with the specimen sizes



Three mode test (bending, twisting, and bend–twist mode) of an active catheter

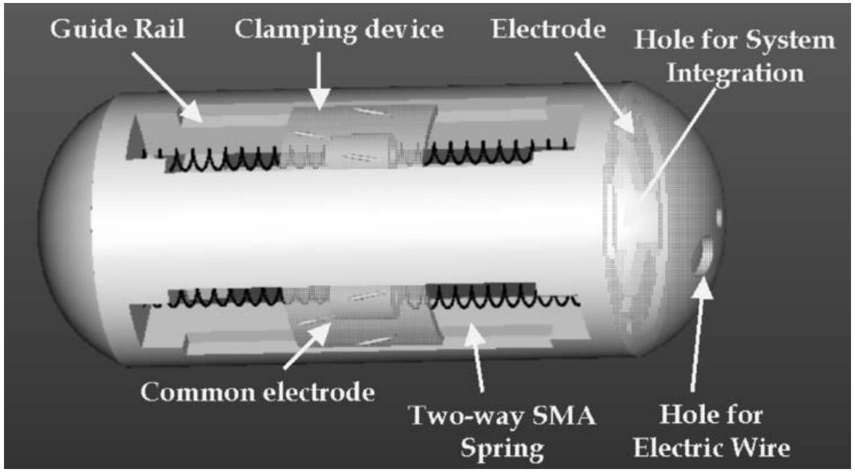


Comparison of active catheters depending on the SMA type, the number of SMA elements, and the outer diameter developed at various research institutes.

Shim J E, et al. A smart soft actuator using a single shape memory alloy for twisting actuation. Smart Materials and Structures, 2015, 24(12): 125033.

Capsule-Type Endoscopes

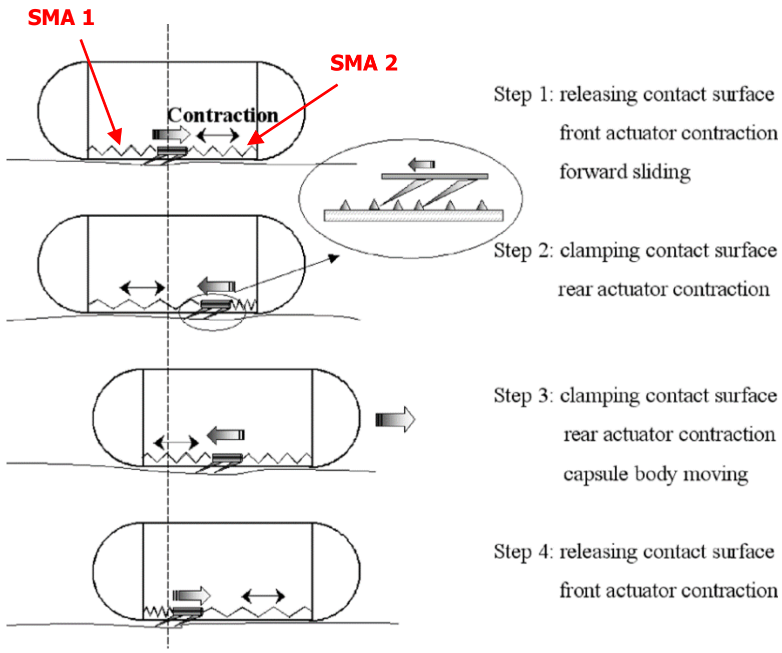
- **Design and Fabrication of a Locomotive Mechanism for Capsule-Type Endoscopes Using Shape Memory Alloys (SMAs)**
  - wireless capsule-type endoscope actuated by four pair of SMA springs
  - controlled with open loop sequence
  - 13mm in diameter
  - 33mm in total length



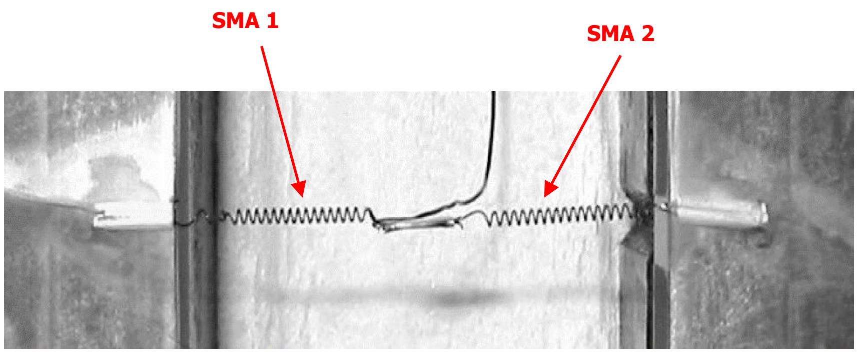
Locomotive mechanism for capsule-type endoscopes.

[3] Kim, B., Lee, S., Park, J.H. and Park, J.O. (2005a), "Design and fabrication of a locomotive mechanism for capsule-type endoscopes using shape memory alloys (SMAs)", IEEE/ASME Transactions on Mechatronics, Vol. 10 No. 1, pp. 77-86.

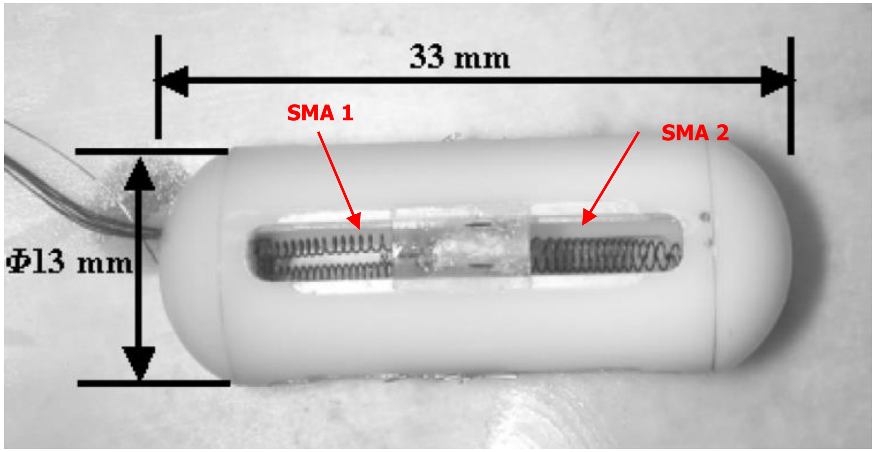
Capsule-Type Endoscopes



Principle of locomotion

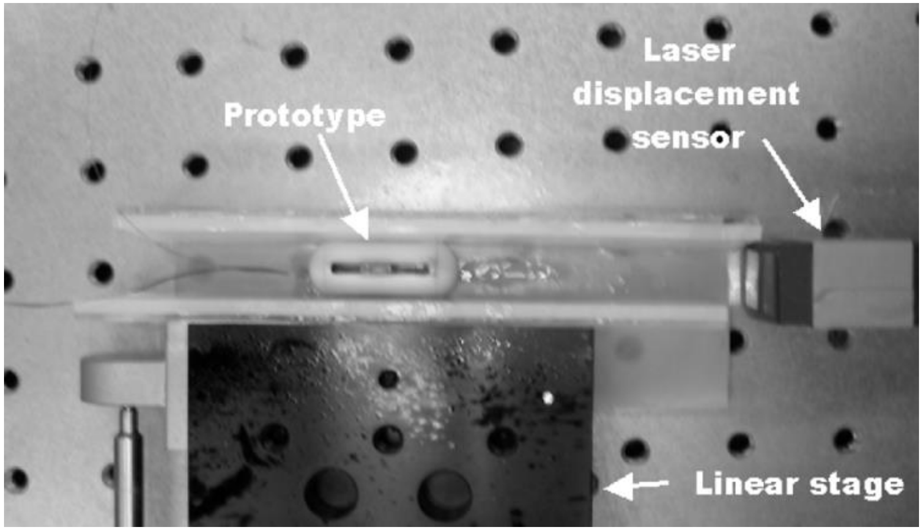


Fabrication of an actuator based on a two-way SMA spring set

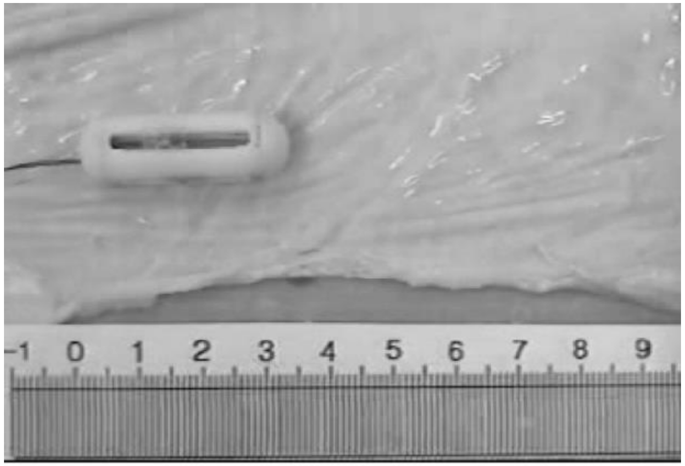


Prototype with a locomotive mechanism

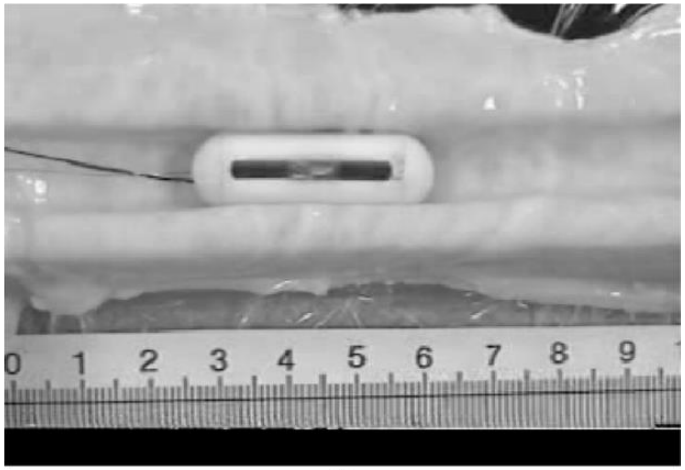
Capsule-Type Endoscopes



Setup for experiments



(a)



(b)

In-vitro test under (a) a single-surface contact and
(b) three-surface contact

SHAPE MEMORY ALLOY FOR MICRO ACTUATORS AND GRIPPERS

Micro actuators and grippers

- **SMAs are ideal actuators for microsystems requiring high performance output**

- **Advantages of miniaturization of SMAs**
  - Response, speed and power density increase
    - Due to enhanced cooling (higher surface-to-volume ratio than macro devices)
  - Generating force increase
    - 150 times higher than hydraulic actuators
    - 400 times higher than magnetic actuators (at the same volume)

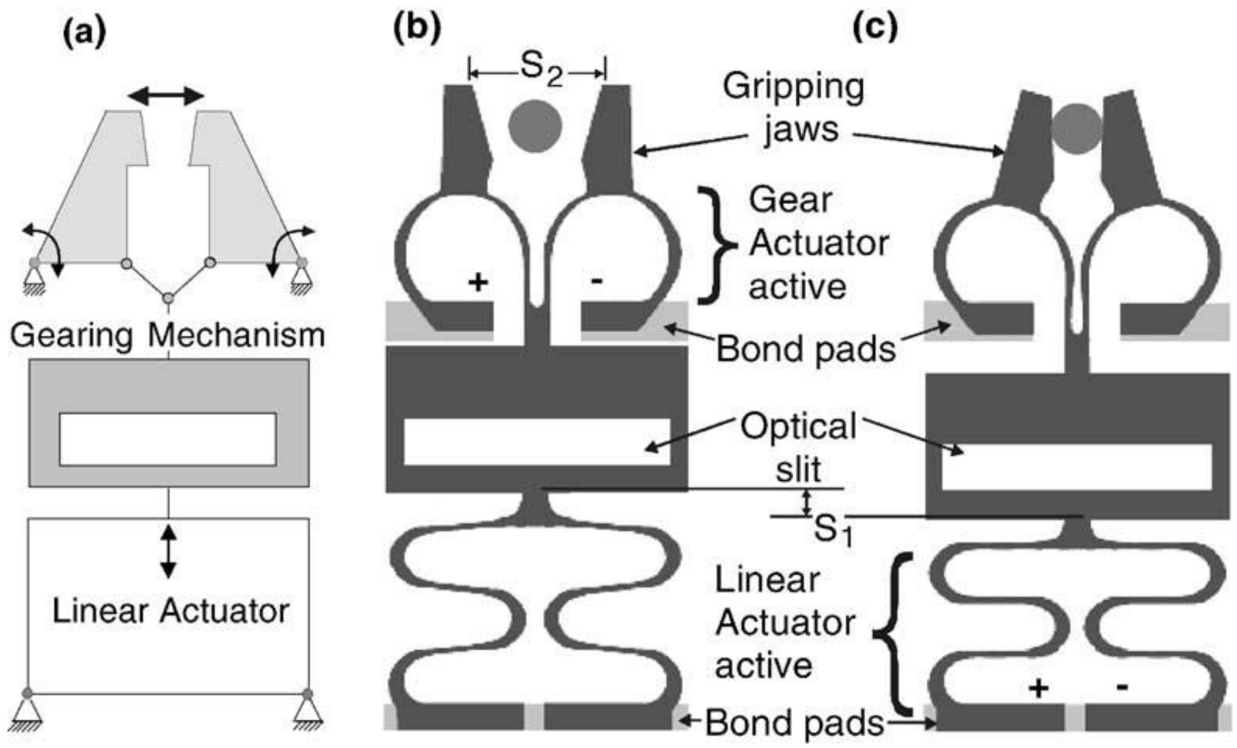
- **Compact micro actuator designs with high work outputs could be well fulfilled by SMAs.**

Micro gripper

- **SMA micro gripper system**
  - Size: 2mm X 5.8mm X 0.23mm
  - Micro fabricated from 100mm thick NiTi cold-rolled sheet using laser cutting
  - Gearing mechanism with five joints
  - Integrated with an optical position sensor
  - Maximum displacement of the gripping jaws: 300μm
  - Maximum gripping force: 35mN
  - Response time: 140 ms
  - The positioning accuracy: 2μm (closed loop PI control)

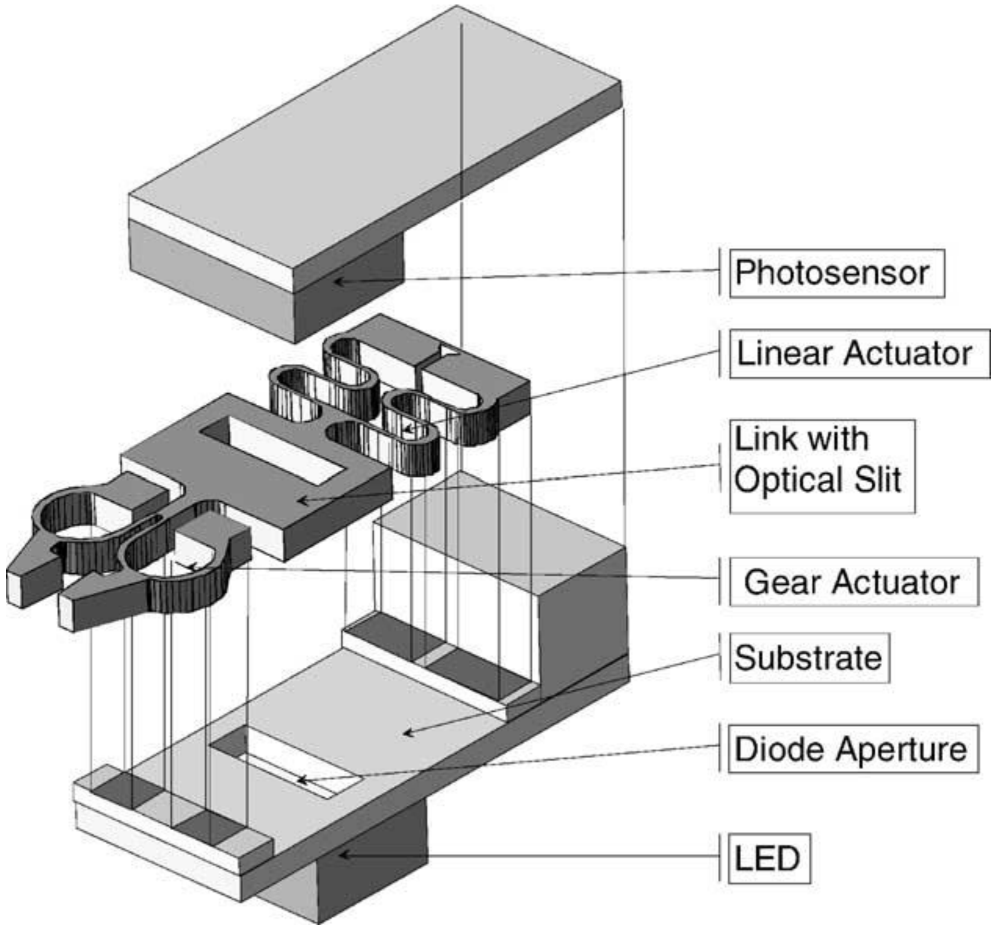
[4] Kohl, M., Krevet, B. and Just, E. (2002), "SMA microgripper system", Journal of Sensors and Actuators A, Vol. 97/98, pp. 646-52.

Micro gripper



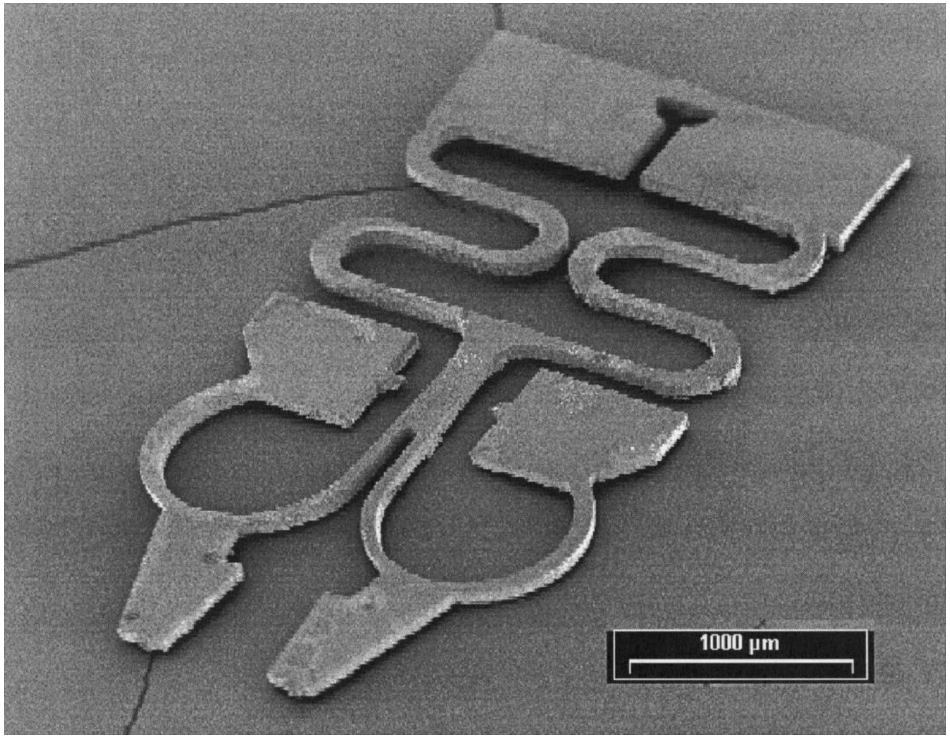
Mechanical gripper: (a) schematic of the gripping device, (b and c) monolithic SMA gripping device in open and closed condition

Micro gripper



Schematic of the SMA micro gripper system

Micro gripper



SMA micro gripper system holding a piece of optical fiber of 140μm diameter

SHAPE MEMORY ALLOY FOR UNDERWATER ROBOTS

Underwater robots

- **For underwater applications,**
  - high-frequency response actuators are unnecessary
  - Low-bandwidth actuators of less than 2Hz (Lagoudas et al., 1999) are adequate
  - Hence, SMA actuators are best suitable for underwater applications

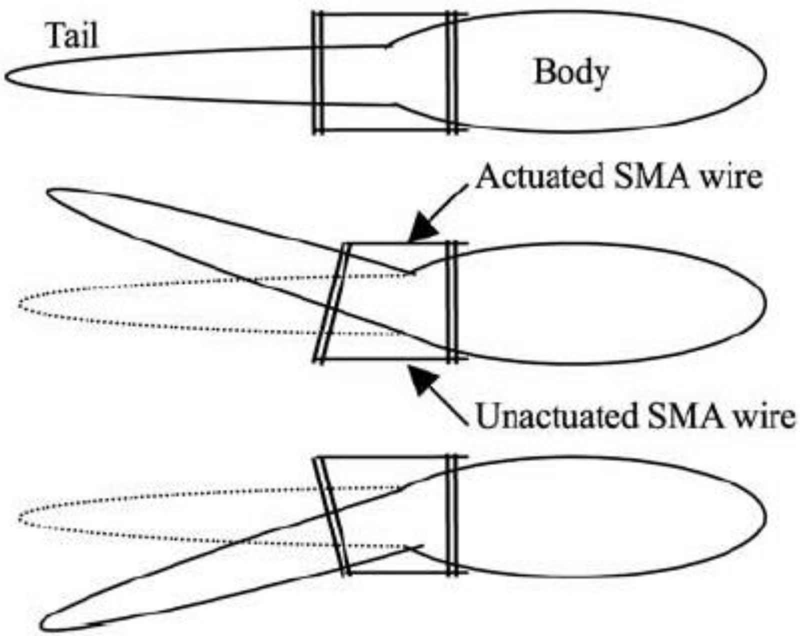
- **Better response is possible with accelerated cooling rates, as the actuator is immersed in the medium**

- **The major disadvantage**
  - Requirement of high power for heating the actuator

- **Generally, SMA actuators are used to imitate the motion of a fish**

  (Figure in next slide)

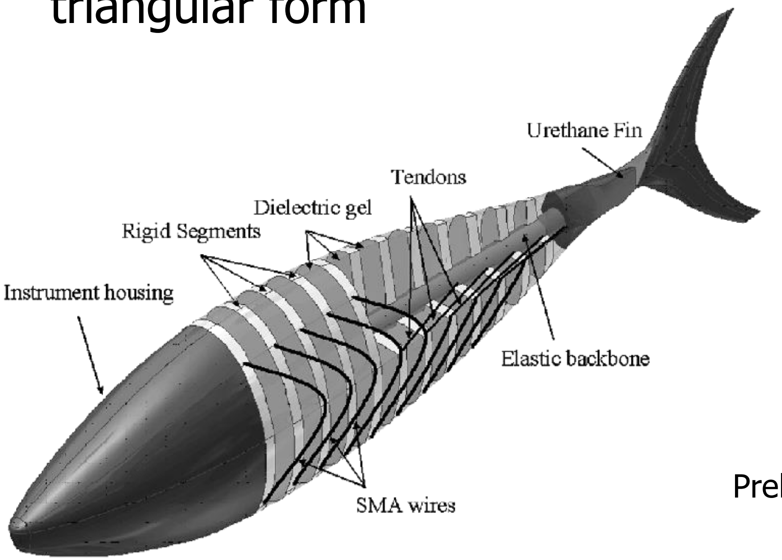
Underwater robots



SMA actuators in underwater application: Typical arrangement

Underwater robots

- **Use of a Shape Memory Alloy for the Design of an Oscillatory Propulsion System**
  - The propulsive system was realized by dielectric gel, elastic material, SMA wires
  - Onboard instrumentation including driver circuit for the actuation of wires
  - Motion obtained from the SMA was enhanced by fixing the wires in a triangular form



Preliminary design of an SMA-based oscillating propulsive system.

[5] Shinjo, N. and Swain, G.W. (2004), "Use of a shape memory alloy for the design of an oscillatory propulsion system", IEEE Journal of Oceanic Engineering, Vol. 29 No. 3, pp. 750-5.

SHAPE MEMORY ALLOY FOR ARTIFICIAL LIMBS

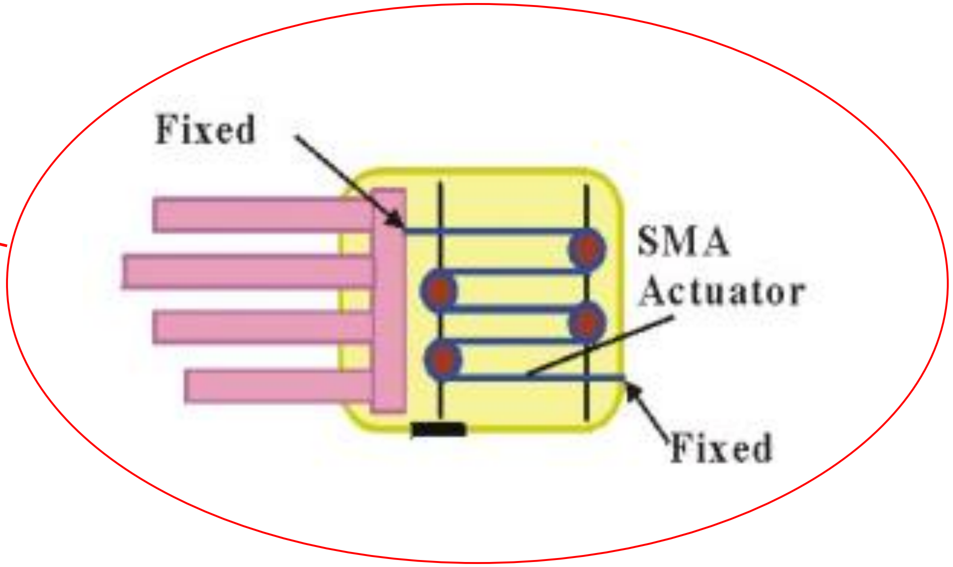
Artificial limbs

- The ultimate aim of robotics is to develop an artificial human being with all kind of intelligence
- Artificial limbs like fingers, hands and arm like manipulators with SMA actuators are being developed
- Researches
  - Tele-operation
  - Tele-presence
  - Sensory substitution
  - 3D surface generation
  - Braille systems
  - Laboratory prototypes and games

Hand-shaped force interface

- **Hand-shaped force interface for human-cooperative mobile robot**
  - An SMA actuated, hand shaped device equipped on a two wheeled autonomous mobile robot
  - Haptic force interaction

Outlook of the robot with the Hand-Shaped Force Interface



Structure of SMA actuator

[6] Hikiji, R. and Hashimoto, R (2000), "Hand-shaped force interface for human-cooperative mobile robot", Proceedings of the First International Workshop on Haptic Human-Computer Interaction, Vol. 2058, pp. 76-87.

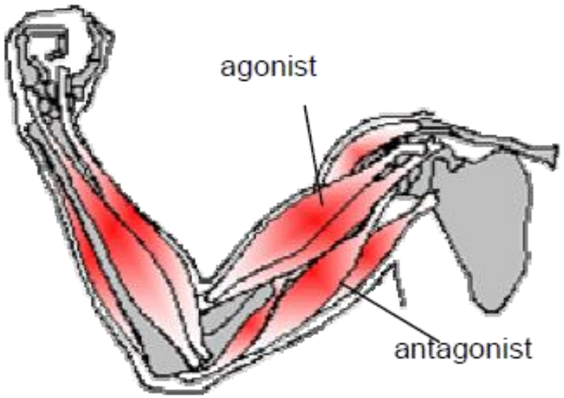
Miniature robot finger

- **Development of a miniature robot finger with a variable stiffness mechanism using shape memory alloy**
  - A scaled miniature robot finger
  - Variable stiffness mechanism using 75μm diameter SMA wire
  - Various control schemes
    - Position control
    - Force control
    - Stiffness control
  - Sensors
    - Encoders
    - Strain gauges

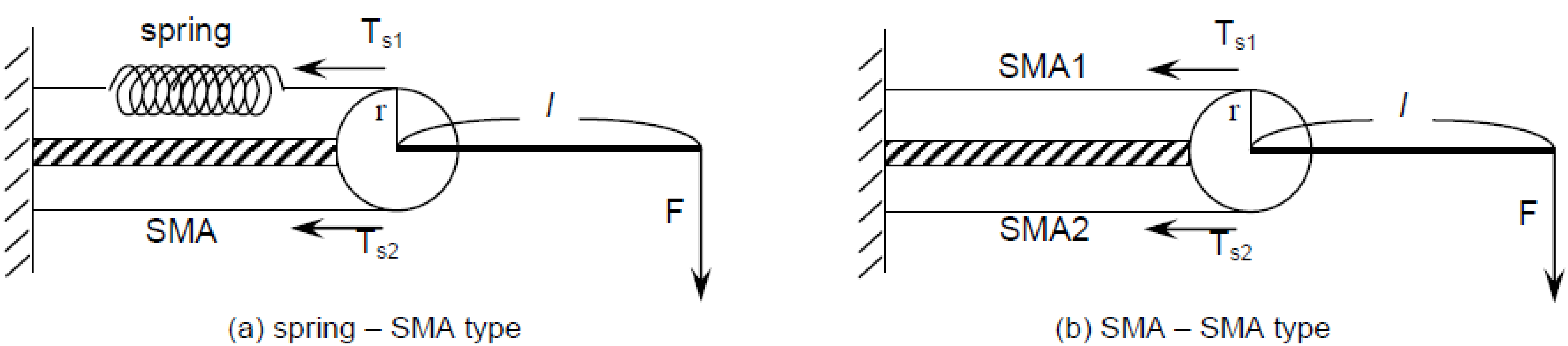
[7] Hino, T. and Maeno, T. (2004), "Development of a miniature robot finger with a variable stiffness mechanism using shape memory alloy", Proceedings of International Symposium on Robotics and Automation, Mexico.

Miniature robot finger

- Two types of driving mechanisms using SMA
  1. Configuration of SMA and a spring (a)
     - Angle of joint rotation arbitrarily for the finger to carry out bending movement
     - Spring force will determine passively when a finger carries out extension movement
  2. Configuration of two SMA wires (b) (called the antagonist SMA model)
     - Angle of joint arbitrarily when a finger carries out extension and bending movements



Human musculoskeletal

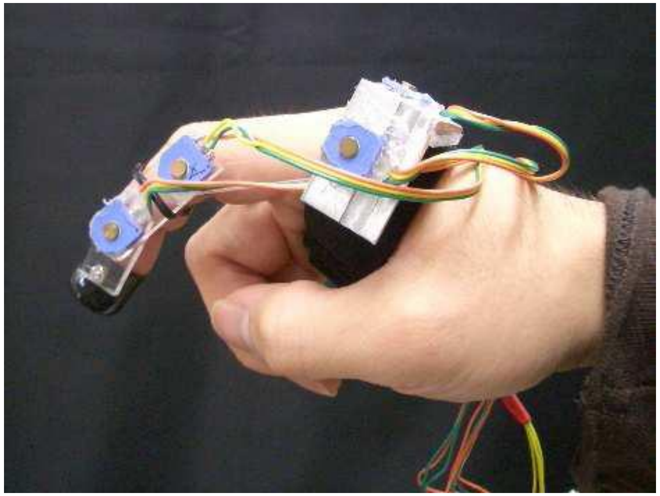


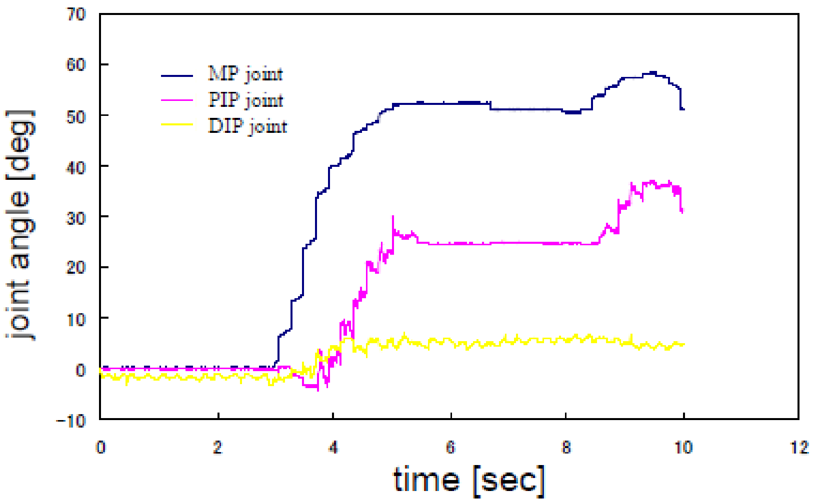
Driving mechanism

Miniature robot finger

Feature of SMA

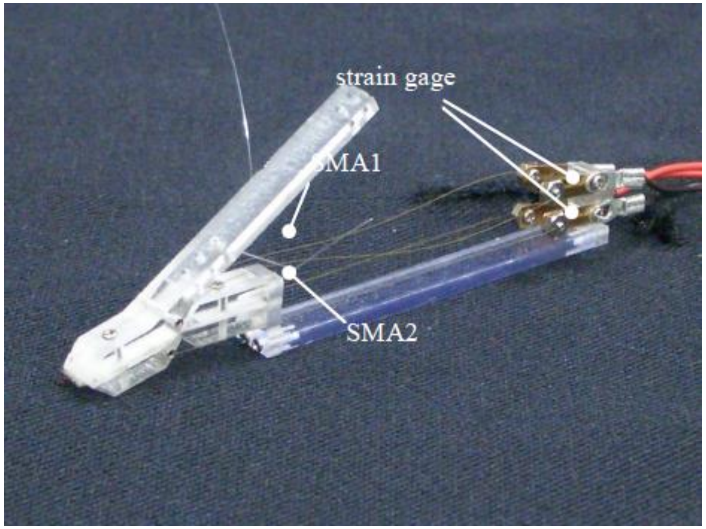
Diameter of wire [mm]	0.05	0.075	0.1	0.15	0.2
Contraction [%]	5	5.4	5	4.2	3
Average contraction velocity [mm/s]	5.6	6.8	6.2	4.7	2.5
Average extension velocity [mm/s]	3.9	1.6	1.2	0.3	0.1
Generative force[N]	0.9	1.9	2.7	3.2	6.7



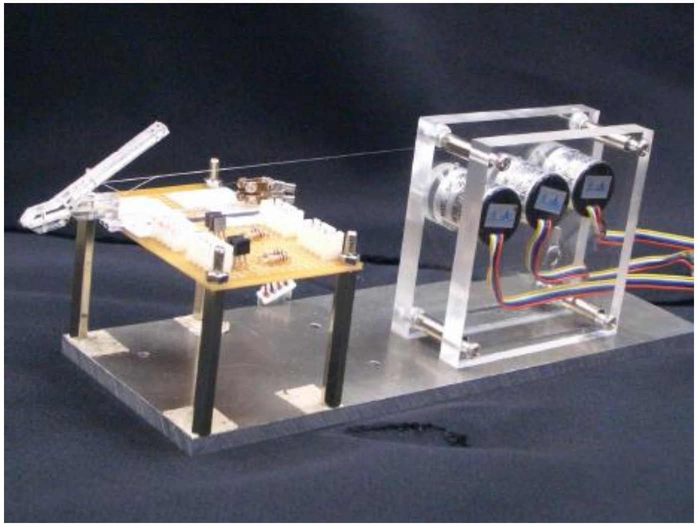


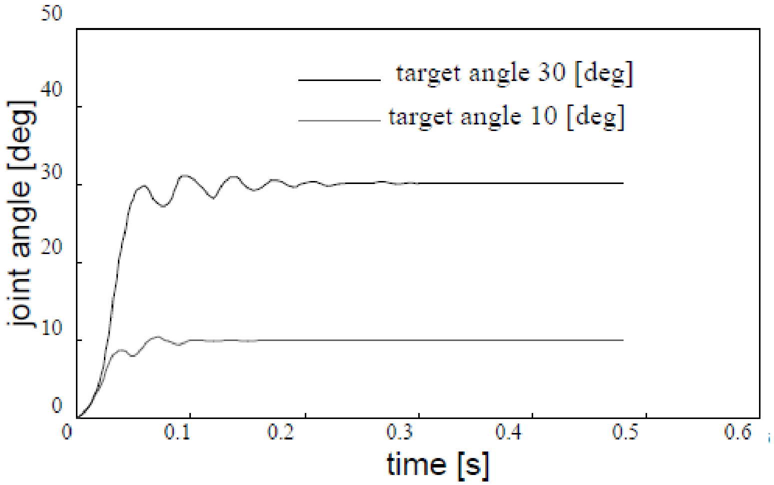
- Measurement of the motion range of real human finger joints in conducting precision grasping of an object
- Maximum joint angle: 58°

Miniature robot finger

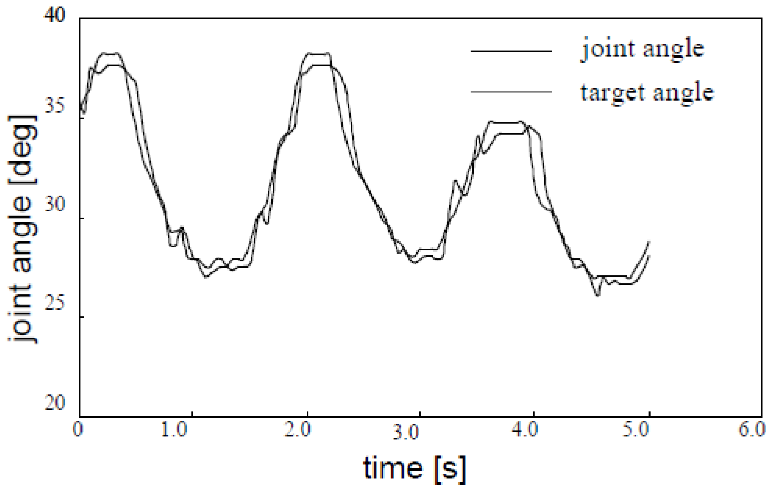


The manufactured miniature robot finger


The experiment device



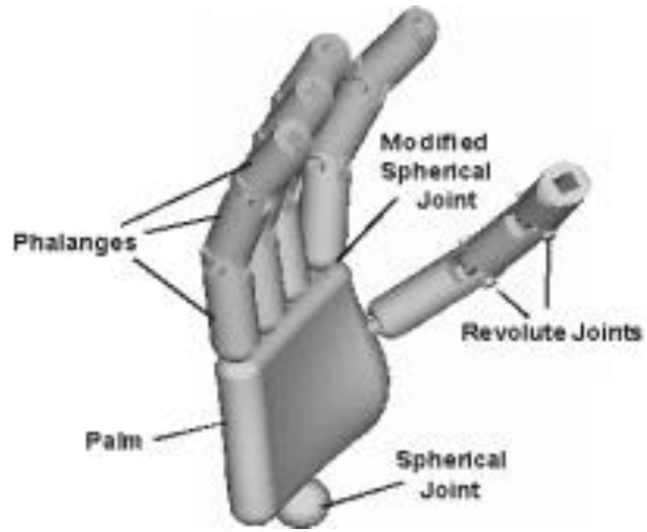
Step response



The response of master-slave

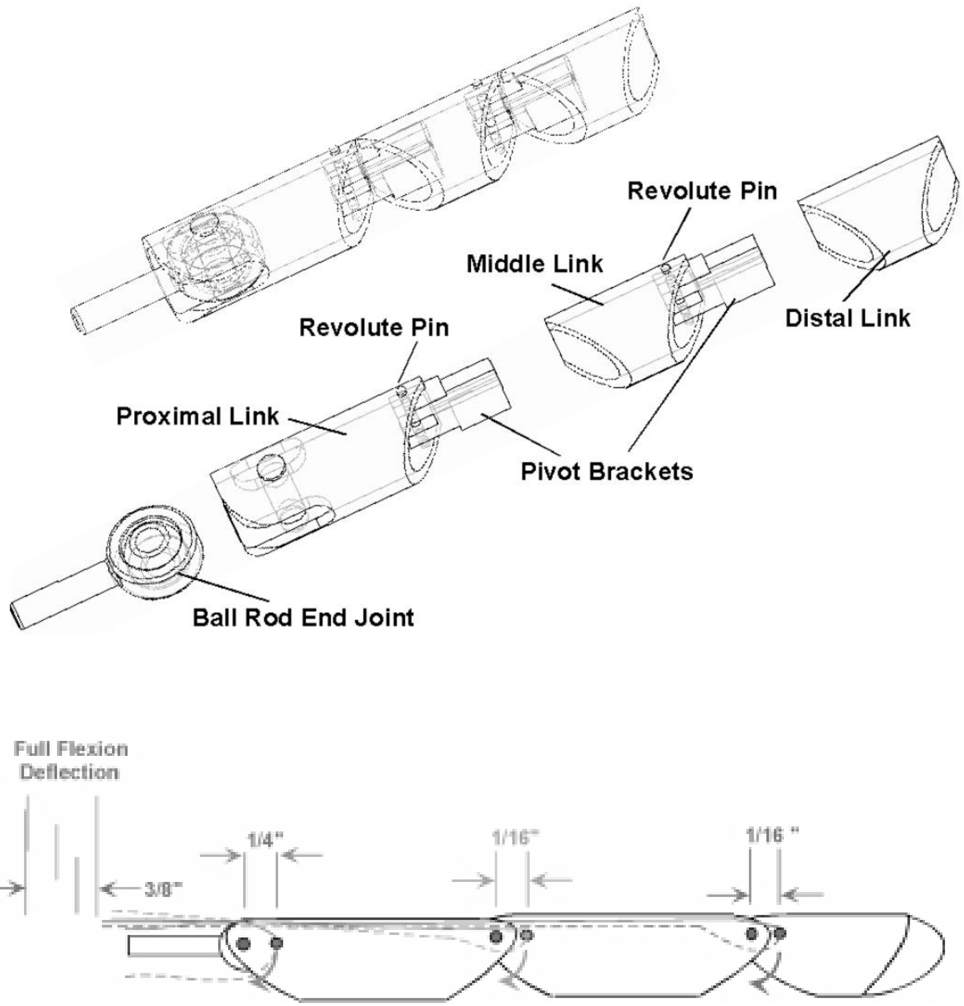
SMA actuated prosthetic hand

- **Mechanical design of a shape memory alloy actuated prosthetic hand**
  - A four-fingered
  - 14 DOF dexterous robotic hand
  - 150μm diameter NiTi SMA wire was used
  - Each finger consumed 4.2W
  - Control had been accomplished by applying 7V at 300 mA

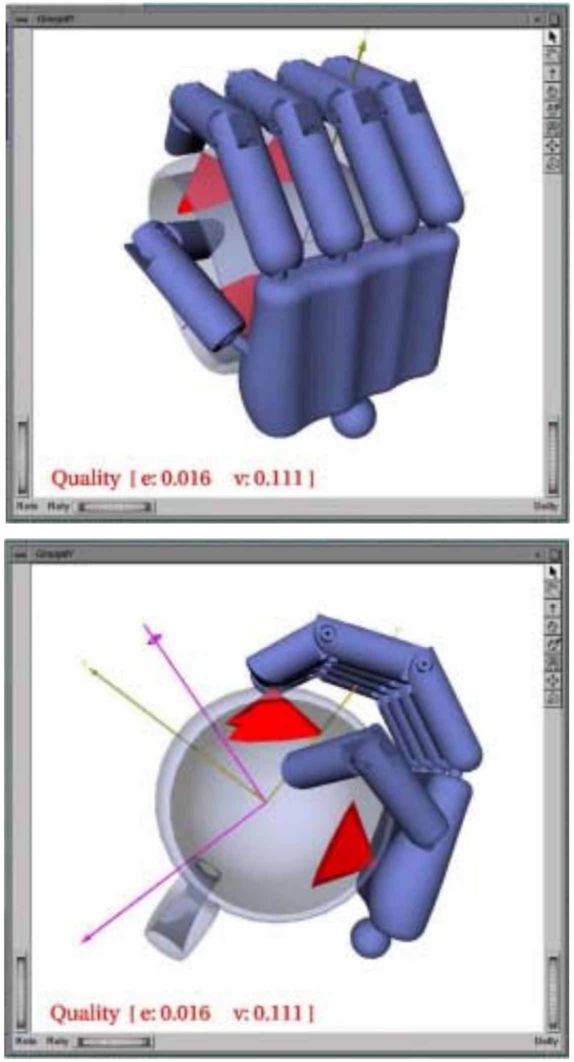


[8] DeLaurentis, K.J. and Mavroidis, C. (2002), "Mechanical design of a shape memory alloy actuated prosthetic hand", Journal of Technology and Health Care, Vol. 10 No. 2, pp. 91-106.

SMA actuated prosthetic hand



Finger prototype assembly design and drawing



Simulations of the hand using software 'GraspIt'

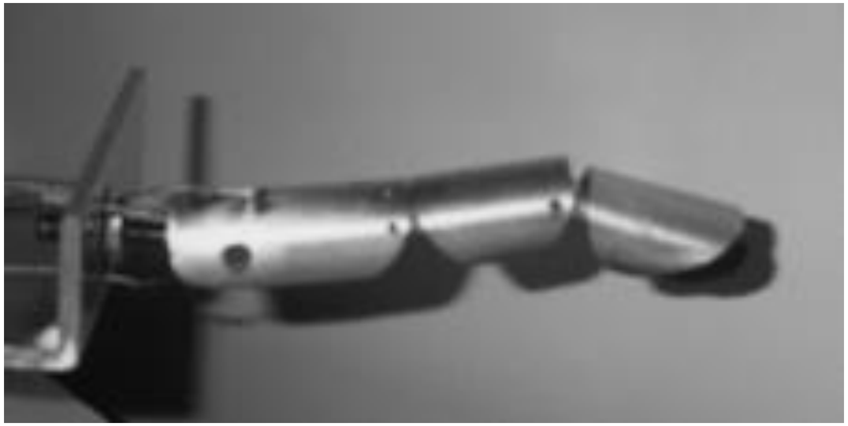
SMA actuated prosthetic hand

Aluminum finger prototype

Robotic finger built with SLS
(Selective Laser Sintering)

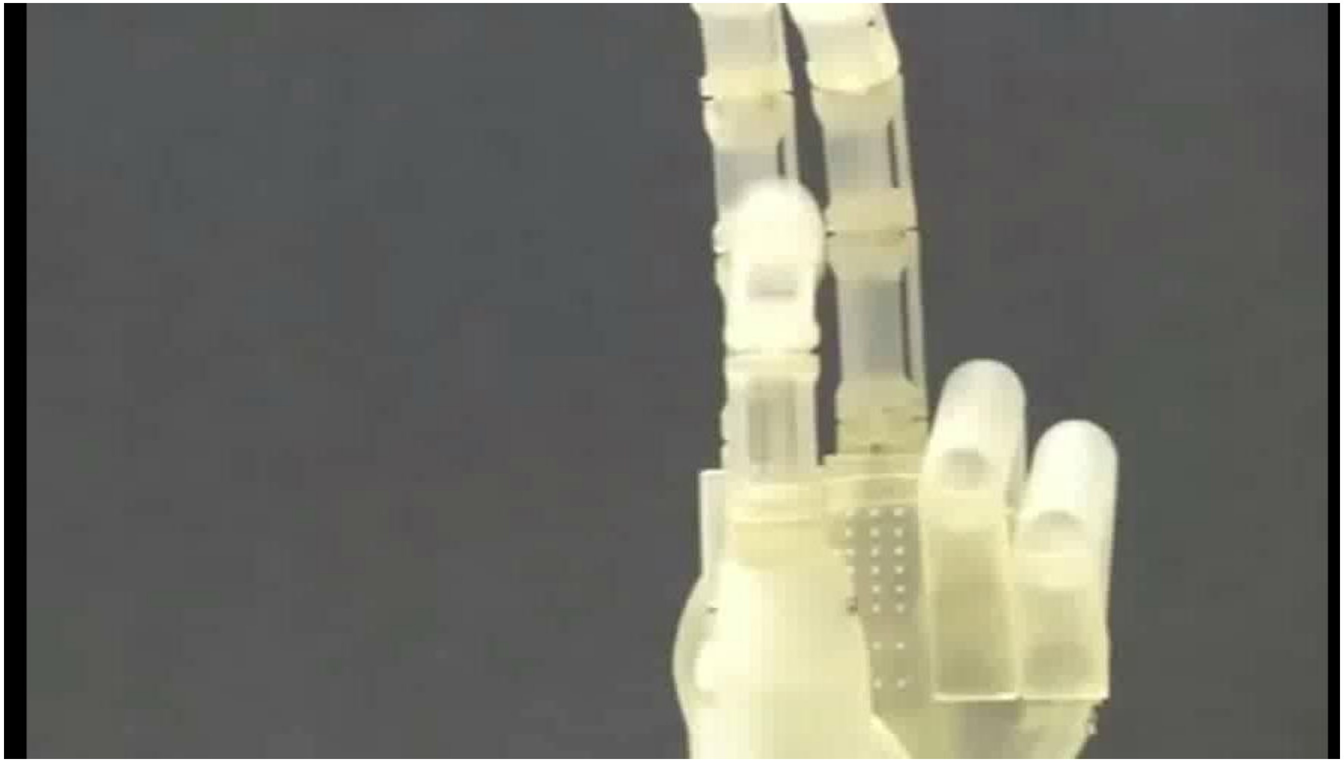
Robotic thumb built with SL
(StereoLithography)

First joint in flexion



First joint in extension

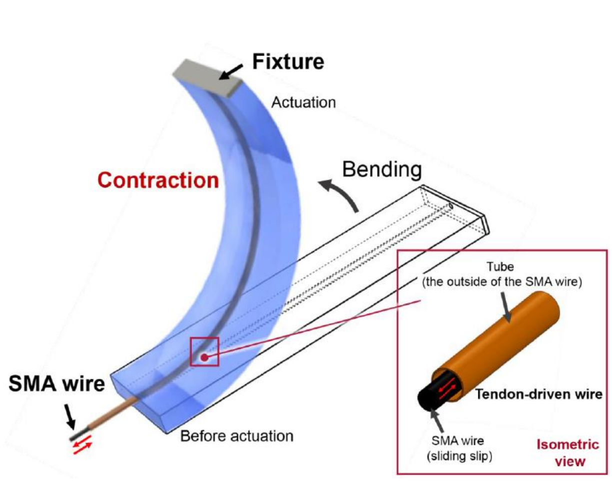
SMA actuated robot hand – movies



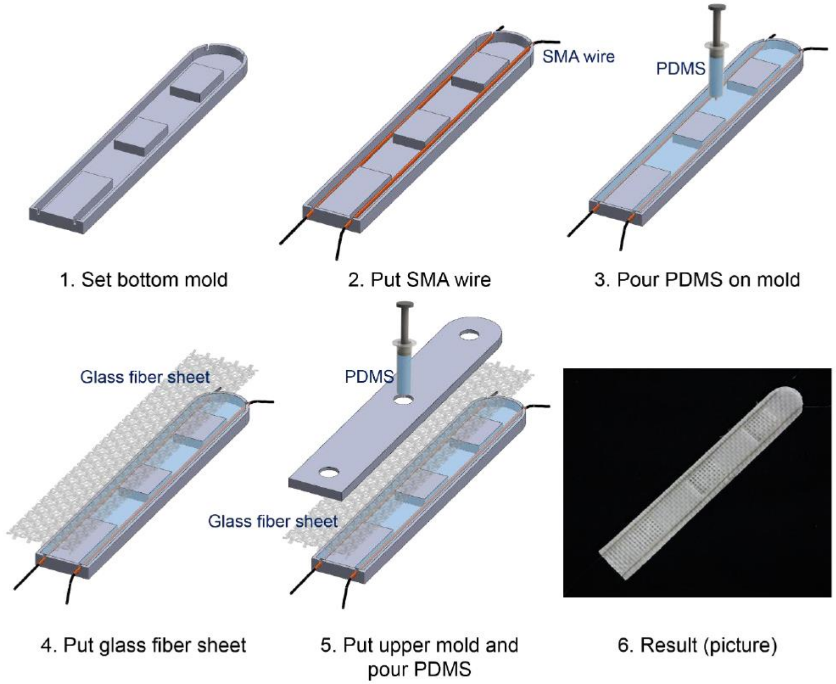
Using bundles of shape-memory 'smart wire', engineers from Saarland University build a bionic hand that could eventually lead to new flexible and lightweight prostheses.

http://www.reuters.com/article/us-germany-bionic-hand-idUSKCN0PW1N820150722

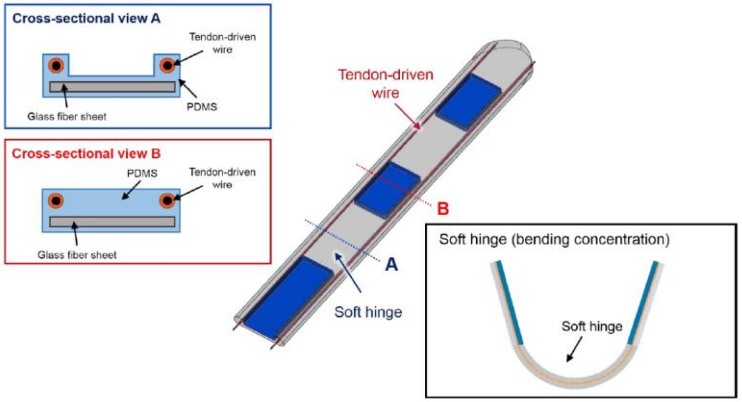
Soft morphing hand driven by SMA tendon wire



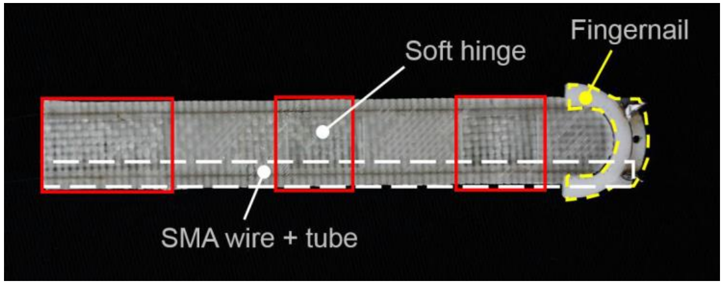
Schematic diagram of the tendon-driven SSC actuator mechanism



Fabrication process for the artificial finger



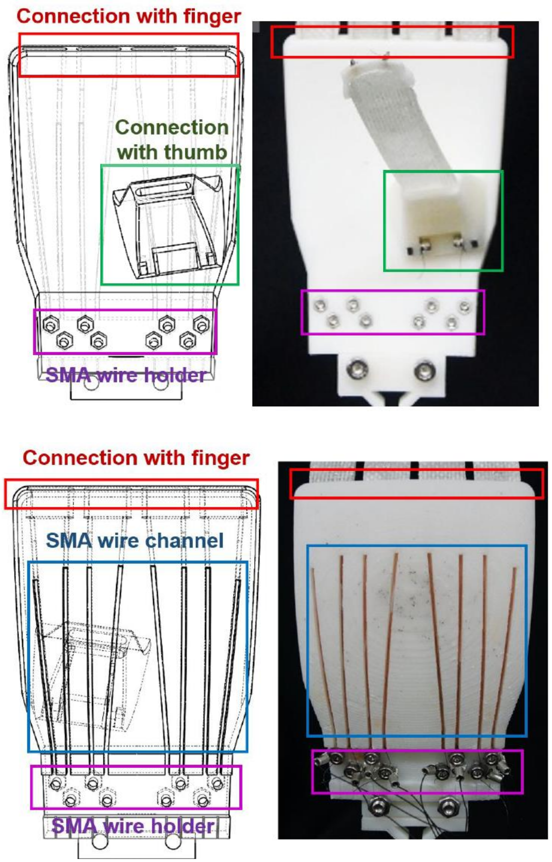
SMA wire-based tendon-driven artificial finger design



Photograph of the tendon-driven SSC bending actuator, illustrating the functional components

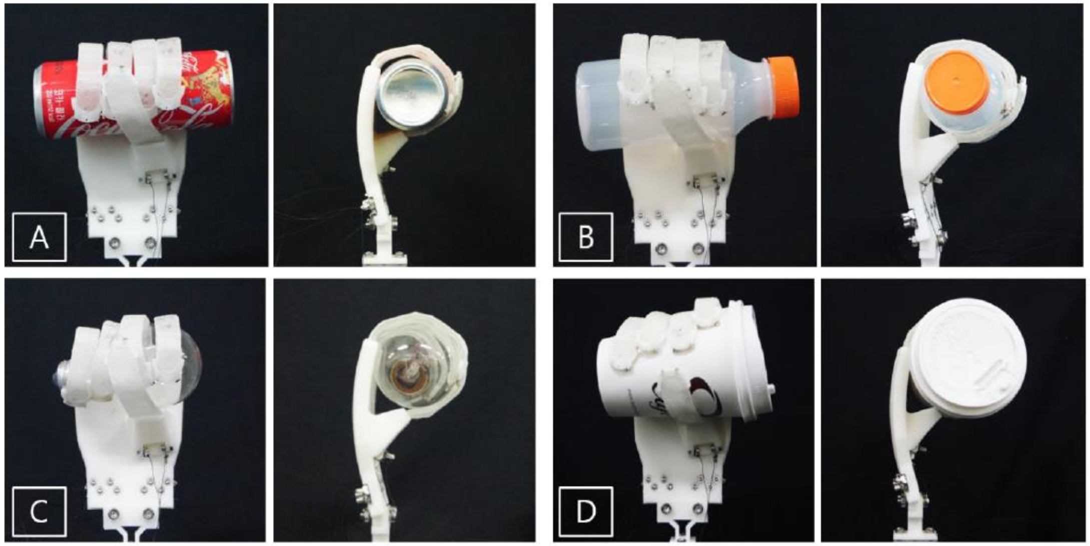
H.I. Kim, et al., Composites Part B, submitted.

Soft morphing hand driven by SMA tendon wire



The palm of the robotic hand

Sequences of images showing the bending actuation of the soft robotic hand prototype with a current of 0.8 A

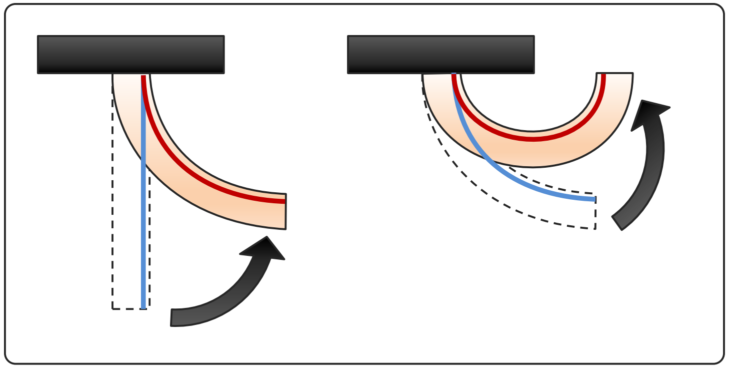


Photographs showing the grasping of various objects by the soft robotic hand

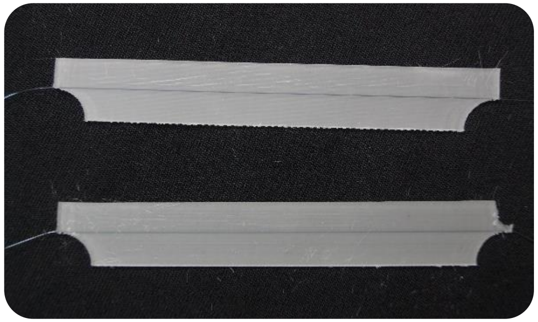
H.I. Kim, et al., Composites Part B, submitted.

Curved bending actuator

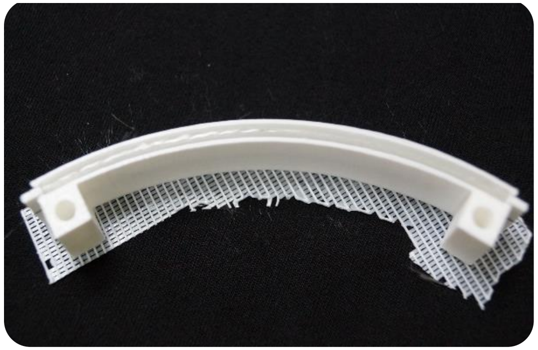
- **Design and manufacturing**
  - First casting process
  - Second casting process
  - Final curved actuator



Flat initial position versus curved initial position



Flat actuator after first mold



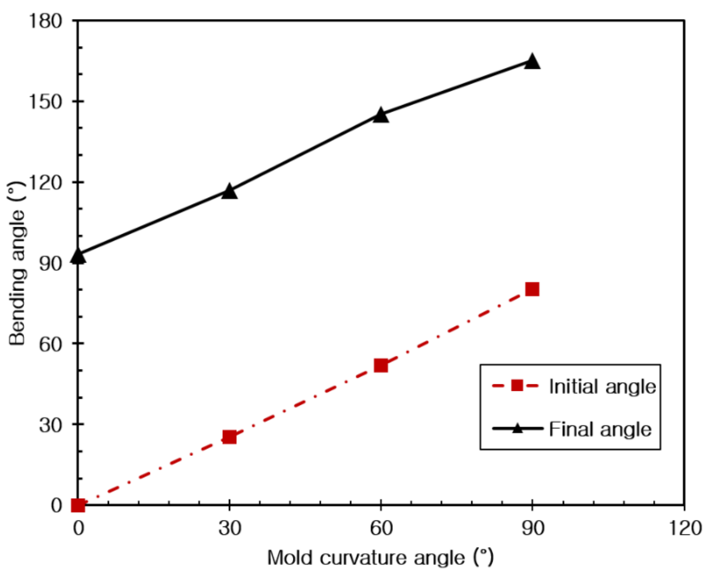
Flat actuators positioned into second mold

Curved actuator

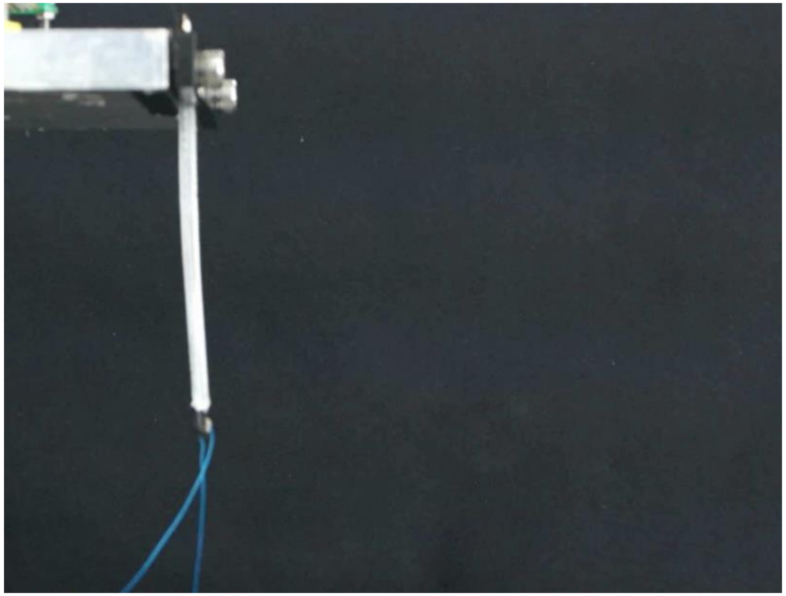
Rodrigue H, et al. TBD.

Curved bending actuator

- **Results**
  - Double casting allows to change the initial curvature without impacting the SMA wire’s pre-strain
  - An increase in initial angle allows a similar increase in final angle
  - Increased bending angle from 90° up to 165°



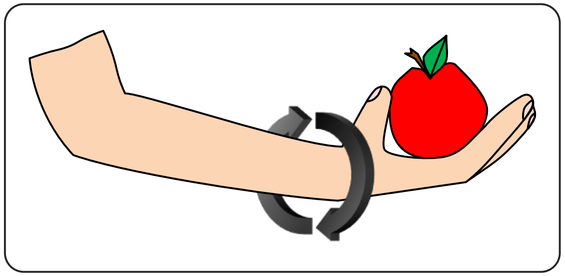
Increase in bending angle from initial curvature



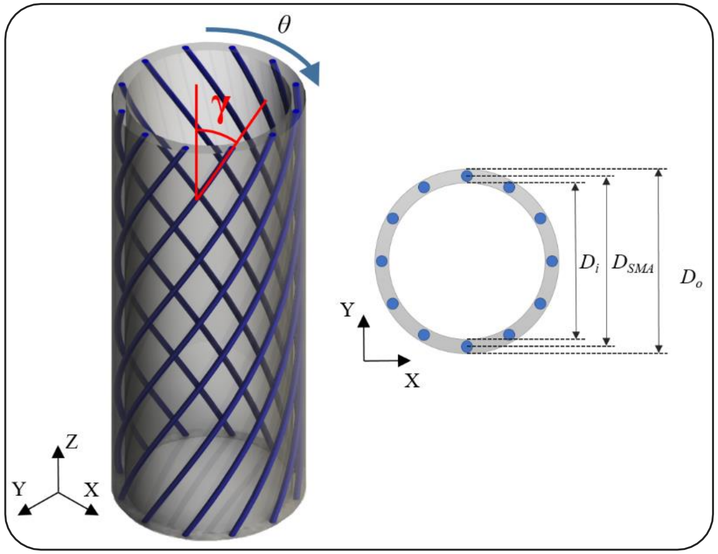
Flat actuator versus curved actuator

Soft robotic wrist

- **Goal of a soft wrist-like actuator**
  - Support a cantilever load
  - Produce a repeatable twisting motion
  - Rigid, compliant and can recover from buckling



Functions of a wrist



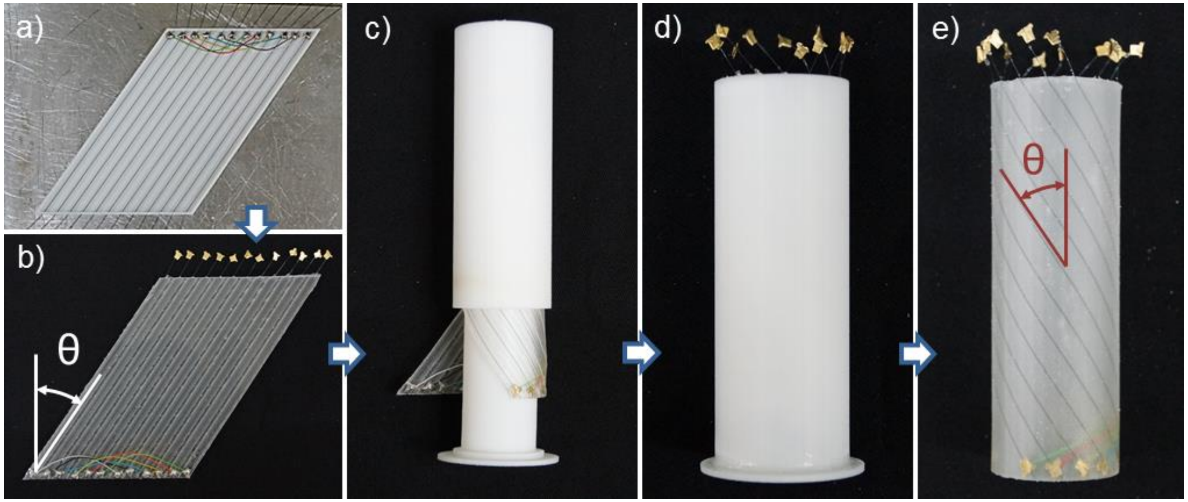
Proposed concept for a SMA-based soft robotic wrist

- **Actuator design**
  - Hollow-tube shape
    - Strong against cantilever loads
    - Minimum structure to contain SMA configuration
  - Multiple SMA wires
    - Large twisting force
  - Helix SMA wire positioning
    - Larger SMA angle in the matrix
  - Cannot be manufactured using a simple mold

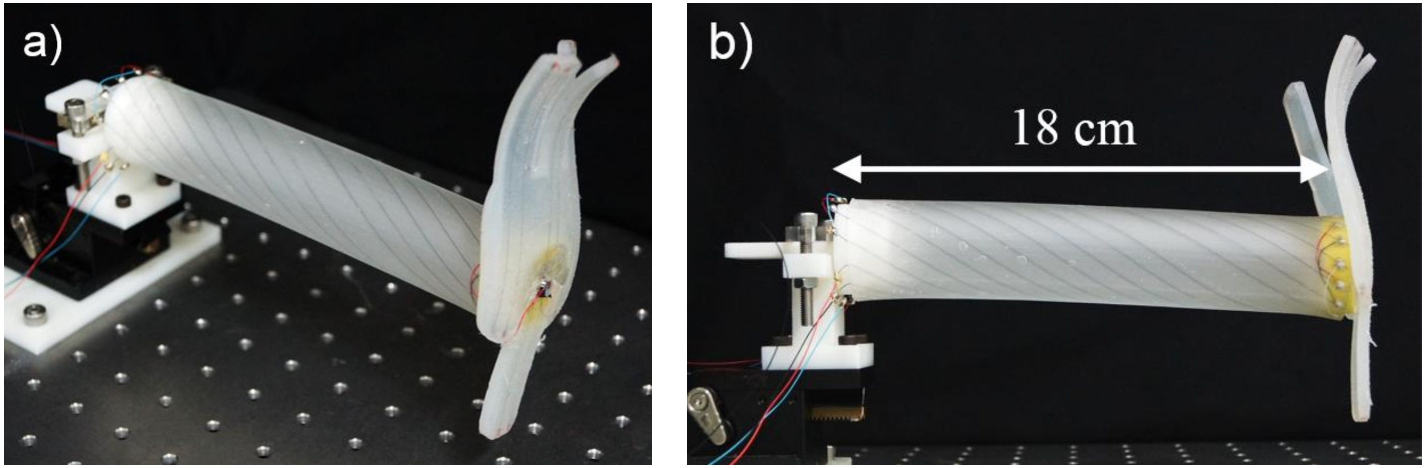
Rodrigue H, et al. Fabrication of wrist-like SMA-based actuator by double smart soft composite casting. Smart Materials and Structures, 2015, 24(12): 125003.

Soft robotic wrist

- **Manufacturing by double casting**



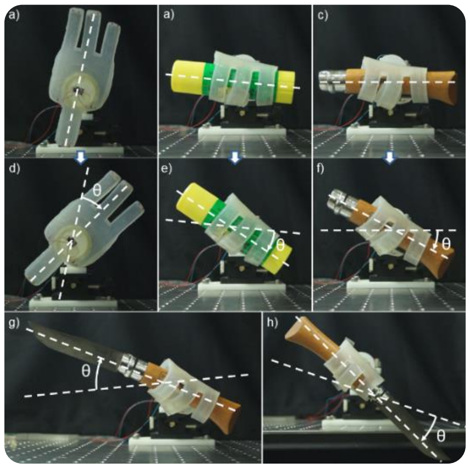
- **Manufactured soft robotic wrist sample**



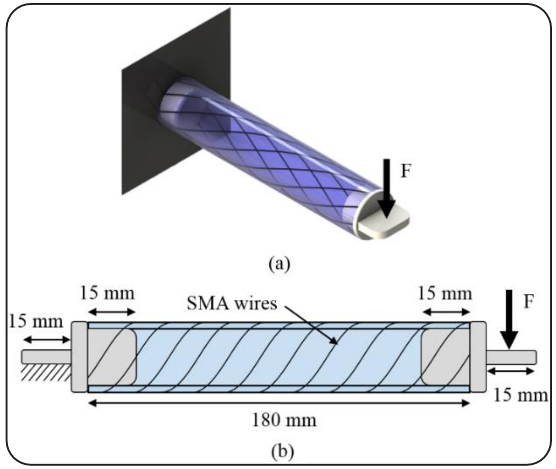
Rodrigue H, et al. Fabrication of wrist-like SMA-based actuator by double smart soft composite casting. Smart Materials and Structures, 2015, 24(12): 125003.

Soft robotic wrist

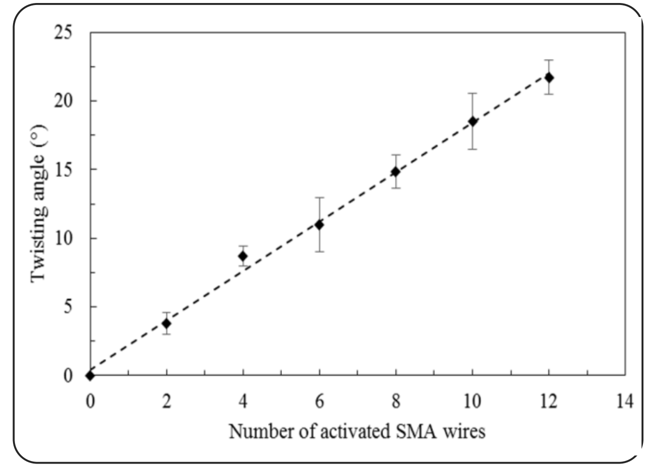
- **Actuation properties**



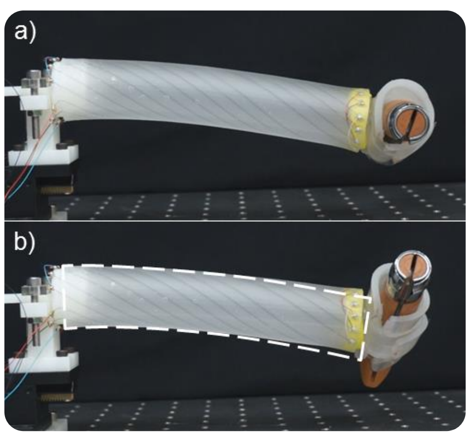
~30° twisting angle



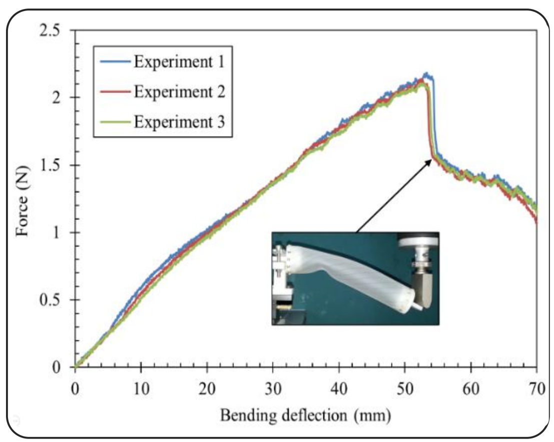
Setup for buckling limit test



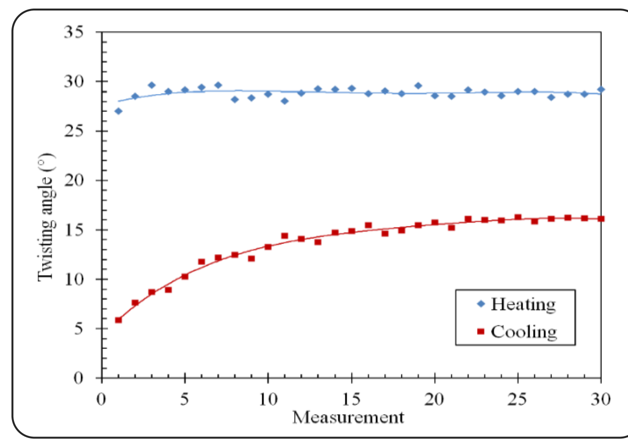
Simple control method



Slight bending recovery



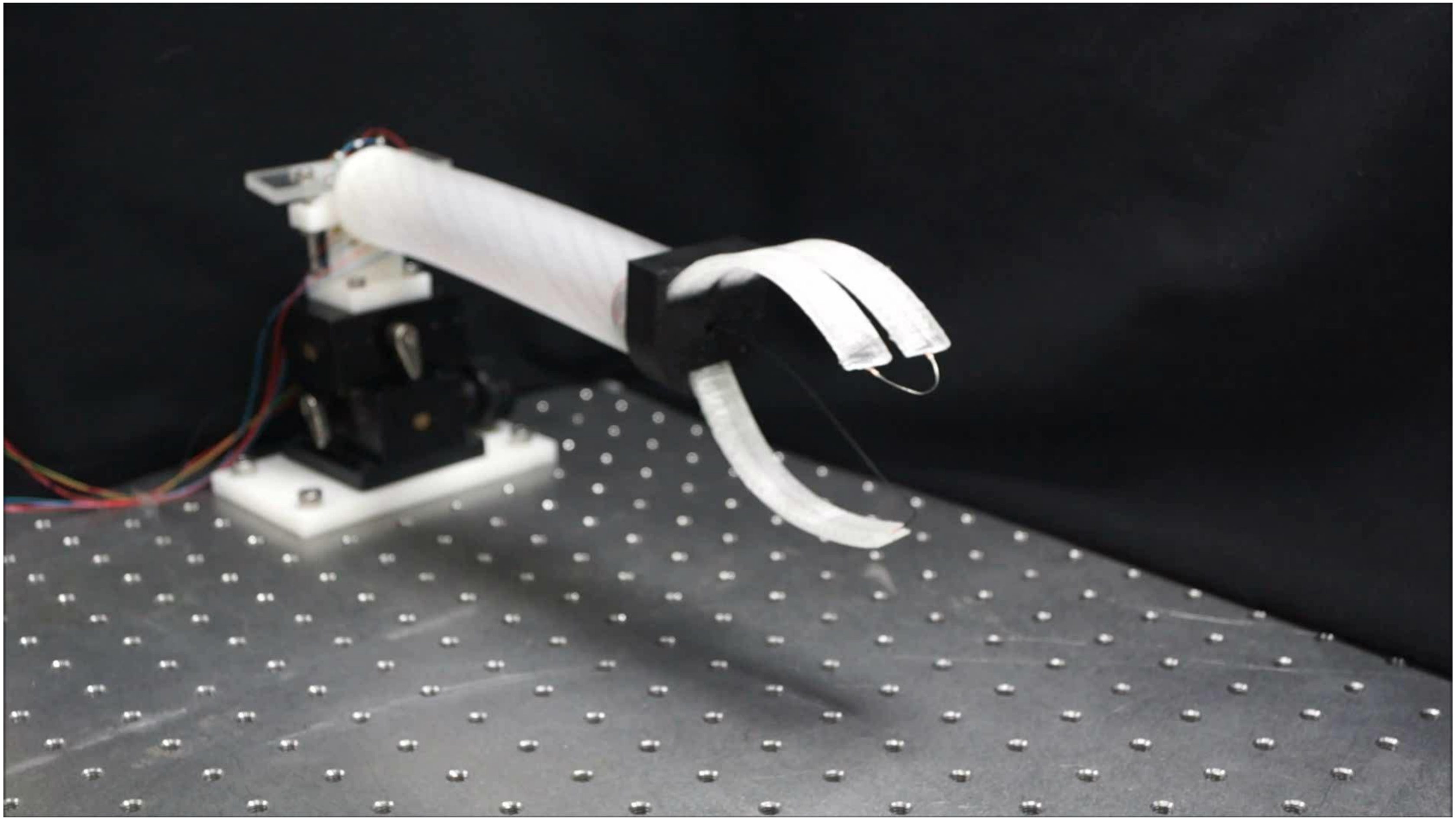
2N buckling limit



Good repeatability

Rodrigue H, et al. Fabrication of wrist-like SMA-based actuator by double smart soft composite casting. Smart Materials and Structures, 2015, 24(12): 125003.

Soft robotic wrist + gripper with curved fingers



Rodrigue H, et al. TBD.

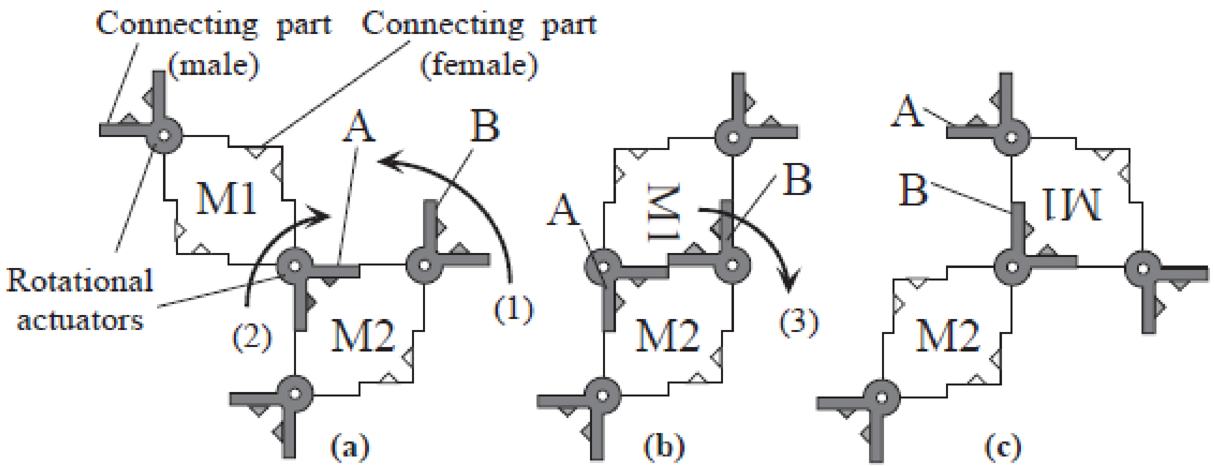
SHAPE MEMORY ALLOY FOR SELF-RECONFIGURABLE ROBOTS

Self-reconfigurable robots

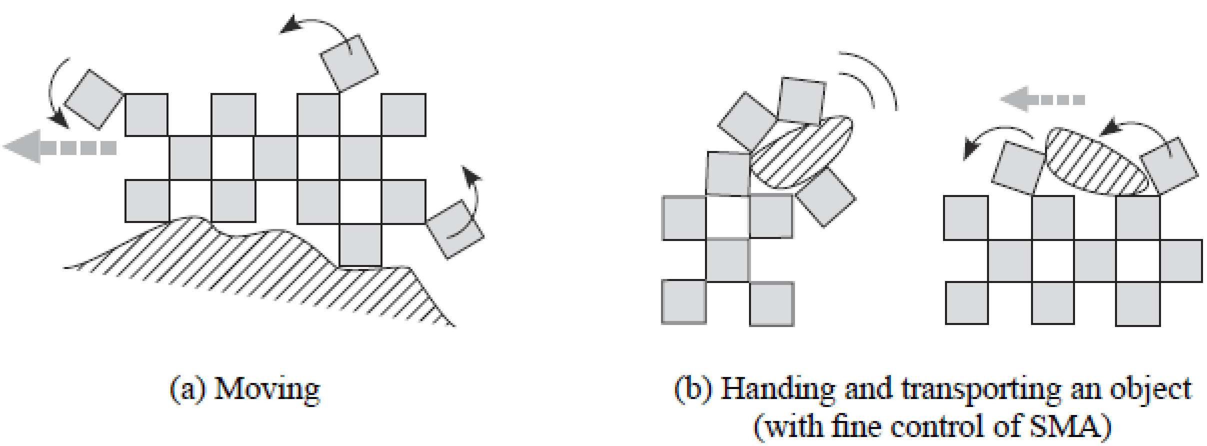
- Modular self-reconfigurable robots
  - Can adaptively change their shape and locomotion patterns or repair themselves
  - Unforeseen circumstances
  - Fire fighting
  - Urban search
  - Search after an earthquake
  - Battlefield reconnaissance
- 3 important aspects of reconfigurable robots
  - Versatility
  - Robustness
  - Lowest cost

[9] Yoshida, E. et al., (2002), "Get back in shape! – A hardware prototype self-reconfigurable modular microrobot that uses shape memory alloys", IEEE Robotics & Automation Magazine, Vol. 9 No. 4, pp. 54-60.

Modular self-reconfigurable robots

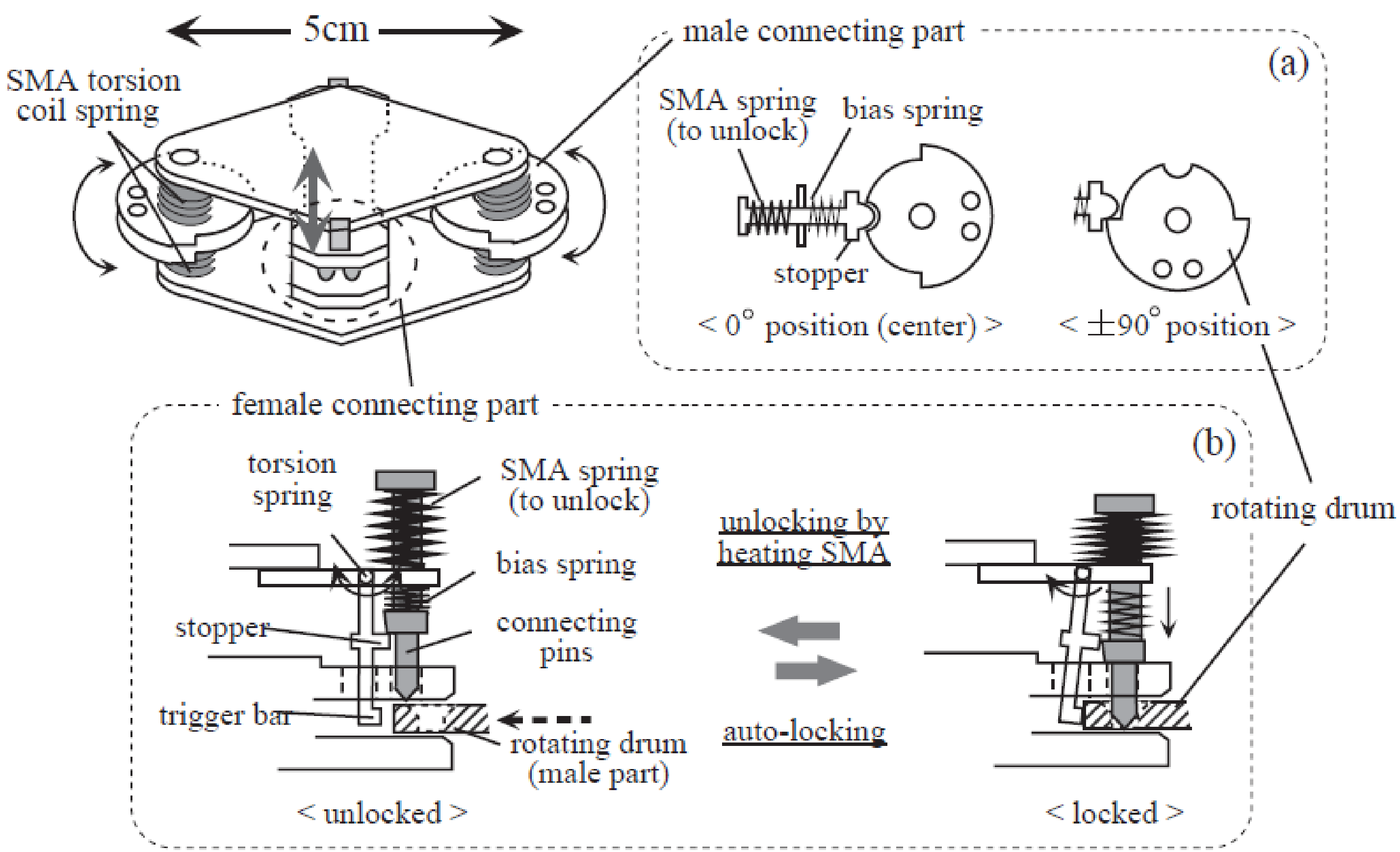


"Step motion" of two modules and module mechanism



Various shapes and movements generated by self-reconfigurable modules

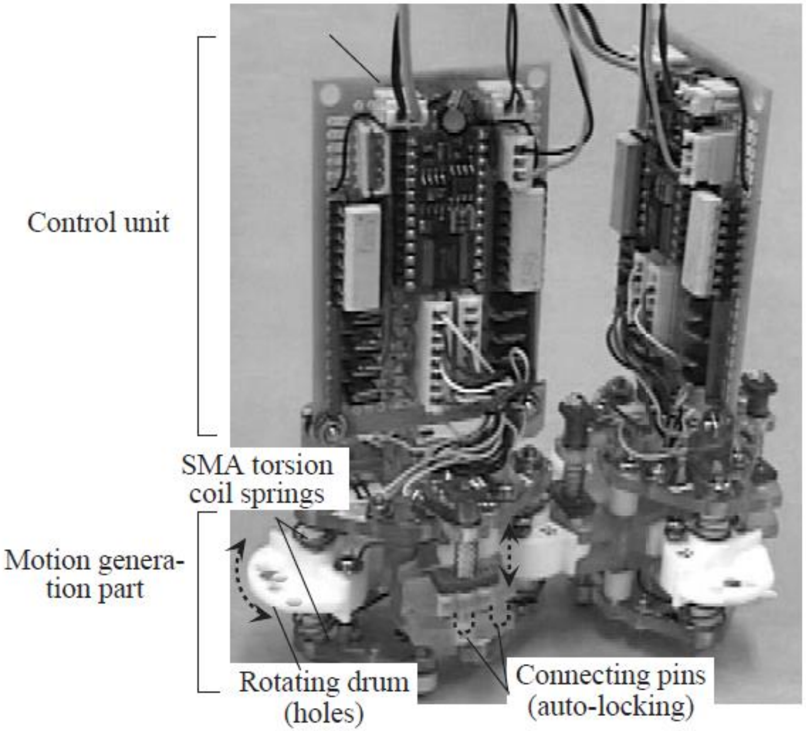
Modular self-reconfigurable robots



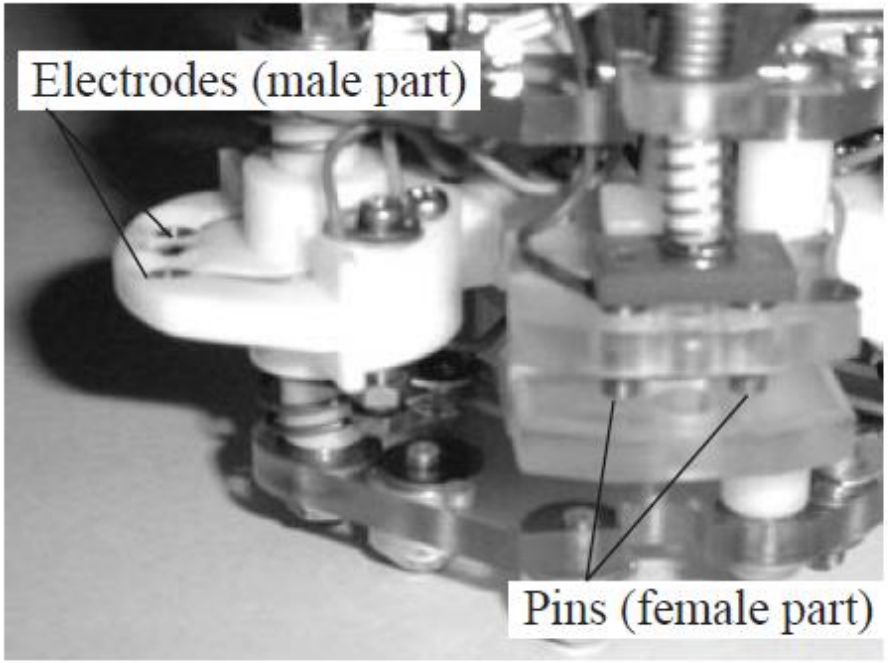
Structure of the prototype module

- The original 0° position of a rotating drum is maintained rigidly by a stopper
- Rotation becomes possible when the stopper is pulled back by heating the connection-releasing SMA spring (a)
- The stopper also limits the drum rotation within the range from -90° to 90°

Modular self-reconfigurable robots

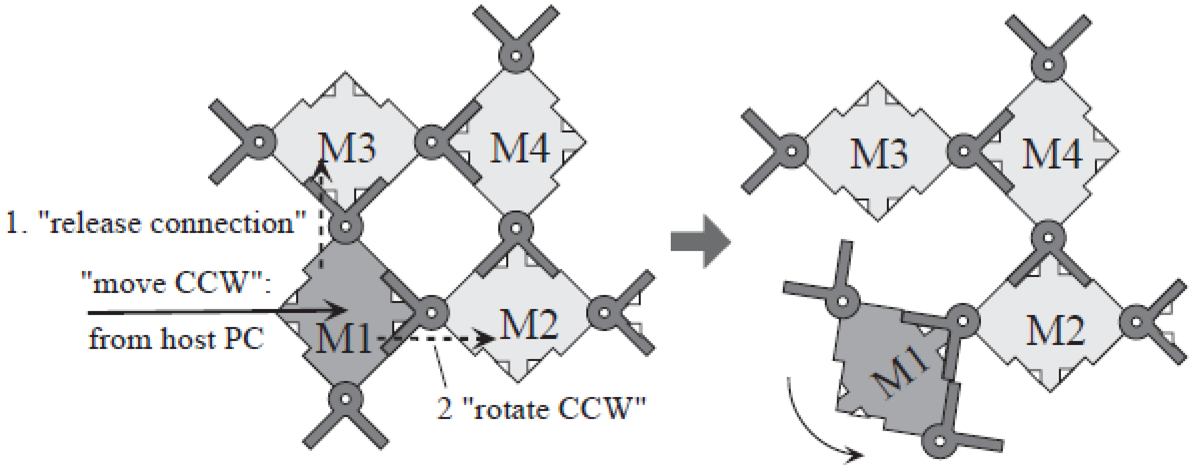


Overview of prototype module

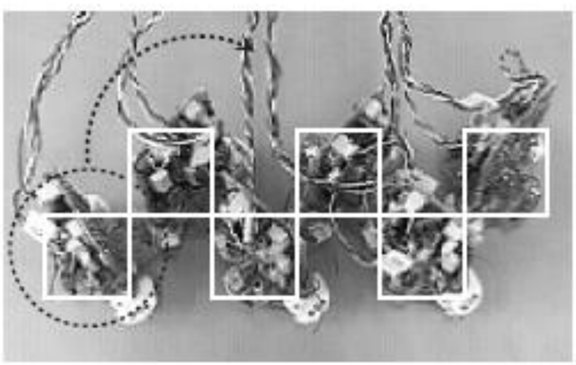


Inter-module connection for communication

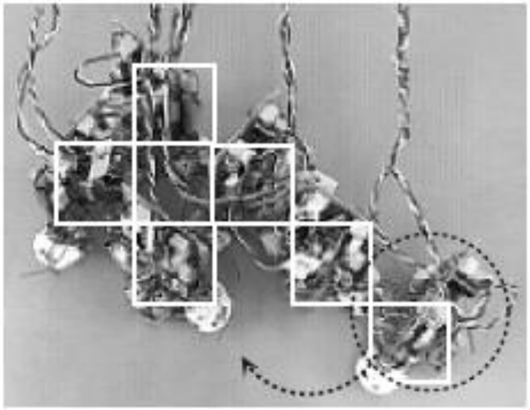
Modular self-reconfigurable robots



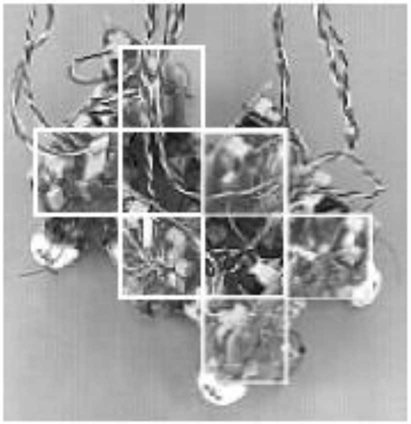
Local motion coordination through inter-module communication



(a) Initial state



(b) Transient state



(c) Self-reconfiguration completed

Self-reconfiguration experiment using six modules

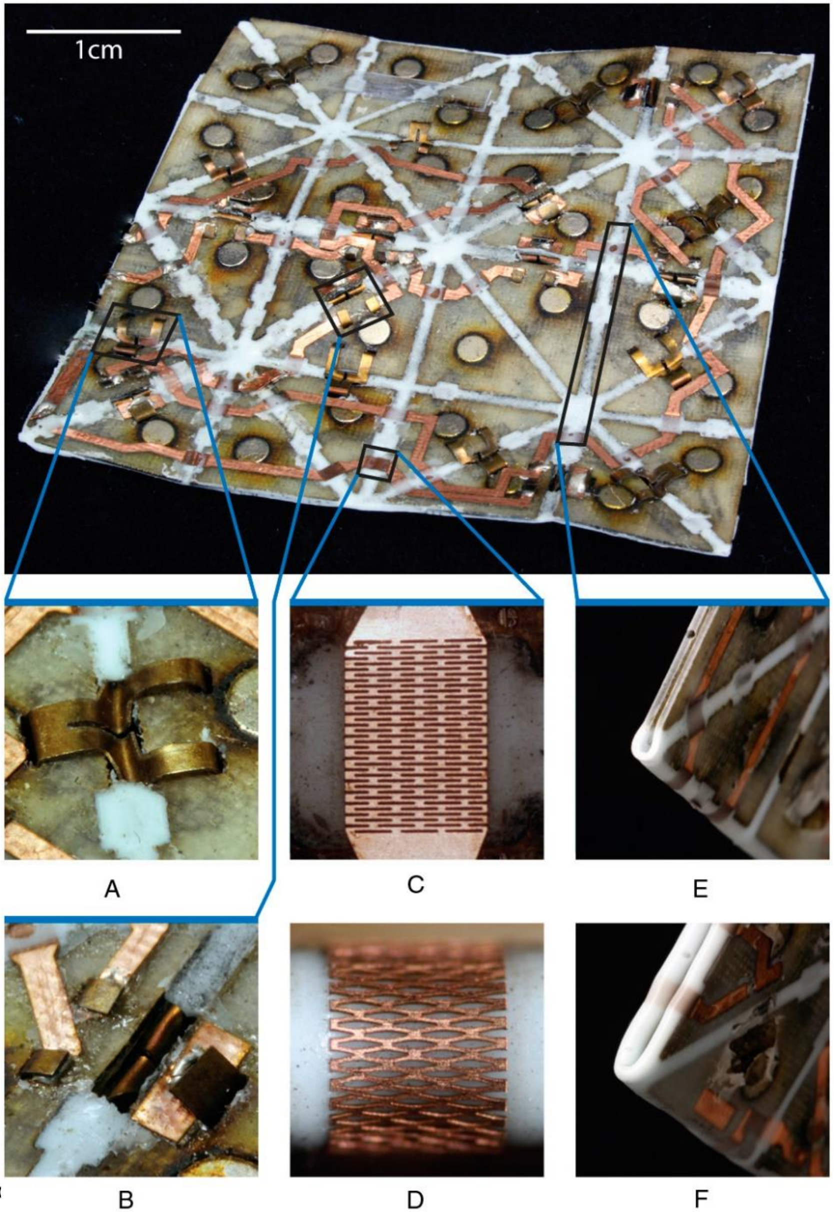
Self-reconfigurable robots

- **Programmable matter by folding**
  - Programmable sheets can form themselves in different shapes autonomously by folding
    - Previous works were limited by,
      - small feature sizes
      - large number of components
      - complexity of communication among the units.

  - Unique concept of self-folding origami with universal crease patterns
  - Single sheet composed of interconnected triangular sections
  - Sheet can fold into a set of predetermined shapes using embedded actuation (SMA)

[11] E. Hawkesa, B. Anb, N. M. Benbernoub, H. Tanakaa, S. Kimc, E. D. Demaineb, D. Rusb, and R. J. Wooda, Programmable matter by folding, Proceedings of the National Academy of Sciences USA, June, 2010

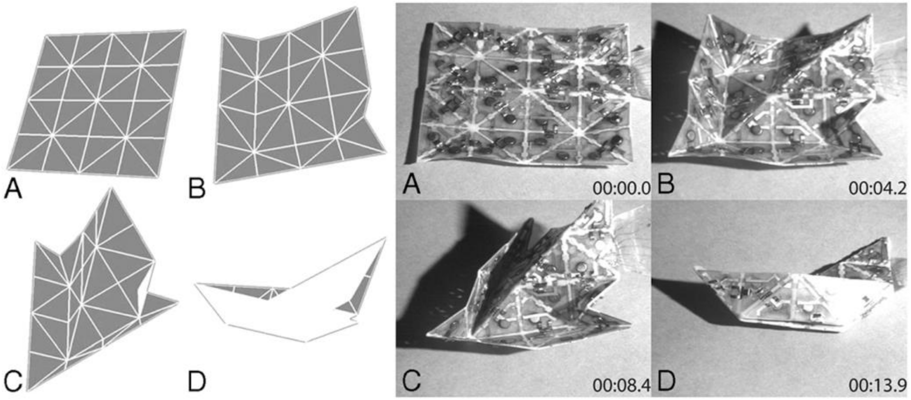
Programmable matter by folding



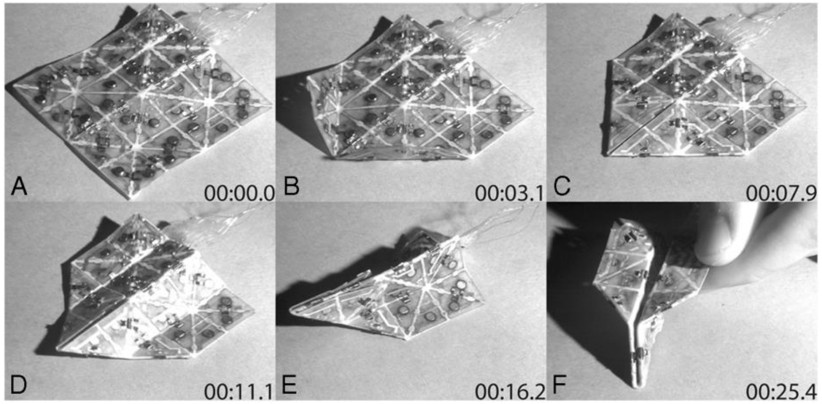
- 32-tile self-folding sheet, capable of achieving **two distinct shapes**: a "paper airplane" and a "boat"
- Joule-heated SMA bending actuator "stapled" into the top (A) and bottom (B) sides of the sheet
- Patterned traces cross the silicone flexures and are shown unstretched (C) and after stretching as a flexure bends 180° (D)
- Silicone flexure bent 180°, with both a single fold (E) and folded again to create a compound fold (four layers thick) (F).

Hawkes E, An B, Benbernou N M, et al. Programmable matter by folding. Proceedings of the National Academy of Sciences, 2010, 107(28): 12441-12445.

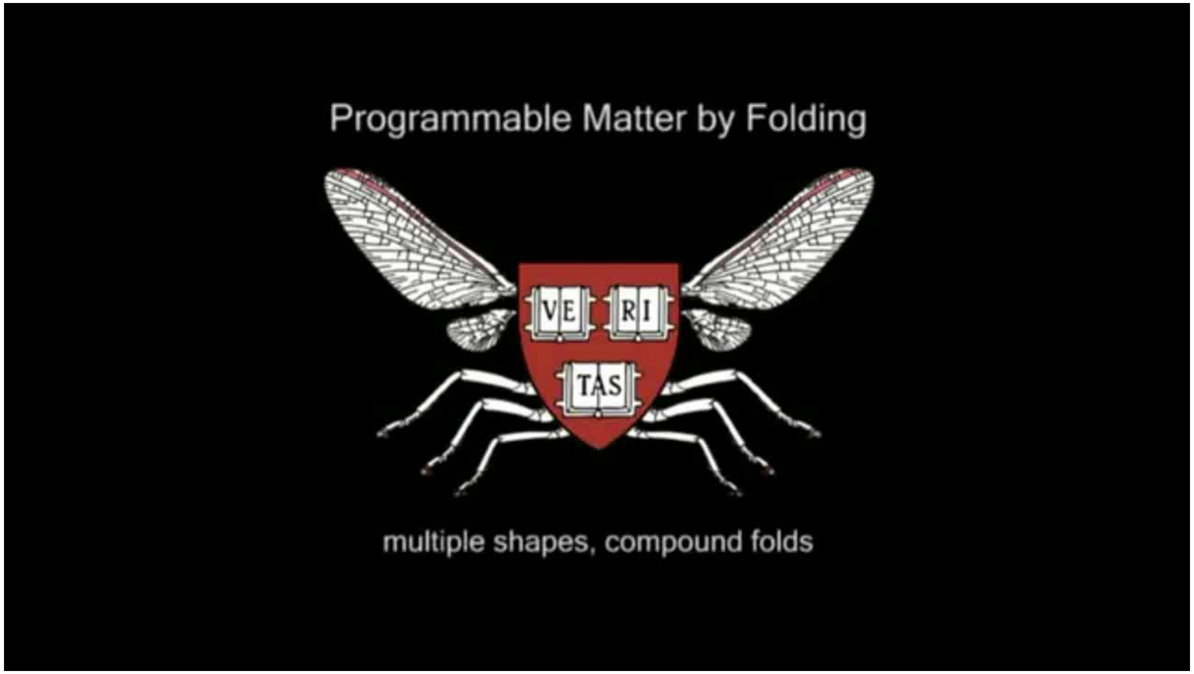
Folding experiments



Simulation (left) and experiments (right) of a self-folding “boat”



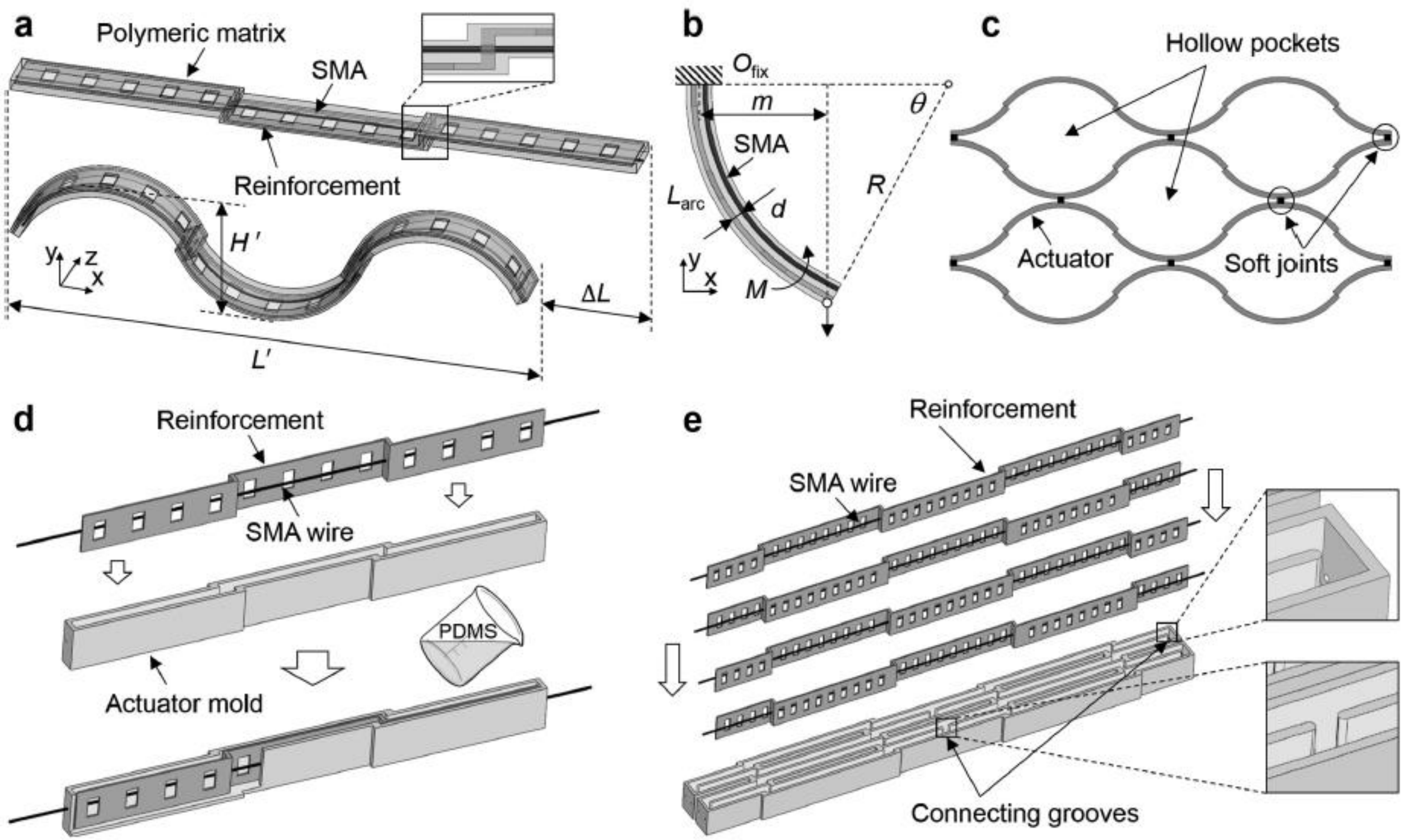
Folding experiments of a self-folding “airplane”



Hawkes E, An B, Benbernou N M, et al. Programmable matter by folding. Proceedings of the National Academy of Sciences, 2010, 107(28): 12441-12445.

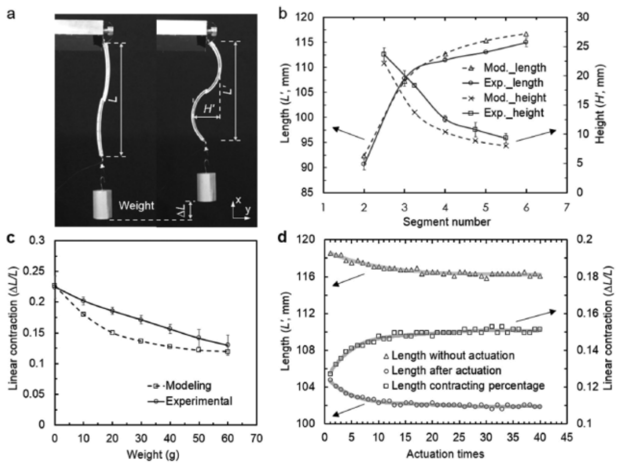
Kirigami/Origami-Based Soft Deployable Actuator

Design and fabrication of the soft deployable structure.

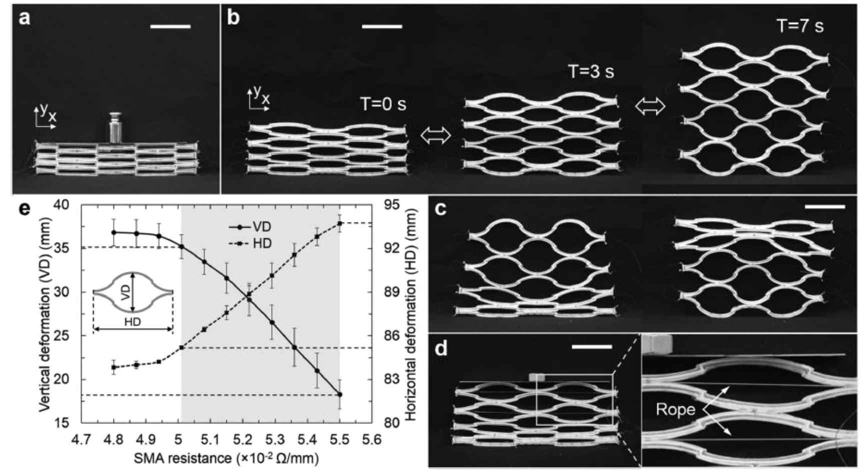


Wang, W., Li, C.Z., Rodrigue, H., Yuan, F.P., Han, M.W., Cho, M.H. and Ahn, S.H., 2017, "Kirigami/Origami-based Soft Deployable Reflector for Optical Beam Steering," Advanced Functional Materials, Volume 27, Issue 7, No.: 1604214, February 17, 2017

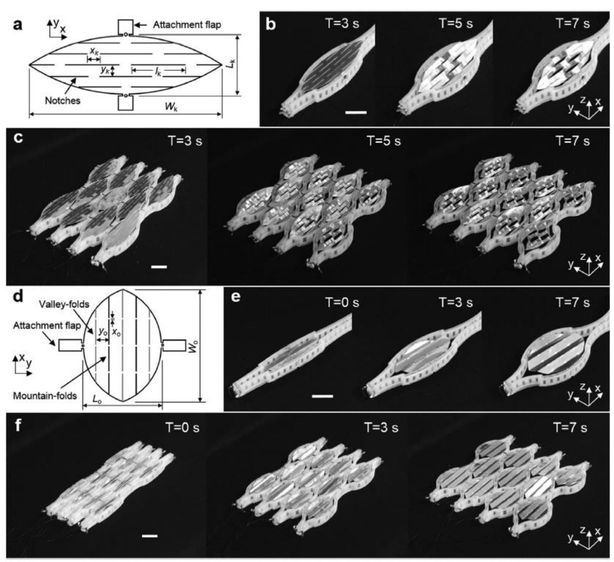
Kirigami/Origami-Based Soft Deployable Actuator



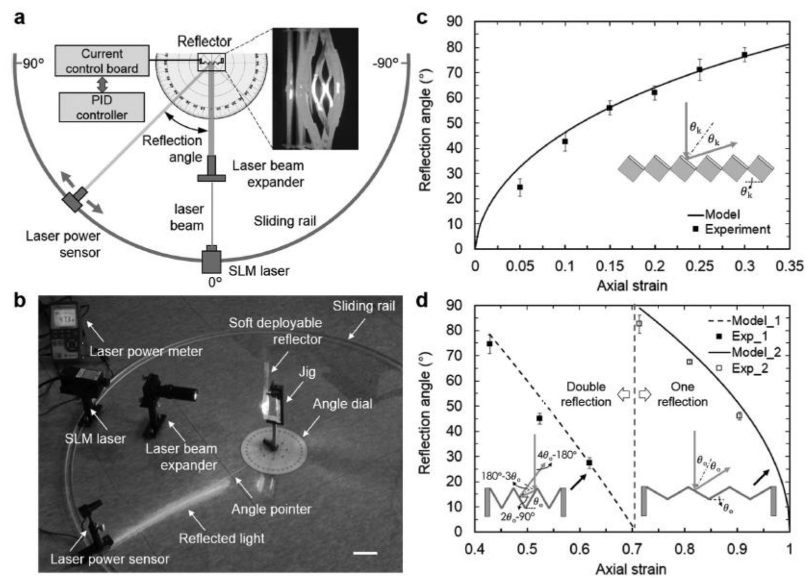
The performance of soft linear actuators



Configurations of the soft deployable structure

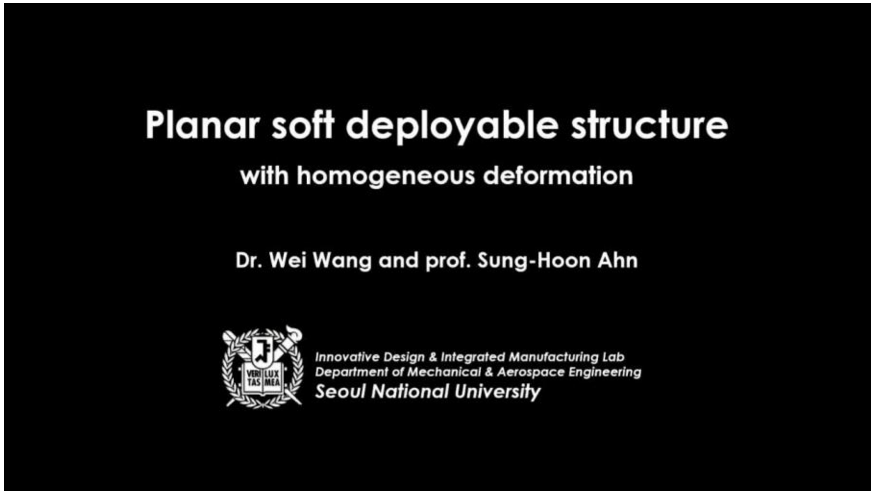


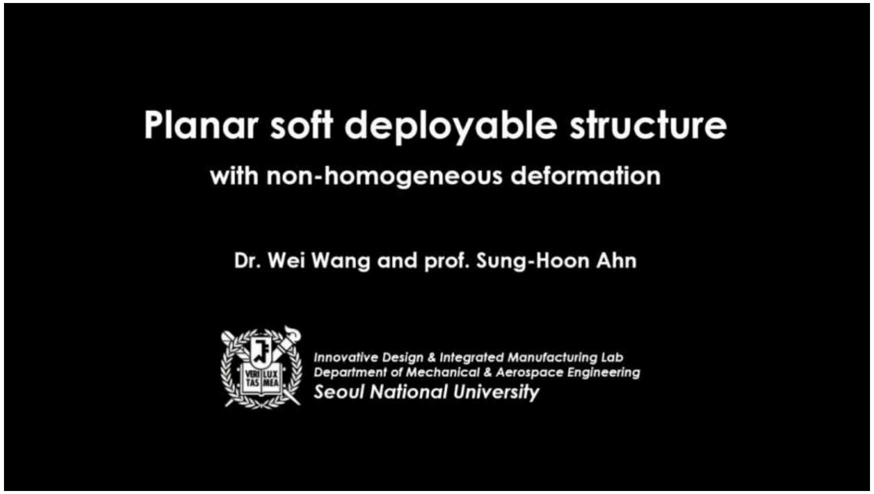
Soft deployable reflectors

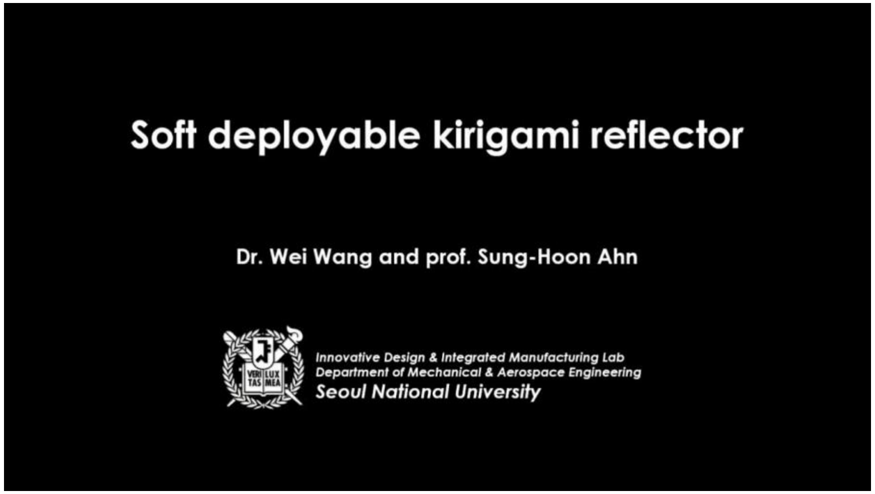


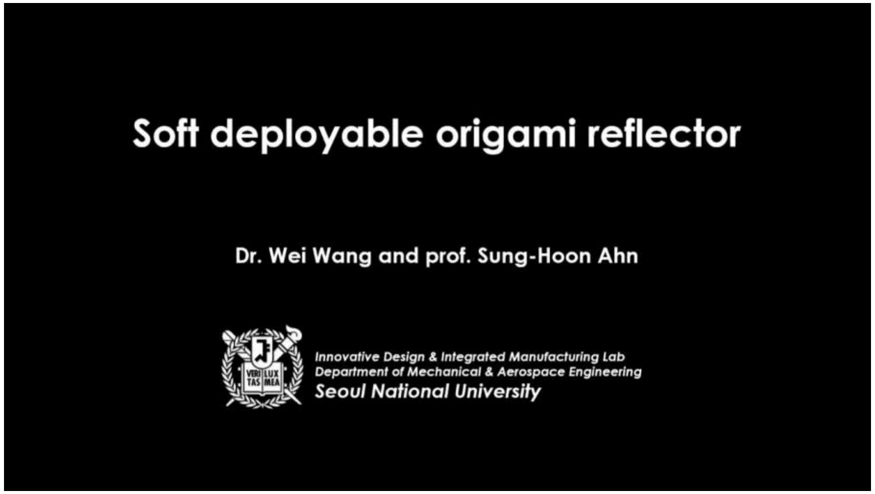
Performance evaluation of soft deployable reflectors

Kirigami/Origami-Based Soft Deployable Reflector



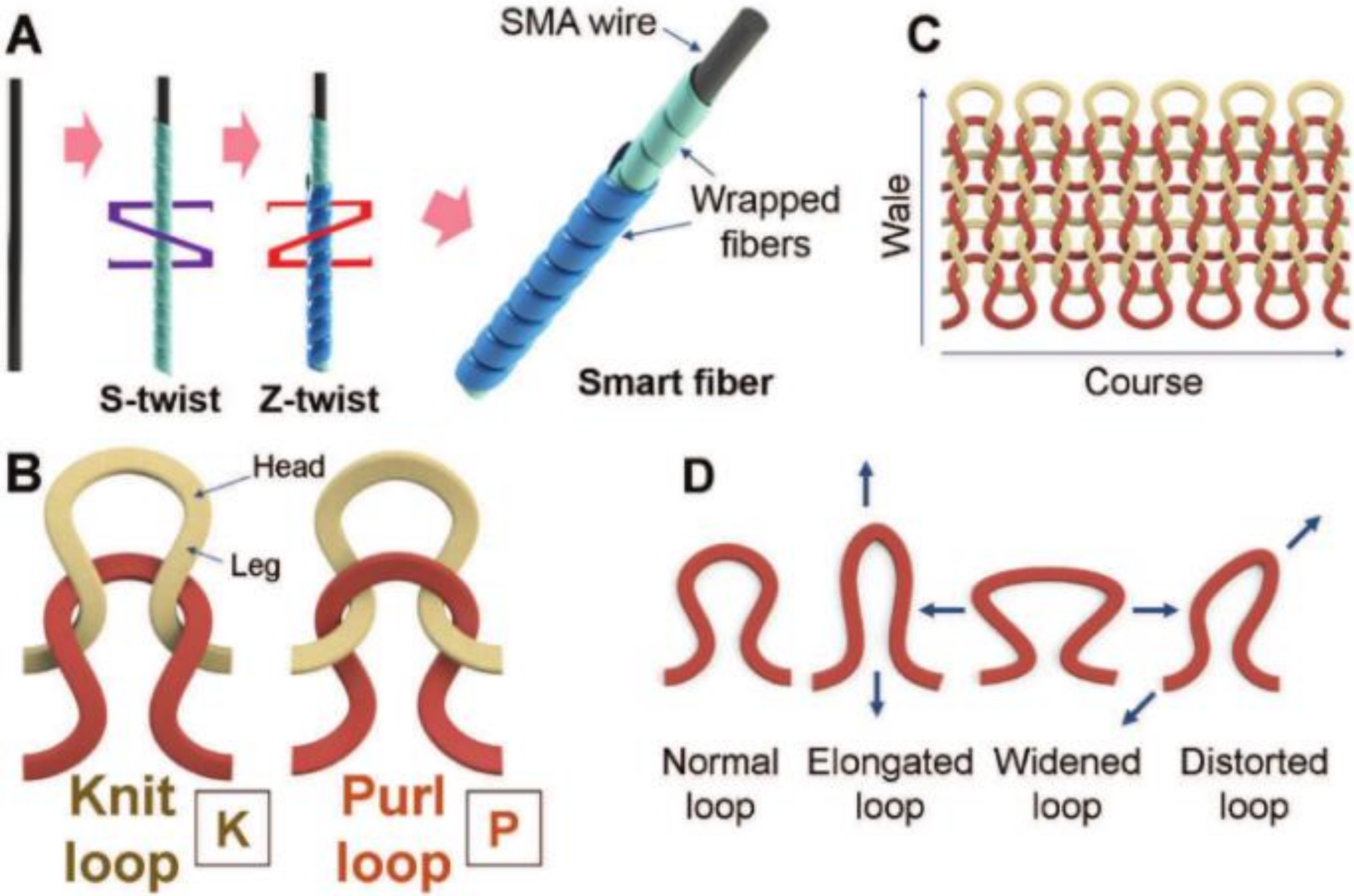






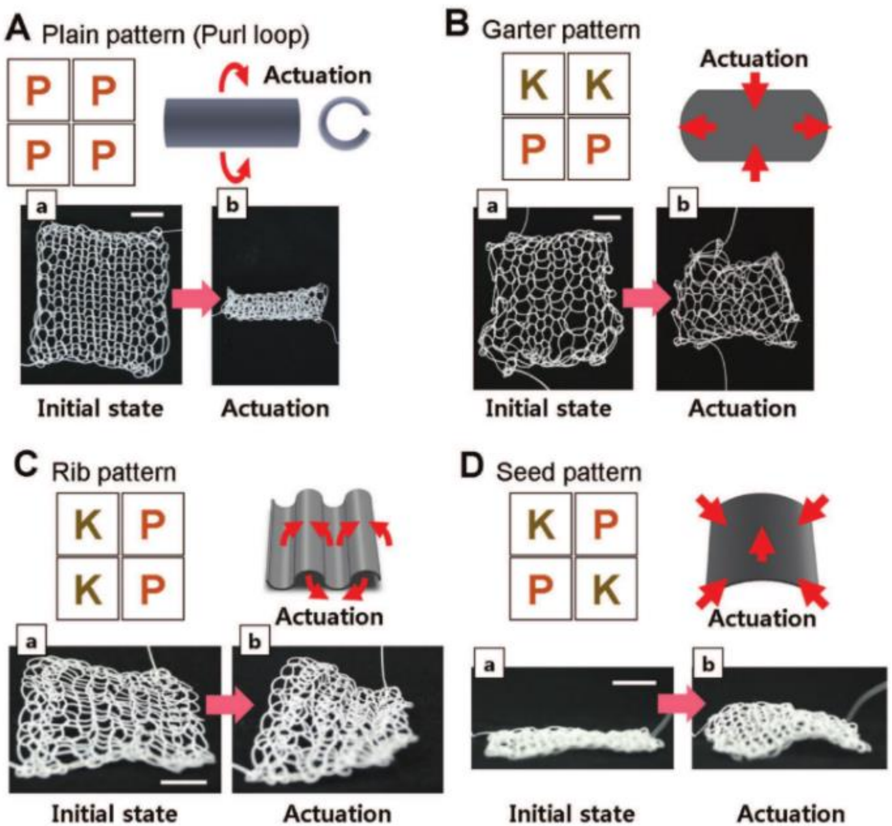
Wang, W., Li, C.Z., Rodrigue, H., Yuan, F.P., Han, M.W., Cho, M.H. and Ahn, S.H., 2017, "Kirigami/Origami-based Soft Deployable Reflector for Optical Beam Steering," Advanced Functional Materials, Volume 27, Issue 7, No.: 1604214, February 17, 2017

Loop-linked soft morphing structure

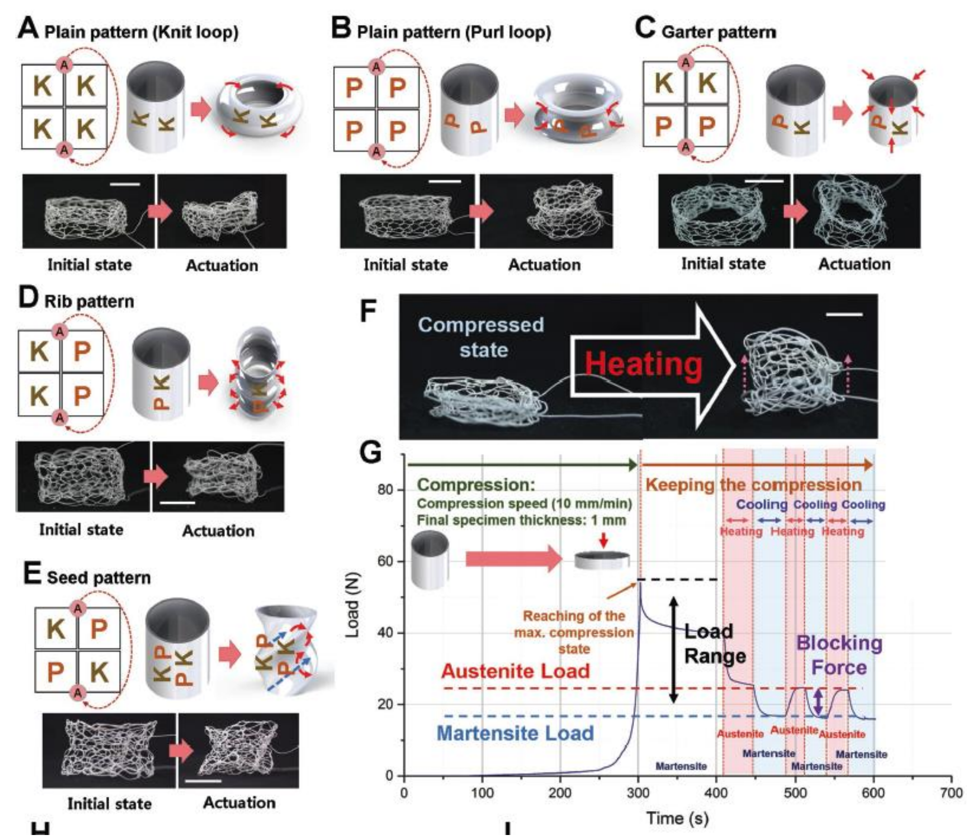


Han, M.W. and Ahn, S.H., 2017, "Blooming Knit Flowers: Loop-linked Soft Morphing Structures for Soft Robotics," Advanced Materials, Wiley-VCH (Germany), Vol. 29, No. 13, 1606580

Loop-linked soft morphing structure



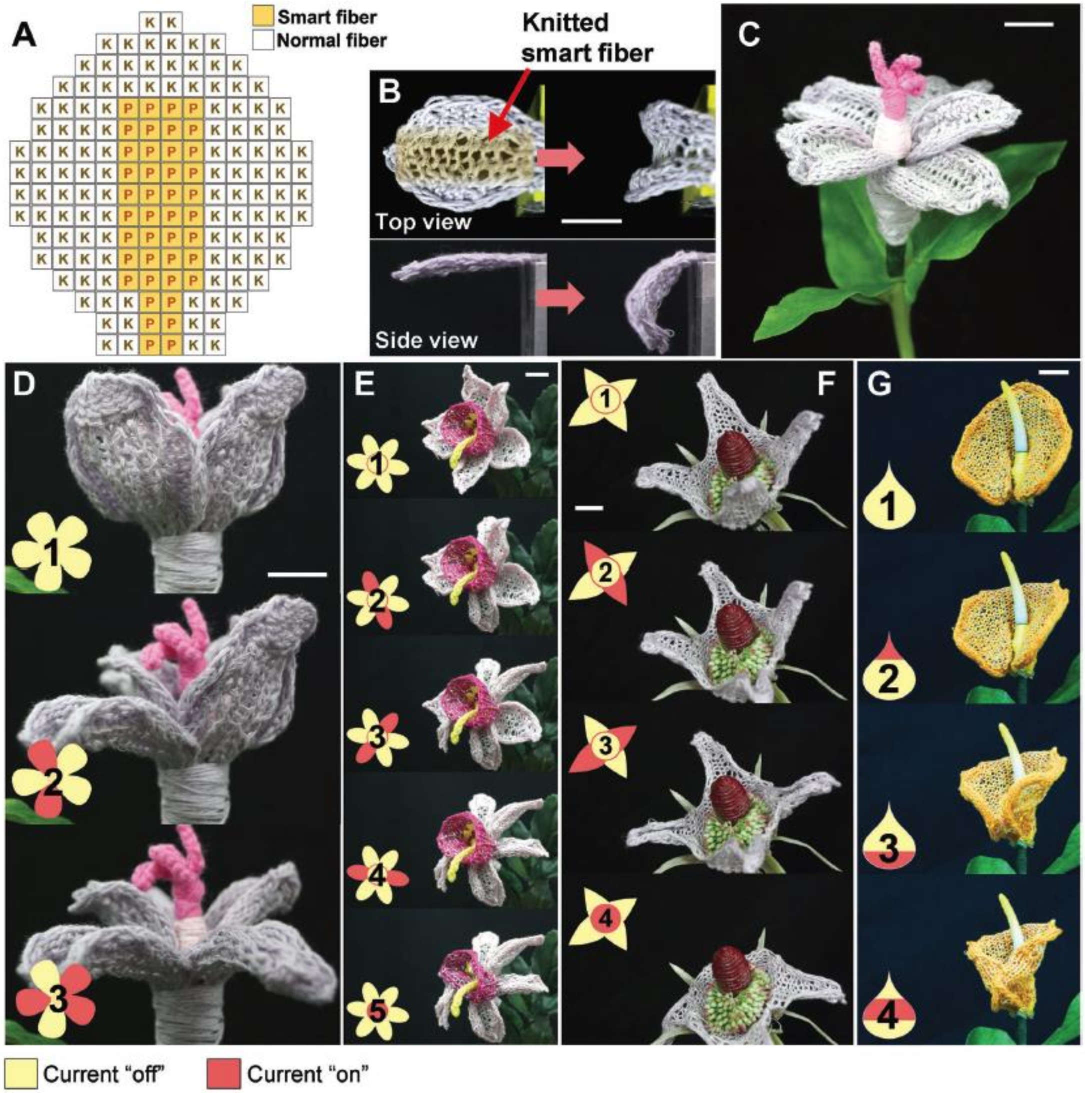
2D open geometry



3D closed geometry

Han, M.W. and Ahn, S.H., 2017, "Blooming Knit Flowers: Loop-linked Soft Morphing Structures for Soft Robotics," Advanced Materials, Wiley-VCH (Germany), Vol. 29, No. 13, 1606580

Morphing flowers



Han, M.W. and Ahn, S.H., 2017, "Blooming Knit Flowers: Loop-linked Soft Morphing Structures for Soft Robotics," Advanced Materials, Wiley-VCH (Germany), Vol. 29, No. 13, 1606580

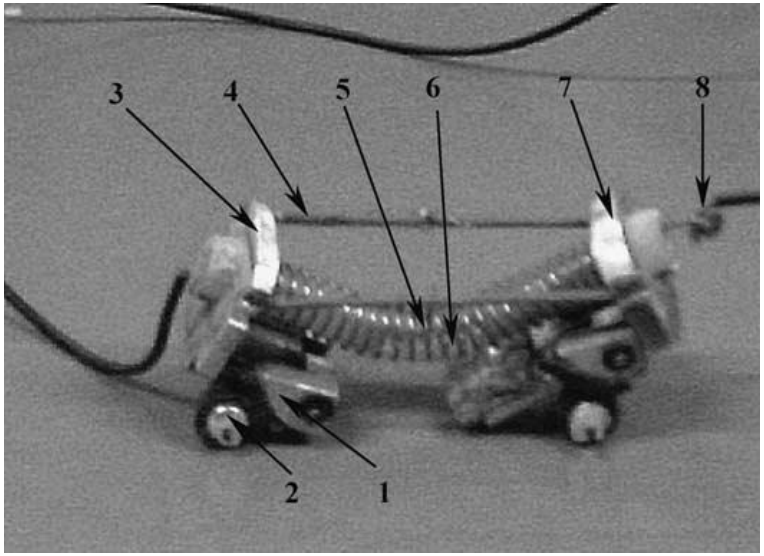
SHAPE MEMORY ALLOY FOR AUTONOMOUS, WALKING AND IN-PIPE ROBOTS

Autonomous, walking and in-pipe robots

- **Micro robots are generally classified as, based on the mode of locomotion**
  - Scolopendrid locomotion
  - Peristaltic locomotion
  - Inchworm locomotion,
- **Applications**
  - Wide range of pipes in building, nuclear power stations, and petroleum sites, etc.
- **Design considerations**
  - Capable of moving inside flexible pipes like veins, arteries
  - Design of SMA spring and bias spring
  - Mechanical modeling of actuators, which produced inchworm motion and heating/cooling cycle

Micro Trolley

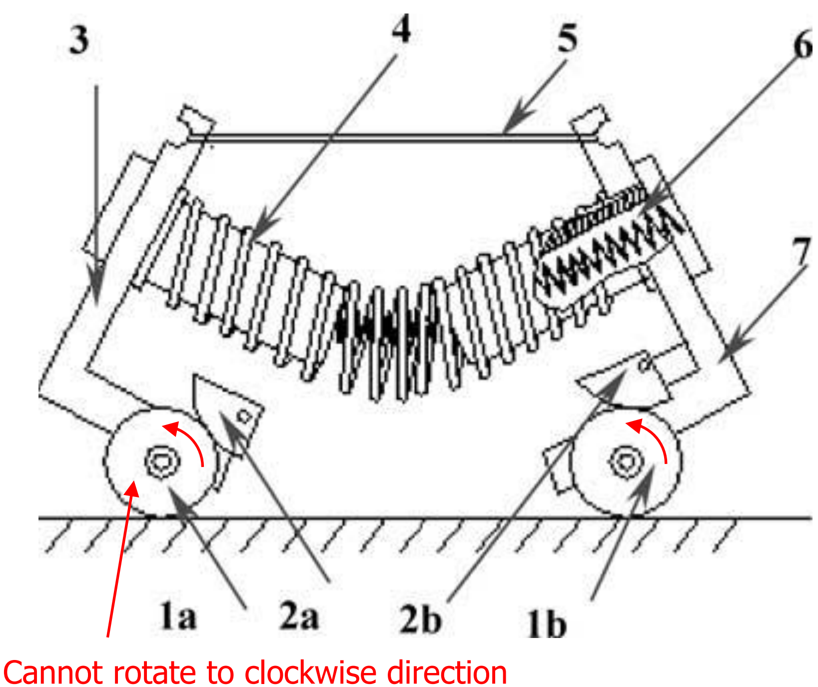
- **The Micro Trolley Based on SMA and its Control System**
  - Micro-trolley imitating an insect
  - Actuated by SMA springs
  - Experimentally tested on rubber and glass surfaces



Mechanical structure
1 – anti-reverse device
2 – wheel
3 – front body of the trolley
4 – elastic rubber band
5 – SMA Spring
6 – ordinary bias spring
7 – back body of
the trolley
8 – the lead connects with control system.

[10] Yao, Q., Jin, S. and Ma, P.N. (2004), "The micro trolley based on SMA and its control system", Journal of Intelligent and Robotic Systems, Vol. 39, pp. 199-208.

Micro Trolley



Scheme diagram of the trolley:
1a – front wheel
1b – back wheel
2a – anti-reverse device attached to the front wheel
2b – anti-reverse device attached to the back wheel
3 – front body of the trolley
4 – ordinary bias spring
5 – elastic rubber band
6 – SMA spring
7 – back body of the trolley.

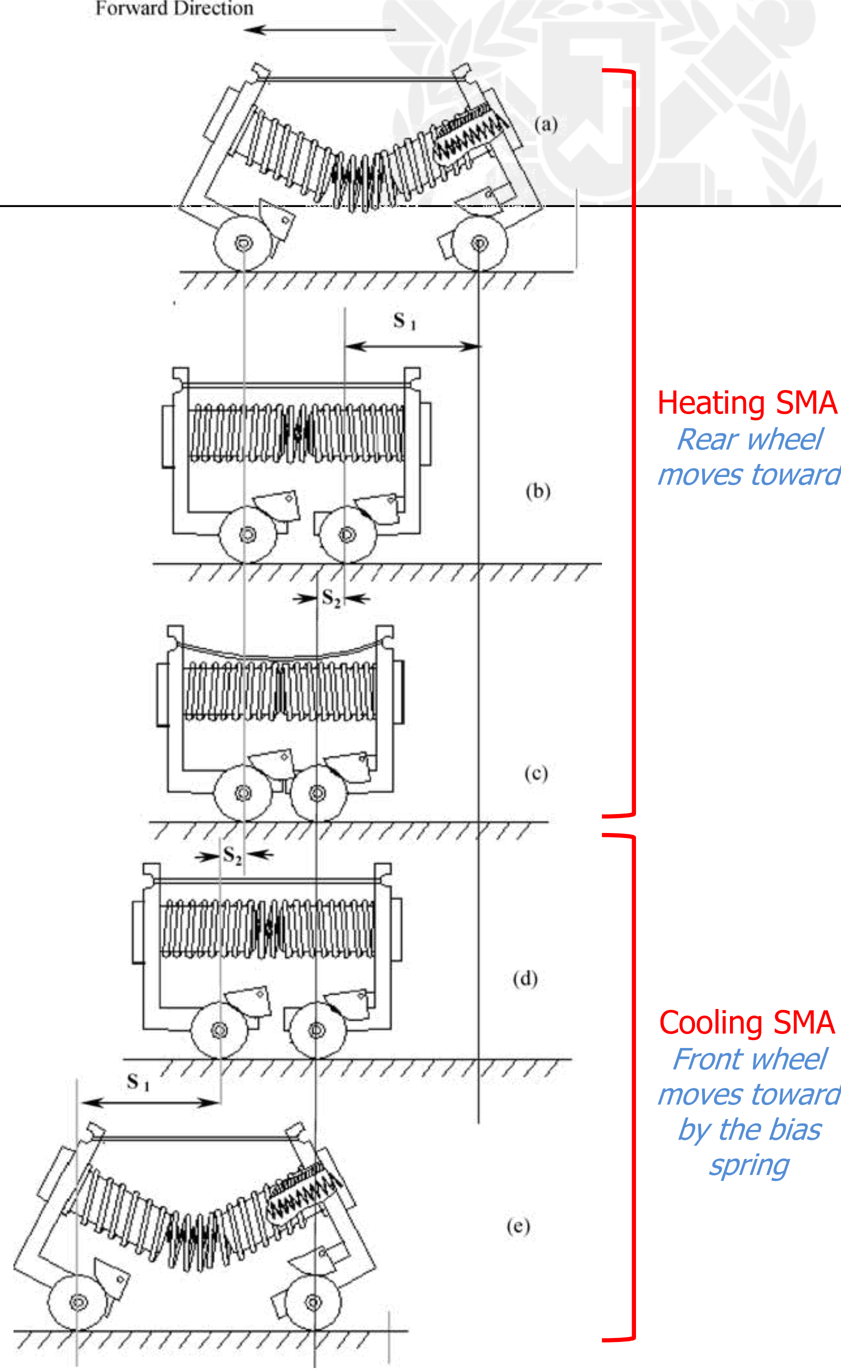


Illustration of movement mechanism

SHAPE MEMORY ALLOY FOR MICRO SYSTEMS

REVIEW 2 : TINI-BASED THIN FILMS IN MEMS APPLICATIONS: A REVIEW

Requirements for TiNi SMA thin film

- **The enabling technologies for TiNi films requires**
  - Reliable and MEMS-compatible deposition methods with precise control of film composition and quality
  - Reliable and precise characterization technologies for various properties
  - Appropriate post-deposition annealing for film crystallization or aging process compatible with MEMS process
  - Precise etching and patterning of TiNi film with MEMS
  - Prediction and modeling of non-linear behavior of TiNi films as well as design and simulation

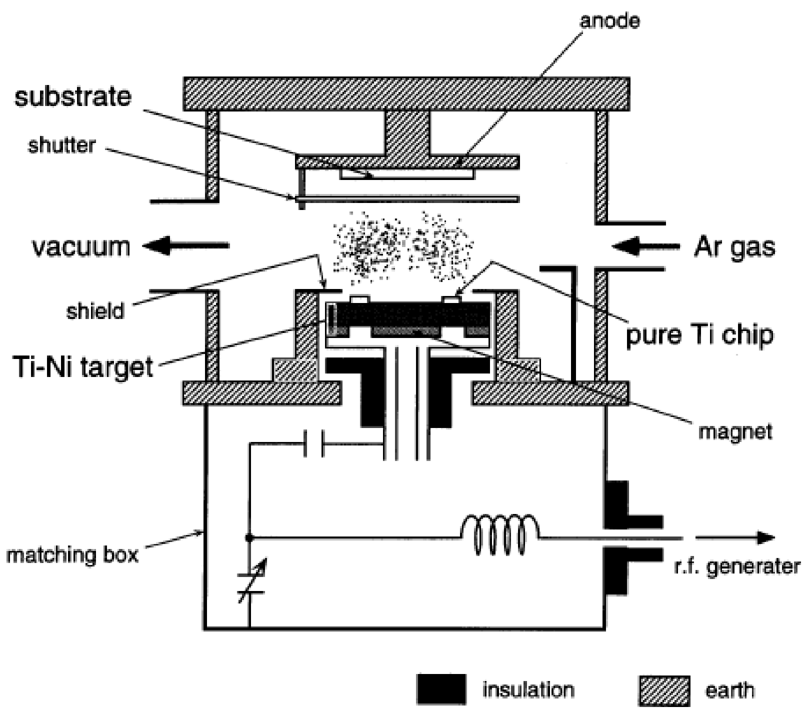
Requirements of TiNi for MEMS applications

- **TiNi film for MEMS application requires**
  - Low residual stress to prevent deformation of MEMS structure
  - High actuation speed and fast response with precise control of deformation and strain
  - Good adhesion on substrate
    - Free of cracking, delamination and spallation
  - Durable and reliable shape memory effects
  - Wide range choice of working temperatures
  - Good resistance to surface wear and corrosion
  - Biocompatible and good corrosion resistance (for Bio-MEMS)

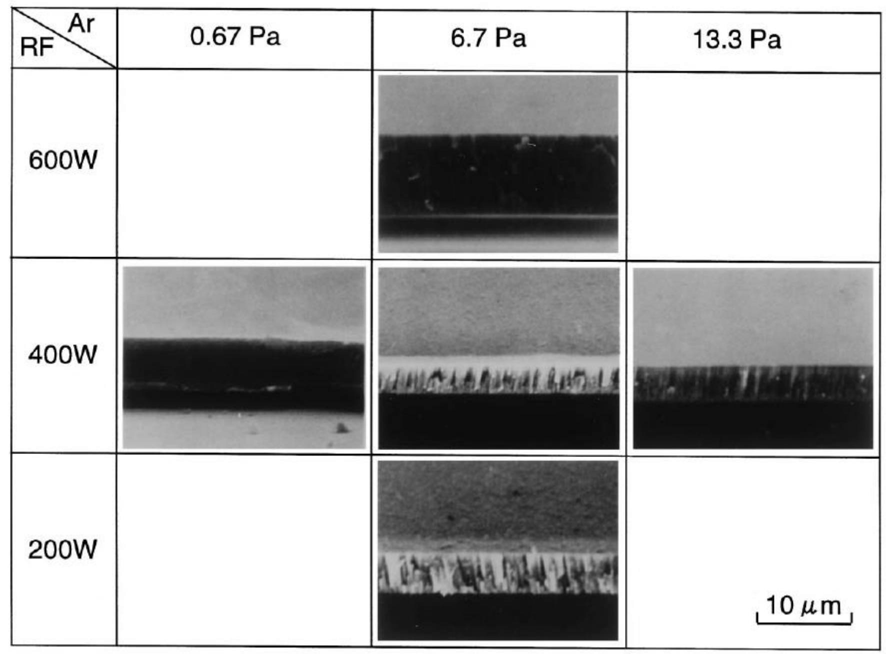
MANUFACTURING OF SHAPE MEMORY THIN FILM

RF magnetron sputtering deposition

- **RF magnetron sputtering method**



RF magnetron sputter deposition system



Structure of TiNi thin films formed under various sputtering conditions

Other manufacturing methods

- **Laser ablation**
- **Ion beam deposition**
- **Arc plasma ion plating**
- **Plasma spray**
- **Flash evaporation**

- **Disadvantages of above methods;**
  - Non-uniformity of film thickness
  - Non-uniformity of composition between Ti and Ni
  - Low deposition rate

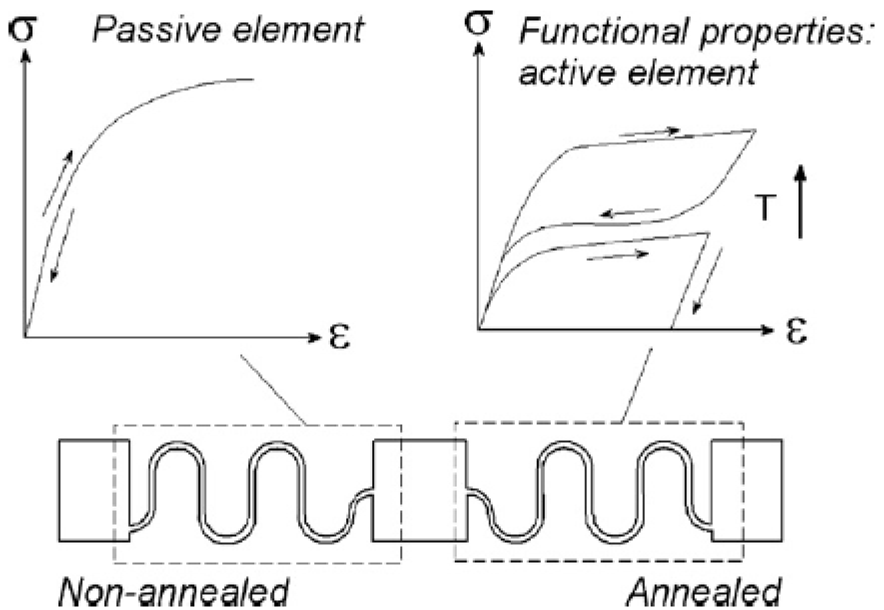
Post-sputtering annealing

- TiNi film can be deposited at room temperature or high temperature
- TiNi film sputtered at room temperature is amorphous
- Post-annealing process over 450°C requires for crystallization
- Martensite transformation and superelasticity are sensitive to post-annealing and/or aging temperature and duration
- Low annealing and aging temperature can conserve the thermal processing budget and minimize the reactions btw film and substrate
- Long term post-annealing and aging temperature can trigger dramatic changes in thin microstructure, mechanical property and shape memory effect

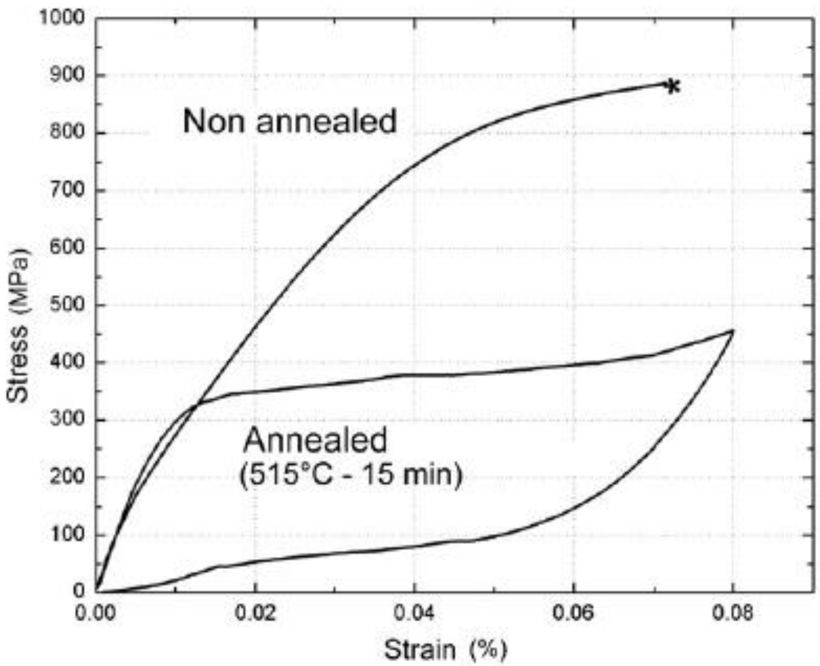
Localized laser annealing

- **Annealing in local area to exhibit shape memory effect**
- **Non-annealed area will be remained amorphous**
  - Acting as a pullback spring during cooling process
- **Advantages**
  - Precision in selection of the areas to be annealed
  - Free of restrictions on design and processing
  - Ease in integration with MEMS process
- **Disadvantages**
  - Energy loss by smooth surface
  - Difficulty in duration control; over exposure can cause damage
  - Need of protection environment such as argon or vacuum

Localized laser annealing



Schematic of monolithic integration. By locally annealing the material, mechanical properties are distributed across the material.

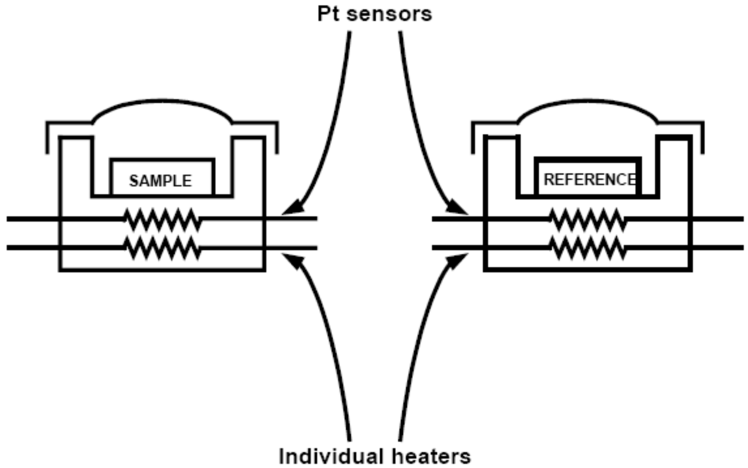


Tensile characteristics of annealed and non-annealed binary Ni–Ti.

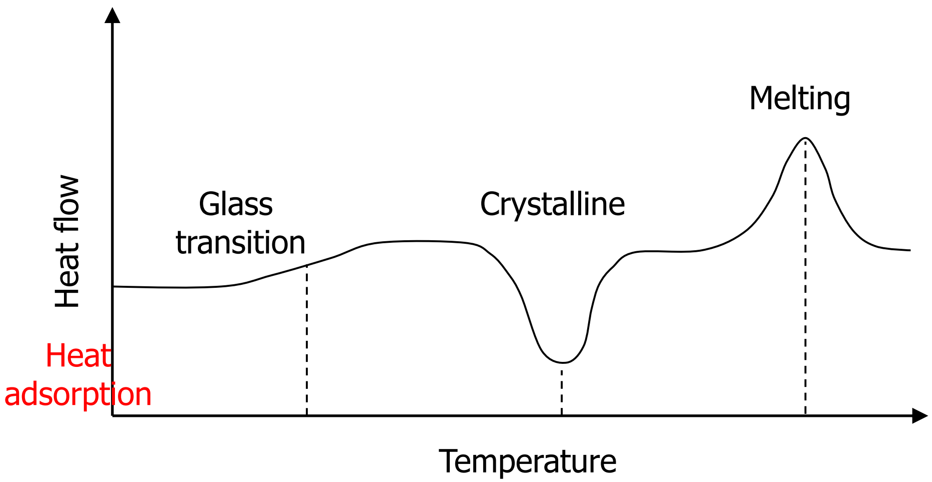
CHARACTERIZATION OF SHAPE MEMORY ALLOY THIN FILM

Differential Scanning Calorimeter

- **Study what happens to sample when they're heated**
- **Measure crystalline temperature**



Schematics of differential scanning calorimeter

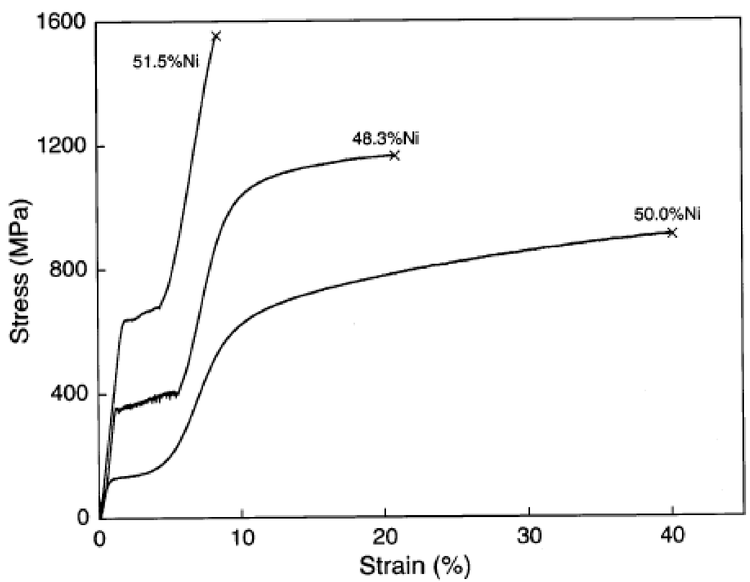


Phase transformation by temperature

Tensile test

- **Stress- strain response**
- **Strain-temperature response**

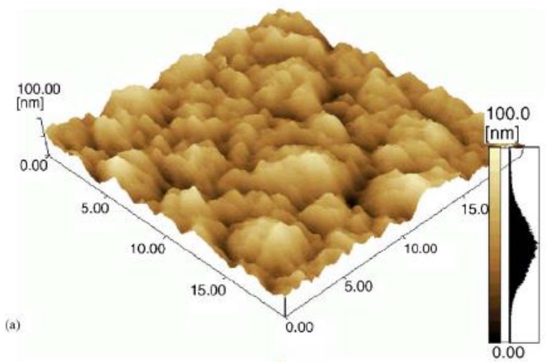
- **Difficulties in tensile testing**
  - To obtain free-standing films without pre-deformation
  - To clamp tightly the films on a tester grips



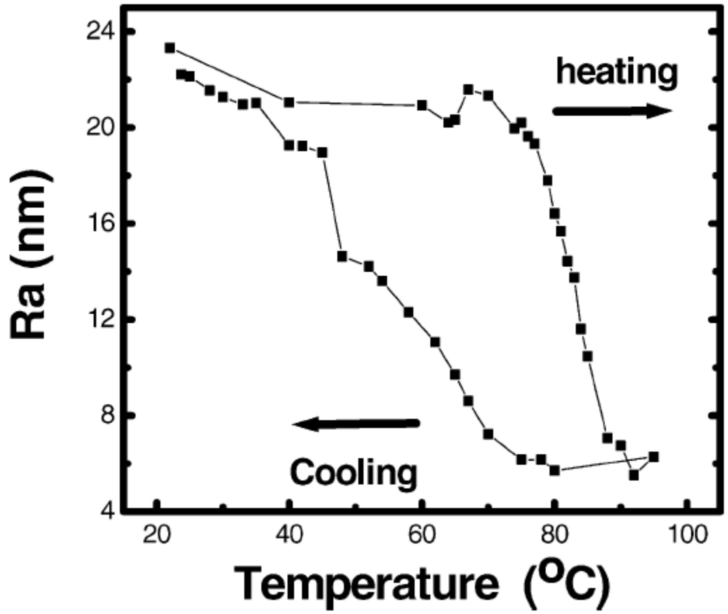
Stress–strain curves of Ti–48.3, 50.0, 51.5at.% Ni thin films at 315 K. The Ti–48.3, 50.0at.%Ni films were annealed at 773 K for 300 s and for 3.6 ks, respectively, and the 51.5at.%Ni film was aged at 673 K for 3.6 ks after solution treatment at 973 K for 3.6 ks.

Atomic force microscopy

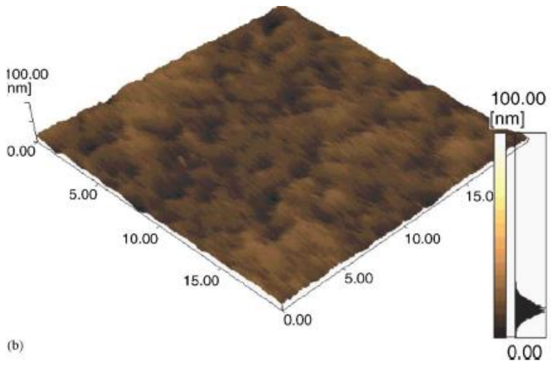
▪ **Surface roughness versus temperature by AFM**



Low temperature in martensite state



Surface roughness evolution by temperature



High temperature in austenite state

SHAPE MEMORY ALLOY THIN FILM APPLICATION

Thin film micro-actuation mechanism

- **Advantages**
  - High power density
  - Large displacement and actuation force
  - Low operation voltage

- **Disadvantages**
  - Low energy efficiency
  - Low dynamic response speed and large hysteresis
  - Non-linearity
  - Complex thermo-mechanical behavior
  - Complex in motion control and force tracking
  - Potential degradation and fatigue

Micro-pump: design

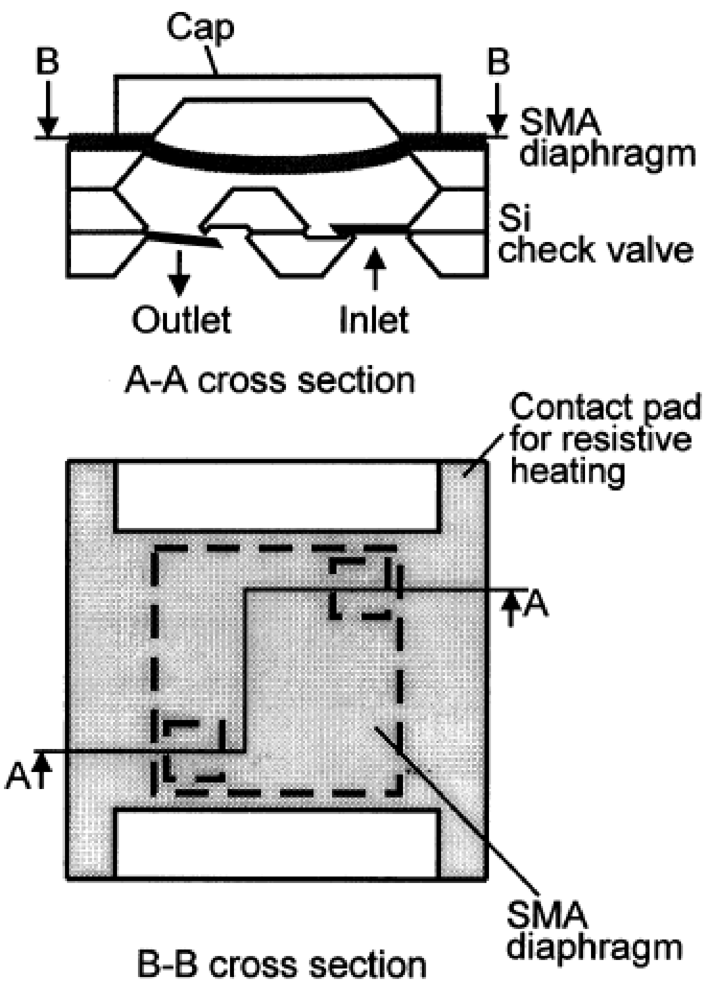
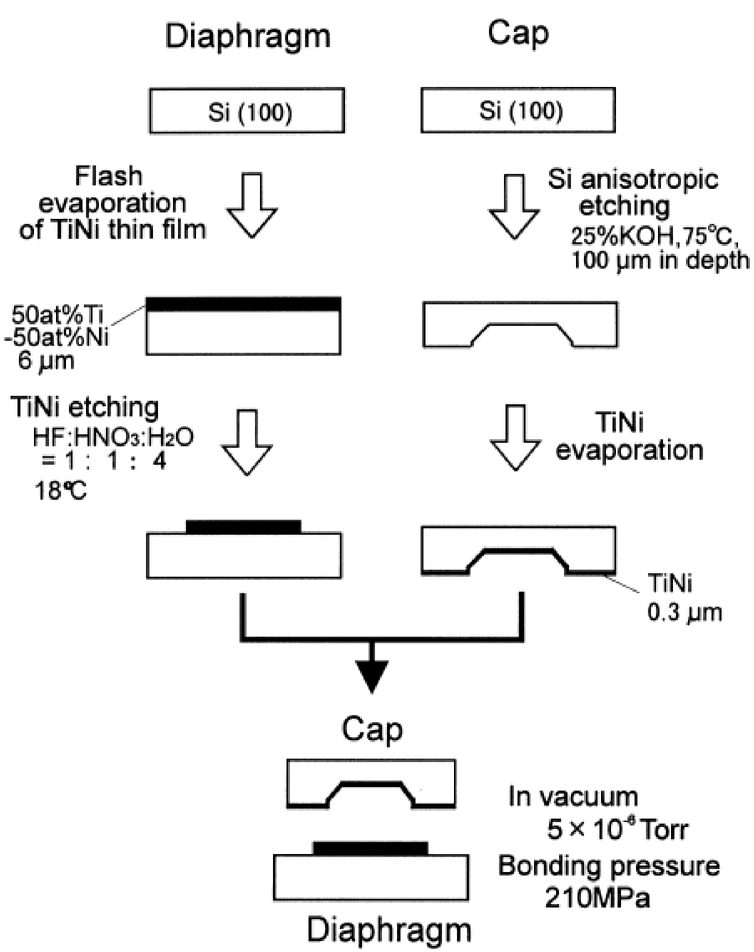


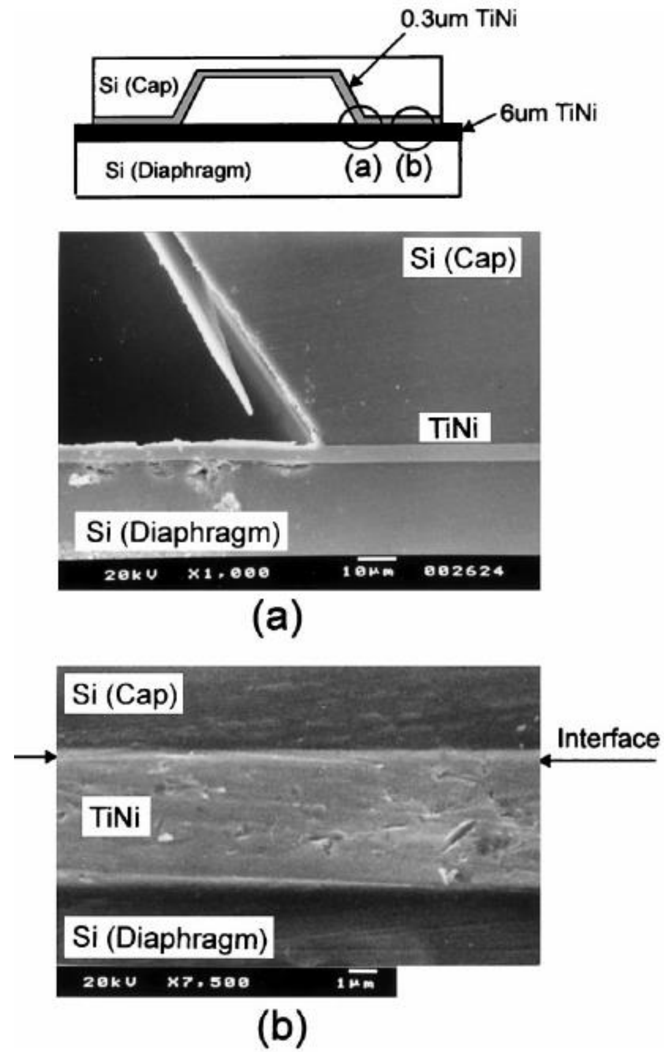
Fig. 1. Schematic diagram of micropump with TiNi diaphragm.

Working principle

- TiNi diaphragm is memorized in flat shape
- Diaphragm and cap have a chamber between them
- The diaphragm deforms when a bias pressure is applied to the chamber at room temperature
- When the diaphragm is heated up, it recovers its initial flat shape
- Outlet and inlet of check valve actuate in accordance with the movement of the TiNi diaphragm

Micro-pump: fabrication





Micro-pump: experiment

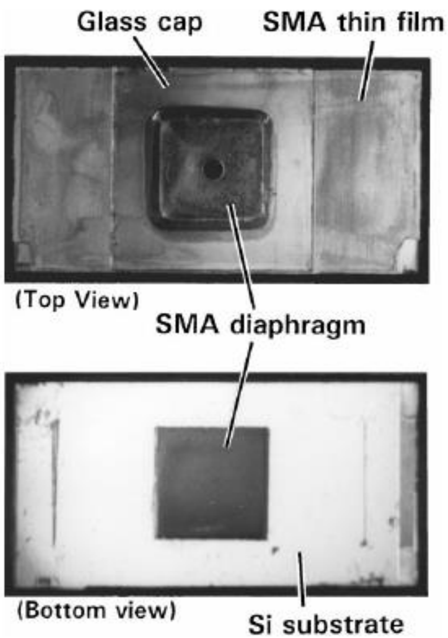


Fig. 5. Completed pressurization type SMA actuator (10 mm × 20 mm × 0.8 mm).

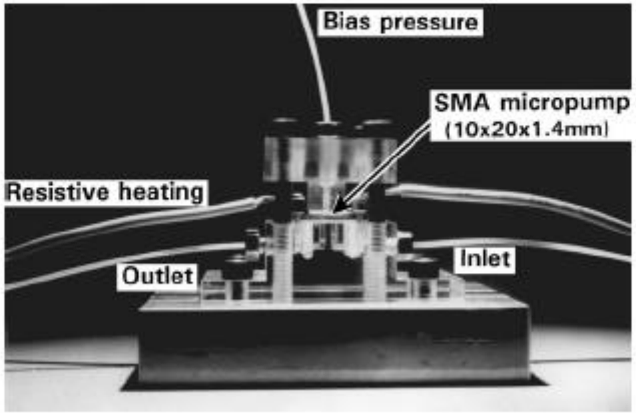


Fig. 11. Setup for pumping rate measurement.

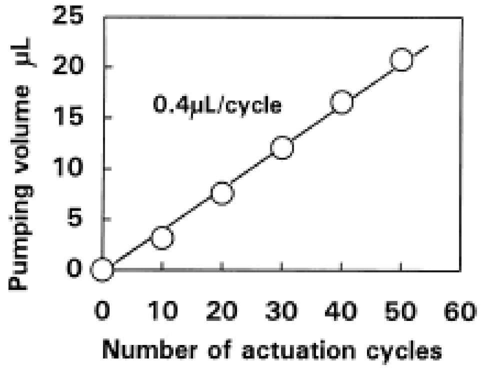
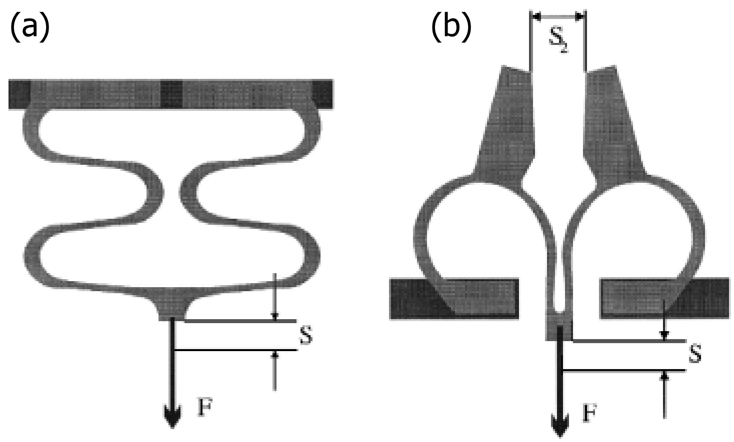


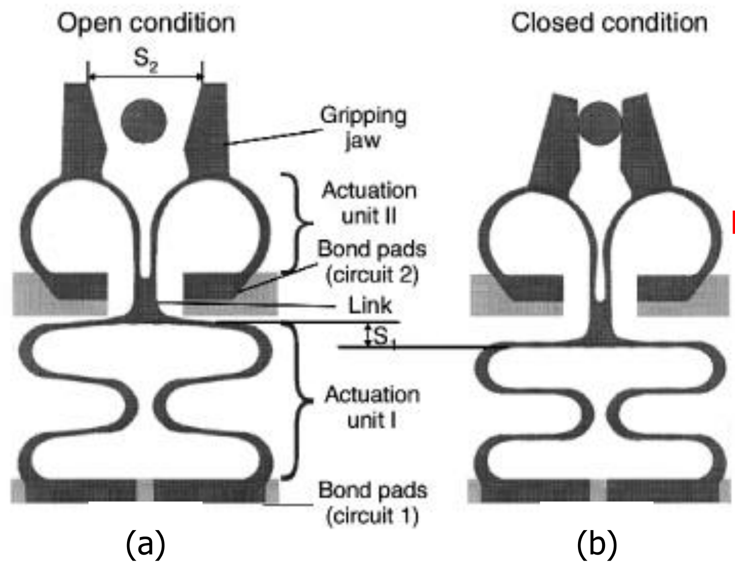
Fig. 12. Change in volumetric flow with number of actuation cycles. Actuation was conducted under the conditions of bias pressure of 100 kPa, diaphragm heating at 2 J for 100 ms, cycle period for actuation of 5 s, and back pressure of 0 kPa.

Micro-gripper: design



Unit operations by shape memory effect

ANTAGONISM MECHANISM



Cooled

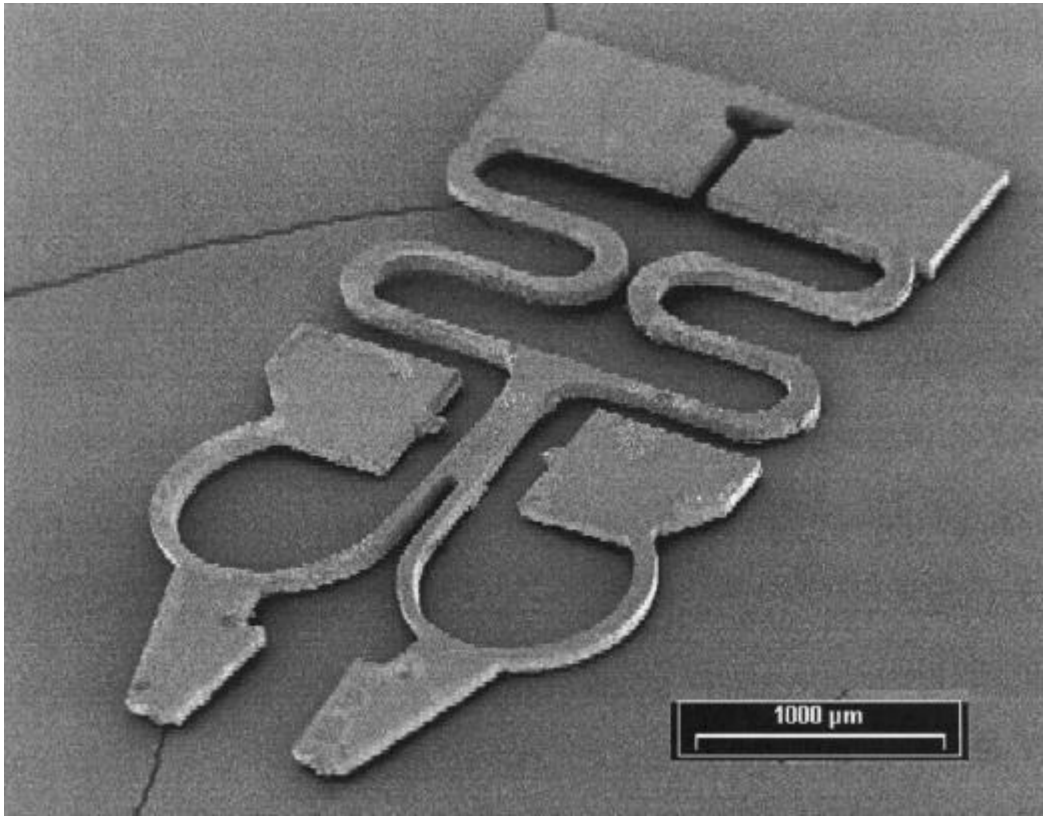
Heated, Memorized

Heated, Memorized

Cooled

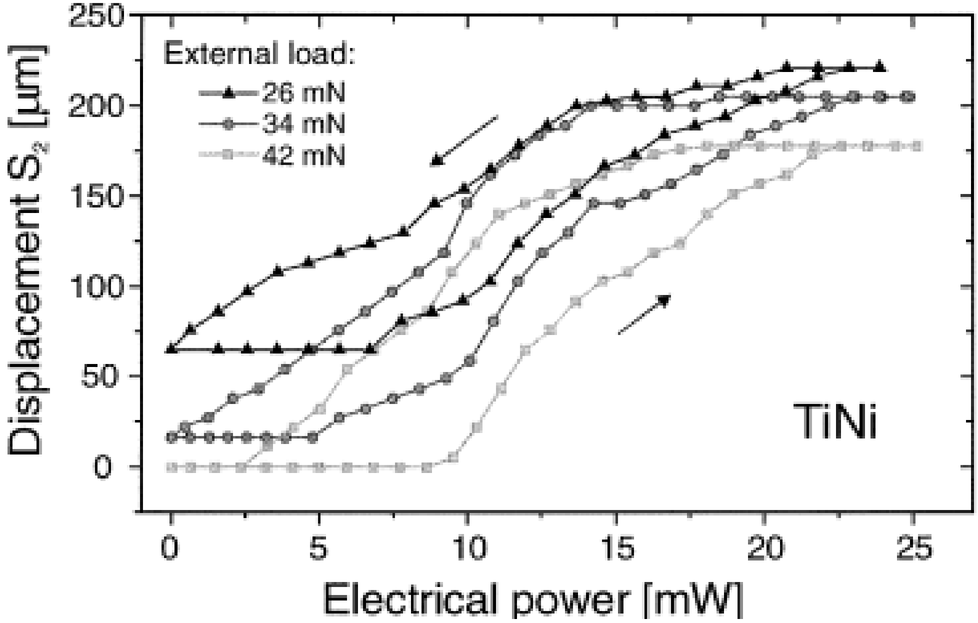
Operation principle of the SMA micro-gripper: (a) Open, when heated in unit 1, and (b) close, when heated in unit 2

Micro-gripper: fabrication



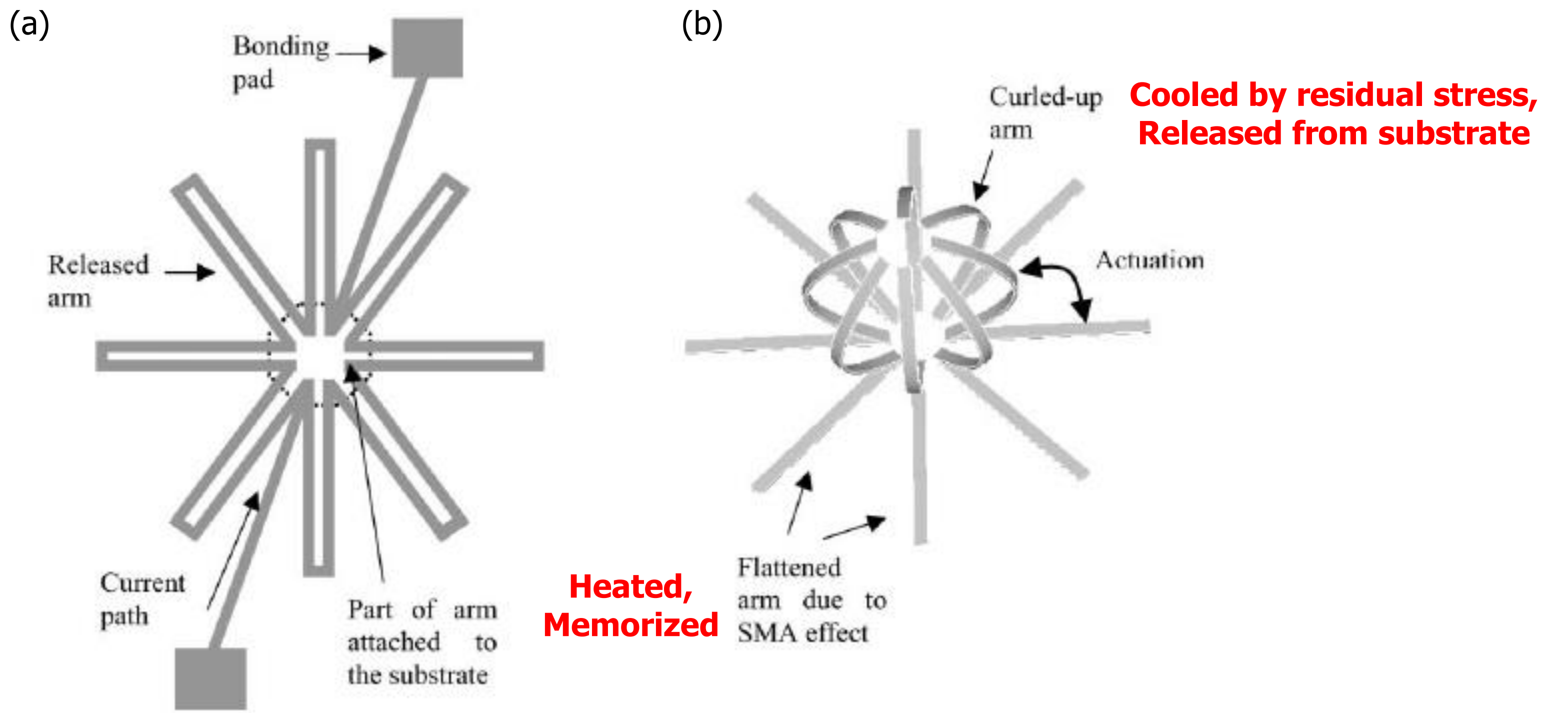
Fabrication of micro-gripper: micro-gripper was micro-machined through laser cutting and then bonded to ceramic substrate

Micro-gripper: experiment



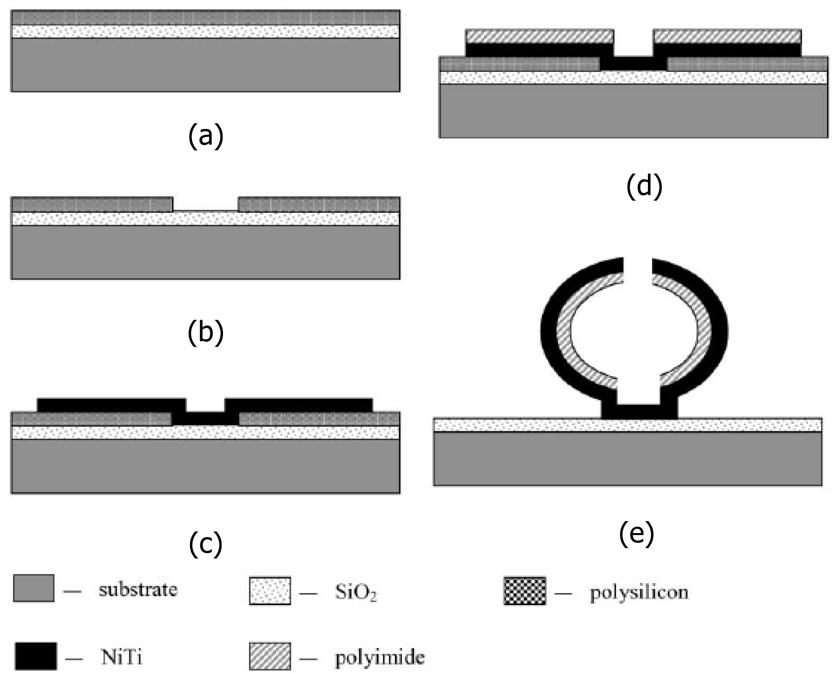
Displacement of the gripping jaws of unit 2: hysteresis broadening is due to the stress induced martensite formed locally in the region of maximum stress along the beam surface

Micro-wrapper: design



Design illustration of micro-wrapper: (a) plan view, and (b) actuation diagram

Micro-wrapper: fabrication



Fabrication process:

(a) wet oxidation and LPCVD polysilicon sacrificial layer deposition,

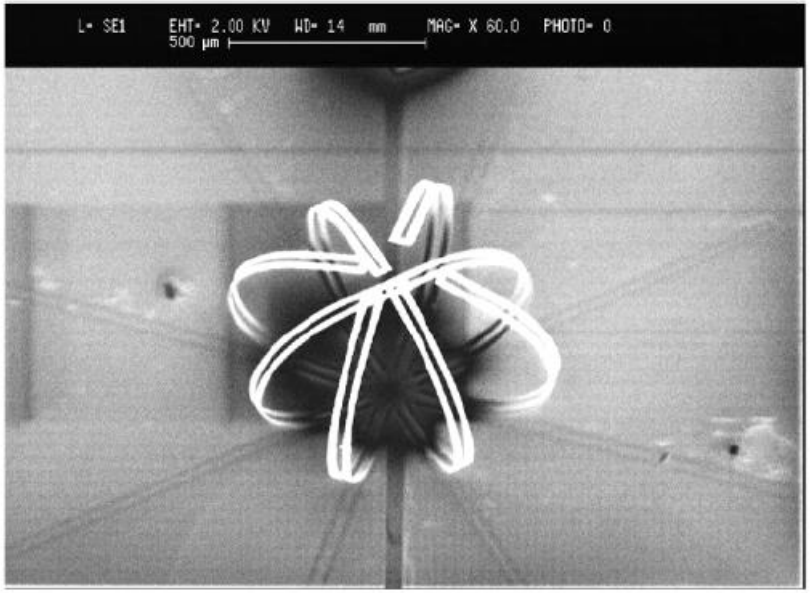
(b) patterning polysilicon layer by XeF_2,

(c) deposition and patterning NiTi film,

(d) deposition and patterning polyimide layer,

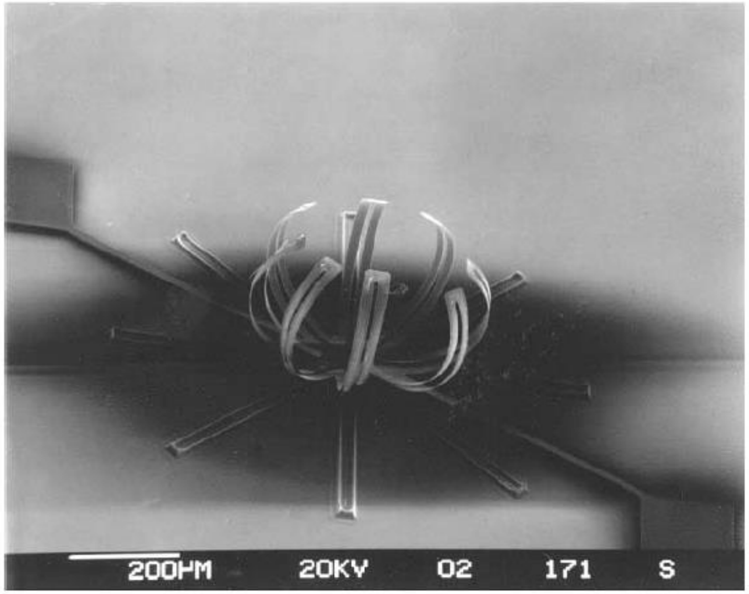
(e) removal of polysilicon layer by XeF_2

Micro-wrapper: fabrication



Fully closed thin film NiTi micro-wrapper

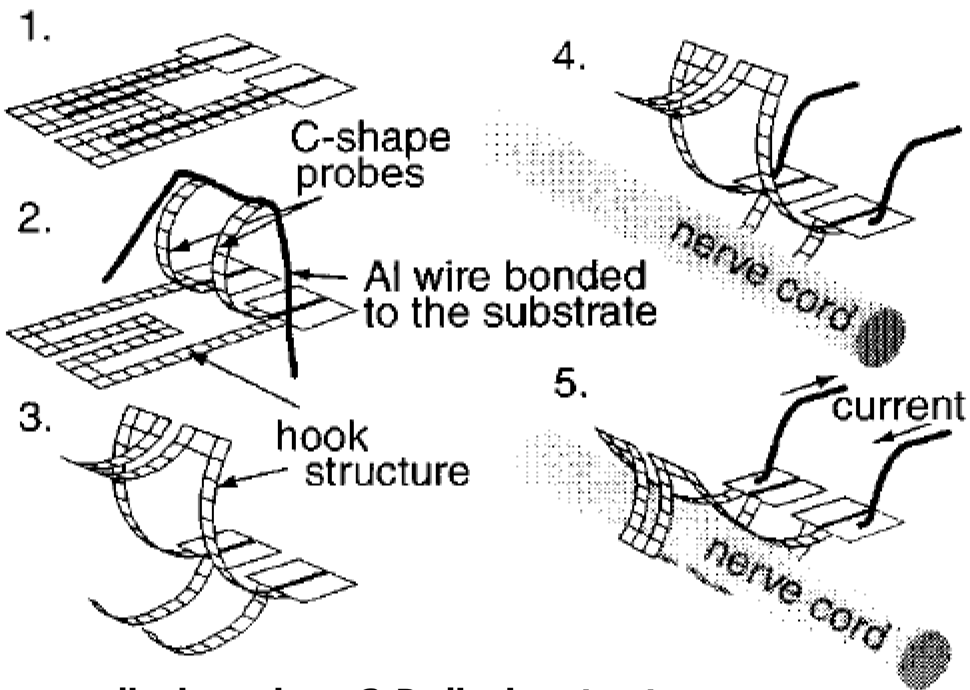
- Residual stress induced actuation between NiTi film and polyimide



Micro-wrapper with NiTi only

- Actuation is induced by functionally gradated NiTi film though thickness (Ni rich layer adjacent to substrate)

Nerve clipping: design



Procedure for nerve clipping using a 3-D clipping structure;

(1) Thin films are deposited by sputtering.

(2) 3-D "C" shape is memorized by attaching to a bonded wire.

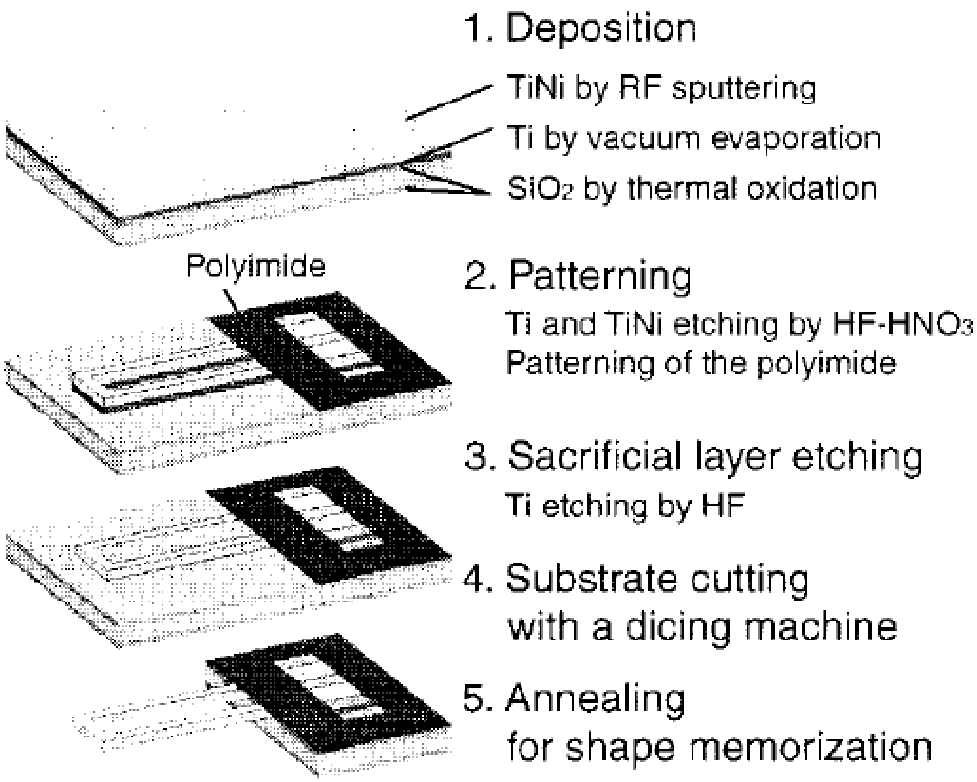
(3) Shapes are deformed at room temperature by using a micromanipulator to have an open gap.

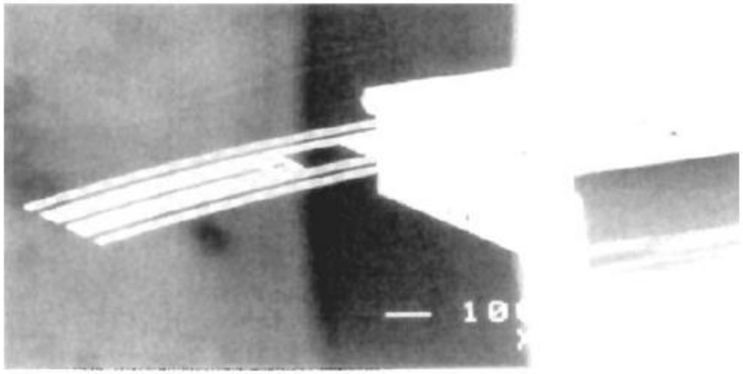
(4) Nerve cord is inserted into the open gap.

(5) Nerve is clipped when a current is applied to the hook structure.

Neural activity can be detected by measuring the potential difference between two probes.

Nerve clipping: fabrication





Fabricated SMA nerve clipping device

Fabrication outlines of an SMA cantilever.

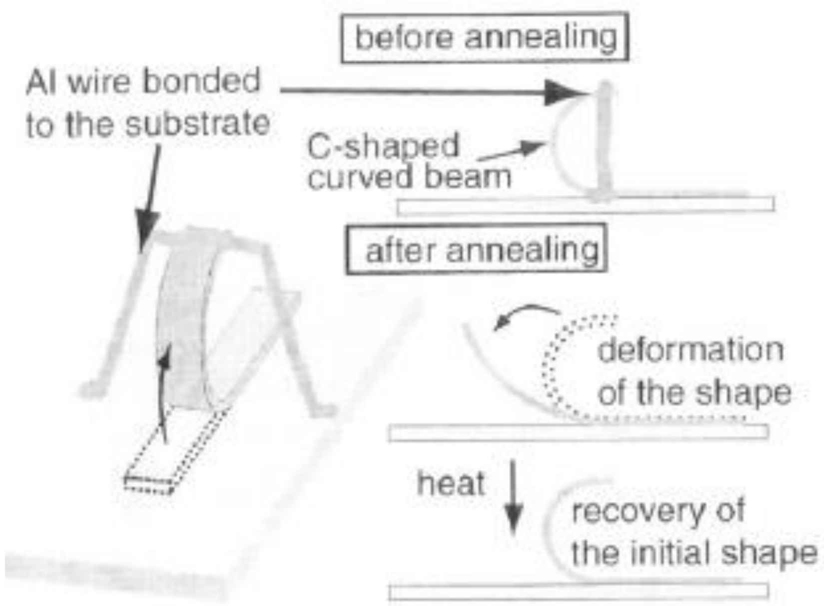
(1) Thin films are deposited by sputtering.

(2) Patterned films are etched.

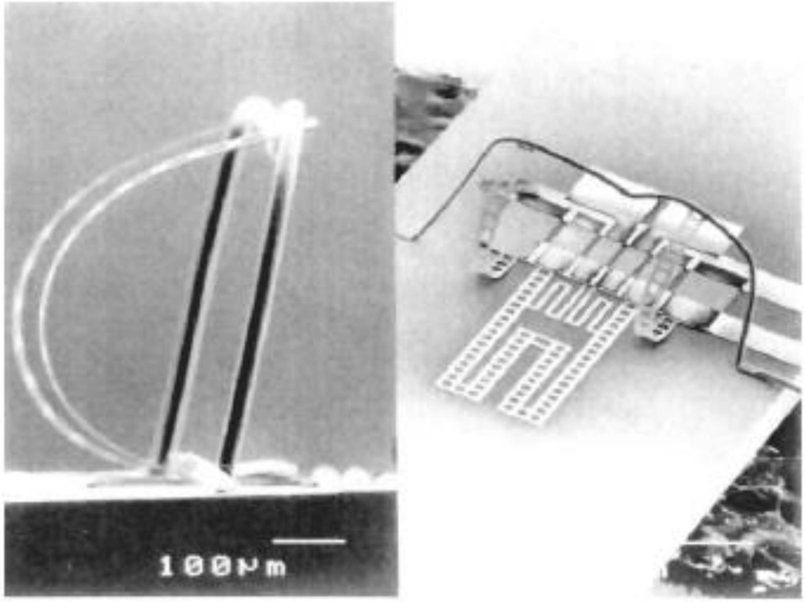
(3) , (4) Structure releasing

(5) annealing with an infrared lamp annealer.

Nerve clipping: memorization

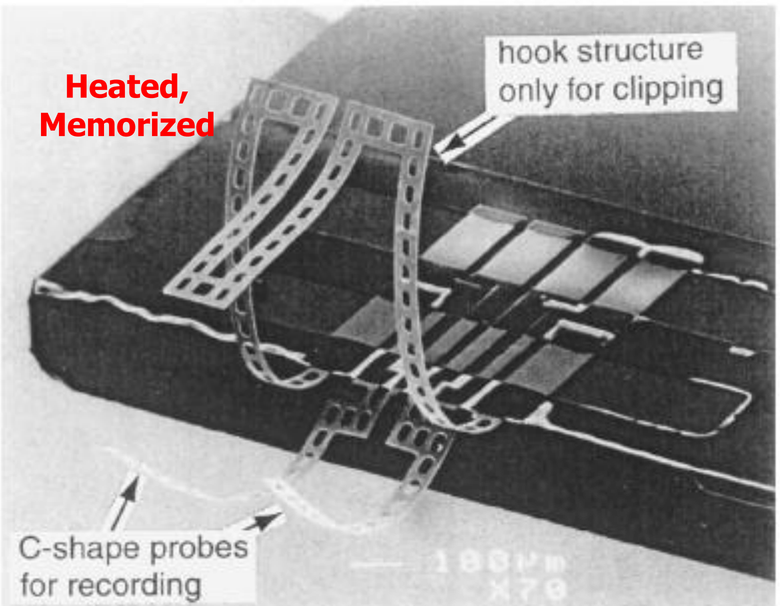


Shape memorization method

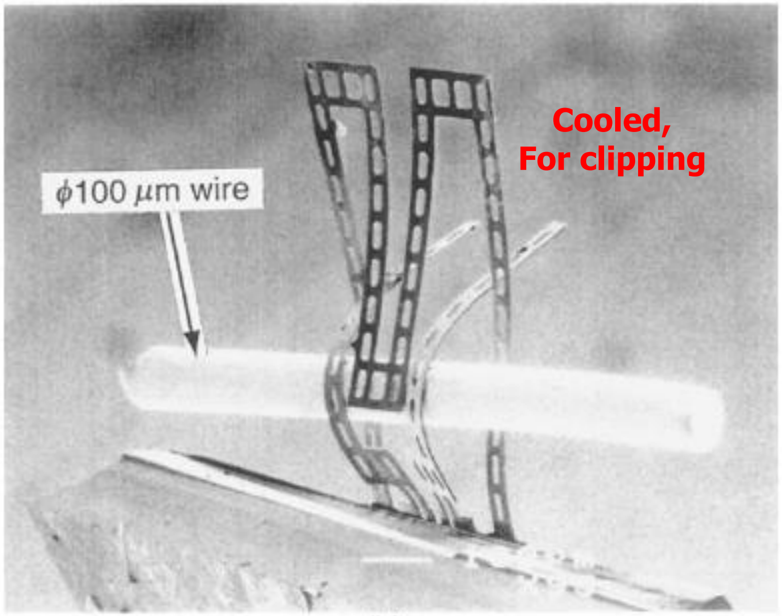


Shape memorization

Nerve clipping: experiment



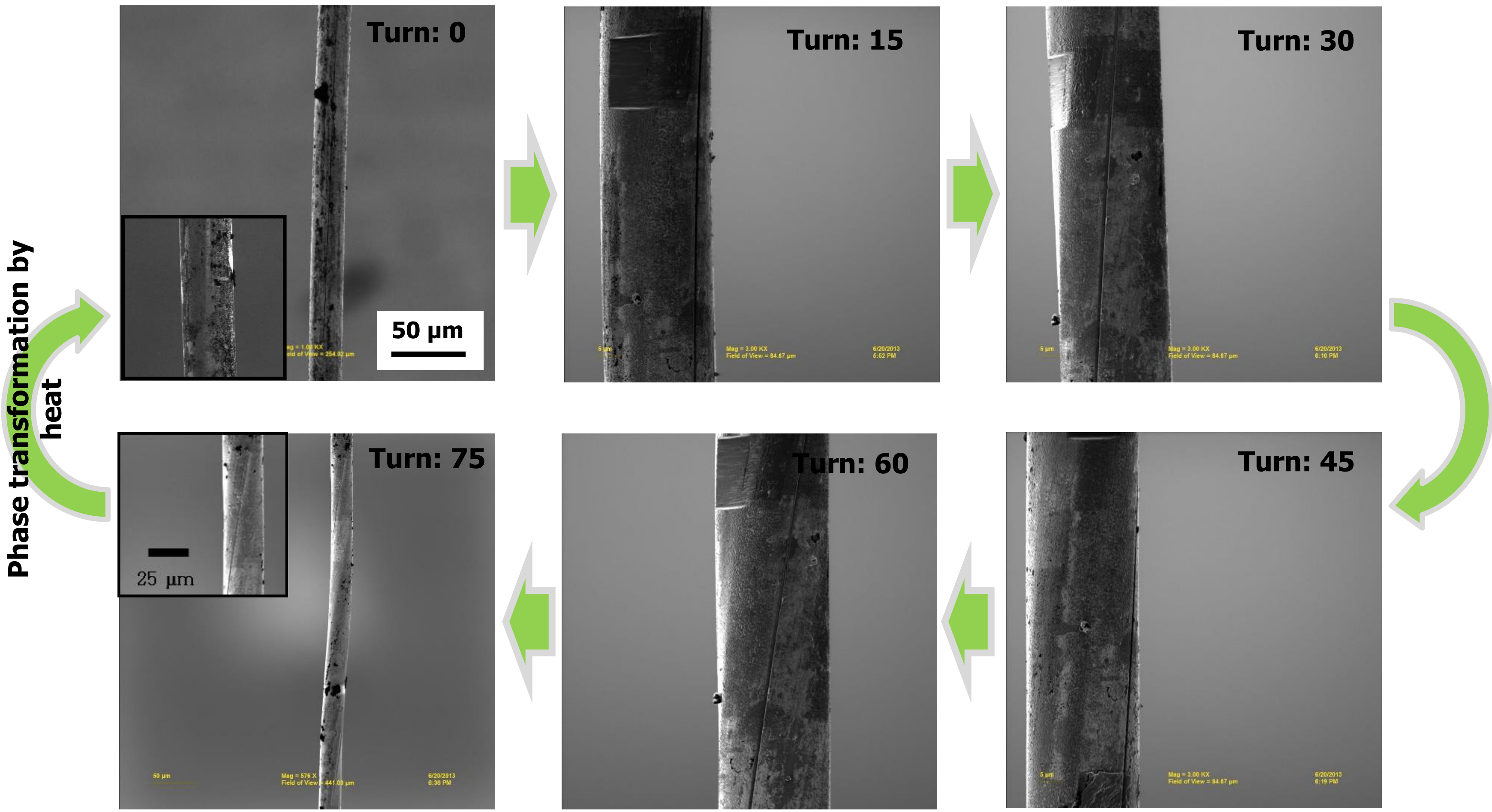
An SMA microelectrode after shape deformation. The hook structure is returned to its memorized shape when it is heated, while the two "C"-shape probes for recording are not heated.



The microelectrode clipping a 100 m wire after the hook structure is heated. Neural recording is performed by measuring the potential

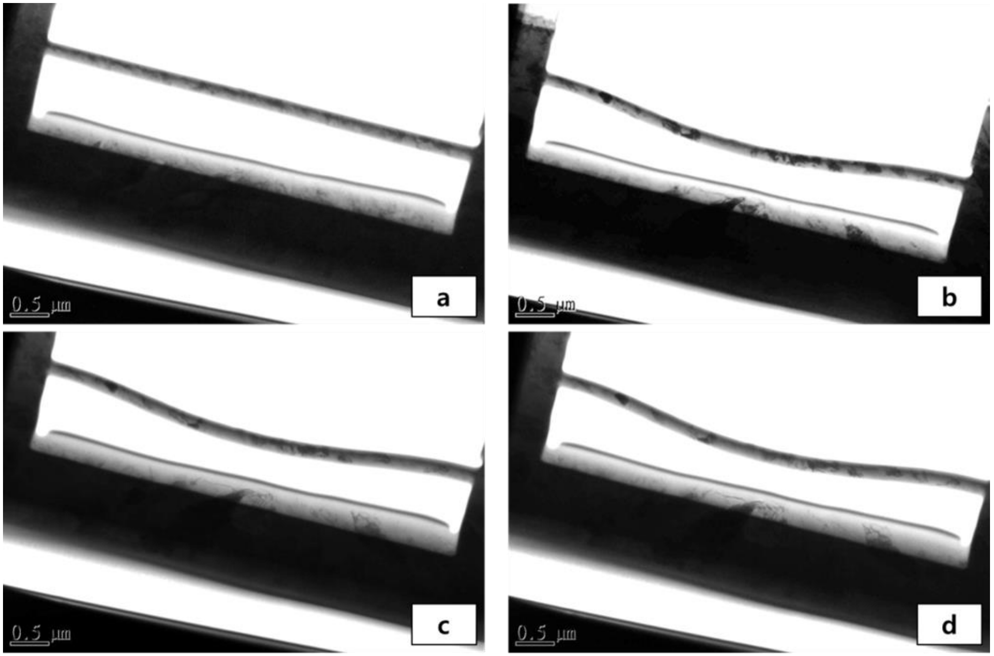
SHAPE MEMORY ALLOY IN MICRO/NANO SCALE

Complex SMA micro twisting actuation

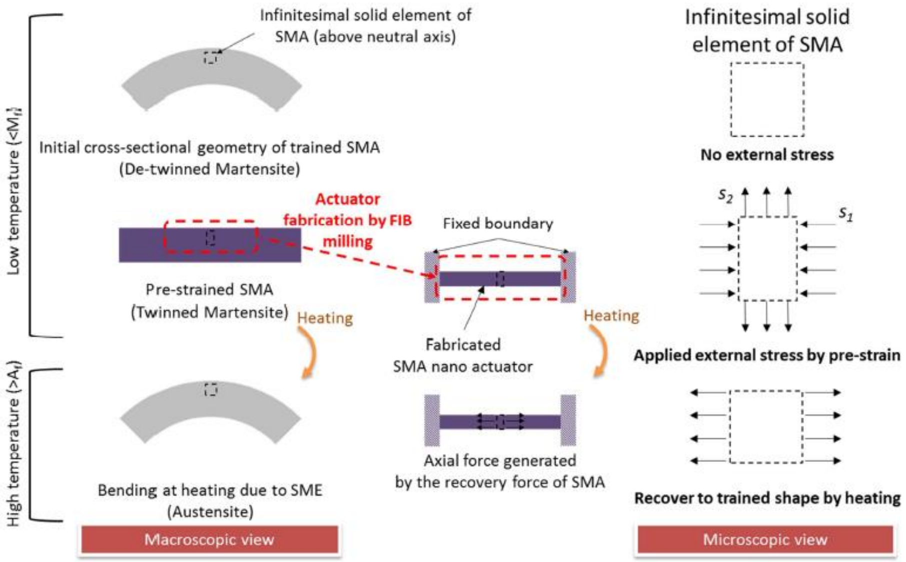


Fabrication of complex functional nanostructure by turning of nano-patterned SMA wire and its operation by applied heat

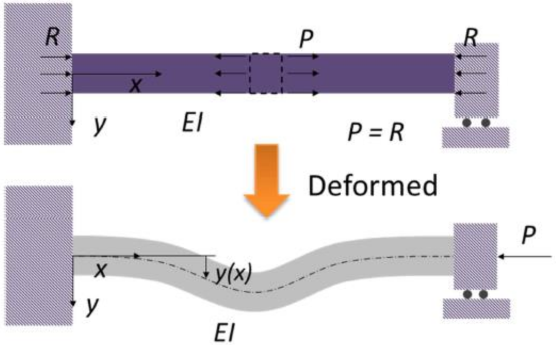
Simple SMA functional nanostructure



Simple functional SMA nanostructure having beam geometry (500 nm x 100 nm x 5,500 nm) and its one-way operation: its operation was taken by in situ TEM.
(a) 25 ˚C, (b)100 ˚C, (C) 150 ˚C (d) 200 ˚C

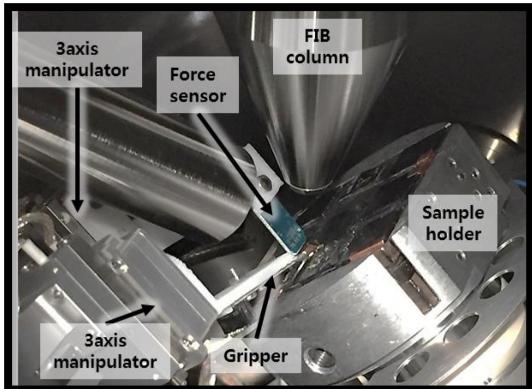


Manipulation principle of nanoscale TiNi beam



Structural model and geometrical configuration on nanoscale TiNi beam

In-situ nanomechanical testing in Focused Ion Beam



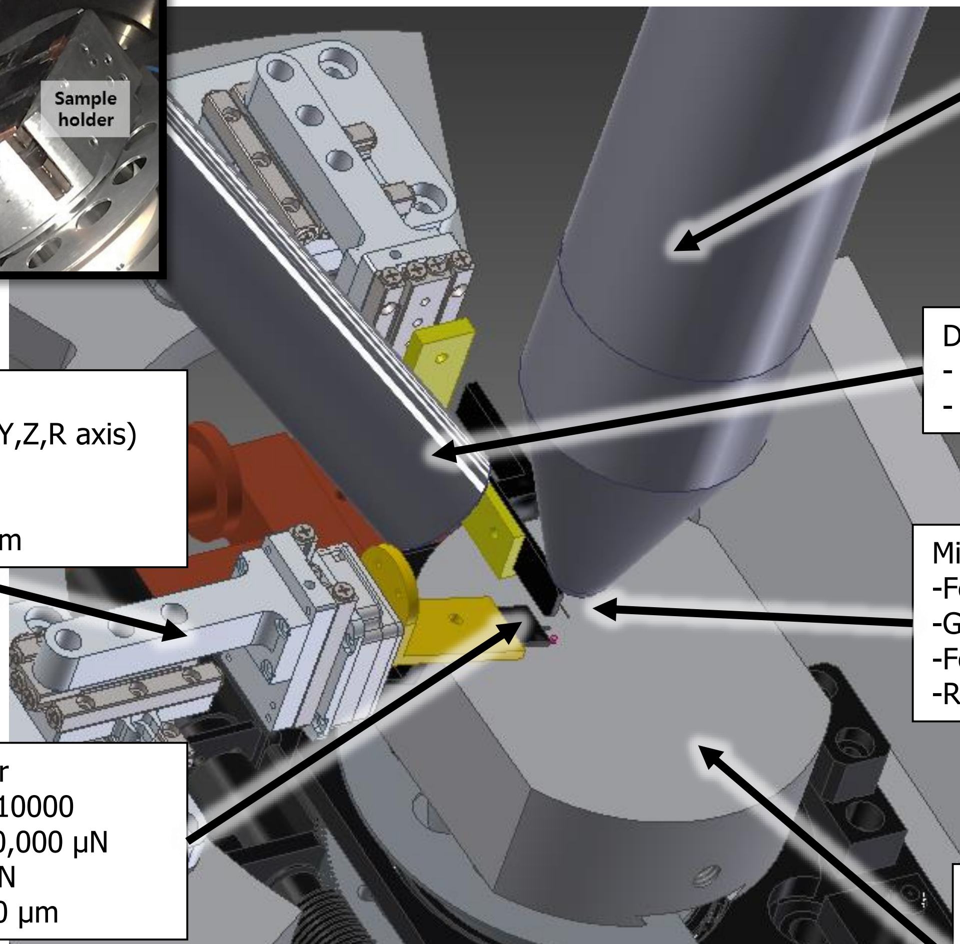
Focused Ion column
- ORSAY PHYSICS COBRA FIB
- Ion source: gallium
- Probe current: < 1 pA - 50 nA
- Patterning resolution < 50 nm
- Accelerating voltage: 5 - 30 kV

Detector for imaging
- Second electron detector
- Image resolution: 2.5 nm

Nanomanipulator
-4-axis nanopositioner (X,Y,Z,R axis)
-3-acis nanopositioner
-Position precision: 1 nm
-Maximum stroke: ±10 mm

Micro Gripper
-FemtoTools FT-G102
-Gripping stroke: 0-100 μm
-Force sensing: ±50 μN
-Resolution: 0.5 μN

Micro Force sensor
-FemtoTools FT-S10000
-Force range: ±10,000 μN
-Resolution: 0.5 μN
-Probe size: 10X50 μm

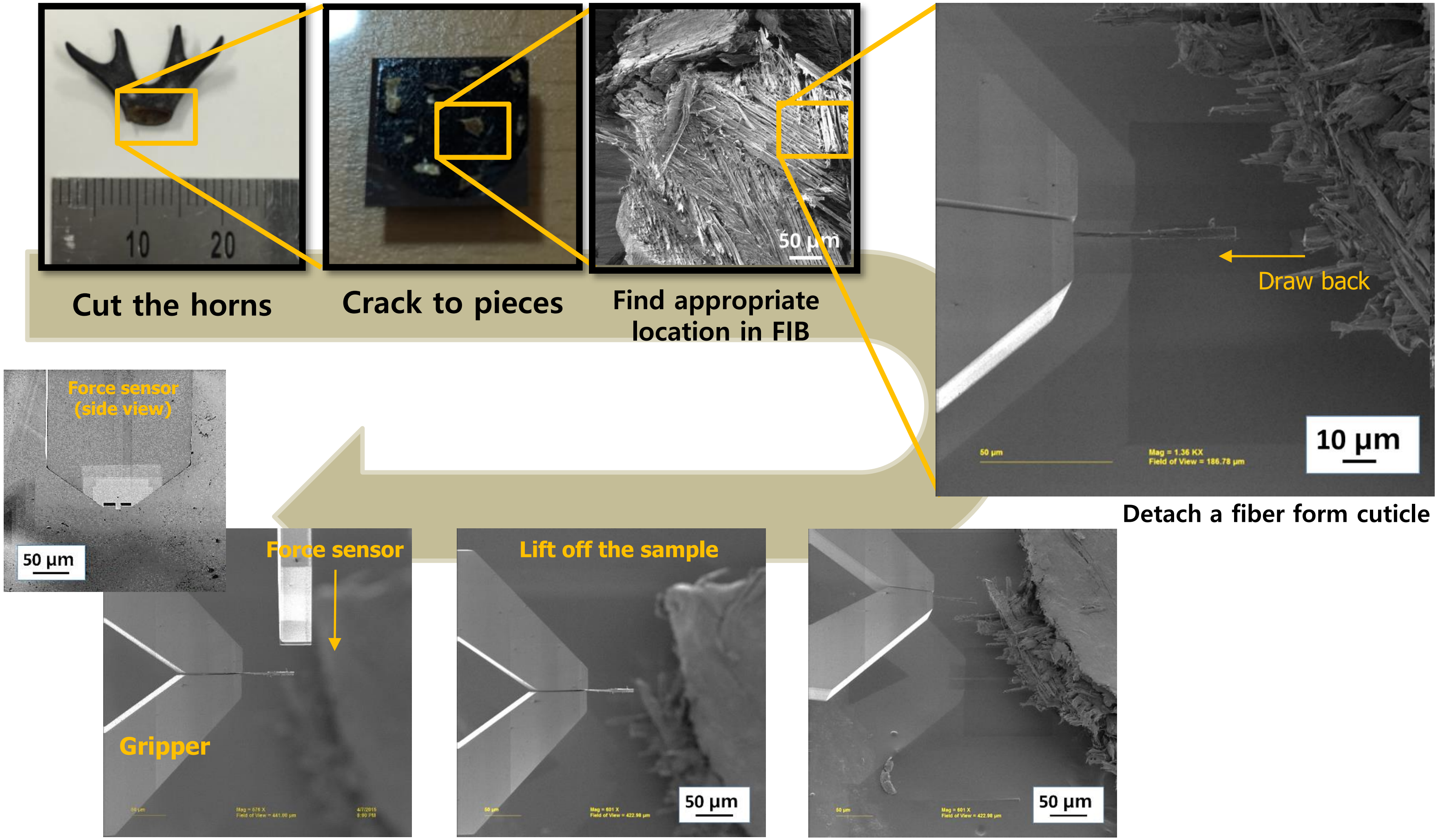


5-axis sample mount
-Eucentric motion available
-5-axis motion (X,Y,Z,R,T axis)
-Step resolution: 2.5 nm
-Stroke: ±50 mm, -10° to 60°

CAD modeling for in-situ mechanical testing system

In-situ nanomechanical testing in Focused Ion Beam

- **Case study: Microbending test of biological material**

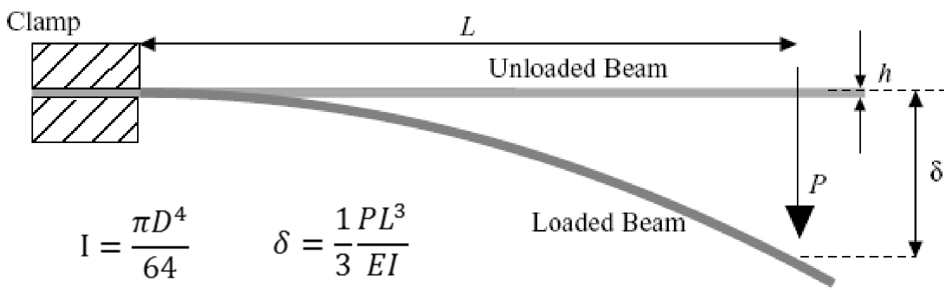


Process flow of sample preparation of in-situ measurement

In-situ nanomechanical testing in Focused Ion Beam

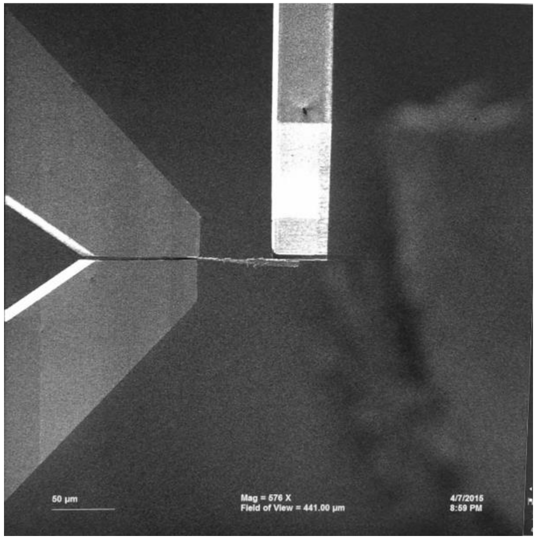
x2 speed

- **Case study: Microbending test of biological material**

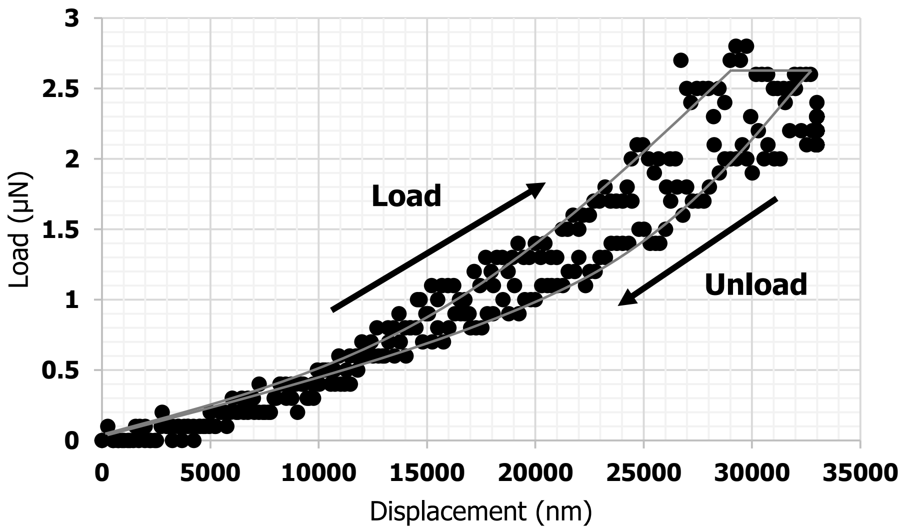


$$I = \frac{\pi D^4}{64} \qquad \delta = \frac{1}{3}\frac{PL^3}{EI}$$

Geometry of the cantilever beam test.



Real time image from FIB



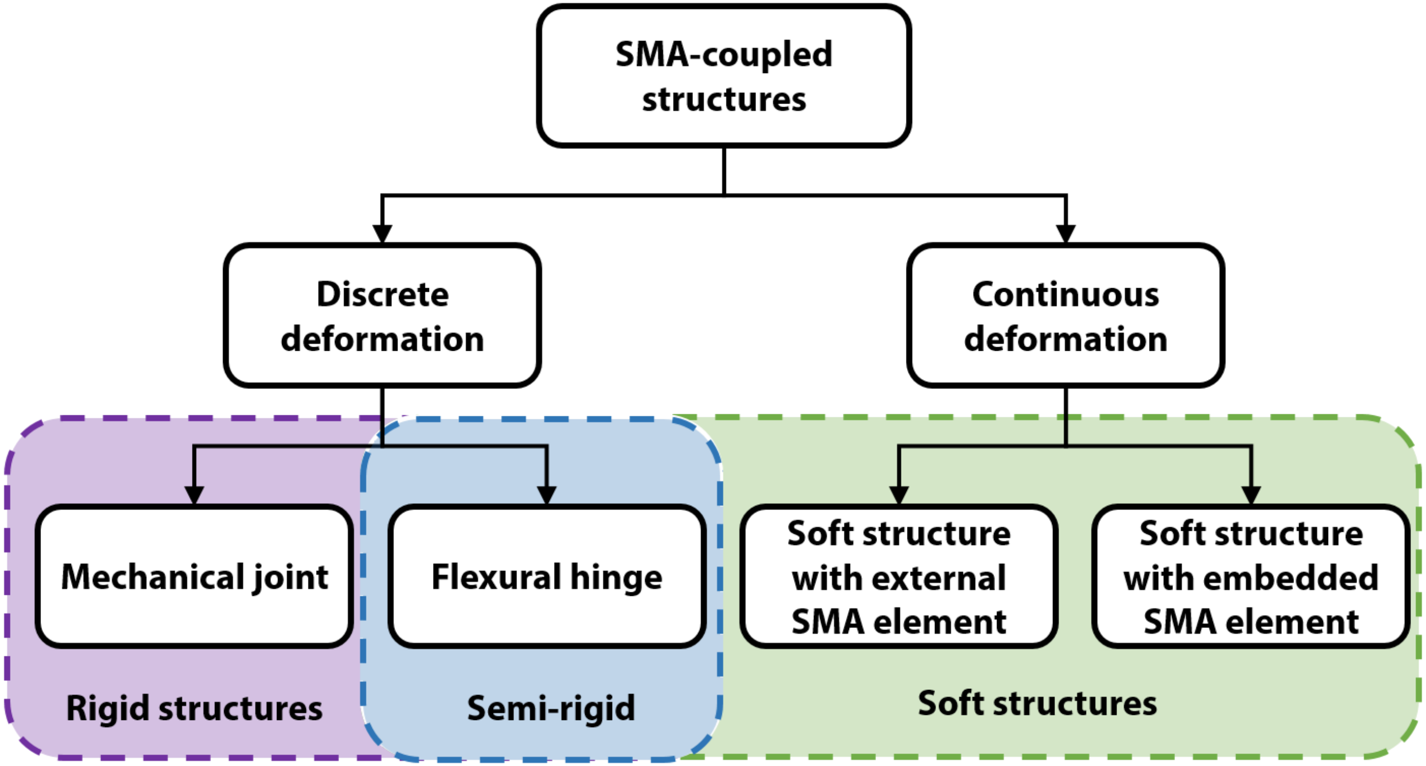
Graph of deflection vs load

Measured Data	
Beam Diameter (D)	2.95 μm
Displace (δ)	32.99 μm
Load (P)	2.63 μN
Beam Length (L)	128.67 μm

Evaluated properties	
Second moment of area (I)	3.71 μm^4
Young's modulus (E)	16.21 G Pa

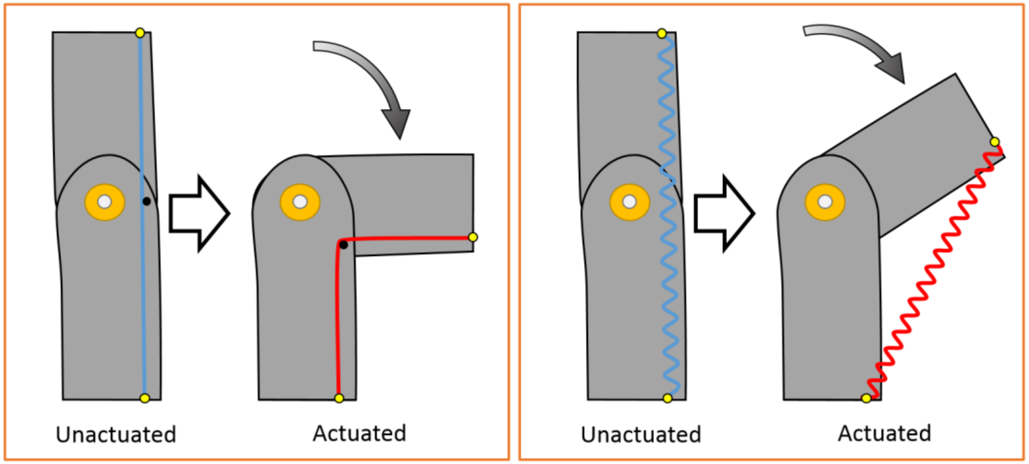
OVERVIEW :
SHAPE MEMORY ALLOY-COUPLED SOFT OR BIOMIMETIC ACTUATORS AND ROBOTS

SMA-coupled structures



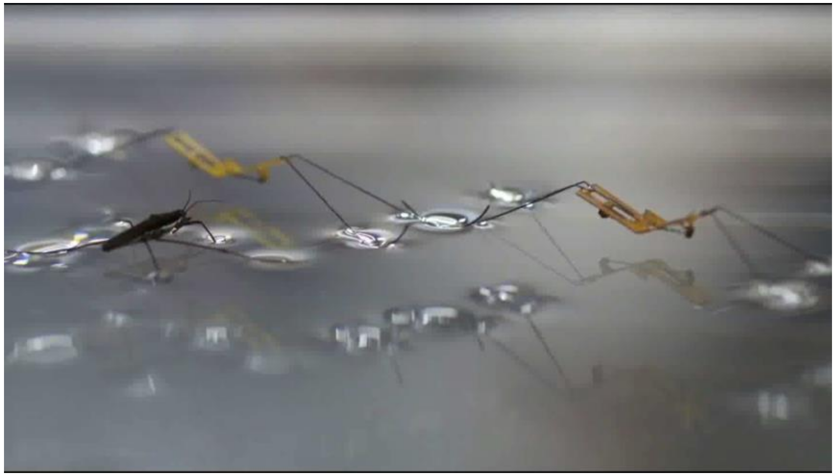
Fabrication Categorization of the different types of SMA-coupled structures.

Discrete deformation



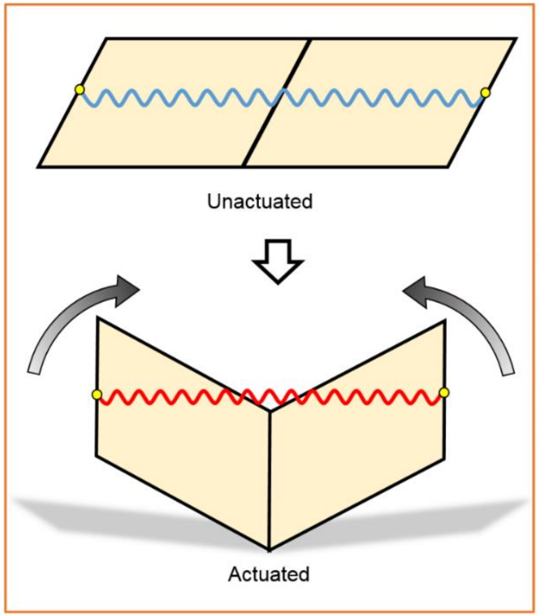
(a) (b)

Different design incarnations of mechanical joint-coupled actuator with (a) an SMA wire, and (b) an SMA spring.

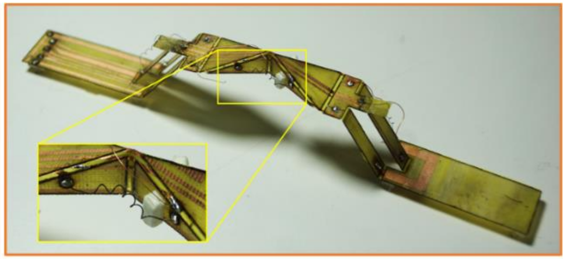


Flexural hinge and its application to an inchworm-inspired robot and a water strider-inspired robot

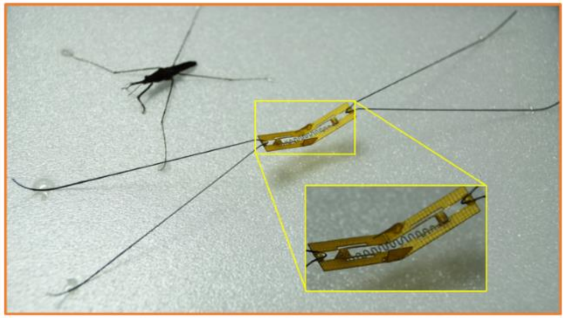
Koh J-S, Cho K-K. *IEEE-ASME T Mech.*, 2013.
Koh J-S, Yang E, Jung G-P, Jung S-P, Son JH, Lee S-I, *et al. Science,* 2015.



(a)

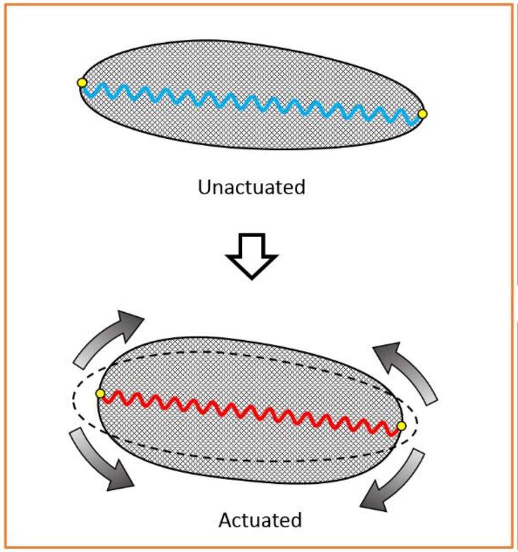


(b)

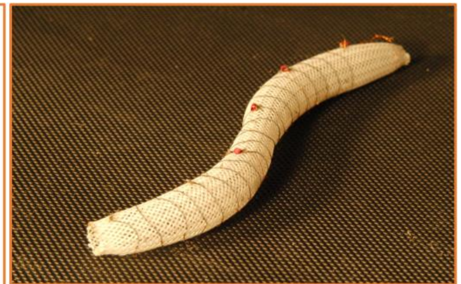


(c)

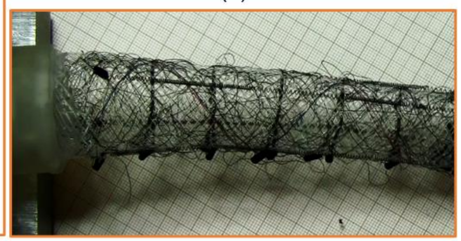
Continuous deformation



(a)



(b)



(c)

Using external SMA elements

(a) Motion of a wire mesh actuated by a SMA element where the mesh contracts longitudinally and expands transversally, (b) **MeshWorm** robot with an SMA-spring driven wire mesh capable of a peristaltic motion, and (c) **arm** of the OCTOPUS robot capable of extending in the radial direction and grasping objects using a mesh and SMA springs.

Seok S, Onal CD, Cho K-j, Wood RJ, Rus D, Kim S. *IEEE-ASME T Mech.*, 2013.
Cianchetti M, Calisti M, Margheri L, Kuba M, Laschi C. *Bioinspir. Biomim.*, 2015.

Soft autonomous earthworm robot

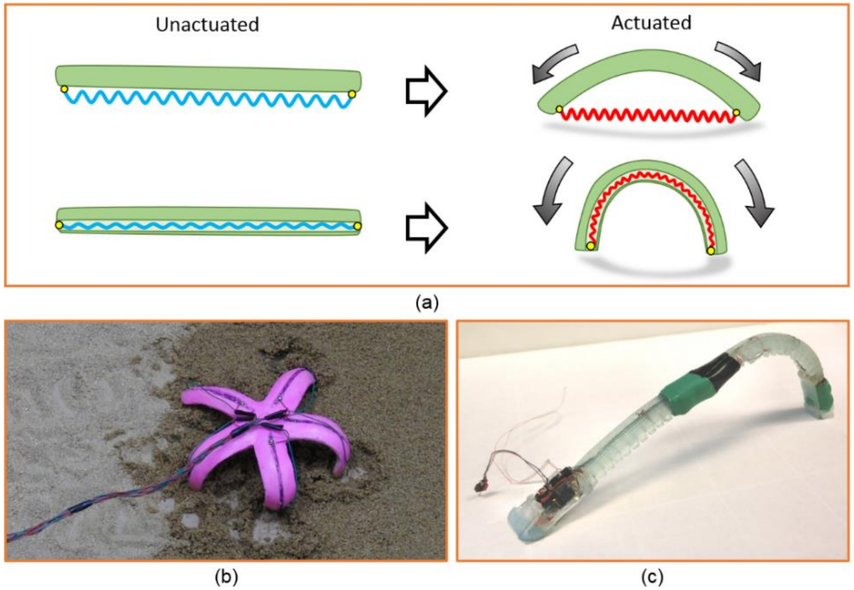
Soft-bodied robotic octopus arm

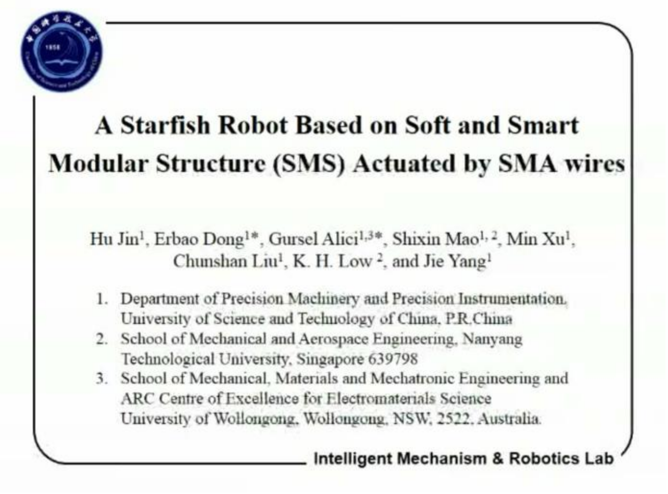
Continuous deformation

Using external SMA elements

(a) Comparison of SMA element attached at both ends of the actuator and located outside versus inside, (b) **starfish-like soft robot** with flexible rays actuated by SMA spring located within the structure, and (c) the **InchBot V** is an untethered SMA spring-driven robot with a silicone polymer body with an integrated power source that can inch and crawl.

Mao S, Dong E, Jin H, Xu M, Zhang S, Yang J, *et al. J Bionic Eng.*, 2014.
Lin HT, Leisk GG, Trimmer B. *Bioinspir. Biomim.*, 2011.

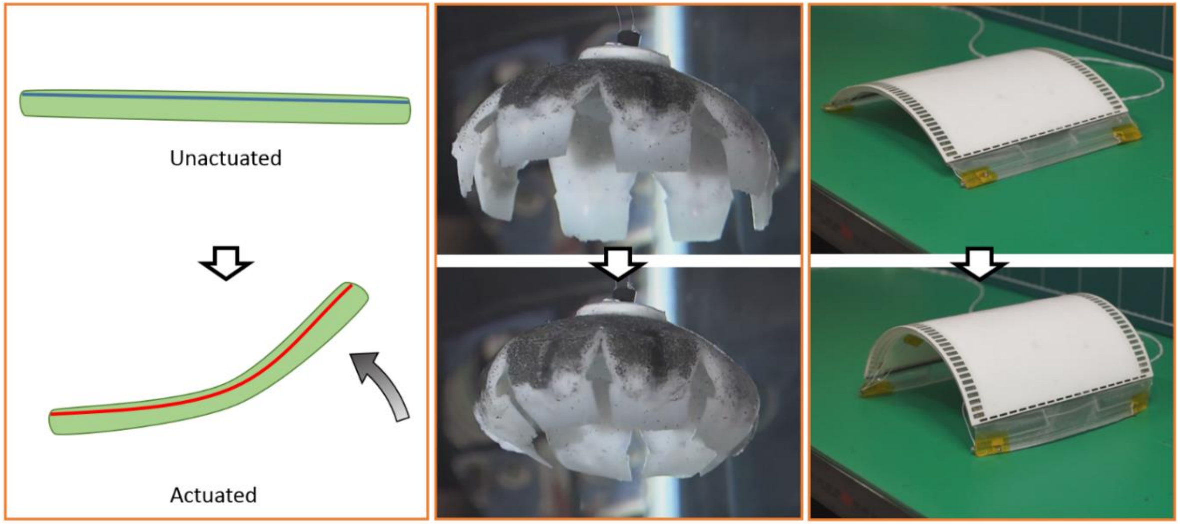




Starfish-Like Soft Robot

GoQBot Insanely Fast Robot Caterpillar

Continuous deformation



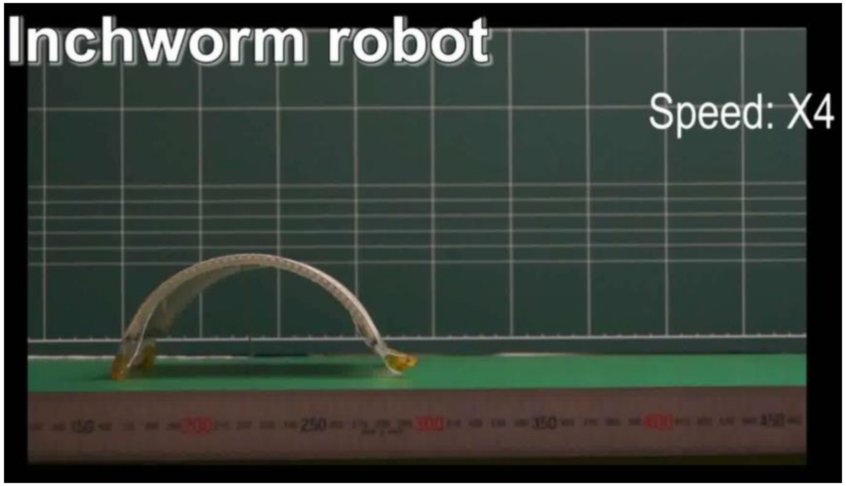
(a) (b) (c)

Using embedded SMA element

(a) Mechanism of a polymeric bending actuator with an embedded SMA wire, (b) the **RoboJelly**, a biomimetic robotic jellyfish making use of steel springs and SMA wires embedded in a polymeric matrix, and (c) an **inchworm-inspired robot** made from a polymeric matrix with embedded SMA wires capable of moving linearly and of turning using soft deformable feet.

Villanueva A, Smith C, Priya S. *Bioinspir. Biomim.*, 2011.
Wang W, Lee J-Y, Rodrigue H, Song S-H, Chu W-S, Ahn S-H. *Bioinspir. Biomim.*, 2014.

RoboJelly Could Cruise Waters To Safeguard Ocean Environment



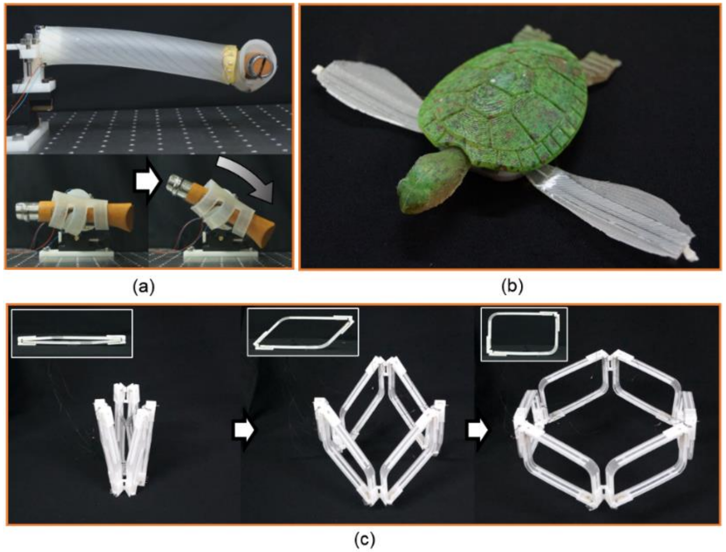
Inchworm-inspired robot

Continuous deformation

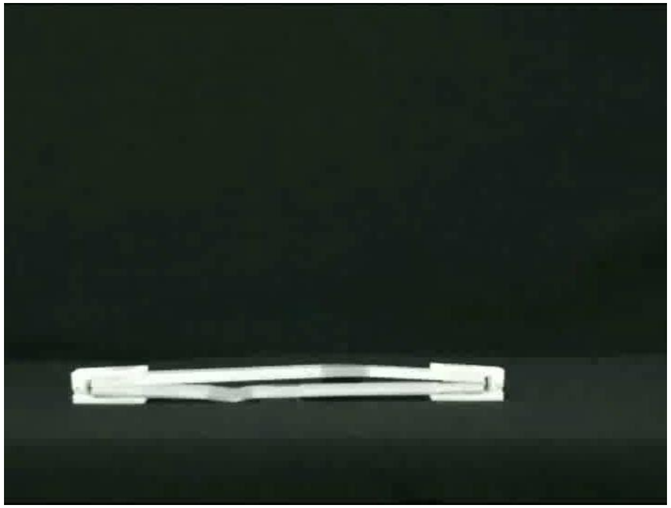
Using embedded SMA element

(a) **Soft robotic wrist** manufactured by double casting that is capable of sustaining a cantilever load and of producing a twisting deformation, (b) **turtle robot** using anisotropic fibers in a polymeric matrix to produce a coupled bend-twist motion, and (c) a **deployable structure** with an hinged-like motion.

Rodrigue H, Wei W, Bhandari B, Ahn S-H. *Smart Mater. Struct.,* 2015.
Kim H-J, Song S-H, Ahn S-H. *Smart Mater. Struct.,* 2013.
Wei W, Rodrigue H, Ahn S-H. *Sci. Rep.,* 2016.
Wei W, Rodrigue H, Ahn S-H. *Comp. Part B,* 2016.



Turtle robot



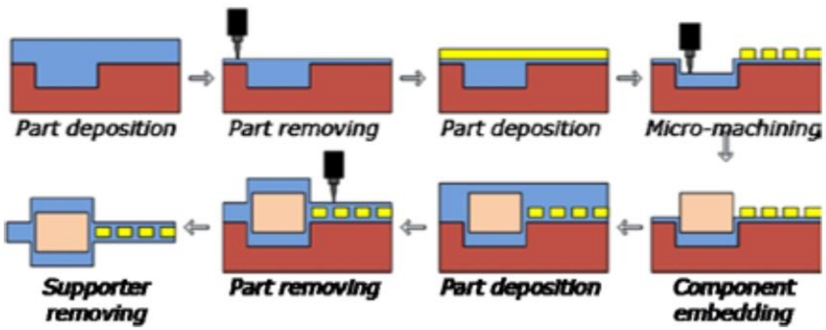
Ring-shape soft deployable structure

Soft gripper with passively adaptive capability

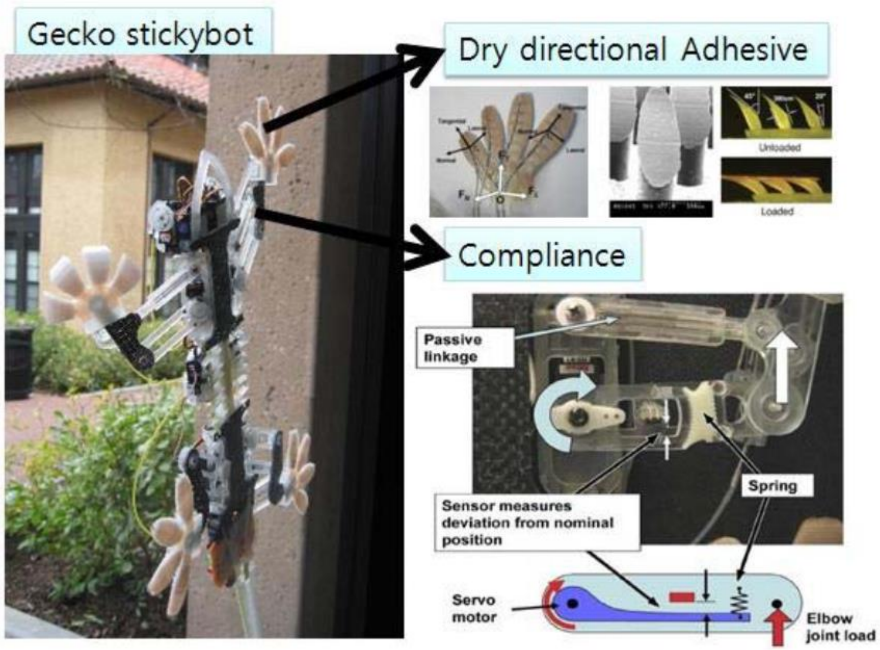
OVERVIEW :
MANUFACTURING PROCESSES FOR SOFT BIOMIMETIC DEVICES

Shape Deposition Manufacturing (SMD)

- **Shape Deposition Manufacturing (SDM)**
  - It was developed for rapid-prototype using metallic materials in the early 1990's.
  - Various parts, i.e. sensors and circuits, can be embedded during the manufacturing process since the SDM is a layer based deposition process.



Schematic diagram of SDM process

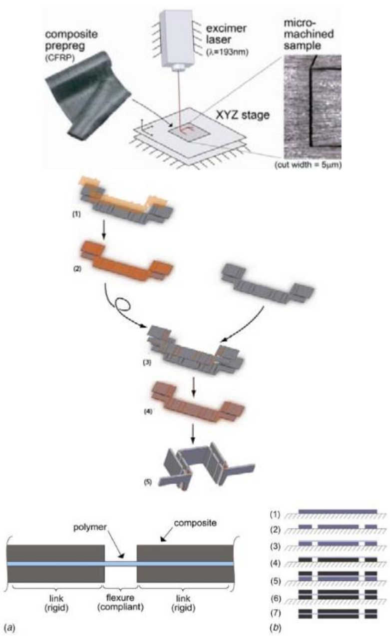


Stickybot – Gecko inspired wall climbing robot

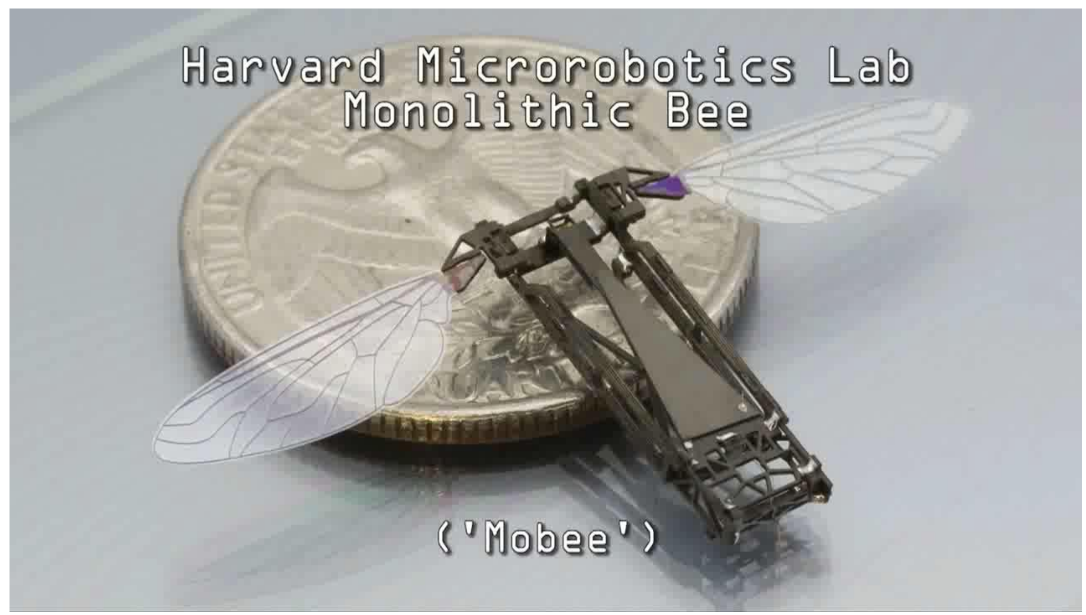
Kim S, Spenko M, Trujillo S, et al. Whole body adhesion: hierarchical, directional and distributed control of adhesive forces for a climbing robot, 2007: 1268-1273.

Smart Composite Microstructure (SCM)

- **Smart Composite Microstructure (SCM)**
  - SCM process is a manufacturing process which enables integration of a rigid link made of carbon fiber composites with flexure joints made of polymer film.
  - This process uses micro laser machining to **cut out** a flat composite and polymer film into the required shape and **laminates** the different materials to create the integrated structure.



Schematic diagram of SCM joint structure and procedure of manufacturing



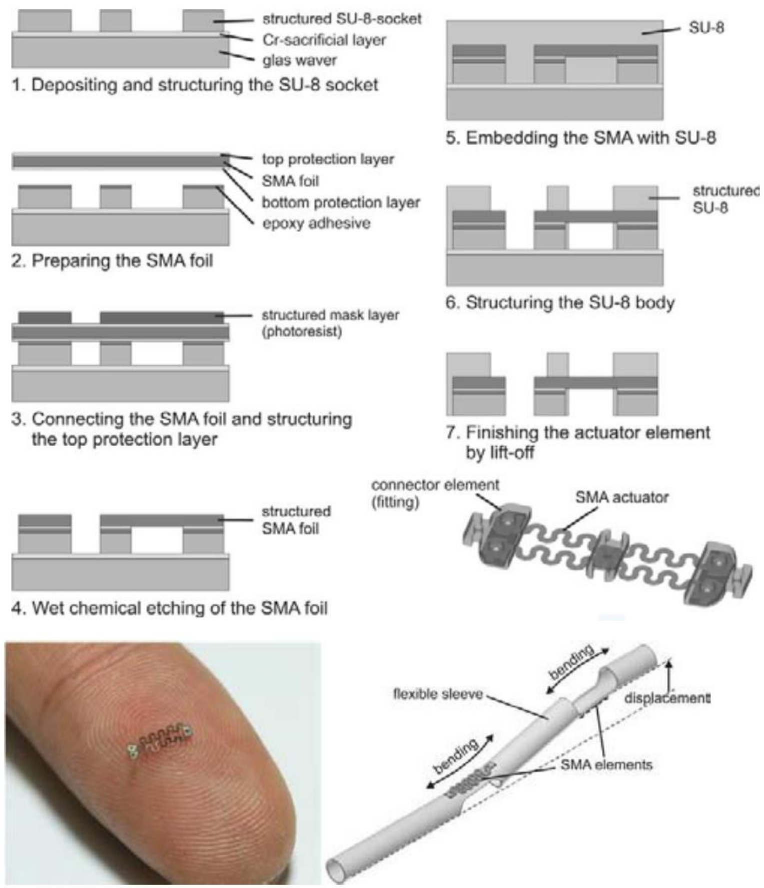
Pop-up Fabrication of Mobee

https://www.youtube.com/watch?v=VxSs1kGZQqc

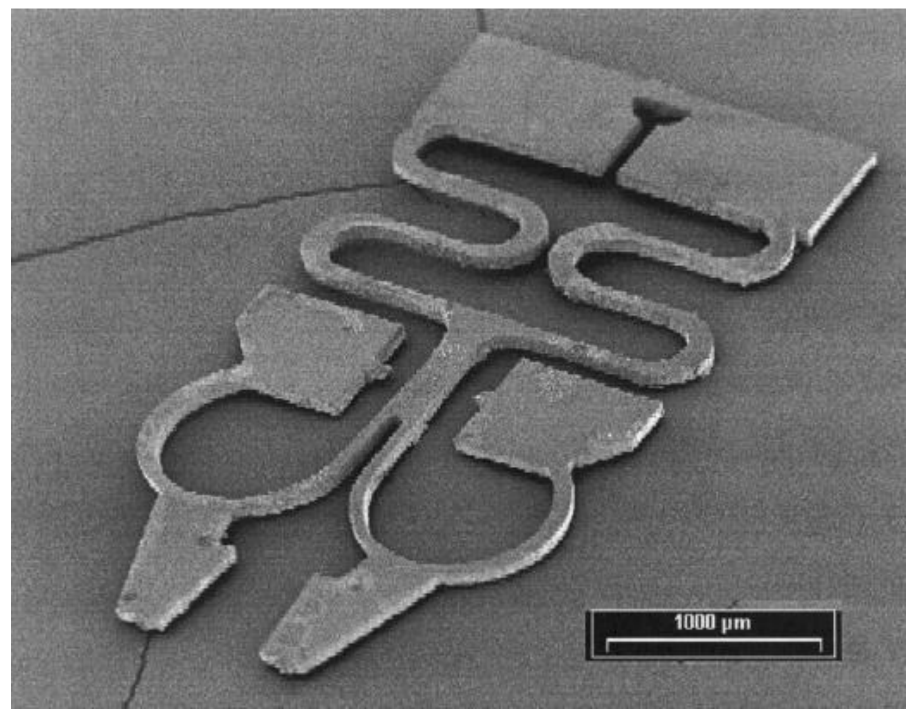
Cho K J, Koh J S, Kim S, et al. Review of manufacturing processes for soft biomimetic robots. IJPEM, 2009, 10(3): 171-181.

Shape Memory Alloy Embedding Process

- **SMA embedding batch process**
  - SMA foil is usually fabricated into the structure by using SCM process



SMA embedding batch process

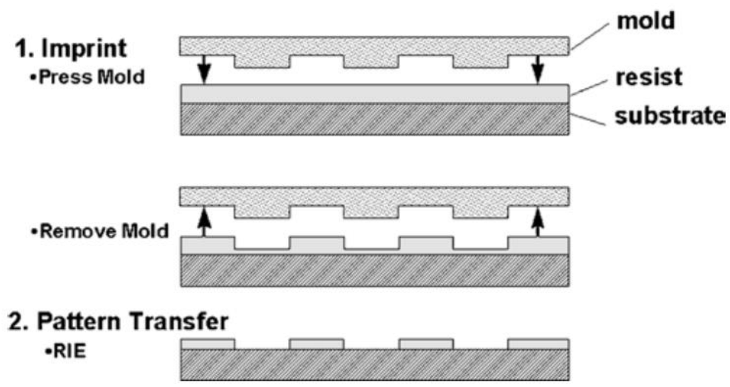


Fabrication of micro-gripper: micro-gripper was micro-machined through laser cutting and then bonded to ceramic substrate

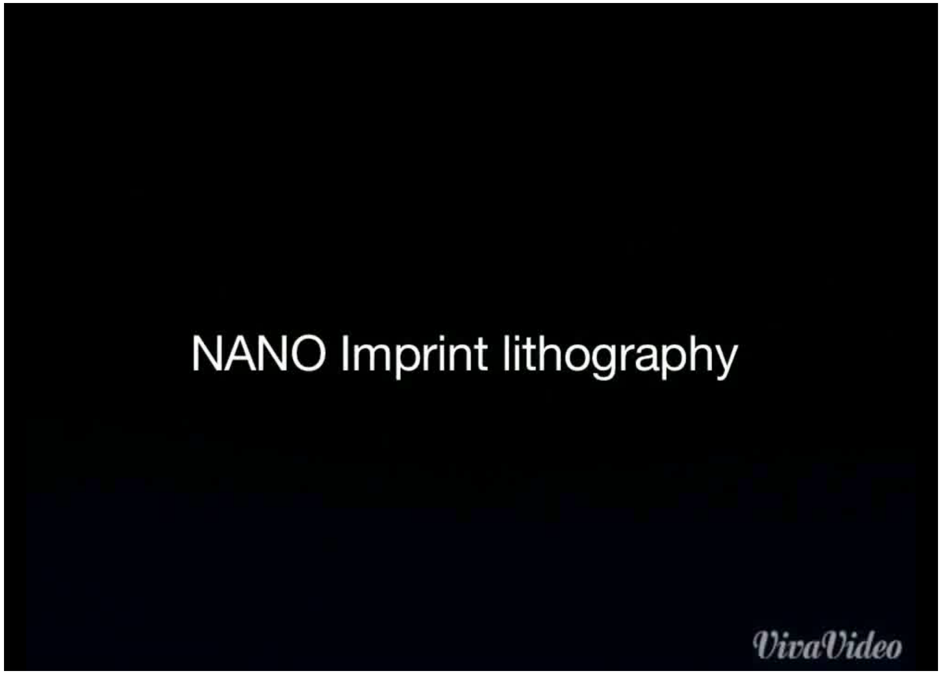
Leester-Schädel M, Hoxhold B, Lesche C, et al. Micro actuators on the basis of thin SMA foils. Microsystem Technologies, 2008, 14(4-5): 697-704.

Nano Imprint

- **Nano Imprint**
  - This method is a stamping on photo resist circuit using patterned template which can skip the complicate exposure process.
  - PDMS which is usually used as template material sometimes causes of deformation by the high pressure when pattern is printed on the material.



A schematic diagram of mold-assisted lithography

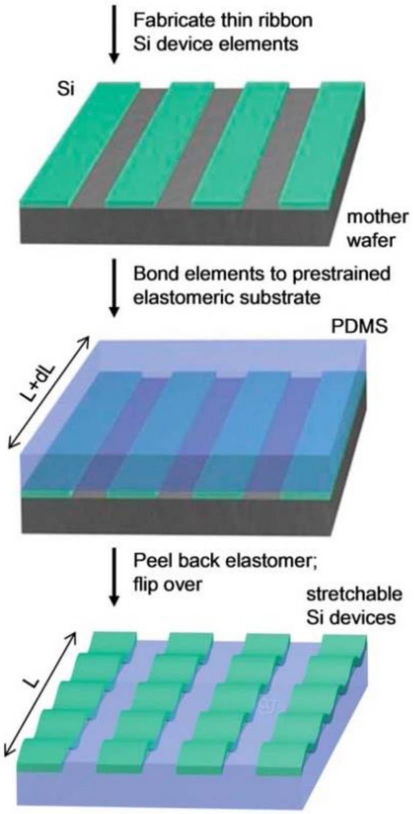


NANO Imprint lithography
https://www.youtube.com/watch?v=K3Xcs6SG9js

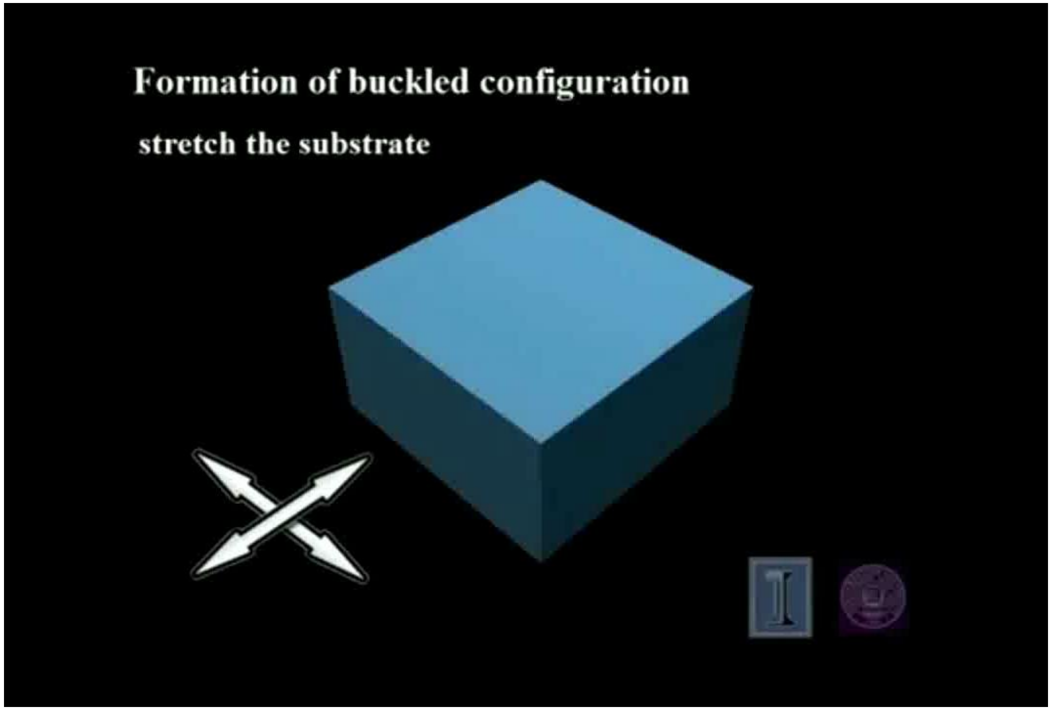
Chou S Y, Krauss P R, Zhang W, et al. Sub-10 nm imprint lithography and applications. JVST B, 1997, 15(6): 2897-2904.

Vertical Ripple (Buckling) Structure

- **Vertical Ripple Structure**
  - It has been embedded into a straight line to improve stretchable property of the conductive line.



Process for building stretchable single-crystal Si devices on elastomeric substrates



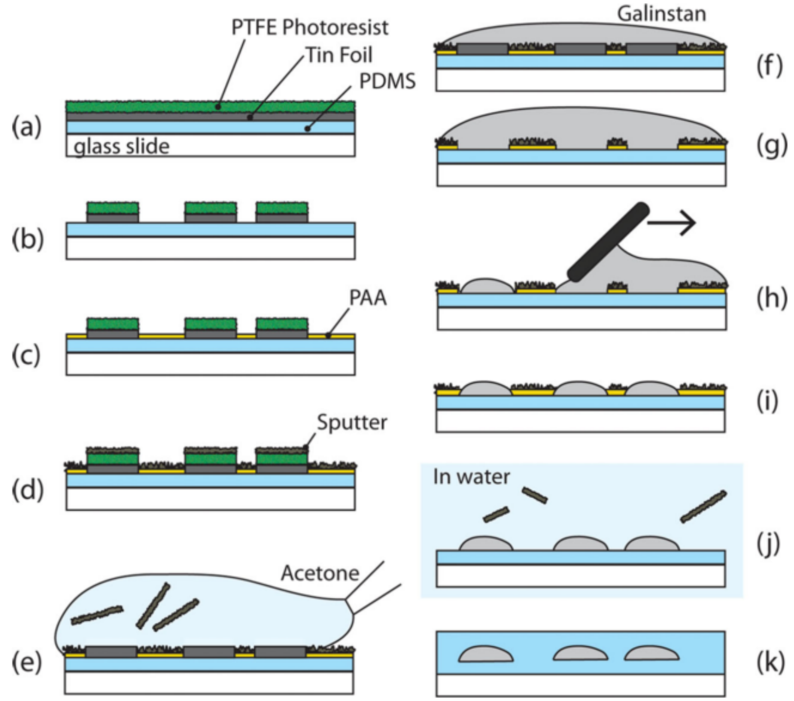
Flexible, stretchable electronics

https://www.youtube.com/watch?v=jlEIvGzthsk

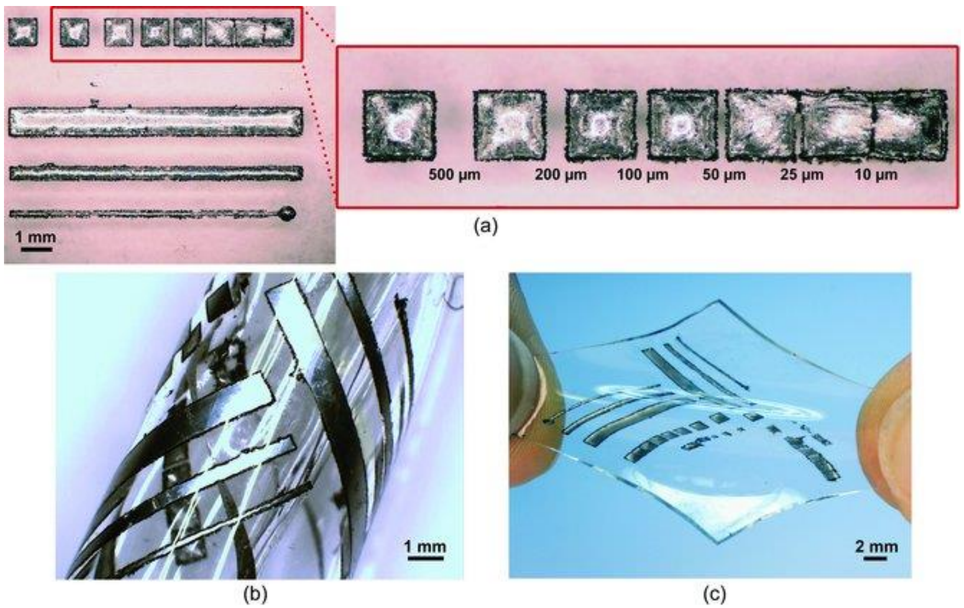
Khang D Y, Jiang H, Huang Y, et al. A stretchable form of single-crystal silicon for high-performance electronics on rubber substrates. Science, 2006, 311(5758): 208-212.

Masked Deposition for liquid-embedded elastomer electronics

- A fabrication method is introduced that utilizes **masked deposition** and **selective wetting** to produce hyper-elastic electronic circuits that are composed of a thin elastomer film embedded with micro-channels of liquid-phase gallium-indium (Ga-In) alloy .



Process flow for **liquid-embedded elastomers** fabricated by selective wetting of gallium-indium alloys.

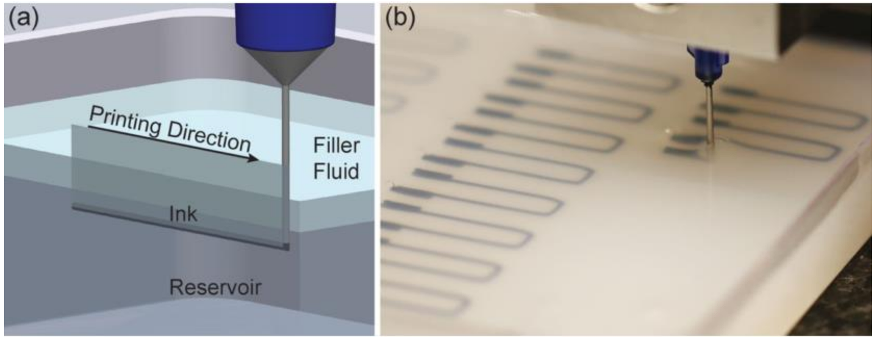


a) A test liquid-embedded-elastomer pattern displaying possible feature sizes and densities enabled by the fabrication process. b,c) The liquid-embedded elastomer is flexible and stretchable.

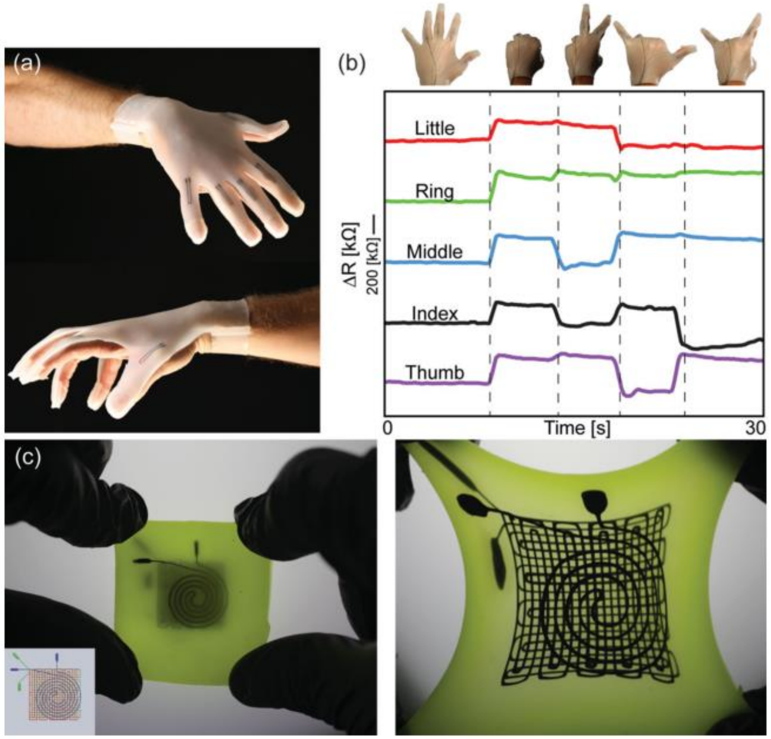
Kramer R K, Majidi C, Wood R J. Masked Deposition of Gallium-Indium Alloys for Liquid-Embedded Elastomer Conductors. Advanced Functional Materials, 2013, 23(42): 5292-5296.

Embedded-3D Printing

- **Embedded-3D Printing** (Direct 3D printing of conductive material)
  - It is developed for fabricating strain sensors within highly extensible elastomeric matrices.
  - e-3DP allows soft sensors to be created in nearly arbitrary planar and 3D motifs in a highly programmable and seamless manner.



(a) Schematic illustration of the **e-3DP** process. A conductive ink is printed into an uncured elastomeric reservoir, which is capped by filler fluid. (b) Photo graph of e-3DP for a planar array of soft strain sensors.

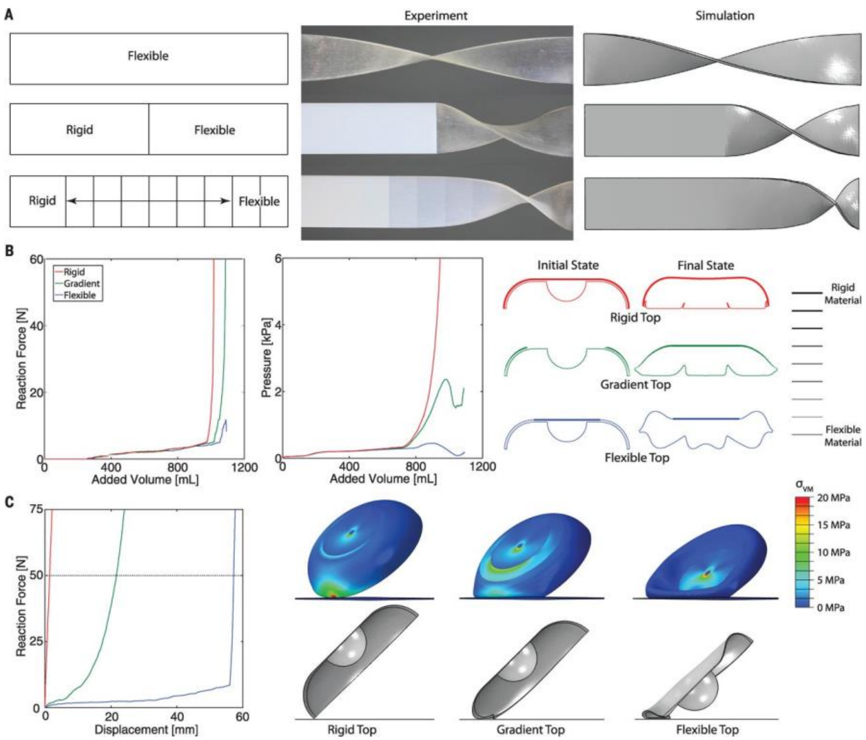


(a) Photograph of a **glove with embedded strain sensors** produced by e-3DP. (b) Electrical resistance change. (c) Photograph of a three-layer strain and pressure sensor in the unstrained state (left) and stretched state (right).

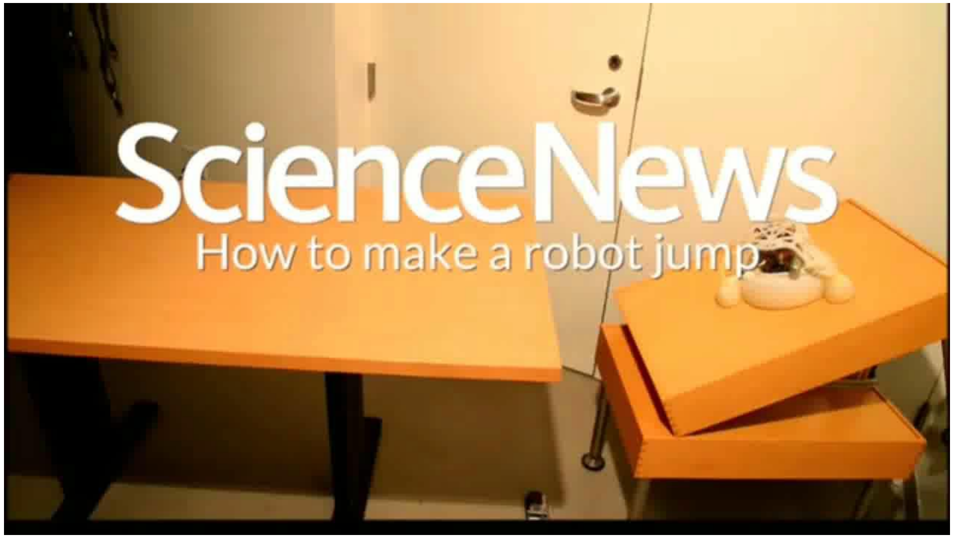
Muth J T, Vogt D M, Truby R L, et al. Embedded 3D printing of strain sensors within highly stretchable elastomers. Advanced Materials, 2014, 26(36): 6307-6312.

Multimaterial 3D Printing

- A multimaterial 3D printer is used to directly print the functional body of a soft robot that employs soft material components for actuation, obviating the need for complex molding techniques or assembly.



Material tests and simulation results.

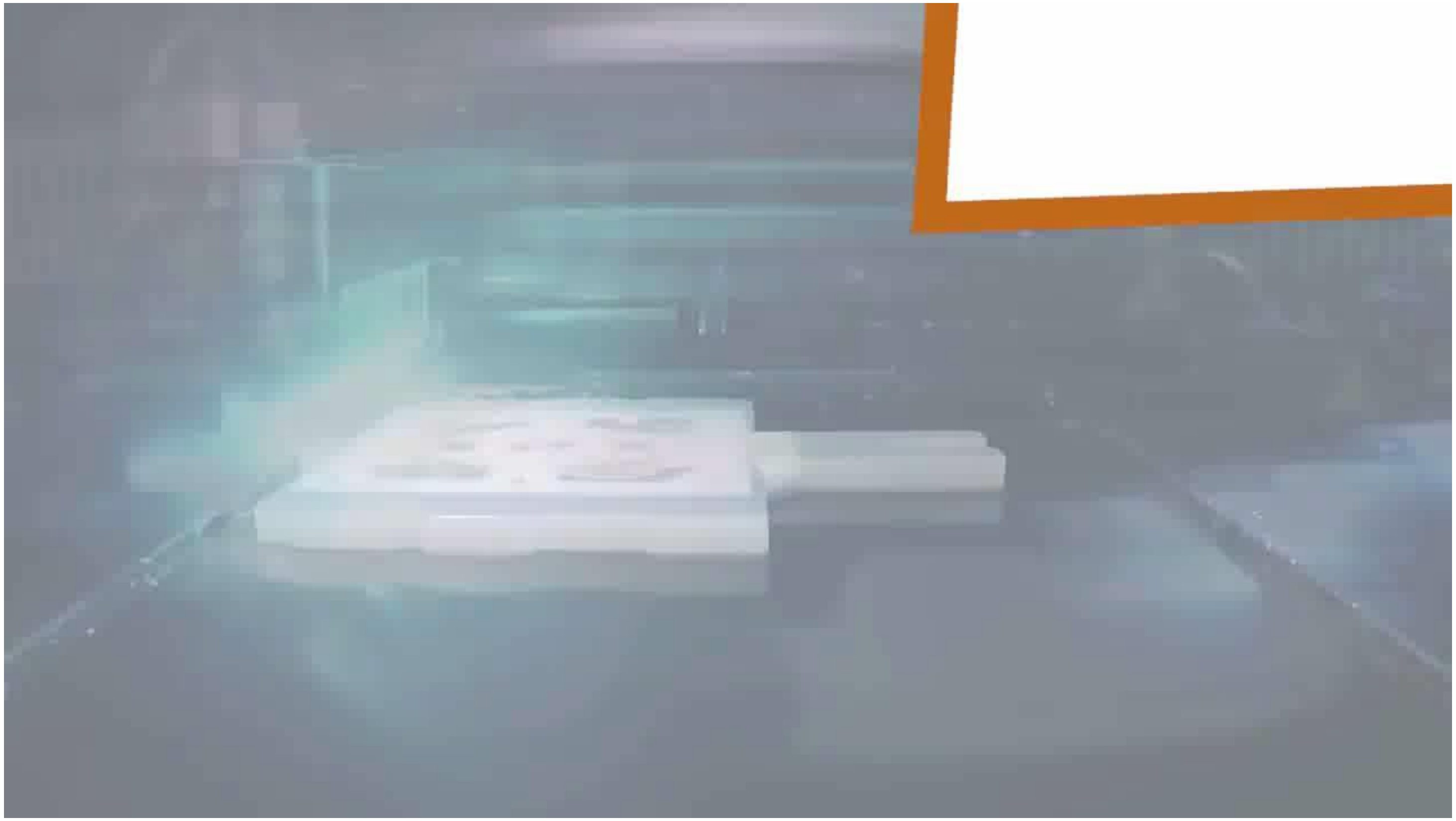


A 3D-printed, functionally graded soft robot powered by combustion

Bartlett N W, Tolley M T, Overvelde J T B, et al. Science, 2015, 349(6244): 161-165.

Multimaterial 3D Printing

- **Printable Hydraulics**
  - A novel technique is introduced for fabricating functional robots using 3D printers. Simultaneously depositing photopolymers and a non-curing liquid allows complex, pre-filled fluidic channels to be fabricated.

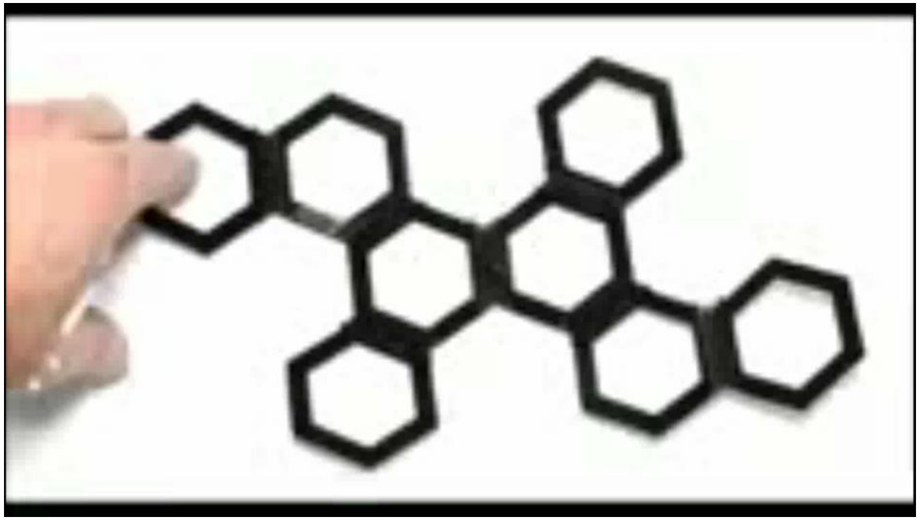


Printable Hydraulic Robots

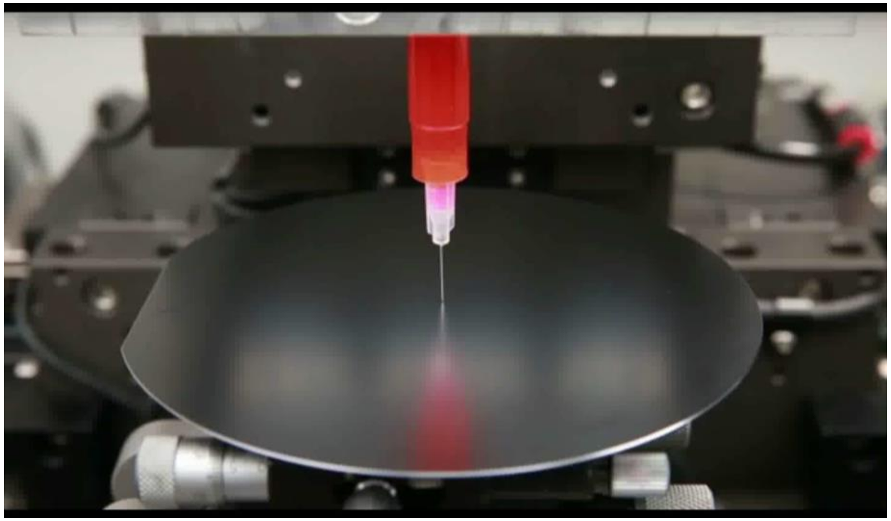
MacCurdy R, Katzschmann R, Kim Y, et al. Printable Hydraulics: A Method for Fabricating Robots by 3D Co-Printing Solids and Liquids. arXiv preprint arXiv:1512.03744, 2015.

4D printing

- With a single multi-material print, a product or mechanism can transform from any 1D strand into 3D shape, 2D surface into 3D shape or morph from one 3D shape into another.
- Using only water, heat, light or other simple energy input, this technique offers adaptability and dynamic response for structures and systems of all sizes.



4D Printing: Multi-Material Shape Change



Harvard Unveils Adaptive 4D Printing Process

http://www.selfassemblylab.net/4DPrinting.php
http://www.digitaltrends.com/cool-tech/harvard-scientists-unveil-4d-printing/