A Review of Shape Memory Alloy Actuators in Robotics

Mohammad Mahdi Kheirikhah, Samaneh Rabiee, and Mohammad Ehsan Edalat

Islamic Azad University, Qazvin Branch, Faculty of Industrial & Mechanical Engineering, Nokhbegan Boulevard, Qazvin, Iran
kheirikhah@qiau.ac.ir, rabiee1982@yahoo.com, m_ehsan_e@yahoo.com

Abstract. Shape Memory Alloys (SMAs) have been used for a wide variety of applications in various fields such as robotics. If these materials subjected to an appropriate thermomechanical process, they have ability to return to their initial shape. Often, they are used as actuators in robotic applications. The purpose of this paper is to present a brief review of literatures which using SMA in different robots' structure. First an introduction about shape memory effect of these materials will present. Then an assessment of done researches in application of these materials in robots' structure will accomplish and is devoted to the following area of robotics: Crawler, jumper, flower, fish, walker, medical and Biomimetic robotic hand.

Keywords: Shape Memory Alloys, robotic, review, actuator.

1 Introduction

SMA constitute a group of metallic materials with the ability to recover a previously defined length or shape when stand under a thermodynamics process.

Although a relatively wide variety of alloys present the shape memory effect (SME), but only those that can recover from a large amount of strain or generate an expressive restitution force are of commercial interest [1]. The typical attribute of these materials is that their parameters can't be determined by simple interpolation of properties of alloys included in the compound. Superplasticity, superelasticty, acid resistance and SME make these compounds technically important [2].

It has been found that many materials exhibit the shape memory effect (SME), such as Cu-Zn, Cu-Zn-Se, Fe-Mn-Se, Au-Cd, etc. The most common SMA is a nickel-titanium alloy known as NiTiNOL. This SMA is believed to be one of the most important candidates for smart materials [3]. SMA based on Ni-Ti are the alloys most frequently used in commercial applications because they combine good mechanical properties with shape memory effect[1].

In 1938, Greninger and Mooradian first observed the SME for copper-zinc alloys (Cu-Zn) and copper-tin alloys (Cu-Sn). Yet nearly 30 years elapsed until Buehler and his colleagues applied in 1965 for the first patent for a NiTiNOL, from the Naval Ordnance Laboratory. Near the end of the 1960s, Raychem developed the first industrial SMA applications in aeronautics with the Cryofit connector for F-14 airplane hydraulic circuits. Meanwhile at the University of Iowa, Andreasen's interest in dental alloys led

J. Ruiz-del-Solar, E. Chown, and P.G. Ploeger (Eds.): RoboCup 2010, LNAI 6556, pp. 206–217, 2011.

to the implantation of the first superelastic dental braces made from Ni-Ti in 1975. Buehler suggested using SMA in dentistry for different implants that could retain the shape memory [4].

The transition from one form of crystalline structure to another creates the mechanism by which the shape change occurs in SMAs. This change involves transition from a monoclinic crystal form (martensite) to an ordered cubic crystal form (austenite)[5]. The austenite phase is stable at high temperature, and the martensite is stable at lower temperatures. So typical SMA, the phase transformation between the two phases, martensite and austenite, is accompanied by variations in its resistivity [6]. The particular mechanical behavior of these materials, related to the existence of a structural phase transformation, allows their use as actuator in many applications such as: aerospace, instrumentation, robotics, biomaterials (medical prostheses or Microsystems) and the other application [7].

SMAs are usually available in the form of a wire, pipes, springs or ribbons. So, it can be used as a low-volume actuator in low-space where it is not possible to use huge actuator. In robotics, the SMAs represent a very interesting alternative within the field of classical drives, such as the electric or hydraulic motors. Thus the drives based on metals with the shape memory effect are the subject of research in many institutions, which are interested in the research of robotics. In this paper, there are presented an assessment of application of SMA actuators in robotics' different branches such as crawler robots, jumper robots flower robots, fish robots, walker robots, medical robots and Bio-mimetic robotic hand.

2 Crawler Robot

Liu and Liao [8] presented the development and testing of a snake robot that uses SMAs as actuators in 2004. An eight-segment robot was designed to move similar to the rectilinear motion of a natural snake. A pair of SMA wires had been implemented into each segment. One of the SMA wires in each segment was heated at a time, and it acted like a muscle to change the shape of the segment. A prototype robot was built, and it could move well with the desired locomotion. As shown in Fig. 1, when the lower wire is activated, the distance between its two ends is extended to 4 cm, and the distance between its two ends of the upper wire is shorten to 2 cm.

In the same year, Lee et al [9] introduced a novel bio-mimetic micro robot with simple mechanism using SMA to generate earthworm-like locomotion. A two-way linear actuator using SMA spring and silicone bellows had been applied to the micro

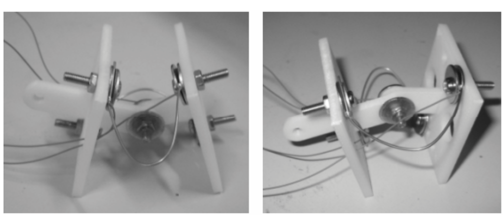

Fig. 1. Segments with activated SMA wires [8]

robot. Fig. 2 shows the locomotive principle of the proposed micro robot. The front needles clamp a contact surface and the rear body slides forward when SMA spring is contracted by heating. After the contraction of the SMA spring, the deformation energy of the silicone bellows makes the SMA spring elongate when it cools. At that time, the rear needles clamp the contact surface and the front body slides forward. Finally, the bellows' spring force is equal to that of SMA spring as initial equilibrium state.

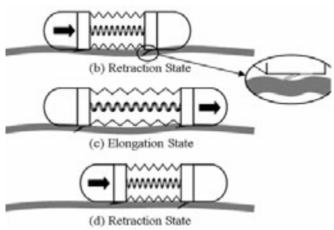

Fig. 2. Principle of locomotion [9]

The undulatory locomotion of living earthworms had been investigated deeply from the biological point of view by Menciassi et al [10] in 2004, but attempts of replication of earthworm models in real size were limited. Their robot had some modules that each module was actuated by one or more SMA springs. Preliminary tests demonstrated that the earthworm prototypes can move with a speed of 0.22 mm/s, thus approximating the behavior of biological earthworms.

Also in 2004, by investigating the biological field, the Menciassi et al [11] developed artificial earthworms by mimicking the structures and locomotion principles of real ones. Prototypes with or without micro-legs (which affect the locomotion performance) had been developed.

Along them, in 2004 Qin et al [12] that presented the design of a SMA driving micro-wheeled-robot, which had a 45mm×15mm×30mm size. Their paper shows the design principles of a resilient-rigid coupling SMA actuator (RRSA). This robot was controlled by Yao et al [13] in the same year. In this robot the SMA spring was heated by pulse current by PIC controller (a kind of single-chip) and was cooled by air.

Pipe inspection is a very important issue in construction. The inspection of low diameter canalizations is a pending issue nowadays, however it would help to repair and maintain a large amount of installations. Conventional in-pipe moving mechanisms for pipe inspection, driven by electromagnetic motors, have large volume and mass. The SMA actuator can be an alternative for a small-sized in-pipe moving mechanism due to its great power-to-weight ratio and simple structure. In 2005, Gambao et al [14] presented a robot that was able to move inside pipes of less than 26mm diameter and negotiate bends while carrying a camera to make an efficient in-pipe search. Each module of this robot had three degrees of freedom (DOF) with 3 SMA wires.

In year 2005, using twelve novel SMA linear actuators, which could stretch and shrink along its axis and could bear some radial force and bend, a miniature worming robot with a cubic form was presented by Yu et al [15]. Besides, the robot had a certain ability of passing through pipelines with large curvature or variable radius in a certain span.

Menciassi et al [16] expanded the development of segmented artificial crawlers with passive hook-shaped frictional microstructures in 2006. There were described the mechanical model, the design and the fabrication of a SMA-actuated segmented microrobot, whose locomotion had been inspired by the peristaltic motion of Annelids, and in particular of earthworms (Lumbricus Terrestris).

Caterpillars are some of the most successful scansorial and burrowing animals and yet they lack a hard skeleton. Their hydrostatic body and prolegs provide astonishing fault-tolerant maneuverability and powerful, stable, passive attachment. Trimmer et al [17] in 2006 described some of the biomechanics of caterpillar locomotion and gripper. They described their recent work to build a multifunctional robotic climbing machine based on the biomechanics and neural control system. This robotic caterpillar under development was a contoured cylinder constructed from highly elastic silicone rubber. It moved by SMA springs as actuators, bonded directly to the inside of the body wall. Also a kind of gripper was designed for this robot that provided its vertical movements by 3 SMA springs.

In the next year, 2007, also an investigation on the structure of caterpillar's body was presented by Kate et al [18] where in each segments of this robot there were used 2 SMA wires as an actuator too.

Spring type SMA actuators are selected to fabricate an inchworm-like moving mechanism that consists of clamping and moving modules (Fig.3). For selection of proper operating type (a bias type or a differential type) for clamping module and moving module, displacements and dynamic characteristics of each operating type were investigated by Lee and Kim [19] in 2008. A moving speed of 34 mm/min and traction force of 0.4N were obtained from the driving experiment in a pipe with the diameter of 39mm.

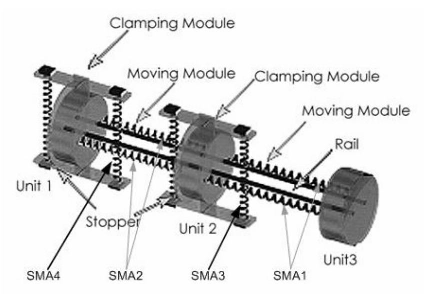

Fig. 3. Structure of in-pipe moving mechanism [19]

3 Jumper Robots

Locomotion over rough terrain has been achieved mainly by rigid body systems including crawlers and leg mechanisms. Sugiyama and Hirai [20] presented an alternative method of moving over rough terrain, one that was employed deformation in 2004.

The circular soft robot consisted of a circular elastic shell with a set of soft actuators inside. The robot has eight SMA actuators which deforms the robot body. Fig. 4 shows a sequence of snapshots of the prototype jumping. The prototype can jump a distance of 80mm, which is twice its diameter.

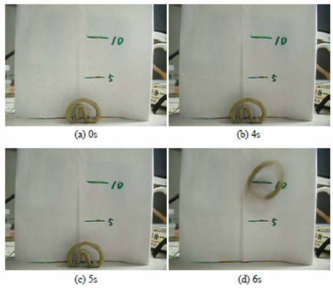

Fig. 4. Circular soft robot jumping [20]

In 2005, the principle of crawling and jumping as performed through deformation of a robot body was described by Sugiyama et al [21]. Then, in a physical simulation, they investigated the feasibility of the approach. Next, authors showed experimentally that prototypes of a circular robot and a spherical robot could crawl and jump.

In the same year, Shiotsu et al [22] created two prototypes of a spherical soft robot to assess experimentally the feasibility of a deformable robot crawling and jumping. Prototype A was for crawling and consisted of 18 SMA coils and shells made of spring steel. The core inside the spherical body included circuits to drive SMA coils, a microprocessor, and a serial communication circuit. Prototype B was for both crawling and jumping. This prototype consisted of 22 SMA coils – 18 for crawling and jumping and 4 for jumping. Circuits to drive SMA coils and a microcomputer were outside of the prototype.

4 Flower Robots

As a smart home service robot, the flower robot has various intelligent functions, such as moving mechanism, sensing ability, and home appliance functions. Especially, the moving function is very important function among the various function. The moving function of flower robot has consisted of the blooming of flower, the swaying of the stem and the stirring of the leaves in the wind.

Huang et al [23] in 2007 focused on the swaying of the stem structure. As an actuator for stem structure, authors adopted coil type SMA and then proposed silicone stem structure with 3 coil type SMA. They designed and fabricated the stem structure with 8mm of diameter and 50mm of length.

After a year, in 2008, Huang et al [24], focused on the movement of the flower robot structure. As an actuator for flower structure, they adopted coil type SMA and proposed silicone stem, petal and leafage structure used 6 coil type SMA. There were embedded 3 coil type SMA actuators in a silica gel rod. In the center hole of the

Fig. 5. The movement of stem and flower petal [24]

silicone rod, a spring and a wire with one side of SMA were connected to drive the petal of the flower robot. In the design of leafage, a SMA wire was bonded to one surface of the leafage. The fashion of motion in leafage was same with the stem structure. Fig.5 shows the movement of stem and flower petal.

5 Fish Robots

Fishes are regarded as highly maneuverable and effortless swimmers due to their extraordinary capability of moving in aquatic environs in terms of noiseless locomotion, rapid turning, fast starting and long distance cruise. Fish robots are inspired from natural fishes. In some of them, SMA is used as an actuator.

In 2006, Tao et al [25] presented the design of a caudal peduncle actuator, which was able to furnish a thrust for swimming of a robotic fish. The caudal peduncle actuator was based on concepts of ferromagnetic shape memory alloy (FSMA) composite and hybrid mechanism that could provide a fast response and a strong thrust. The caudal peduncle actuator was inspired by Scomber Scombrus. The morphology of an average size Scomber Scombrus was investigated, and a 1:1 scale caudal peduncle actuator prototype was modeled and fabricated. The tail was a composite consisted of superelastic NiTi SMA framework and two polymer impermeable membranes, which were adhered mutually by a superglue.

After two years, in 2008, Cho et al [26] presented the design and fabrication of a centimeter-scale propulsion system for a robotic fish. SMA spring actuators were customized to provide the necessary work output for the microrobotic fish. The flexure joints, electrical wiring and attachment pads for SMA actuators were all embedded in a single layer of copper laminated polymer film. Finally this package was sandwiched between two layers of glass fiber. Instead of using individual actuators to rotate each joint, each actuator rotated all the joints to a certain mode shape and undulatory motion was created by a timed sequence of these mode shapes.

During this year, an embedded SMA wire actuated bio-mimetic fin was presented by Wang et al [27]. Fish swims by their undulating body and/or fins.To simplify engineering modeling, the undulating swimming movement was assumed to be the integration of the movements of many flexible bending segments connected in parallel or in series. The musculature of a cuttlefish fin was investigated to aid the design of the bio-mimetic fin. SMA wires acted as muscle fibers to drive the bio-mimetic fin just like the transverse muscles of the cuttlefish fin. During the bending phase, elastic energy was stored in the elastic substrate and skin, and during the return phase, it was released to power the return movement.

6 Walker Robots

Walker robots are a kind of robots which can move with some legs and something like them. They can be in various areas like a gecko, hexapods and so many other kinds of bio-mimetic robots.

The design, fabrication, and evaluation of two novel bio-inspired climbing robots were presented by Menon and Sitti [28] in 2005. Both were inspired by the locomotion of Geckos, a highly skilled natural climber. There were developed for terrestrial and extra-terrestrial environments. The first relatively large robot actuated by conventional motors was designed to operate at both in Earth and space scenarios. The second robot, whose motion was controlled using SMA actuators and size could be miniaturized to few centimeters scale, was designed for terrestrial applications. Preliminary prototypes of these robots were developed. One of these robots had a composite material frame and SMA wires provided motion that mimicked gecko muscles (Fig. 6). Also in the other paper, these authors [29] presented some other kinds of analysis of this gecko robot.

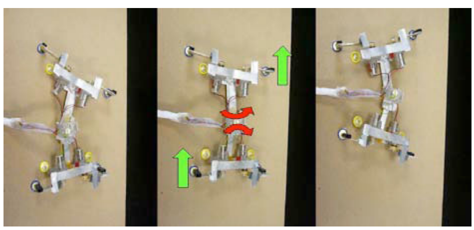

Fig. 6. Locomotion of Rigid Gecko Robot (RGR)[28]

In 2006 Nishida et al [30] presented a study on the development and control of a micro biped walking robot using SMAs. They proposed a flexible flat plate (FFP) consisted of a polyethylene plate and SMAs. Based on a detailed investigation of the properties of the SMA-based FFP structure, they developed a lightweight micro walking robot incorporating multiple SMA-based FFPs. This walking robot had four DOF and was controlled by switching the on-off current signals to the SMA-based FFPs.

Hoover et al [31] presented the design, fabrication and testing of a novel hexapedal walking millirobot using only two actuators in 2008. Actuation was provided by SMA wire. First, SMA was integrated very nicely with the smart composite microstructures (SCM) process. Alignment and routing features could be directly achieved into the composites to enable easy attachment and tensioning of the SMA wire. On the Second, SMA wire provided a force in a single direction.

In the same year, Berry and Garcia [32] presented the design and testing of a SMA and spring steel flexture actuator to use in a meso-scale 18 DOF hexapod. In the field of walking robots, the use of SMA as an actuator is mainly limited to micro-scale applications, in which they considered robots measuring less than 5cm in any dimension micro-scale.

7 Medical Robots

One of the other application areas of SMAs is in medical robots. In 1999, Reynaerts et al [33] described a prototype gastro-intestinal intervention system based on an inchworm-type of mobile robot which was a kind of vehicle for inspection through the colon. The robot consisted of three main modules that all these modules were actuated by SMA elements.

Also in 2001, Mi et al [34] presented the robot mainly consisted of soft mobile mechanism for earthworm locomotion and turning mechanism based on SME. The soft mobile mechanism contacted colon wall with air-in inflatable balloons, so the robot had better soft and non-invasive properties. The turning mechanism could be actively bent by SMA components. Therefore, this colonoscopic robot had good safety, lower working strength of surgeon and higher efficiency of colonoscopy.

The other kinds of these automotive tools and robots are Paris intestinal endoscope which were investigated by Cepolina and Michelini [35] in 2004. The Laboratorie de Robotique de Paris (L.R.P.) endoscope had been made by a series of modules articulated to each other by pin joints. On every link, two SMA springs had antagonist configuration to change the relative orientation. Although, there were investigated on Leuven intestinal worm and Pisa intestinal worm which used SMA as an actuator.

8 Bio-mimetic Robotic Hands

The ideology of this research is to utilize advanced actuators to design and develop innovative, lightweight, powerful, compact, and dexterous robotic technology. The key to satisfying these objectives is the use of advanced or smart materials, such as SMAs to power the joints of a prosthetic hand, and other dexterous robotic hands.

DeLaurentis and Mavroidis [36] in 2000 presented the mechanical design of a four fingered, fourteen DOF dexterous robotic hand, patterned human anatomy. A lightweight aluminum four DOF finger prototype had been made. The robotic hand concept was presented based on the using of SMA artificial muscles.

Alsoin 2002, DeLaurentis and Mavroidis [37] presented the mechanical design for a new five fingered, twenty DOF dexterous hand patterned human anatomy and actuated by SMA artificial muscles. Two experimental prototypes of a finger, one fabricated by traditional means and another fabricated by rapid prototyping techniques, were described and used to evaluate the design. The using of SMA actuators combined with the rapid fabrication of the non-assembly type hand to reduce considerably its weight and fabrication time.

After two years, Hino and Maeno [38] described a miniature robot finger which used SMA as the actuator. The miniature robot finger proposed in this paper, was driven by SMA wires. The structure of the robot finger imitated the musculo-skeletal system of humans, since SMA wires exhibited nonlinear features similar to human muscles.

Fig.7 show miniature five fingered robot hand was developed by Maeno and Hino [39] in 2006, for dexterous manipulation of small tissues and parts in medical and industrial fields. The size of this robot hand was about one third of human hands. It had 4 DOF per a finger that was almost the same as humans. The entire DOF of the hand was 20. The hand was driven by SMA wire actuator.

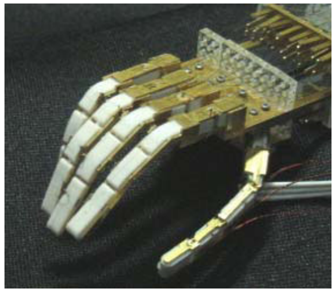

Fig. 7. Developed five-fingered robot hand [39]

Ashrafiuon et al [40] in the same year proposed a small planar 3 DOF robot arm actuated by two SMA actuators and a servomotor. The servomotor drove the first link while the SMA actuators rotated links 2 and 3. There was also an additional servomotor operating the gripper.

A finger spelling robot hand was also recently developed by Terauchi et al [41] which was driven by a combined action of a DC motor and SMA wires. The hand developed had 20 joints and DOF. The DC motor actuated the first joint (knuckle) of the finger. The second and third finger joints were directly driven by SMA wires. A pair of SMA wires was used in a push-pull configuration to actuate one finger joint.

Price [42] in 2007 presented SMA enabled devices promise to be of major importance in the future of dexterous robotics, and of prosthetics in particular. He investigated the design, instrumentation, and control issues surrounding the practical application of SMAs as artificial muscles in a three-fingered robot hand.

Also in the same year, O'Toole and McGrath [43] proposed mechanical design of a 12 DOF SMA actuated artificial hand. It was proposed that the SMA wires be embedded intrinsically within the hand structure which will allow for significant flexibility for use either as a prosthetic hand solution, or as part of a complete lower arm prosthetic solution.

A new bio-mimetic tendon-driven actuation system for prosthetic and wearable robotic hand applications was presented by Bundhoo et al [44] in 2008. It was based on the combination of compliant tendon cables and one-way SMA wires that form a set of agonist–antagonist artificial muscle pairs for the required flexion/extension or abduction/adduction of the finger joints. The performance of the proposed actuation system was demonstrated using a 4 DOF (three active and one passive) artificial finger tested, also developed based on a bio-mimetic design approach.

9 Conclusions

Based on the above discussions, the following conclusions can be drawn:

1. The SMA actuators can be an alternative for small robots due to their great power-to-weight ratio and ease of construction.
2. NiTinol alloys are compatible with human body, thus they can be used as either finger tendons or actuators in the medical robots.
3. The SMA actuators can be used in pipe inspection robots to move into the pipes and repair a large amount of installations.
4. One of most important applications of SMA actuators is in crawler robots such as snakes or earthworm robots.
5. The SMA actuators can be produced required loads for slowly or highly movement of some robots such as flower or fish robots.
6. Another application of SMA actuators is in walker robots such as gecko, hexapods and so many other kinds of bio-mimetic robots.

References

1. Machado, L.G., Savi, M.A.: Medical applications of shape memory alloys. Brazilian Journal of Medical and Biological Research 36, 683–691 (2003)
2. Vasina, M.: Untraditional Actuators For Robotics - Shape Memory Alloy. Dept. of Control and Instrumentation, FEEC, BUT
3. Chung, C.Y.: Applications of Shape Memory Alloys. Department of Physics and Materials Science, City University of Hong Kong
4. Mantovani, D.: Shape Memory Alloys: Properties and Biomedical Applications. JOM (Octobrer 2000)
5. Wakjira, J.F.: The VT1 Shape Memory Alloy Heat Engine Design. Virginia Polytechnic Institute and State University, Copyright (2001)
6. Yee. H., Featherstone, R.: A new control system for fast motion control of SMA actuator wires. Dept. Systems Engineering, Research School of Information Sciences and Engineering, The Australian National University, Canberra, Australia (2004)
7. Hessissen, L., Essaaidi, M.: Thermomécanical Behavior of Polycristalline Shape Memory Alloys in Martensitic Transformation. European Journal of Scientific Research 23(3), 474–481 (2008) ISSN 1450-216X
8. Liu, C.Y., Liao, W.H.: A Snake Robot Using Shape Memory Alloys. In: Proc. IEEE Int. Conf. on Robotics and Biomimetics, China (2004)
9. Young, P.L., Byungkyu, K., Moon, G.L., Jong-Oh, P.: Locomotive Mechanism Design and Fabrication of Biomimetic Micro Robot Using Shape Memory. In: Proc. IEEE Int. Conf. on Robotics & Automation, New Orleans (April 2004)
10. Menciassi, A., Gorini, S., Pernorio, G., Dario, P.: A SMA artificial earthworm. In: Proc. IEEE Int. Conf. on Robotics and Automation, New Orleans (2004)
11. Menciassi, A., Gorini, S., Pernorio, G., Weiting, L., Valvo, F., Dario, P.: Design, Fabrication and Performances of a Biomimetic Robotic Earthworm. In: Proc. IEEE Int. Conf. on Robotics and Biomimetics, China (2004)
12. Qin, C.J., Ma, P.S., Yao, Q.: A prototype micro-wheeled-robot using SMA actuator. Research Institute of Robotics, Mechanical Engineering, Shanghai JiaoTong University, Shanghai 200030, China (2004)

13. Yao, Q., Jin, S., Ma, P.S.: The Micro Trolley Based on SMA and its Control System. Journal of Intelligent and Robotic Systems 39, 199–208 (2004)
14. Gambao, E., Hernando, M., Brunete, A.: Multiconfigurable Inspection Robots for Low Diameter Canalizations. In: 22nd International Symposium on Automation and Robotics in Construction ISARC, Ferrara Italy, September 11-14 (2005)
15. Yu, H., Ma, P., Cao, C.: A Novel In-pipe Worming Robot Based in SMA. In: Proc. IEEE Int. Conf. on Mechatronics & Automation (2005)
16. Menciassi, A., Accoto, D., Gorini, S., Dario, P.: Development of a biomimetic miniature robotic crawler. Auton. Robot. 21, 155–163 (2006), doi:10.1007/s10514-006-7846-9
17. Timmer, B.A., Takesian, A.E., Sweet, B.M., Rogers, C.B., Hake, D., Rogers, J.: Caterpillar locomotion: A new model for soft-bodied climbing and burrowing robots. In: 7th International Symosium on Technology and Mine Problem, Monterey, CA, May 2-5 (2006)
18. Kate, M., Bettencourt, G., Marquis, J., Gerratt, A., Fallon, P., Kierstead, B., White, R., Trimmer, B.: SoftBot: A soft-material flexible robot based on caterpillar biomechanics. Tufts University, Medford, MA 02155
19. Lee, S., Kim, B.: Design parametric study based fabrication and evaluation of in-pipe moving mechanism using shape memory alloy actuators. Journal of Mechanical Science and Technology 22, 96–102 (2008)
20. Sugiyama, Y., Hirai, S.: Crawling and Jumping by a Deformable Robot. In: Proc. Int. Symp. on Experimental Robotics, Singapore (June 2004)
21. Sugiyama, Y., Shiotsu, A., Yamanaka, M., Hirai, S.: Circular/Spherical Robots for Crawling and Jumping. In: Proc. IEEE Int. Conf. on Robotics and Automation, Barcelona (April 2005)
22. Shiotsu, A., Yamanaka, M., Matsuyama, Y., Nakanishi, H., Hara, Y., Tsuboi, T., Iwade, T., Sugiyama, Y., Hirai, S.: Crawling and Jumping Soft Robot KOHARO. Dept. Robotics, Ritsumeikan Univ., Kusatsu, Shiga 525-8577, Japan (2005)
23. Huang, H.L., Park, S.H., Park, J.O., Yun, C.H.: Development of stem structure for flower robot using SMA actuators. In: IEEE Int. Conf. on Robotics and Biomimetics, ROBIO, December 15-18 (2007)
24. Huang, H.L., Park, S.H., Park, J.O.: Shape Memory Alloy based Flower Robot. In: 39th International Symposium on Robotics, Seoul, Korea (October 2008)
25. Tao, T., Liang, Y.C., Taya, M.: Bio-inspired Actuating System for Swimming Using Shape Memory Alloy Composites. International Journal of Automation and Computing 4, 366–373 (2006)
26. Cho, K.J., Hawkes, E., Quinn, C. Wood R.J.: Design, fabrication and analysis of a body-caudal fin propulsion system for a microrobotic. In: IEEE Int. Conf. on Robotics and Automation, ICRA, May 19-23 (2008)
27. Wang, Z., Hang, G., Wang, Y., Li, J., Du, W.: Embedded SMA wire actuated biomimetic fin: a module for biomimetic underwater propulsion. School of Mechatronics Engineering, Harbin Institute of Technology, PO Box 421, Harbin 150001, Heilongjiang, People’s Republic of China (2008)
28. Menon, C., Sitti, M.: Biologically Inspired Adhesion based Surface Climbing Robots. In: IEEE Int. Conf. on Robotics and Automation Barcelona, Spain (April 2005)
29. Menon, C., Sitti, M.: A Biomimetic Climbing Robot Based on the Gecko. Journal of Bionic Engineering 3, 115–125 (2006)
30. Nishida, M., Tanaka, K., Wang, H.O.: Development and control of a micro biped walking robot using shape memory alloys. In: Proc. IEEE Int. Conf. on Robotics and Automation, May 15-19 (2006)
31. Hoover, M.A., Steltz, E., Fearing, R.S.: ROACH: An autonomous 2.4g crawling hexapod robot. University of California, Berkeley, CA 94720 USA
32. Berry, M., Garcia, E.: Bio-inspired shape memory alloy actuated hexapod robot. Laboratory for Intelligent Machines Systems. Cornell University, Ithaca, NY, USA 14853 (2008)

33. Reynaerts, D., Peirs, J., Van Brussel, H.: Shape memory micro-actuation for a gastro-intestinal intervention System. Sensors and Actuators (1999)
34. Mi, Z.N., Gong, Z.B., Qian, J.W., Mi, Z.W., Shen, L.Y.: Study on moving Principle of Colonoscopic Robot. Journal of Shanghai University (English Edition) 5(2), 143–146 (2001) ISSN1007-6417
35. Cepolina, F., Michelini, C.R.: Robots in medicine: A survey of in-body nursing aids. In: International Symposium on Robotics, France (March 2004)
36. De Laurentis, K.J., Mavroidis, C.: Development of A Shape Memory Alloy Actuated Robotic Hand. The State University of New Jersey, USA (2000)
37. DeLaurentis, K.J., Mavroidis, C.: Mechanical design of a shape memory alloy actuated prosthetic hand. Technology and Health Care 10 (2002)
38. Hino, T., Maeno, T.: Development of a Miniature Robot Finger with a Variable Stiffness Mechanism using Shape Memory Alloy. International Simposium on Robotics and Automation, Querétaro México, August 25-27 (2004)
39. Maeno, T., Hino, T.: Miniature five-fingered robot hand driven by sape memory alloy acturator. In: Proceedings of the 12th IASTED International Conference on Robotics and Applications, Honolulu, Hawaii, USA (August 2006)
40. Ashrafiuon, H., Eshraghi, M., Elahinia, M.H.: Position Control of a Three-Link Shape Memory Alloy Actuated Robot. Journal of Intelligent Material Systems and Structures 17, 381 (2006) doi: 10.1177/1045389 X06056780
41. Terauchi, M., Zenba, K., Shimada, A., Fujita, M.: Controller Design on the Fingerspelling Robot Hand using Shape Memory Alloy. In: SICE-ICASE International Joint Conference, Busan, South Korea (October 2006)
42. Price, A.D., Jnifene, A., Naguib, H.E.: Design and control of a shape memory alloy based dexterous robot hand. Smart Mater. Struct. 16, 1401–1414 (2007)
43. O'Toole, K.T., McGrath, M.M.: Mechanical Design and Theoretical Analysis of a Four Fingered Prosthetic Hand Incorporating Embedded SMA Bundle Actuators. Proceedings of World Academy of Science, Engineering and Technology 25 (November 2007) ISSN 1307-6884
44. Bundhoo, V., Haslam, E., Birch, B., Park, E.J.: A shape memory alloy-based tendon-driven actuation system for biomimetic artificial fingers, part I: design and evaluation. In: Robotica ©. Cambridge University Press, Cambridge (2008) doi: 10.1017/S 026357470800458X