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APPLICATIONS OF SHAPE MEMORY ALLOY ACTUATORS IN BIOMEDICAL ENGINEERING

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Abstract: In this paper there are presented new type of actuators, especially actuators based on shape memory effect, performed by certain materials. Their applications are systematized and representative examples in the field of biomedical engineering are analyzed. New developed systems for active bending of minimal invasive surgery equipment, as well as for grasping in minimal invasive procedures are described. The paper presents other potential applications of shape memory actuators in the field of rehabilitation engineering and assistive technology.

1. INTRODUCTION

Biomedical Engineering is an interdisciplinary branch of engineering in which the principles and tools of traditional engineering fields, such as mechanical, materials, electrical, computer and chemical engineering, are applied to biomedical problems, [1]. Its role consists in identification of the needs of a health care system and of the means of meeting these needs using available technology, [5]. The permanent interaction with biological systems requires new and improved actuation systems. The most important elements of these actuation systems are the *actuators* that convert an input energy into controllable motion. Their actuation effect is achievable by three different means: *field interaction*, *mechanical interaction* and *induced limited strain*. The actuators in last category include elements made of so-called *intelligent* or *smart* materials.

According to [3], [6], [13], in case of the *piezoelectric* materials (e.g. lead-zirconate-titanate ceramic - PZT) a tensile mechanical stress is induced that elongates and contracts the material due to the inverse piezoelectric effect, when they are placed in an alternative electric field. Closely analogous to the piezoelectric behaviour is the *magnetostrictive* one: the material exhibits mechanical strain when subjected to a magnetic field. Magnetostrictive alloys (terbium-dysprosium-iron-Terfenol D) are recommended for precise movements in the nanometre range and very high reaction speeds. *Electrostrictive* materials (lead-magnesiun-niobate ceramic–PMN) and *photostrictive* materials (lead-lanthanum-zirconium-titanium ceramic-PLZT) are also used in the structure of the actuators. *Electrorheological* liquids change their viscosity under the influence of an electric field and switch from a liquid to a plastic state within a few milliseconds. In the presence of a magnetic field, *magnetorheological* fluids change from a fluid state to a semi-solid one, which is directly proportional to the applied magnetic field. Interest in the above-mentioned controllable fluids is offered by their ability to provide simple, rapid-response interfaces between electronic controls and mechanical systems. *Hydrogen absorbing alloys* are capable of storing as much hydrogen gas as approximately 2000 times their own volume. By heating the alloy, hydrogen is desorbed, whereas by cooling it, hydrogen is absorbed (it is, therefore, possible to use the energy of the hydrogen gas pressure by manipulating heat). The characteristic of the *electroactive polymers* is their operational similarity to biological muscles, particularly their resilience and large actuation strains. The specific features of the actuators based on smart materials are: good controllability, rapid actuation potential, low power consumption, small size, simple design.

2. SHAPE MEMORY ALLOY ACTUATORS AND THEIR APPLICATIONS

Among other advanced functional materials which have recently been developed, there are the *shape memory alloys* (SMA) which possess attractive characteristics as sensorial and actuation elements. The shape memory effect is the property of recovering some previous shape or size when subjected to a heating procedure. The shape memory alloys can be plastically deformed at low temperature and upon exposure to higher temperature, return to the shape prior to the deformation. The basis of this effect is that the materials can easily transform to and from martensite [2], [7].

Shape memory applications can be divided into four categories:

a – *free recovery* (includes applications in which the sole function of SMA element is to cause motion or strain);

b – *constrained recovery* (includes applications in which the SMA element is prevented from changing shape and generates a stress);

c – *superelastic* or *pseudoelastic* applications are isothermal and involve the storage of potential energy;

d – *actuator* or *work production* are those applications in which there is motion against a stress and thus work is being done.

Actuators based on shape memory alloys are generally of two types: thermal and electrical. The first ones are driven by changes in ambient temperature. Electrical actuators are actuated via direct current. Designing these actuators is an interdisciplinary approach covering the design of the components shown in Fig. 1 [6].

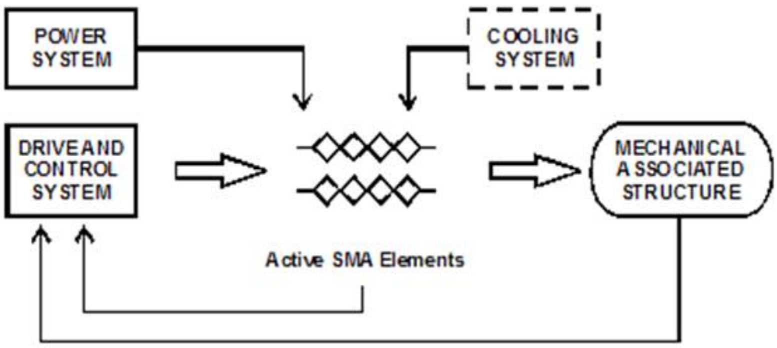

Fig. 1 The structure of shape memory alloy actuators

The advantages of SMA actuators are: small size, light weight, low complexity, high power to weight ratio, smooth and silent operation, long life and precise controllability. The slow response on cooling and the restricted energy efficiency are their drawbacks. The performances depend on the surrounding temperature and heat conduction conditions, as well as the strain level and cycling.

The SMA and SMA based actuators are widely used in various fields, such as: mini and micro robotics, automotive industry, aeronautical industry, precision engineering, electrical engineering, entertainment industry and biomedical engineering.

The most representative applications of these materials in biomedical field are: aids for disabled, arterial clips, Braille print punch, catheter guide wires, contraceptive devices, graft stents, intraocular lens mount, eyeglass frames, minim invasive surgery (MIS) instruments, orthodontic archwires, penile implants, scoliosis correction devices, intervertebral artificial joints, drug delivery systems, stents, orthopedic implants and other [1], [2], [8]. Figure 2 shows some examples of SMA applications in biomedical engineering, [9], [11], [12], [15], [16]. The “active endoscope” with multiple degrees of freedom, driven by a SMA servo actuator (Fig. 2a) consists of several unit segments, the bending angles of which are independently controlled with a joystick through electric-resistance feedback. In Fig. 2b a new polymer-links active catheter with an integrated interfaces, within a 2 mm diameter is presented. It is actuated by three SMA helical coils formed by electroless

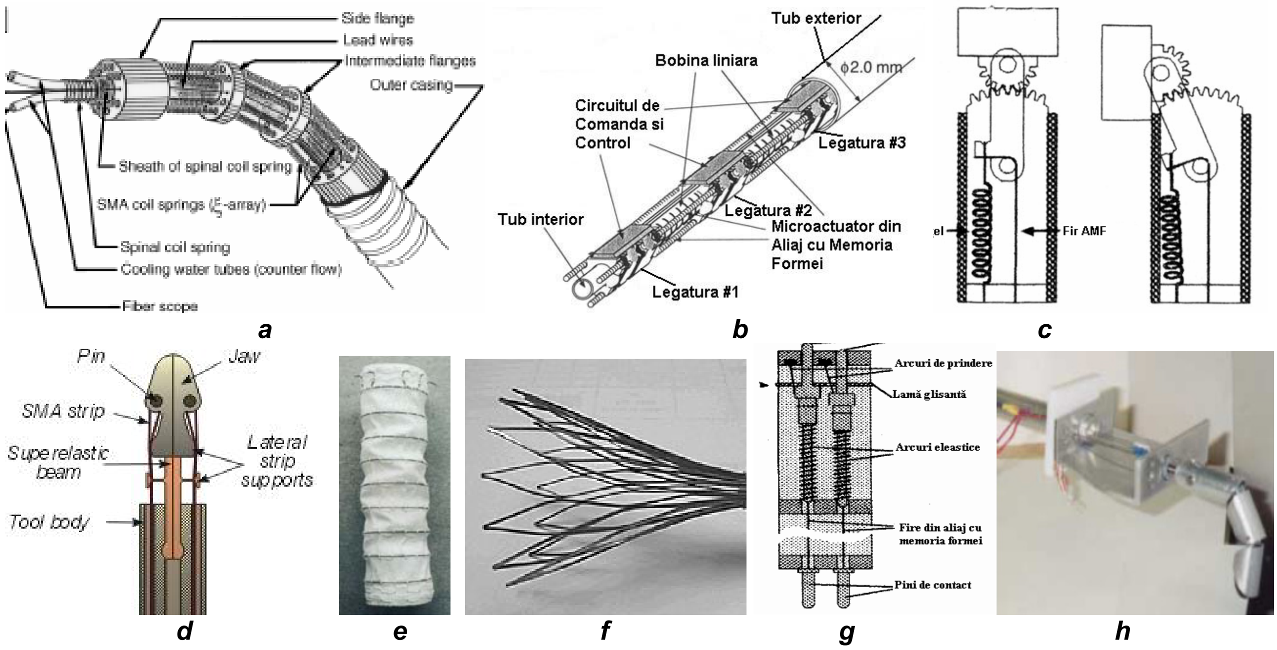

Fig. 2 Examples of representative applications of SMA actuators in Biomedical Engineering

plating. Fig. 2c illustrates a geared mechanism actuated by SMA wire for tip orientation of a self-propelling colonscopic instrument. It gives 180˚ rotation available at the tip of the instrument. A miniature gripping device based on compliant joints and SMA strips as actuators is presented in fig. 2d. A stent (Fig. 2e) can be introduced in a “deformed” shape, with a smaller diameter, by traveling through the arteries with the stent contained in a catheter. When deployed, the stent expands to the appropriate diameter with sufficient force to open the vessel lumen and reinstate blood flow. The vena-cava filter (Fig. 2f) is introduced in a compact cylindrical form about 2.0-2.5mm in diameter. When released it forms an umbrella shape. Other examples are: tactile display with pins in vertical motion (Fig. 2g), anthropomorphic finger (Fig. 2h). Due to the biocompatibility of the shape memory alloys and the high performances of the actuators, there are a lot of possibilities to develop improved and innovative products applied successfully in biomedical field.

3. THE DEVELOPED APPLICATIONS WITH SMA ACTUATORS

Within the Department of Mechanisms, Precision Engineering and Mechatronics, the research activity in the field of SMA actuators was conducted in last ten years. In the following, some projects will be described. Our efforts were focussed on developing new actuating systems specific to biomedical applications, such as: active bending structures and gripping systems for MIS, Braille display for people with seeing disabilities, active hand prosthesis and other.

Based on the physical properties and overall dimensions of all the organs (the oral cavity, pharynx, oesophagus and stomach) involved in a minimal invasive therapy procedure (for example, an endoscopy exploration) the geometrical constrains and functional parameters for an instrument with active bending capabilities were established [11]. Few variants were developed. According to Fig. 3a, the actuation of the mobile platform *1* is ensured by three tendons *6* actuated by three SMA elements. A central helical spring 4 and the inner flexible tube *3* support the mobile platform and bring it back.

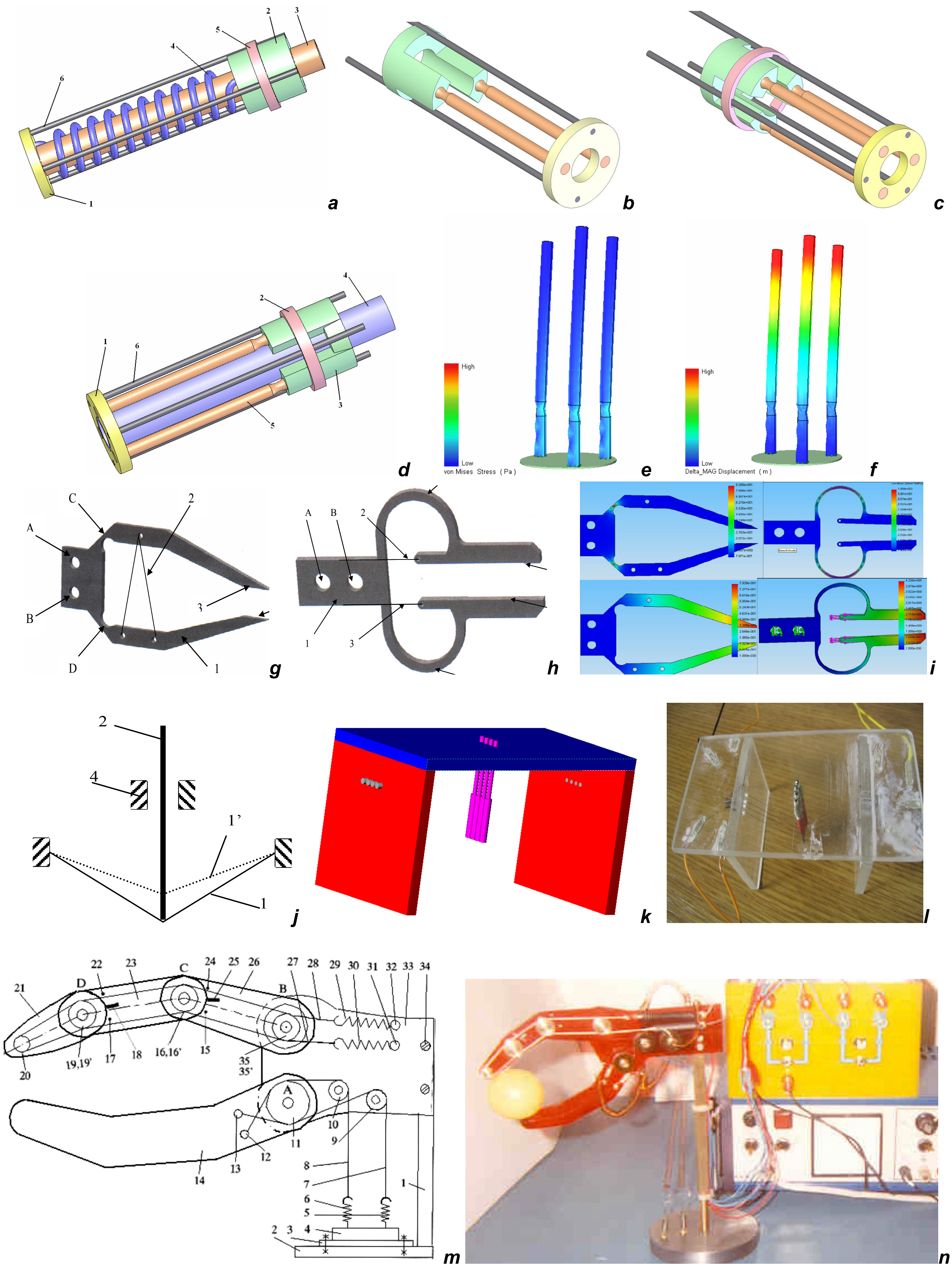

Fig. 3 The developed biomedical applications of SMA actuators

Improved solutions are presented in Fig. 3 b (with two tendons and 1 DOF) and 3c (with three tendons and 2 DOF). They use compliant (flexible) joints to support the mobile platform. Being monolithic with the links it connects, the compliant joint is highly energy-efficient since it has zero friction and backlash. The monolithic construction also simplifies production, enabling low-cost fabrication. Compliant mechanisms can be miniaturized for use in simple mini and microstructures. The common components of these systems are the SMA actuators in form of SMA helical springs which actuate each tendon. The finite element technique – which is an adequate tool for analyzing compliant mechanisms due to the speed of analysis, different analysis types (static, dynamic, thermal, mixed), and direct interaction with CAD tools – was applied and von Mises stress and the displacements were determined (Fig. 3e, f).

Two different types of microgrippers including in their structure elastic joints and SMA actuators are described in Fig. 3 g, h. We note: A, B – holes for fixing, C, D – elastic joints; 1 – lower finger, 2 – SMA wire for actuating, 3, 4 – the gripping surfaces in contact with the grasped objects. By heating the wire, it contacts and both fingers are simultaneously actuated (the fingers move to each other due to the elasticity of joints D and C). The traditional mathematical models of these microgrippers were developed, that connect the geometrical characteristics, material properties, external loads and their behavior. Figure 3i gives the results of Finite Element Method (FEM) analysis: the von Mises stress distributions, the deformations of compliant mechanisms and the displacements of the fingertips.

We developed a tactile display with following parameters (Fig. 3j, k, l): pin diameter: 1,5 mm, center-to-center spacing of the pins: 2,5 mm, force at each pin: 2 N, vertical displacement of the pins: 1,5 mm. Electrical current heats the SMA wires, which undergo a phase transformation and shorten, thus pushing the pins up. The mechanical design of one pin that we have chosen is shown in figure 3j. Based on the input data and on the SMA wire actuators design methodology, we determined the necessary length and diameter of the wire, the elastic force of the biasing spring. We adopt the distance between the ends of the wire 50 mm and the high of the pin 25 mm. It results the length of the wire at low temperature, in the martensite phase: l = 71 mm. For a shape memory effect about 3 %, results the length of the contracted wire at high temperatures, in the austenite phase: l' = 68,8 mm.

Next example belongs to prosthetics. The adaptability to the form and size of the grasped objects can be achieved by articulation of the phalanges, coordination of the phalanges of each articulated finger, coordination of the fingers, especially, opposition and the coordination of the thumb. Ensuring these functions through tendon driven-mechanisms leads to the following advantages: light weight, small size, actuators can be installed at a certain distance, low backlash, no shocks, overloading protection and good efficiency. The small size of the tendons permits large bending radius and thus large flexion-extension of the fingers. More, the tendon-driven mechanisms offer a gentler grasping compared with linkage based prehension devices. In Fig. 3 m, n is presented a prototype of a two-finger prosthetic hand module. Each finger has one degree of freedom. An actuator based on shape memory alloy drives the finger corresponding to the index with two-antagonist helical spring active element, through tendon cables. Three parallel axis joints provide flexion-extension of the phalanx. The finger corresponding to the thumb is actuated via an actuator based on shape memory wires. Both fingers are actuated by differential actuators. The drive and the control systems were also designed and developed.

CONCLUSIONS

The main objectives of Biomedical Engineering are design, development and properly use of materials, devices, apparatus, equipment and techniques for diagnosis, treatment and rehabilitation of the patients. It is a very dynamic and interdisciplinary field which requires improved systems for a more efficient medical act. New and innovative actuation systems are implemented in modern medical apparatus. Among these, the shape memory alloy actuators have a well-defined applicability.

Commercially available shape memory wires and springs are currently used by the authors in order to develop some applications of SMA actuators. The control and driver systems are developed according with the requirements of each application. Our future developments will concentrate on the improvement and control of the actuating system and the integration of the required sensors on the developed biomedical systems, as well as on the development a modular family of linear and rotary actuators, designed in multiple typo dimensions.

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