Materials and Design 56 (2014) 1078–1113

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Review

A review of shape memory alloy research, applications and opportunities

Jaronie Mohd Jani [a,b,*], Martin Leary [a], Aleksandar Subic [a], Mark A. Gibson [c]

[a] School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, Melbourne 3083, Australia
[b] Institute of Product Design and Manufacturing, Universiti Kuala Lumpur, Kuala Lumpur, Malaysia
[c] CSIRO Process Science and Engineering, Private Bag 33, Clayton South MDC, Victoria 3169, Australia

ARTICLE INFO

Article history:
Received 17 September 2013
Accepted 16 November 2013
Available online 17 December 2013

Keywords:
Shape memory alloy
Shape memory materials
Automotive
Aerospace
Biomedical
Robotics

ABSTRACT

Shape memory alloys (SMAs) belong to a class of shape memory materials (SMMs), which have the ability to 'memorise' or retain their previous form when subjected to certain stimulus such as thermomechanical or magnetic variations. SMAs have drawn significant attention and interest in recent years in a broad range of commercial applications, due to their unique and superior properties; this commercial development has been supported by fundamental and applied research studies. This work describes the attributes of SMAs that make them ideally suited to actuators in various applications, and addresses their associated limitations to clarify the design challenges faced by SMA developers. This work provides a timely review of recent SMA research and commercial applications, with over 100 state-of-the-art patents; which are categorised against relevant commercial domains and rated according to design objectives of relevance to these domains (particularly automotive, aerospace, robotic and biomedical). Although this work presents an extensive review of SMAs, other categories of SMMs are also discussed; including a historical overview, summary of recent advances and new application opportunities.

1. Introduction

The technology push, towards 'smart' systems with adaptive and/or intelligent functions and features, necessitates the increased use of sensors, actuators and micro-controllers; thereby resulting in an undesirable increase in weight and volume of the associated machine components. The development of high 'functional density' and 'smart' applications must overcome technical and commercial restrictions, such as available space, operating environment, response time and allowable cost [1]. In particular, for automotive construction and design: increased mass directly results in increased fuel consumption, and automotive suppliers are highly cost-constrained. Research on the application of smart technologies must concentrate on ensuring that these 'smart' systems are compatible with the automotive environment and existing technologies [1]. The integration and miniaturisation of integrated micro-controllers and advanced software has enabled considerable progress in the field of automotive sensors and control electronics. However, the technical progress for automotive actuators is relatively poorly advanced [2]. Currently, there are about 200 actuation tasks are performed on vehicles with conventional electro-magnetic motors, which are potentially sub-optimal for weight, volume and reliability [3].

Shape memory alloy (SMA) or "smart alloy" was first discovered by Arne Ölander in 1932 [4], and the term "shape-memory" was first described by Vernon in 1941 [5] for his polymeric dental material. The importance of shape memory materials (SMMs) was not recognised until William Buehler and Frederick Wang revealed the shape memory effect (SME) in a nickel-titanium (NiTi) alloy in 1962 [6,7], which is also known as nitinol (derived from the material composition and the place of discovery, i.e. a combination of NiTi and Naval Ordnance Laboratory). Since then, the demand for SMAs for engineering and technical applications has been increasing in numerous commercial fields; such as in consumer products and industrial applications [8–10], structures and composites [11], automotive [2,12,13], aerospace [14–17], mini actuators and micro-electromechanical systems (MEMS) [16,18–21], robotics [22–24], biomedical [16,18,25–30] and even in fashion [31]. Although iron-based and copper-based SMAs, such as Fe–Mn–Si, Cu–Zn–Al and Cu–Al–Ni, are low-cost and commercially available, due to their instability, impracticability (e.g. brittleness) [32–34] and poor thermo-mechanic performance [35]; NiTi-based SMAs are much more preferable for most applications. However, each material has their own advantage for particular requirements or applications.

* Corresponding author at: School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, Melbourne 3083, Australia. Tel.: +61 405552605.

E-mail addresses: jaronie@iprom.unikl.edu.my (J. Mohd Jani), martin.leary@rmit.edu.au (M. Leary), aleksandar.subic@rmit.edu.au (A. Subic), mark.gibson@csiro.au (M.A. Gibson).

0261-3069/$ - see front matter
http://dx.doi.org/10.1016/j.matdes.2013.11.084

In this work, a brief summary of SMA, its design feasibility and the variety of SMA applications are compiled and presented. SMA applications are divided into several sections based on the application domain, such as automotive, aerospace, robotics and biomedical, as well in other areas. Most of the work presented here has an emphasis on NiTi SMAs, but other forms or types of smart materials such as high temperature shape memory alloys (HTSMAs), magnetic shape memory alloys (MSMAs), SMM thin film (e.g. NiTi thin film) and shape memory polymers (SMPs) are also discussed. However, intensive topics such as metallurgy, thermodynamics and mechanics of materials will not be addressed in detail.

2. Shape memory alloy overview

SMAs are a group of metallic alloys that can return to their original form (shape or size) when subjected to a memorisation process between two transformation phases, which is temperature or magnetic field dependent. This transformation phenomenon is known as the shape memory effect (SME).

The basic application of these materials is quite simple, where the material can be readily deformed by applying an external force, and will contract or recover to its original form when heated beyond a certain temperature either by external or internal heating (Joule heating); or other relevant stimuli such as a magnetic field for MSMAs.

2.1. Shape memory effect and Pseudoelasticity

Practically, SMAs can exist in two different phases with three different crystal structures (i.e. twinned martensite, detwinned martensite and austenite) and six possible transformations [36,37] (see Fig. 1). The austenite structure is stable at high temperature, and the martensite structure is stable at lower temperatures. When a SMA is heated, it begins to transform from martensite into the austenite phase. The austenite-start-temperature (A_s) is the temperature where this transformation starts and the austenite-finish-temperature (A_f) is the temperature where this transformation is complete. Once a SMA is heated beyond A_s it begins to contract and transform into the austenite structure, i.e. to recover into its original form. This transformation is possible even under high applied loads, and therefore, results in high actuation energy densities [38]. During the cooling process, the transformation starts to revert to the martensite at martensite-start-temperature (M_s) and is complete when it reaches the martensite-finish-temperature (M_f) [6] (see Fig. 2). The highest temperature at which martensite can no longer be stress induced is called M_d, and above this temperature the SMA is permanently deformed like any ordinary metallic material [39]. These shape change effects, which are known as the SME and pseudoelasticity (or superelasticity), can be categorised into three shape memory characteristics as follows:

(1) One-way shape memory effect (OWSME):
The one-way SMA (OWSMA) retains a deformed state after the removal of an external force, and then recovers to its original shape upon heating.

(2) Two-way shape memory effect (TWSME) or reversible SME:
In addition to the one-way effect, a two-way SMA (TWSMA) can remember its shape at both high and low temperatures. However, TWSMA is less applied commercially due to the 'training' requirements and to the fact that it usually produces about half of the recovery strain provided by OWSMA for the same material [40–42] and it strain tends to deteriorate quickly, especially at high temperatures [43]. Therefore, OWSMA provides more reliable and economical solution [44]. Various training methods have been proposed [42,45–49], and two of them are: Spontaneous and external load-assisted induction [50].

(3) Pseudoelasticity (PE) or Superelasticity (SE):
The SMA reverts to its original shape after applying mechanical loading at temperatures between A_f and M_d, without the need for any thermal activation.

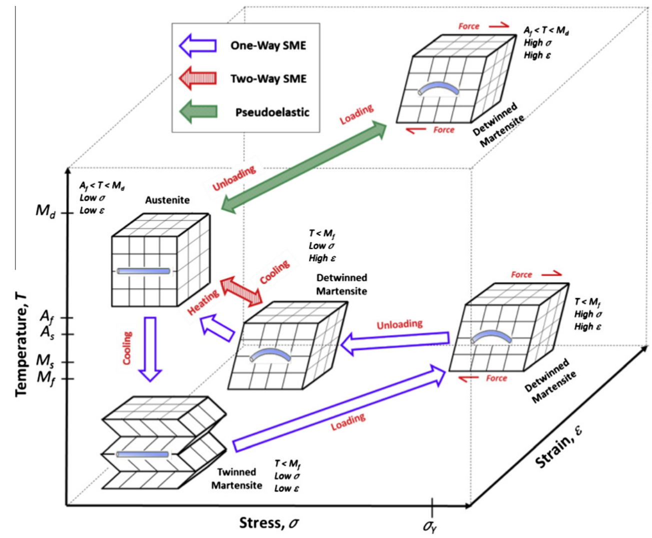


Fig. 1. SMA phases and crystal structures [36–38].

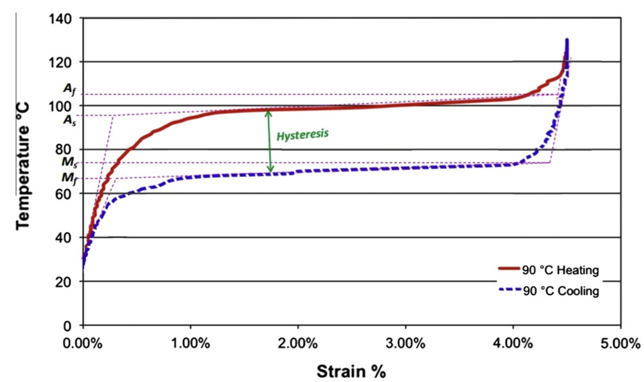


Fig. 2. Flexinol NiTi SMA (HT) phase transformation [57].

In addition to the 'material TWSME' above, a biased OWSMA actuator could also act as a 'mechanical TWSME' at a macroscopic (structural) level; which is more powerful, reliable and is widely implemented in many engineering applications [18].

The SME is a diffusionless solid phase transition between martensitic and austenitic crystal structures [49,51–53]. There are other transformations associated with shape memory such as rhombohedral (*R*-phase), bainite [49,54] and the 'rubberlike behaviour' (RLB) in martensite stage [55,56], which are not discussed in detail, in this work.

Hysteresis is a measure of the difference in the transition temperatures between heating and cooling (i.e. $\Delta T = A_f - M_s$), which is generally defined between the temperatures at which the material is in 50% transformed to austenite upon heating and in 50% transformed to martensite upon cooling [53]. This property is important and requires careful consideration during SMA material selection for targeted technical applications; e.g. a small hysteresis is required for fast actuation applications (such as MEMSs and robotics), larger hysteresis is required to retain the predefined shape within a large temperature range (such as in deployable structures and pipe joining) [58]. In addition, the transition temperatures referred to identify the operating range of an application. These transition temperatures and the hysteresis loop behaviour are influenced by the composition of SMA material, the thermomechanical processing tailored to the SMA and the working environment of the application itself (e.g. applied stress) [44]. These transition temperatures can be directly measured with various techniques such as differential scanning calorimetry (DSC), dilatometry, electrical resistivity measurement as a function of temperature, and can be indirectly determined from a series of constant stress thermal cycling experiments [43].

Some of the SMAs physical and mechanical properties also vary between these two phases such as Young's modulus, electrical resistivity, thermal conductivity and thermal expansion coefficient [37,59,60]. The austenite structure is relatively hard and has a much higher Young's modulus; whereas the martensite structure is softer and more malleable; i.e. can be readily deformed by application of an external force [34,37] (see Table 1).

When an external stress is applied below the martensite yield strength (approximately 8.5% strain for NiTi alloys and 4–5% for copper-based alloys [34,57,61]), the SMA deforms elastically with recoverable strain. However, a large non-elastic deformation (permanent plastic deformation) will result beyond this point. Most applications will restrict the strain level; e.g. to 4% or less, for NiTi alloys [35,57].

2.2. History of SMA development

In 1932, the solid phase transformation in SMA was first discovered by Ölander [4], a Swedish physicist who determined that the gold-cadmium (Au–Cd) alloys could be plastically deformed when cool, and returned to its original configuration when heated. Later in 1938, Greninger and Mooradian [62] first observed the SME for copper-zinc (Cu–Zn) alloys and copper-tin (Cu–Sn) alloys. The fundamental phenomenon of the memory effect governed by the thermoelastic behaviour of the martensite phase was widely reported a decade later by Kurdjumov and Khandros [63] in 1949 and also by Chang and Read [64] in 1951. Similar affects in other alloys such In–Tl and Cu–Al–Ni were also observed in the 1950's. These discoveries had captured the interest of many researchers and inventors, but practical and industrial applications could not be realised due to their material high costs, manufacturing complexity and unattractive mechanical properties.

Although the NiTi alloy was discovered by William Buehler in 1959 [7], the potential to commercialise SMA applications was only became available after the SME in NiTi alloy was revealed by William Buehler and Frederick Wang in 1962 [6,7]. Nitinol alloys are cheaper to produce, easier and safer to handle, and have better mechanical properties compared to other existing SMAs at that time [6,53]. The first commercial success for a SMA application was the Raychem Corporation's CryoFit™ "shrink-to-fit" pipe coupler in 1969 for the F-14 jet fighter built by the Grumman Aerospace Corporation and followed subsequently by the orthodontic bridge wires by George B. Andreasen in 1971 [7].

Since the 1980's, the commercial application of NiTi alloys has developed in many areas due to the greater demands for lighter and more compact actuators, especially in the biomedical sector (see Figs. 4 and 3).

2.3. Recent developments

In the 1990's, the term shape memory technology (SMT) was introduced into the SMM community [65]. SMA application design has changed in many ways since then and has found commercial application in a broad range of industries including automotive, aerospace, robotics and biomedical [16,18,23,66–69]. Currently, SMA actuators have been successfully applied in low frequency vibration [70] and actuation applications. Therefore, much systematic and intensive research work is still needed to enhance the performance of SMAs [71,72], especially to increase their bandwidth, fatigue life and stability [73].

Recently, many researchers have taken an experimental approach to enhance the attributes of SMAs, by improving the material compositions (quantifying the SMA phase transition temperature [74–78]) to achieve a wider operating temperature range, and better material stability, as well as to improve the material response and stroke with better mechanical design (or approach), controller systems and fabrication processes. Research into alternative SMMs, forms or shapes, such as MSMA, HTSMA, SMP, shape memory ceramic, SMM thin film or a combination of them (i.e. hybrid or composite SMMs), are also intensively being conducted, and the number of commercial applications is growing each year (see Fig. 4). More details of recent applications and development of SMA are described in the subsequent sections.

A literature analysis has been carried out using the Scopus and USPTO search engines with search keywords of 'shape memory alloy' or 'nitinol' for related areas are presented in Figs. 3 and 4.

BCC research [79] reported that the global market for smart materials was about USD19.6 billion in 2010, estimated to approach USD22 billion in 2011 and forecasted to reach over USD40 billion by 2016 with a compound annual growth rate (CAGR) of 12.8% between 2011 and 2016. The largest application segment of the market is actuators and motors, with sales of nearly USD10.8 billion (55% of the total market) in 2010 and forecasted to reach USD25.4 billion (approximately 64% of the market) by 2016 with CAGR of 15.4% between 2011 and 2016 (see Fig. 5).

3. Designing with SMAs

To date, more than 10,000 United States patents and over 20,000 worldwide patents have been issued on SMAs and their

Table 1
Commercial NiTi SMA physical properties [34,46].

Property	Symbol	Units	Value	
			Martensite	Austenite
Corrosion Resistance	–	–	Similar to 300 series SS or Ti-alloy	
Density	ρ_D	kg/m^3	6450–6500	
Electrical Resistivity (approx.)	ρ_R	μΩ cm	76–80	82–100
Specific Heat Capacity	c	J/kg K	836.8	836.8
Thermal Conductivity	k	W/m K	8.6–10	18
Thermal Expansion Coefficient	α	m/m K^{-1}	6.6×10^{-6}	11.0×10^{-6}
Ultimate Tensile Strength	σ_{UTS}	MPa	895 (Fully annealed)/1900 (Hardened)	
Young's Modulus (approx.)	E	GPa	28–41	75–83
Yield Strength	σ_Y	MPa	70–140	195–690
Poisson's Ratio	ν	–	0.33	
Magnetic Susceptibility	χ	μemu g	2.5	3.8

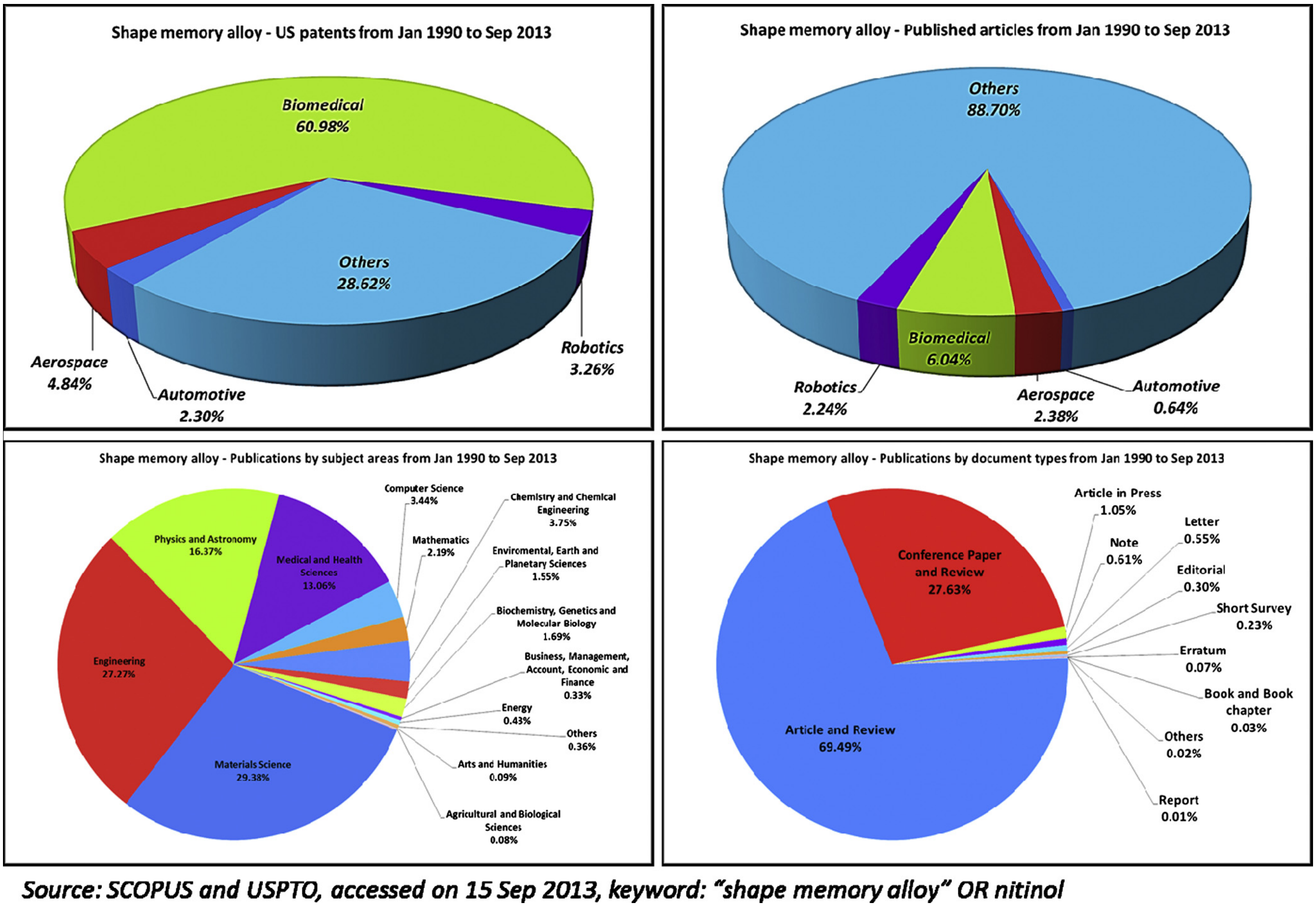


Fig. 3. SMA publications and US patents from January 1990 to June 2013.

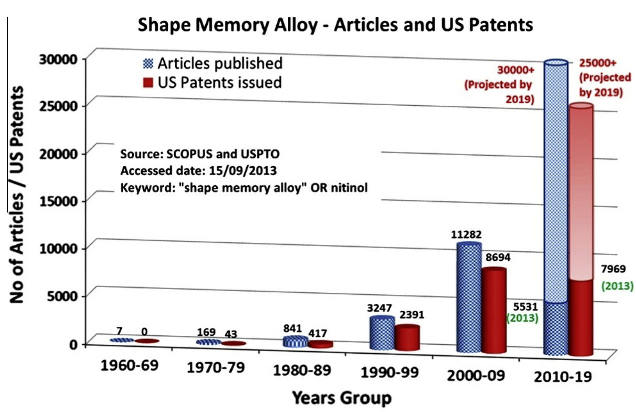


Fig. 4. Number of "Shape Memory Alloy" articles and patents by years-group.

applications, but the realisation of viable products from all this intellectual property has thus far been limited [61,80,81]. The reason for this lies primarily with the lack of understanding by scientists and engineers on both the technical limitations of SMAs and the methods to apply SMAs in a robust manner to achieve technical requirements of longevity and stability [69,80–83].

3.1. SMA design advantages

Recent research work has shown that SMA actuators provide an excellent technological opportunity to replace conventional actuators such as electric motors, pneumatics and hydraulics [15,84], due to their unique characteristics and ability to react directly to environmental stimuli [81]; thus promoting the development of more advanced and cheaper actuators with a significant reduction in mechanical complexity and size [2,85]. For instance, the NiTi SMA displays one of the highest work density at 10 J cm^{-3} (see Table 2), which is a factor of 25 times greater than the work density of electric motors [19] and is able to lift more than 100 times of its weight [86]. Furthermore, the NiTi SMA is bio-compatible [29,87], exhibits high wear resistance [34,53], and the tribological behaviour has been investigated and compared to many conventional

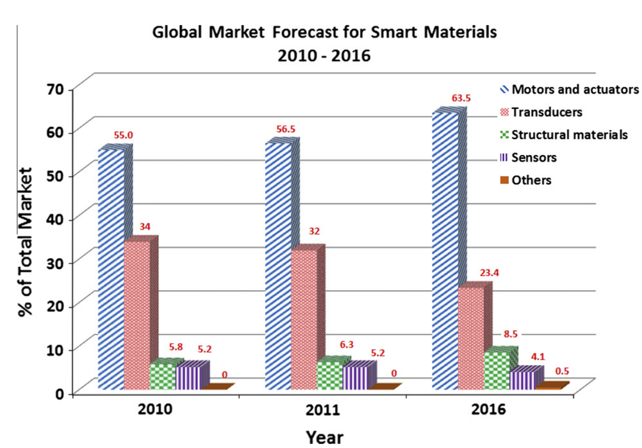


Fig. 5. Global market forecast for smart materials for 2010–2016 [79].

engineering materials such as steels, Ni-based and Stellite alloys [19,88–90].

With reference to Table 2, the NiTi SMA is the obvious choice for designers for actuators that provide significant displacement and forces, with no critical requirements for a short response time or high efficiency. This makes NiTi SMA an attractive candidate for a variety of industrial applications, 'smart' structures and 'intelligent' systems [94,95]. A composite airframe with a combination of piezoelectric crystals, as the vibration sensors, and NiTi as the actuators to counteract the vibration, is a good example of a 'smart' structure application [81].

Commonly, designers make use of the benefit of the engineering effects described above to design their applications, where the SME is primarily employed for actuation and pseudo-elasticity for vibration isolation and dampening (see Table 3). For example, the two unique pseudoelastic behaviours of SMA, provide a valuable advantage in dampening vibrations, where its non-linear behaviour allows vibration isolation and a large deformation recovery, and its hysteresis behaviour dissipates the energy [96,97]. SMAs are also capable of actuating in a fully three-dimensional manner, allowing the fabrication of actuation components which can extend, bend, twist, in isolation or combination; and can be used in various configurations and shapes such as helical springs, torsion springs, straight wires, cantilever strips, and torsion tubes [13,98]. SMAs can provide a highly innovative approach to solve a wide range of engineering problems and may in fact be the only viable technical option for complex applications, due to their attributes and unique advantages.

An overview of the features and possibilities of SMA actuators is provided in Fig. 6, which characterises the SMA actuators according to their relevant requirements and can be considered as a useful checklist for the development of SMA applications [99]. A series of charts to aid the selection of SMAs (NiTi, Cu–Zn–Al and Cu–Al–Ni) is also presented by Huang [35], based on a number of performance indices and criteria [100], with special reference to the unique features of SMA actuators.

3.2. SMA design challenges

The challenges in designing SMA applications are to overcome their limitations, which include a relatively small usable strain, low actuation frequency, low controllability, low accuracy and low energy efficiency. The major obstacle is the low operational frequency and narrow bandwidth of SMA materials, which have a relatively high heat capacity and density, and as a result they experience difficulty in transferring the heat rapidly into and more importantly out of the active element, which leads to a severe bandwidth problem. In several studies [101–103], it has been shown that rapid heating of SMA actuators can be achieved easily with several methods, such as applying large electrical currents (Joule heating) to increase the heating rate. However, without proper monitoring and control this may overheat and damage the actuator. Nonetheless, the most significant concern in bandwidth limitation is the very slow cooling process, where the heat energy removal rate is limited by the mechanisms of heat conduction and convection. The size and shape of the SMA actuator affects the actuator response time, where actuators with smaller diameter heat faster due to their higher resistivity, and cool faster due to their higher surface-to-volume ratio [57,104]. Therefore changing the wire diameter could change the application bandwidth dramatically (see Table 4). In addition, the preloading stress, loading condition and amplitude of activation potential also influence the response time of SMA actuators [105]. Several strategies have been developed to improve the control of the heating process [35,106] and to expedite the cooling process with active cooling such as forced air [105,107,108], flowing liquids [105,109–111], thermoelectric modules (i.e. Peltier or semiconductor heat pumps) [112–117], heat sinks [103,105,118] and conductive materials [85,119,120]. Table 4 shows the ratio of actuation speed improvement with several cooling methods [57].

Higher cooling rates are obtained when cooling with a fluidic medium, but this requires a special design to prevent any leakage to the environment. A small amount of air circulation around the wire is sufficient to obtain a substantial improvement compared to the natural convection case, however, several studies have also indicated that increasing the air flow would only produce a minor effect on the cooling performance and has several drawbacks such as higher energy consumption and noise production [84]. Therefore, active cooling is not practical in numerous situations since it contributes to increases in cost, weight, physical volume, as well the mechanical and control complexity [38,106]. Alternatively, bandwidth improvement with passive cooling is also achievable

Table 2
Comparison of actuator performance [91–93].

Actuator type	Stress (MPa)	Strain (%)	Efficiency (%)	Bandwidth (Hz)	Work per Volume (J/cm^3)	Power per Volume (W/cm^3)
NiTi SMA	200	10	3	3	10	30
Piezoceramic	35	0.2	50	5000	0.035	175
Single crystal piezoelectric	300	1.7	90	5800	2.55	15,000
Human Muscle	0.007–0.8	1–100	35	2–173	0.035	0.35
Hydraulic	20	50	80	4	5	20
Pneumatic	0.7	50	90	20	0.175	3.5

Table 3
Summary of various SMA properties and their effects [15].

SMA traits	Practical consequences
Shape memory effect	Material can be used as an actuator, providing force during shape recovery
Pseudoelasticity	Material can be stressed to provide large, recoverable deformations at relatively constant stress levels
Hysteresis	Allows for dissipation of energy during pseudo-elastic response
High actuation stress (400–700 MPa)	Small component cross-sections can provide substantial forces
High actuation strain (ca. 8%)	Small component lengths can provide large displacements
High energy density (ca. 1200 J/kg)	Small amount of material required to provide substantial actuation work
Three-dimensional actuation	Polycrystalline SMA components fabricated in a variety of shapes, providing a variety of useful geometric configurations
Actuation frequency	Difficulty in achieving high component cooling rates limits use in high frequency applications
Energy efficiency (10–15%)	Amount of thermal energy required for actuation is much larger than mechanical work output
Transformation – induced plasticity	Plastic accumulation during cyclic response eventually degrades material and leads to failure

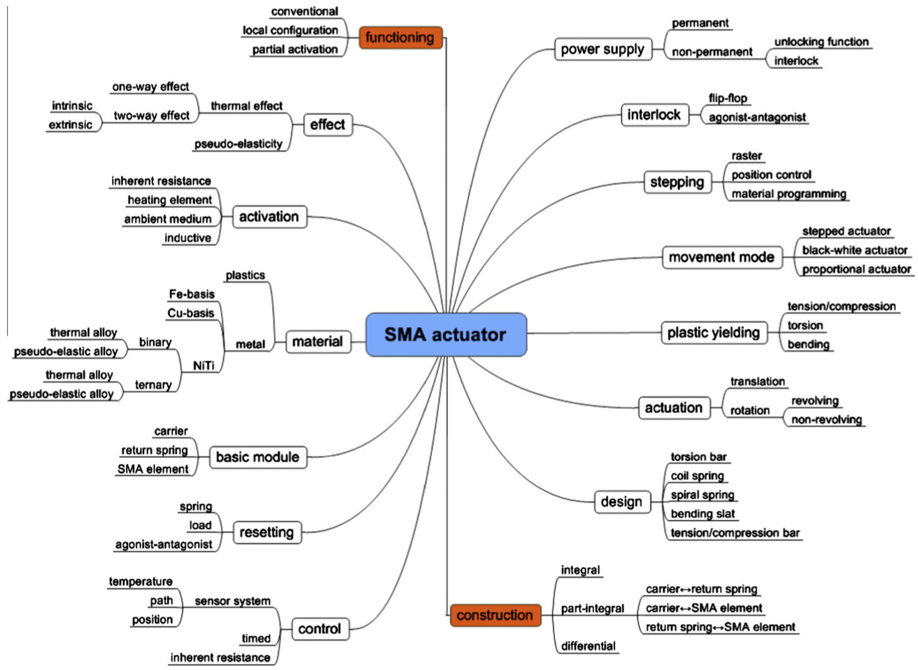


Fig. 6. SMA actuator element features [99].

Table 4
Cooling methods [57].

Cooling methods	Improvement in speed
Increasing Stress	1.2:1
Using higher temperature wire	2:1
Using solid Heat Sink materials	2:1
Forced air	4:1
Heat conductive grease	10:1
Oil immersion	25:1
Water with Glycol	100:1

Note: Typical heating (joule heating) and cooling time (passive cooling) for HT-type (90 °C) *Flexinol* wire at standard environmental condition (i.e. static air, vertical position and atmospheric pressure):
- Ø0.05 mm: Heating (85 mA) = 1 s, Cooling = 0.3 s.
- Ø0.51 mm: Heating (4000 mA) = 1 s, Cooling = 14 s.

via improvements in mechanical design and control systems, such as the application of an agonistic-antagonistic system [83,121], high surface-to-volume ratio design (e.g. thin film SMA), and controller optimisation (e.g. gain optimisation [106]). An assessment of transient cooling opportunities has been completed by Huang et al. [122].

The second challenge is the low associated energy efficiency. Theoretically the maximum energy efficiency of SMAs is in the range of 10–15% [123], which may fall to 10% [124] based on the Carnot cycle efficiency in some studies, and is often less than 1% in practical applications [16]. Hence SMA actuator applications must be limited to areas where energy efficiency is not an issue, and it should be noted that there is a difference between SMA efficiency and actuator efficiency (i.e. efficiency of the entire system versus efficiency of SMA wire) [125]. Mechanically, SMA actuators come in various loading configurations. Most of the proposed actuator designs are based on a SMA spring as the active element, where large macroscopic displacements can be generated out of a relatively small microscopic strain. However, the stress distribution over the cross-section of the SMA spring is not constant, and therefore requires greater material volume to generate the same force, which has a negative effect on the efficiency and the bandwidth of the actuator (i.e. for the same output, a larger material volume has to be heated and cooled) [60,84]. Therefore, straight SMA wires are more advantageous due to the optimal use of material (i.e. more work generated from a minimal amount of SMA material) and the loading in tension configuration (see Table 5).

The next challenge is the durability and reliability of SMA actuators when subjected to multiple transformation cycles, which is significantly important to be assured of long-term stability, functionality and safety for any applications such as in 'automotive safety systems' [66]. Many factors influence the long-term performance and reliability of SMA actuators such as maximum temperature, stress, strain and the number of transformation cycles accumulated. SMAs have been shown to exhibit a softening of behaviour (i.e. reducing the amount of recoverable strain) as the actuator is cycled, either by heating and cooling the SMA under load [77,126–128] or by mechanically cycling the wire in its super-elastic state [129]. Many researchers have concluded that thermal effects are highly relevant in determining fatigue-life, particularly for the NiTi SMA [130–138]. For fatigue-limited applications, the SMA actuator temperature should be controlled precisely and overheating the SMAs reduces the fatigue life considerably [73]. Recent studies [77,128,139] have also shown that SMA actuators with constant loading, which are higher than the recommended load (stress), experienced a reduction in stroke (strain) as the number of cycles increased. It was also reported that overstraining of the SMA material also degraded performance, either in tension [140], torsion [141] or bending [142,143]. Increasing both stress and strain reduces the lifetime of SMA materials, and it is therefore essential to select the appropriate working

Table 5
Comparison of loading configuration for SMA actuators [84].

Loading configuration	Efficiency (%)	Energy density (J/kg)
Tension	1.3	446
Torsion	0.23	82
Bending	0.013	4.6

Note: The values in this table are calculated based on a pure elastic deformation which is only a rough estimate for comparing the three loading configurations.

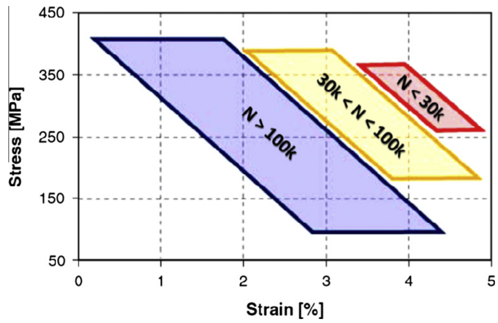


Fig. 7. Fatigue lifetime for Smartflex 76 under different stress–strain [140].

boundary conditions to obtain high fatigue resistance and high reliability from SMA materials (see Fig. 7) [140]. In terms of fatigue performance, SMA wires were reported to be better than SMA springs, where the recovery force and strain of SMA springs decreased by 30% after 1000 cycles and by 60% after 10,000 cycles [144]; in addition, the SMA springs deflection against the bias force degraded by at least 20% after ageing at 95 °C for 2000 h [145].

Therefore, SMA actuators should be prevented from overheating, overstressing and overstraining for long durations. Generally, to guarantee the applications are designed to perform safely over a large number of cycles (about 10^6 cycles) before reaching yield point and mechanical breakage, the active elements should prevented from overheating; and not allowed exceed the recommended fatigue strength and strain of the SMA material (i.e. maximum load of 350 MPa [35], safe design load at 100 MPa [84] and 3–4% strain [35,57,146]). The advancement in materials development and processing has reduced degradation and fatigue, and as a result over millions of cycles are readily achievable with appropriate training and usage [57]. Application of electronics controllers such as temperature sensors [147], position feedback [148], resistance feedback [149,150], limit curve [151], and adaptive resetting [83] are capable to resolve the overstress and overheating problems in commercial applications. Other methods to enhance the fatigue life of SMAs such as improvement of materials [152,153], fabrication processes [154,155], thermomechanical treatments [156–159] and mechanical design optimisation [83] are not discussed in this work.

4. Other forms or types of shape memory materials

Other forms or types of SMMs have been explored due to some obvious limitations or disadvantages of SMA, such as high manufacturing cost, limited recoverable deformation, limited operating temperature and low bandwidth. Some of the SMMs can be categorised in multiple forms or types, such as Co–Ni–Ga and Ni–Mn–Ga can be categorised as HTSMA and MSMA, and Ni–Ti–Pt/Pd also can be fabricated as SMM thin film.

4.1. High temperature shape memory alloys

Extensive research for HTSMAs with other ternary additions to the NiTi SMA (e.g. Au, Hf, Pd, Pt and Zr) has been undertaken [43,160,161], due to the increasing demands for high-temperature applications. Practically, HTSMAs are defined as SMAs that are operating at temperatures above 100 °C, and can be categorised into three groups based on their martensitic transformation ranges [43] (see Table 6).

Unfortunately, most HTSMAs are very difficult to process and to train due to their limited ductility or poor fatigue resistance at room temperature, and making them very expensive to manufacture. Therefore, alternative low cost materials or compositions such as copper and cobalt have been researched. At present, only TiNiPd, TiNiPt, NiTiHf, NiTiZr and CuAlMnNi alloys are useful at 100–300 °C, and the rest of them had significant challenges to commercial application and require further work [43].

4.2. Magnetic shape memory alloys

Magnetic shape memory alloys (MSMAs), which are also known as ferromagnetic shape memory alloys (FSMAs) can actuate at higher frequencies (up to 1 kHz) because the actuation energy is

Table 6
HTSMA groups and their properties [43,162–164].

Group	Alloy composition	Transformation temperature range (°C)	Thermal hysteresis (°C)	Strain (%)	Recovery (%)	Comments
100–400 °C	Ti–Ni–Pd	100–530	20–26	2.6–5.4	90^{PE}–100	High work output, most commercial ready and high materials cost
	Ti–Ni–Pt	110–1100	31–55	3–4	100	
	Ni–Ti–Hf	100–400	60	3	100	Reasonable SME, large hysteresis and relatively low materials cost
	Ni–Ti–Zr	100–250	54	1.8	100	
	Cu–Al–Ni	100–400	21.5	$3–5^{PE}$	$80–90^{PE}$	Low cost, poor to reasonable SME, and brittle in tension (Cu–Al–Ni)
	Cu–Al–Nb		59–170	5.5–7.6	–	
	Co–Al	100–400	121	2	90	Good workability, large hysteresis and high temperature PE (Co–Ni–Al)
	Co–Ni–Al		15.5	5^{PE}	100^{PE}	
	Ni–Al	100–300	-	-	-	Low materials cost, low hysteresis and poor tensile ductility
	Ni–Mn	100–670	20	3.9	90	
	Ni–Mn–Ga	100–400	85	10	70	
	Zr–Cu	100–600	70	8	44	Good ductility and workability, but poor SME
	Ti–Nb	100–200	50	2–3	97–100	Good ductility and SME, but suspect to oxidation and contain Uranium (U–Nb)
	U–Nb	100–200	35	7		
400–700 °C	Ti–Pd	100–510	40	10	88	Good ductility (Ti–Pd), but high materials cost (Ti–Pt)
	Ti–Au	100–630	35	3	100	
>700 °C	Ti–Pt–Ir	990–1184	66.5	10^{PE}	40^{PE}	High yield strength.
	Ta–Ru	900–1150	20	4	50	Stable microstructural, but poor oxidation resistance and small hysteresis
	Nb–Ru	425–900		4.2	88	

Note: PE = Pseudoelastic.

transmitted via magnetic fields and is not hindered by the relatively slow heat transfer mechanism [165]. FSMA strain rate is quite comparable to magnetostrictive and piezoelectrics active elements, but at strains as large as SMAs (see Fig. 8, [43]). FSMA can also provide the same specific power as SMAs, but deliver it at higher frequencies (see Fig. 8, [43]). The maximum strain of FSMA is 32 times more than the giant magnetostrictive Terfenol-D ($TbDyFe_2$), and the trade-off for greater strain is 46 times lower for lower elastic modulus (stiffness) [166]. Consequently, FSMAs are suitable to fill the technological gaps between SMAs and magnetostrictive materials, and would be a niche for motor and valve applications [167] that require significantly larger displacement at lower actuation force [166].

However, in general MSMA also experience similar design issues as described above for SMAs [168]. Furthermore, MSMAs are very brittle, stiff and only operable at low temperature [166,169,170]. Therefore, MSMAs are difficult to shape and to form, and are not suitable for many present applications at present which require high temperatures and high force. Fundamental research continues to develop a better understanding of the constitutive behaviour of these MSMAs (such as Ni–Mn–Ga, Fe–Pd and Ni–Mn–Al) in order to further improve the materials.

4.3. Shape memory material thin film

SMM thin films evolved from the advancement of fabrication technology, where SMMs are deposited directly onto micro-machined materials or as stand-alone thin films to become micro-actuators [86,171–175]. Moreover, in the rapidly growing field of micro-electro-mechanical systems (MEMSs), NiTi thin films have become the actuator of choice at the micro-scale level, due to the attributes as described earlier (i.e. higher actuation force and displacement), but at relatively low frequency (up to 100 Hz) and efficiency as well as the non-linear behaviour [20,172–174] (see Table 7). The versatility of NiTi thin film with multiple degrees of freedom and compact structure, expand the potential of NiTi in biomedical, aerospace, automotive, and consumer products applications. Miniature NiTi actuated devices based on sputtered NiTi films are anticipated to capture a huge slice of the commercial market, especially for medical micro-devices and implantable applications [172].

4.4. Shape memory polymers

Shape memory polymers (SMPs) are relatively easy to manufacture and fast to train (or program) as well being able to be tailored for a variety of applications. SMPs are claimed to be a superior alternative to SMAs for their lower cost (at least 10% cheaper than SMAs), better efficiency, biodegradable and probably by far surpass SMAs in their mechanical properties (see Table 8) [176–180]. In addition, SMPs can sustain two or more shape changes [181–183] when triggered by thermal (heating [184] or cooling [185]), electricity [186], magnetic field [187], light [188] or solutions [189] (e.g. chemical [184] or water [190,191]). Generally, there are three categories of SMPs [46], and most of them are naturally either thermo- or chemo-responsive [184]. When one considers the vast commercial application of polymer products, it is apparent that SMPs have significant commercial application [181,192–194], such as smart fabrics [195], self-repairing (or seal-healing) plastic components [196], spacecraft sails [197], biomedical devices [179,198–200] and intelligent structures. Some of the characteristics of SMPs are summarised in Table 8.

Table 7
Micro-actuators comparison [172–174].

Micro-actuators	Maximum energy density (J/m^3)	Maximum frequency (Hz)	Efficiency (%)
NiTi thin film	2.5×10^7	<100	1
Electrostatic	1.8×10^5	<10,000	50
Electromagnetic	4.0×10^5	<1000	<1
Piezoelectric	1.2×10^5	<5000	30
Bimetallic	4.0×10^5	<100	0.01
Thermo-pneumatic	5.0×10^5	<100	10
Conductive polymer	3.4×10^6	<1000	60

There are three basic working mechanisms for the SME in polymeric materials: Dual-state mechanism, dual-component mechanism (DCM) and partial-transition mechanism (PTM) [184]. The recovery precision of more than 99% makes SMPs suitable for highly demanding applications [180]. Similar to SMAs, the SME of SMPs varies depending on the composition of the material used, i.e. weight fraction of the switching segments and the molecular weight of the polymer-chain employed. The biodegradable nature of certain SMPs provide advantages over metal implants, where the removal of the implant after regeneration can be avoided, thus gentler, more effective and more economical treatments can be offered. However, despite the advantages described above, SMAs are still preferred for applications that require higher actuation forces and faster response.

4.5. Miscellaneous

A summary of existing shape memory materials are described in Table 9 below.

5. Shape memory alloy applications

Generally, the shape memory applications can be divided into four categories according to their primary function of their

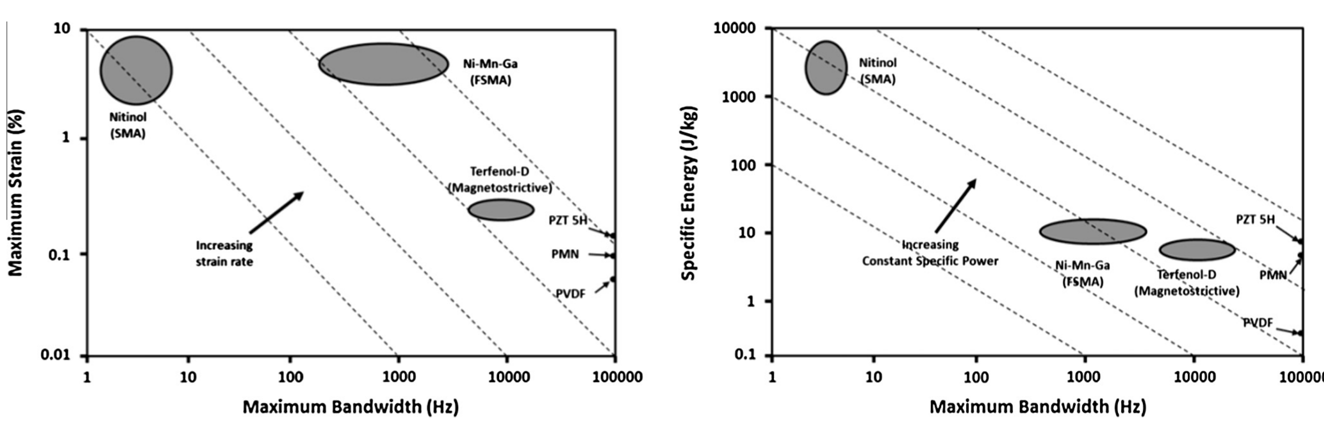


Fig. 8. Maximum strain and specific energy versus maximum bandwidth for different classes of active materials [43].

Table 8
Comparison of SMP and SMA properties [177,178].

Property	SMP	SMA
Density (g cm^{-3})	0.9–1.25	6–8
Transition breath (°C)	10–50	5–30
Phase transformations	Glass transition	Martensitic transformation
Strain (%)	Up to 400, and possibly above 800	Up to 8%
Young's modulus (GPa) at $T < T_{Trans}$ at $T > T_{Trans}$	0.01–3 (0.1–10) $\times 10^3$	83 (NiTi) 28–41
Deform stress (MPa)	1–3	50–200
Recovery stress (MPa)	1–3	150–300
Recovery speeds (s)	<1 s to several min.	<1 s
Thermal conductivity (W/m K)	0.15–0.30 W/m K	18 (NiTi, Austenite)
Bio-compatibility and degradability	High	Not all biocompatible. Not biodegradable
Corrosion performance	Excellent	Excellent
Condition at high temperature	Soft	Hard
Condition at low temperature	Hard	Soft
Cost	Cheap (ca. USD10/lb)	More expensive (ca. USD250/lb)
Shape training	Easy and fast	Difficult
Fabrication/processing condition	<200 °C, low pressure	>1000 °C, high pressure

memory element as shown in Table 10 [34,201]; where the SME can be used to generate motion and/or force, and the SE can store the deformation energy. [44].

The unique behaviour of NiTi SMAs have spawn new innovative applications in the aerospace, automotive, automation and control, appliance, energy, chemical processing, heating and ventilation, safety and security, and electronics (MEMS devices) industries. Some of these applications apply similar methods, concepts or techniques, which are also applicable for other areas; such as the NiTi thermovariable rate (TVR) springs, which are used to control the opening door in the self-cleaning oven, is also used to offer smooth gear shifting for Mercedez-Benz automatic transmissions, for domestic safety devices to control the hot water flow (e.g. Memrysafe® antiscald valves from Memry Corporation), and for industrial safety valves to prevent flammable and dangerous gasses from flowing (e.g. Firechek® from Memry Corporation) [44,201–203] (see Fig. 9). More interesting, these actuators can act as both a sensor and an actuator in these applications [202].

Selected state-of-the-art and relevant SMA applications and patents are presented in this section, particularly from the automotive, aerospace, robotics and biomedical domains. A brief summary of other related SMA applications and discoveries till mid 2013 are summarised in the appendices.

5.1. Automotive applications

In modern vehicles, the number of sensors and actuators are increasing tremendously due to the demand for safer, more comfortable vehicles, with better performance. The emerging drive-by-wire technology, offers a wide range of opportunities for SMA actuators as an alternative to electromagnetic actuators in automotive applications [2,13,67]. The existing and potential SMA applications for passenger vehicles are presented in Table 11, which categorises them according to vehicle functional areas [67]. Most of the selected components are occasionally functioning as linear actuators (e.g. rear-view mirror folding, climate control flaps adjustment and lock/latch controls) and as active thermal actuators (e.g. engine temperature control, carburetion and engine lubrication, and powertrain clutches) [13,204]. However, due to the SMAs attractive morphing capability (active and adaptive structures), the applications are also expanding into other areas, such as aerodynamics and aesthetics applications (see Table 11).

The mechanical simplicity and compactness (miniaturisation possibilities) of SMA actuators reduce the scale, weight and cost of automotive components significantly and provide substantial performance benefits in comparison to conventional actuators as demonstrated by the example provided by Neugebauer et al. [206] (see Table 12). The versatility of SMA actuators to adapt with other design mechanisms and techniques such as 'pantograph' for the electrically actuated antiglare rear-view (EAGLE) mirror by Luchetti et al. [207]; make it an excellent actuator for automotive applications (see Fig. 10).

General Motors (GM) claim that their engineers have been working with SMA applications since the mid-1990s, and it would be likely first implemented on their 2013 model-year cars [208]. So far GM has earned 247 patents and recently the seventh-generation of the Chevrolet Corvette was to be the first vehicle with a SMA actuator to actuate the hatch vent that releases air from the trunk for easier closing of the trunk lid [3]. Some of their future technologies with SMAs are an electric generator to generate electricity from exhaust heat, a situation-dependent active louver to control the airflow into the engine compartment, on-demand air dam to reduce aerodynamic drag at highway speeds and an adaptive 'grab handle' to ease the opening vehicle doors [209,210] (see Fig. 11).

Several other SMA applications that have been developed for the automotive industry are the SMA activated automotive tumble flaps [211] to replace conventional electromagnetic and pneumatic effectors, an automatic pedestrian protection system (pop-up bonnet) to minimise pedestrian injuries during impact collisions [212], a cost effective side mirror actuator [213,214,216], and a micro-scanner system for optical sensing of an objects distance and angle with a FSMA actuator [217] (see Table 11).

Currently, there are many potential applications that have been suggested and these can be found in the patent literature as listed in this work, but only very few of them have actually been implemented or seem technically and economically feasible due to the limited range of SMA transformation temperatures. However, other limitations such as lifetime, hysteresis width, and stability also have to be considered, especially when dealing with extreme conditions and very stringent requirements (e.g. safety), such as summarised in Table 13 (see Fig. 12). One of the challenges specific to automotive applications is the compatibility of SMA with automotive batteries, this challenge is directly assessed by Leary et al. [215].

The majority of these feasible applications are covered with the commercially available binary NiTi SMA, where its operational temperature range lies approximately within the standard range of environmental temperature extremes to which a passenger vehicle may be exposed during service (i.e. between −40 °C to approx. +125 °C, see Table 13 and Fig. 13 [12,13]). The standard binary NiTi SMA with transformation temperatures from −50 °C to approximately +110 °C [34] performs well for multiple cycles within locations of vehicle within this temperature range [13], but not

Table 9
Materials with SME [19,43,166,178].

Materials	Examples	Notes
Metals	SMA: • NiTi-based alloys: NiTi, NiTiCu, NiTiPd, NiTiFe, NiTiNb, NiFeGa, NiTiCo • Cu-based alloys: CuZn, CuZnAl, CuAlNi, CuAlNiMn, CuSn ... • Fe-based alloys: FePt, FeMnSi, FeNiC ... • Ag-based alloys: AgCd ... • Au-based alloys: AuCd ... • Co-based alloys: CoNiAl...	The best choice is NiTi SMA E.g. NiTi-based: Frequency: ⩽3 Hz, dia. 100 μm with natural cooling (Very Slow).Strain: max. 10% (High), Recommended: 4%.Stress: up to 500 MPa (High), Recommended: 100 MPa.Max. operating temp: ca. 100 °C (Low).
	MSMA/FSMA: NiMnGa, FePd, NiMnAl, FePt, Dy, Tb, LaSrCuO, ReCu, NiMnIn, CoNiGa...	NiMnGa was first discovered in 1984 [411] and have received increasing interest since the principle of the MSMA was presented by Ullakko et al. [412,413] E.g. NiMnGa: Frequency: max. 2 kHz (High), Recommended: 500 Hz Strain: max. 10% (High), Typical: 6% Stress: max. 9 MPa (Low), Typical: 3.4 MPa Young modulus: 0.5 GPa (Very Low) Max. operating temp: 72 °C. (Low), full austenite transition at 48 °C.
	HTSMA: TiNiPd, TiNiPt, NiTiHf, NiTiZr, ZrRh, ZrCu, ZrCuNiCo, ZrCuNiCoTi, TiMo, TiNb, TiTa, TiAu, UNb, TaRu, NbRu, FeMnSi and etc.	So far, TiNiPd and TiNiPt produced the best results and commercially ready E.g. TiNiPd [414]: Frequency: <1 Hz with natural cooling (Very Slow) Strain: 1.5–4.0% (Med) Stress: max. 295 MPa (High) Max. operating temp: 83–513 °C (Very high)
Polymers	PTFE, PU, Poly-caprolactone, EVA + nitrile rubber, PE, Poly-cyclooctene, PCO–CPE blend, PCL–BA copolymer, Poly(ODVE)-co-BA, EVA + CSM, PMMA, Copolyesters, PET-PEG ...	First publication described SME in polymers was in 1941 [5] that is much earlier than SMA E.g. PU-based: Frequency: max 1 Hz (Very Slow) Strain: >800% (Very High) Stress: 3 MPa (Low)
Ceramics	ZrO_2 (PSZ), MgO, CeO_2, PLZT, PNZST ...	Shape memory ceramics has limited shape memory effect (below 0.5 %) [33,415,416] E.g. PNZST: Frequency: ca. 1 kHz (High) Strain: <1% (Very low) Stress: max. 100 MPa (High), Typically: 35 MPa. Operating temp: 200–500 °C (Very high).
Others	SMM thin film: NiTi, SMP and etc.	This technology is based on smart materials applied to a thin film to produce SME for MEMS applications [174] E.g. NiTi-based: Frequency: <100 Hz (Med) Strain: max. 10% (High), Typically: 7%. Stress: up to 500 MPa (High), Recommended: 100–350 MPa. Max. operating temp: ca. 100 °C (Low).

in locations with higher temperatures such as under the engine hood. The SMAs should have an M_f temperature well above the maximum operating temperatures (see the red dotted lines in Fig. 13) in order to work properly [13]. The comparison of the transformation temperature ranges of the most common SMAs under development in Fig. 13 shows that the cheaper Cu–Al–Ni SMAs can perform the transformation with temperatures up to 200 °C, but these SMAs are brittle, unstable, have low fatigue strength and not suitable for multiple cyclic operations [13,32,34,44,160]. A wide selection of HTSMAs are available, but these materials are still expensive for automotive applications [13].

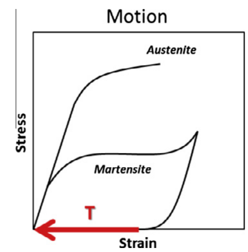
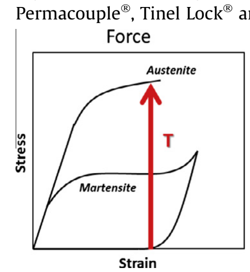
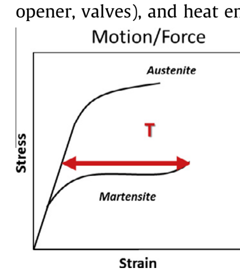
5.2. Aerospace applications

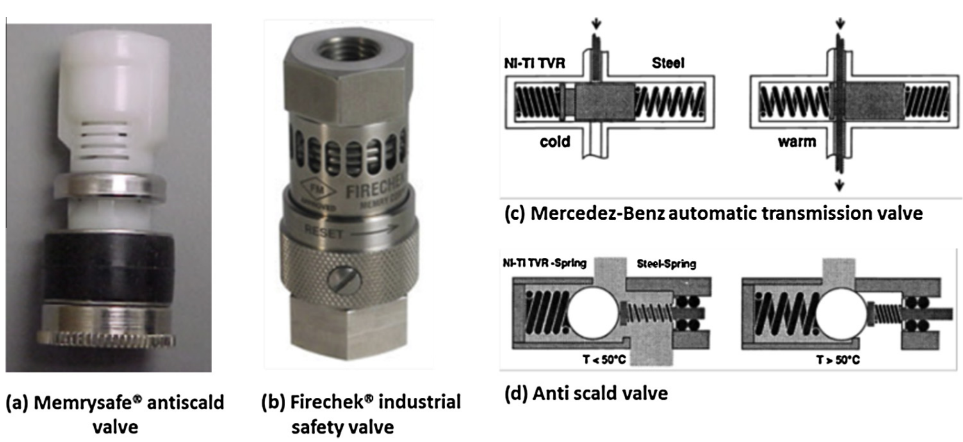
Since the success of the SMA coupling for hydraulic lines in the F-14 fighter jets in the 1970s [219], the unique properties of SMAs have gathered greater interest in aerospace applications [16,17,96,220], which are subjected to high dynamic loads and geometric space constraints. A few examples of these applications are actuators [15,221], structural connectors, vibration dampers, sealers, release or deployment mechanisms [222–226], inflatable structures [227,228], manipulators [229,230], and the pathfinder application [96,231].

In the 1990s, aerospace researchers focussed on active and adaptive structures toward morphing capability and system-level optimisation under various flight conditions, such as in the Defense Advanced Research Projects Agency (DARPA) program for aircraft 'smart wings' [232], the Smart Aircraft and Marine Propulsion System Demonstration (SAMPSON) program for jet engines [233], and a number of other programs [234–237]. Boeing has developed an active serrated aerodynamic device with SMA actuators, which is also known as a variable geometry chevron (VGC) and has been installed on a GE90-115B jet engine (for the Boeing 777-300 ER commercial aircraft). This device has proven to be very effective in reducing noise during take-off by maximising the chevron deflection, and also increasing the cruise efficiency by minimising the chevron deflection during the remainder of the flight [238–240] (see Fig. 14). The high temperature requirement for a core exhaust chevron design was resolved by the identification, testing, and validation of the new TiNiPt HTSMA at the NASA Glenn Research Center [241,242].

Following the VGC success, more SMA based technology programs have been initiated by Boeing, DARPA, NASA and other

Table 10
Shape memory application categories [34,44,201].

Category	Description	Examples
Free recovery	The sole function of the memory element is to cause *motion* or *strain* on the applications Working principle: The memory element is stretched and then released (no load applied). It remains in stretched condition until heated above the transition temperature and shrink back to its original form, and subsequent cooling below the transition temperature does not cause any macroscopic shape change (e.g. OWSMA)	NiTi eyeglass frames (TiFlex™, TITANFlex®) and Simon IVC filter 
Constrained recovery	The memory element is prevented from changing shape and thereby generates a *stress* or *force* on the applications Working principle: The memory element is prevented from returning to its original form after being stretched and considerable force generated if heated above the transition temperature	Hydraulic couplings, fasteners and connectors: CryoFit™, Cryocon®, UniLok®, CryOlive®, CryoFlare®, CryoTact®, Permacouple®, Tinel Lock® and BetaFlex™ 
Actuator or work production	There is *motion* against a *stress* and thus work is being done by the memory element on the applications	Electrical actuators (VEASE™, SMArt Clamp™), thermal actuators (Memrysafe®, circuit breaker, window or louvre opener, valves), and heat engines
(Force actuator, proportional control and two-way-effect with external reset force)	Most of applications fall in this category. Can be either OWSMA or TWSMA. Three types of actuators: Force actuator: The memory element exerts force over a considerable range of motion, and often for many cycles Proportional control: The memory element used only part of its selected portion of shape recovery to accurately position the mechanism, because the transformation occurs over a range of temperatures rather than at a single temperature Two-way-effect with external reset force: The memory element generates motion to overcome the opposing force, and thus do work. The memory element contracts upon heating to lift a load, and the load will stretch the heating element and reset the mechanism upon cooling (e.g. TWSMA)	
Superelasticity	The applications are isothermal in nature and involve the storage of potential energy	Eyeglass frame, orthodontic archwire, Mammelok® breast hook, guidewires, anchors and underwire brassiere

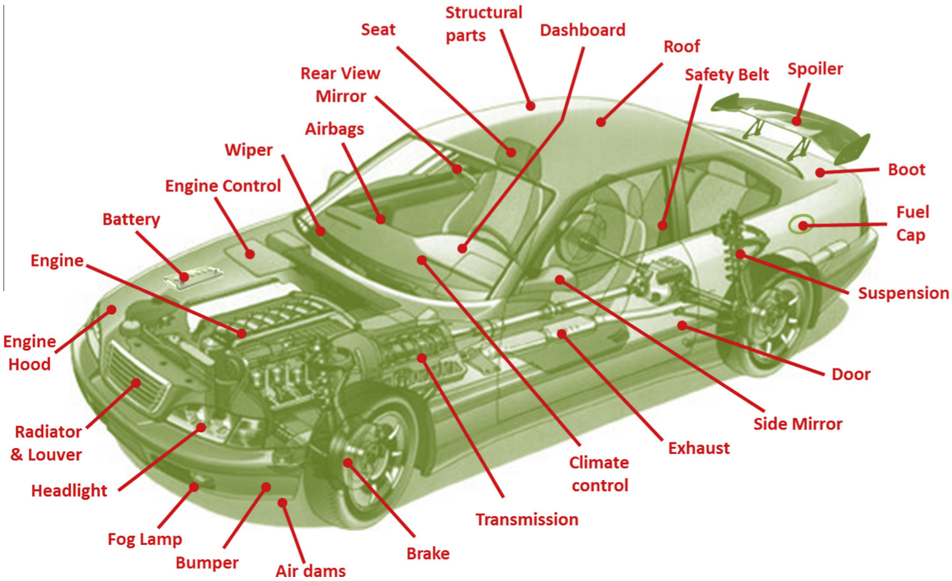


(a) Memrysafe® antiscald valve
(b) Firechek® industrial safety valve
(c) Mercedez-Benz automatic transmission valve
(d) Anti scald valve

Fig. 9. NiTi thermovariable rate (TVR) springs applications [202,203].

related research agencies, which have been reviewed by Calkins and Mabe [243], such as in the smart inlet that could provide fighter aircrafts with a variable engine inlet capability, the reconfigurable rotor blade, which is highly robust, and the twist-able rotor blade to optimise rotor aerodynamic characteristics. Most recently, the variable geometry fan nozzle, which is based

Table 11
Existing and potential SMA applications in the automotive domain [13,67,205].



Parts	References	Parts	References
ENGINE ROOM /UNDERHOOD		BODY AND EXTERIOR	
Radiator	[417–420]	Headlights/lamps	[13,421,422]
Fan clutch	[423]	Wiper	[13,424,425]
Engine control (sensors and actuators)	[426]	Sunroof/sunshade	[418,427–429]
Start-up clutch	[430]	Door and locking mechanism	[13,210,431–434]
Tumble flaps	[211]	Side mirror	[213,214,216]
Fuel injector/fuel system	[435–438]	Boot	[3,431]
Piston rings	[439]	Engine hood	[212,440]
Booster/charger	[13]	Petrol cap	[206]
Valves	[13,441]	Bumpers and crash structures	[442–445]
Battery	[446]	Air dams	[210,447]
DRIVETRAIN		Grill/louver	[210,417,418]
Transmission control	[13,448,449]	Spoiler	[450]
		Structural parts/panels	[418,451–454]
SUSPENSION/STEERING/WHEEL AND TYRE		INTERIOR/PASSENGER ROOM	
Brake	[449,455]	Dashboard	[444]
Absorber	[13]	Rear view mirror	[207]
Tyre	[456]	Seats	[442,453,457–463]
		Airbags	[464,465]
		Structural parts/impact structures	[444,451,466]

Table 12
Comparison of DC-Drive and SMA-Drive for fuel door actuator [206].

Parameters	DC-Drive	SMA-Drive
		
Actuation time (Complete cycle open-close)	3 s	2–3 s
Installation space	Compact	Stretched along the air duct
Acoustics emission (from drive)	Slight noise	No noise
Mechanical complexity	High	Low
Mass	Approx. 65 gm.	Approx. 20 gm
Positioning accuracy	±1.5°	±2.25°
Energy consumption	1 W during flap movements	1 W permanent

on the VGC technology, has demonstrated to improve jet engine performance.

Sofla et al. [235] have provided a comprehensive review of aircraft wing morphing technologies, and they have also developed a shape morphing wing design for small aircraft by applying antagonistic SMA-actuated flexural structural forms that enable the changing of the wing profile by bending and twisting, to improve the aerodynamic performance (refer Fig. 15). A preliminary design study with finite element simulations presented by Icardi and Ferrero [236] has verified that an adaptive wing for a small unmanned aircraft (UAV), which is totally driven by SMA devices, could bear the aerodynamic pressure under any flight conditions, without weight increase or stiffness loss compared to other conventional actuators.

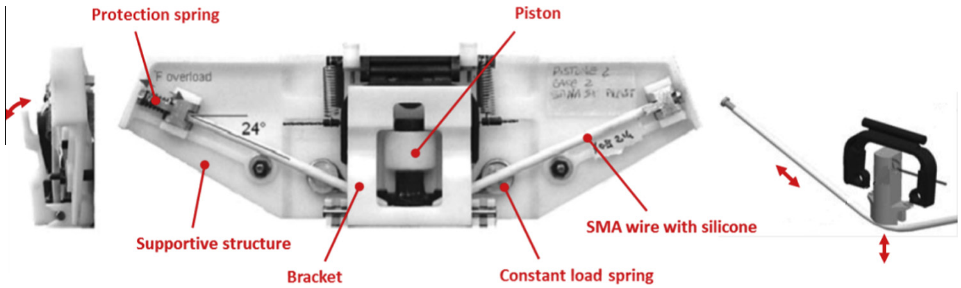


Fig. 10. EAGLE mirror prototype [207].

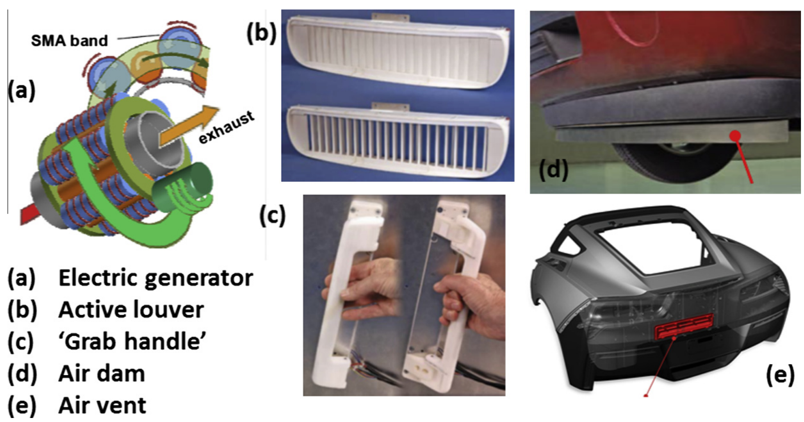


Fig. 11. Emerging General Motors' SMA applications [3,209,210].

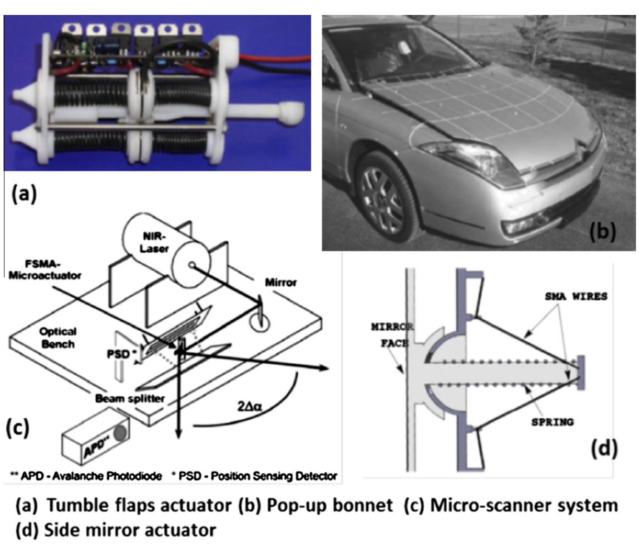


Fig. 12. Other SMA application in the automotive domain [211–213,217].

There has also been significant research in rotor technology (rotorcraft) with SMAs conducted by several researchers, including rotor blade twisting [229,244,245], rotor blade tracking tab [220,246], rotor control [247] and rotor blade tip morphing [248].

SMAs have been used for many years in spacecraft as low-shock release mechanisms because they can be actuated slowly by gradual heating, can absorb vibration very well and can be fabricated in simple and compact designs, which are most suitable for average and smaller sized spacecraft (e.g. microsatellite) [96,250,251]. A few samples of small devices with SMA are the QWKNUT [252], Frangibolt® [253], Micro-Sep-Nut, and Rotary Latch; as described in previous reviews [15,224,254].

As mentioned earlier, SMAs are suitable for vibration damper and isolator applications due to their unique behaviour [96,97]. Considerable new research has been performed to study this in detail [255–257], and a few patents have been filed to exploit these advantages [258–260]. Several other proposed or developed SMA applications for aerospace are the telescopic wing system [261], wing span morphing [262], retractable landing gear [263], jet engine components [264–268], morphing structures [269], flap edge fence [270], aircraft related actuators [271] and aerostructures [272–274] (see Table 14).

5.3. Robotic applications

Since the 1980s, SMAs have been used in a diverse range of commercial robotic systems, especially as micro-actuators or artificial muscles [275–279]; as described by Furuya and Shimada [24] and Sreekumar et al. [23]. Today, most of the SMA robotic applications are biologically inspired (i.e. biomechanics) and widely utilised in biomedical areas but are also used extensively in other fields as well. The primary challenges relevant to the robotics domain are: to increase the performance and miniaturisation of the hardware platform and to increase the intelligence of the integrated system (i.e. small, faster, reliable and autonomous). Several technical issues have been highlighted and need to be resolved, such as clamping difficulties, low electrical resistance, miniature electrical connection (for micro-robots), small strain output, control issues and very low efficiency. However, some of these issues have been tackled by selecting suitable modelling techniques, control techniques and feedback sensors. As an example, the resistance feedback control is ideal for micro-robots as it eliminates the necessity of additional sensors, although with limited accuracy [23].

As mentioned earlier, the SMA actuators response rate depends significantly upon its shape and size, and these have a high impact

Table 13
Typical automotive electronic components specifications [12].

Requirements	Engine room	Passenger room
Operating temperature	−40 °C to +125 °C (+175 °C for some parts mounted to engine)	−40 °C to +85 °C
Storage temperature	+100 °C for 500 h	−50 °C to 100 °C for 500 h
Thermal shock	100 Thermal cycles	20 Thermal cycles
Relative humidity	0–100%	95% @ +65 °C for 100 h
Shock	20 g	Maximum 25 g
Drop test	4 ft. drop	4 ft. drop
Vibration	50–2000 Hz, 10 g RMS, 16 h	50–2000 Hz, 4 g RMS
Operating voltage	5 V, ±0.5 V	12 V, ±4.0 V
Reliability	95% Reliable for 10 years, 120 k miles	90% Reliable for 10 years, 100 k miles
Other		Minimal radiated or conducted emissions. Not susceptible to conducted/radiated emissions
Contaminant resistance	Salt spray, engine oil, ATF, windshield washer fluid, ethylene, glycol, gasoline, power steering fluid, battery acid, engine cleaner, methanol, mud and exhaust gases	

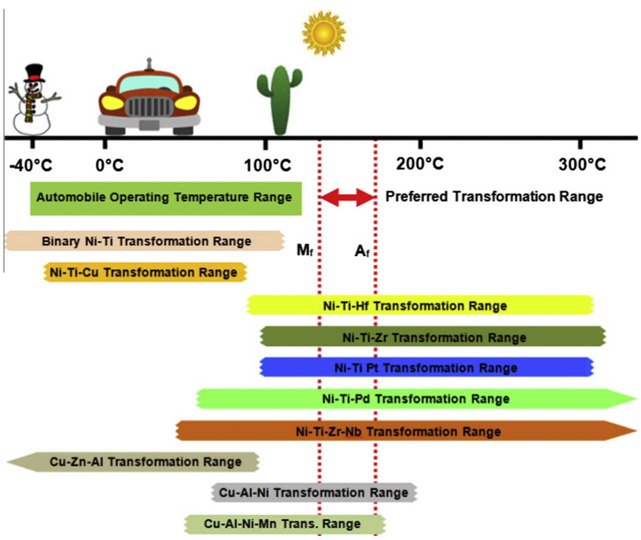


Fig. 13. Operating temperature range for automobiles applications and the transformation temperatures for selected commercially available and developed SMAs [13,34,161,218].

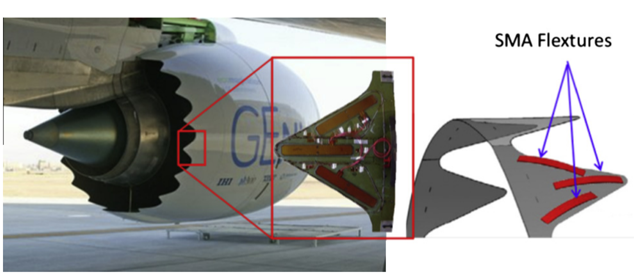


Fig. 14. Boeing's variable geometry chevron (VGC) [238].

on the overall size and degrees of freedom of the robotic device. Resistive heating is generally used for small SMA actuators (up to 400 μm diameter), and indirect heating techniques are applied for thicker actuators [23]. To increase the actuation frequency, capacitors are incorporated with thicker actuators to obtained a rapid heating response, and several cooling strategies can be adopted as mentioned earlier, to enhance the cooling process, but these would make the device bulkier [23]. Furthermore, to increase the degrees of freedom of the robots, the number of actuators has to be increased, which leads to complex control problems.

A new SMA actuator design for a prosthetic hand was introduced by Chee Siong et al. [103], where two SMA actuators are used to actuate the robotic finger, instead of using the conventional push–pull type and the biased spring type (see Fig. 16). The two actuators are inserted from both ends of the outer stainless tube, which functions as a heat sink and guide simultaneously. The current passed asynchronously through the wires via electrode points, which are located at the centre of the tube (where the wires join) and each end of the tube. The two actuators are used to actuate the robotic finger, which can almost replicate the actions of the human finger actions (flexion and extension). A PWM controller is used to pulse periodically high voltage in milliseconds to the actuators to avoid overheating and excessive power usage.

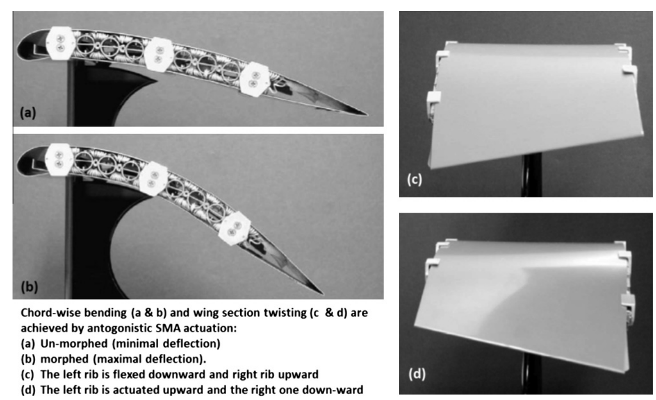
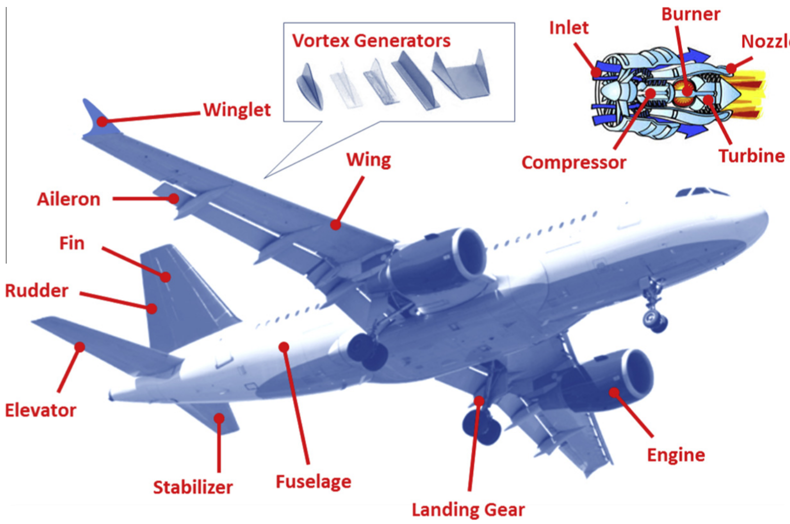


Fig. 15. Wing morphing with antagonistic SMA actuators [235,249].

In a recent review by Kheirikhah et al. [22], they divided the robots into several categories based on their locomotion styles and applications such as crawler, jumper, flower, fish, walker, medical and biomimetic robotic hand. Many robotics researchers are more interested in developing biomemitics and humanoid robots. These robots are useful in solving problems that are challenging for humans, by providing pertinent information from underwater, space, air and land. Comprehensive details and challenges in developing these robots are summarised by several researchers, focusing on the actuation technologies, especially SMA actuators (see Table 15). Tao et al. [280] designed a robotic fish with a caudal peduncle actuator based on the concept of a FSMA hybrid mechanism that can provide fast response and a strong thrust.

Mohamed Ali and Takahata [281] have developed passive (i.e. without internal power source) micro-grippers (i.e. about 600 μm displacement) that can be actuated wirelessly with a RF magnetic field. The fabrication of the micro-gripper is similar to the wafer fabrication processes in the semiconductor industry, where the SMA actuator is bonded to or near an inductor-capacitor (LC) resonant circuit with photo-defined electroplating technology, and

Table 14
Existing and potential SMA applications in the aerospace domain [14,15].



Parts	References	Parts	References
FUSELAGE		ENGINE	
Aerostructure/composite body	[274,467]	Inlet	[233,405,468]
Skin/panel	[273]	Nozzle	[239,269,405]
Wing/fin/stabilizer		Rotor	[220,229,230,244,246]
Wing	[232,235,249,261,262]	LANDING GEAR	[263]
Winglet	[467]	ELECTRO-MECHANICAL CONTROL	
Vortex generator	[469]	Hydraulic lines	[219]
Flap edge	[270]		
Structure/spars	[470]		

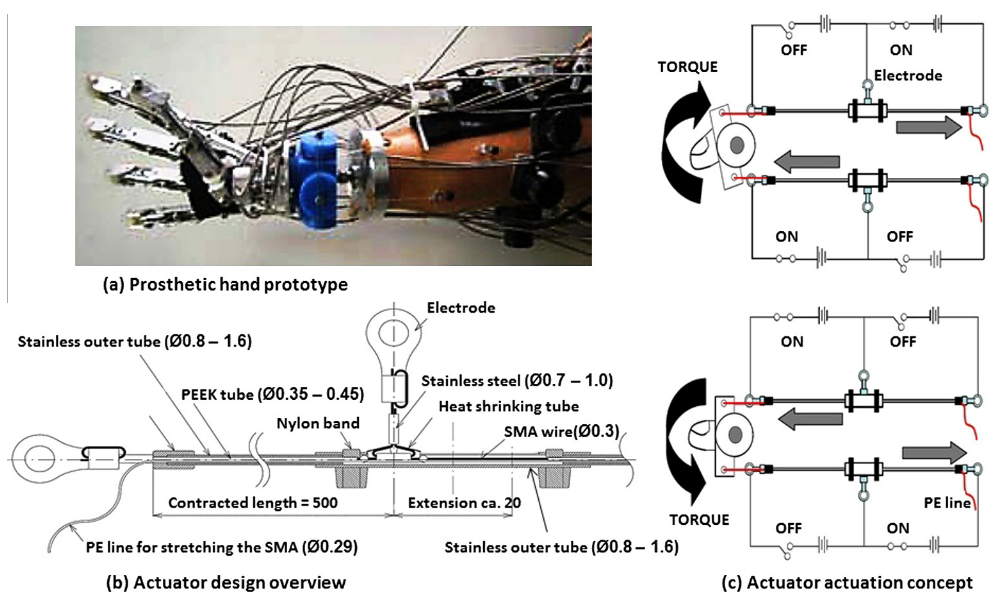
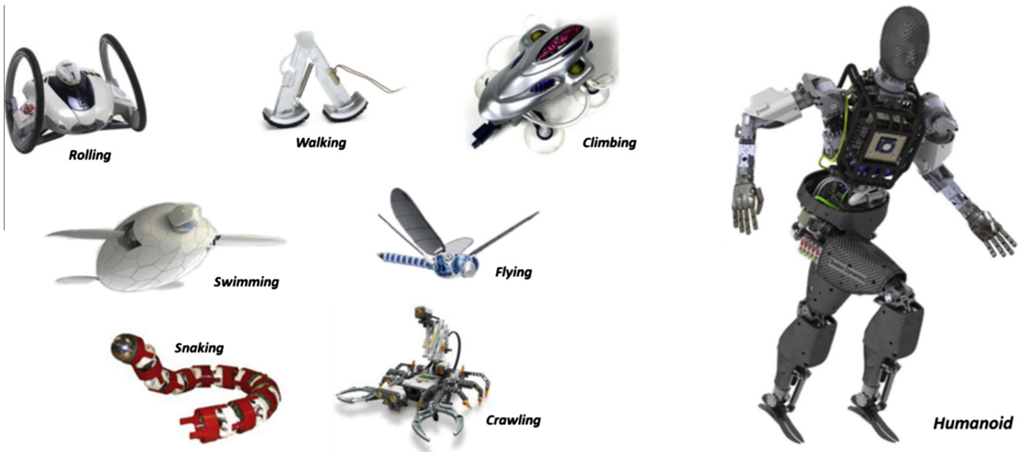


Fig. 16. Prosthetic hand powered by SMA actuators [103].

then micro-machined with a μEDM process. The working principle of the micro-gripper is quite simple. The frequency-sensitive LC resonant circuit is heated when a RF magnetic field passes through it, and then transfers the heat energy to the SMA actuator for activation. The opportunity to control multiple selections of micro-SMA actuators is possible by applying different resonant frequencies, either selectively or simultaneously to the actuators (see Fig. 17).

A novel sensory system for robotics has been developed by researchers at Northwestern University, Illinois applying the SE characteristic of a NiTi SMA to create an artificial rat whisker, utilising the rat's sensing capabilities. The artificial whisker technology has the great potential to enhance robotic sensing capabilities, and could be used to examine and navigate into small and tight interiors, or to locate and identify micro-features on surfaces [282].

Table 15
Existing and potential SMA applications in the robotics domain[22–24].



Categories	References	Categories	References
BIOMIMETICS		BIOMEDICAL ROBOTS	
Crawling/snaking	[471–479]	Endoscopic	[480–482]
Walking/jumping	[476,483–486]	HUMANOID ROBOTS	
Rolling/skating	[485,487]	Fingers/hands	[103,488–494]
Climbing	[495,496]	Head/facial expression	[497,498]
Swimming	[280,499–502]	MISCELLANEOUS	
Flying	[284–286]	Controller	[147,278,503,504]
Others	[505]	Actuators	[281]
		Sensors	[282]

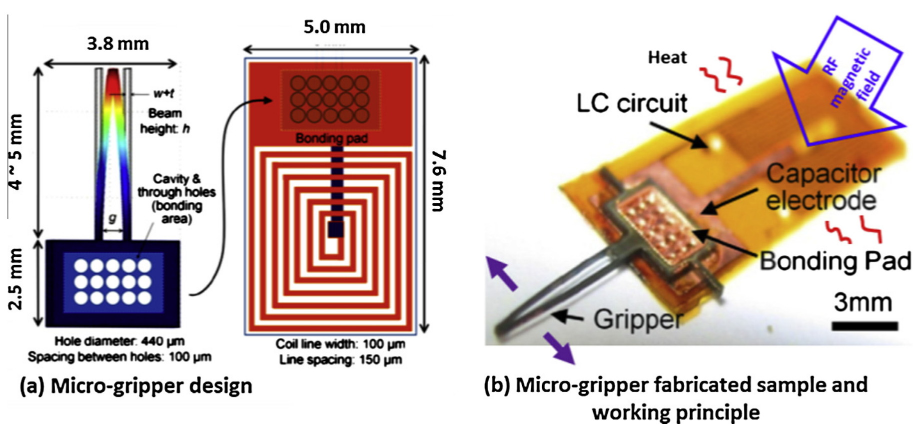


Fig. 17. Micro-gripper with SMA actuator [281].

Several flying robots have been developed with SMAs, such as the BATMAV [283,284] and Bat Robot [285]. Recently, a 44 cm length dragonfly with a wingspan of 63 cm was developed by Festo Group, equipped with four SMA actuators to control the movements of its head from side to side and its tail up and down for flight manoeuvre and stability. The 'dragonfly', also known as 'BionicOpter', has 13 degrees of freedom, can hover in mid-air and manoeuvre in all directions [286] (see Fig. 18).

Fig. 18. Festo BionicOpter – inspiration dragonfly flight [286].

5.4. Biomedical applications

After the discovery of the SME in nitinol by Buehler et al. in 1962, they proposed to use this material for implants in dentistry, and a few years later, the first superelastic braces made from a NiTi alloy were introduced by Andreasen in 1971 [7,287,288]. SMA made a significant breakthrough into biomedical domain after its introduction in minimally invasive surgery (MIS) [26], and more biomedical applications are developed and introduced into the market after the approval of the Mitek surgical product (i.e. Mitek Anchor) for orthopaedic surgery by US Food and Drug Administration (FDA) in September 1989.

Although NiTi alloys are significantly more expensive than stainless steels, SMAs have exhibited excellent behaviour for biomedical applications such as high corrosion resistance [34,53], bio-compatible [29,87], non-magnetic [37], the unique physical properties, which replicate those of human tissues and bones [27] (see Fig. 19), and can be manufactured to respond and

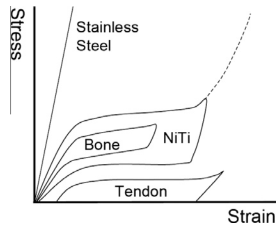
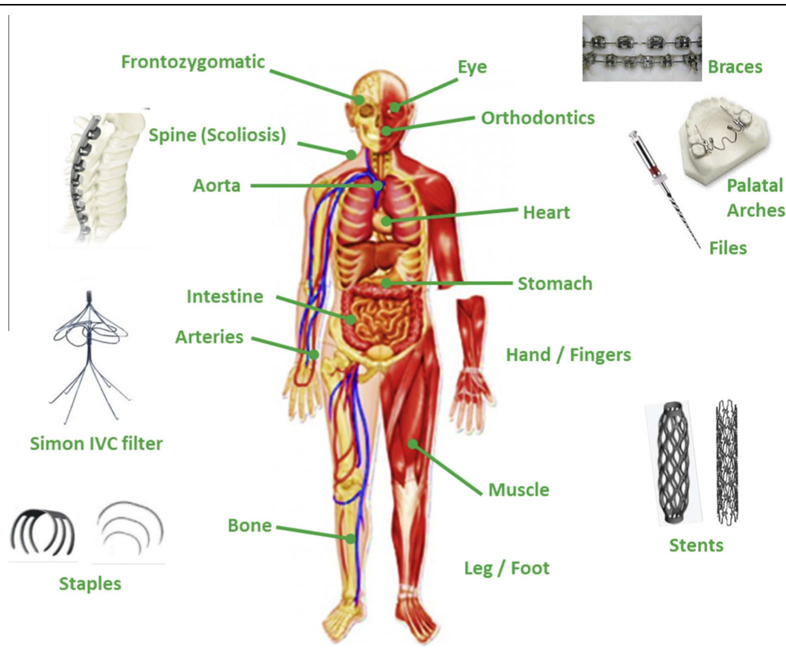


Fig. 19. The stress versus strain relationship for superelastic nitinol, stainless steel, bone and tendon tissues [27].

change at the temperature of the human body [28]. The need for precise and reliable miniature instruments to achieve accurate positioning and functioning for complex medical treatments and surgical procedures provides SMAs with substantial advantages and great opportunities for further commercial success in this area. SMAs are used in medical equipment and devices in many fields including orthopaedics, neurology, cardiology and interventional radiology [27]; and other medical applications include: endodontics [289], stents [26], medical tweezers, sutures, anchors for attaching tendon to bone, implants [290,291], aneurism treatments [292], eyeglass frames [9] and guide wires [293] (see Table 16).

The superelastic behaviour of SMA, which fits the stress–strain behaviour of human bone and tendons, makes it an excellent material to meet some of the challenges presented by stenting operations. SMA stents are much more compliant to bends in the vessels and contours in the lumen, whereas stainless steel stents tend to force blood vessel straight. In addition, the superelastic hysteresis behaviour of SMA can resist crushing during the normal physiological process (provide radial resistive force) and exert a small outward force on the vessel during recovery, which is ideal for stenting applications [27] (see Fig. 20). The first SMA stent was made by Dotter's group in 1983 [294], and since then it has evolved remarkably (from simple coiled wire form to the complex laser cut structures), growing in the global market (nearly half of stent products are fabricated from SMA and was forecast to reach USD6.3 billion by 2010 [295]), and has expanded the usage to other parts of the human body [26].

Table 16
Existing and potential SMA applications in the biomedical domain [25–28,30].



Fields	References	Fields	References
ORTHODONTIC		BIOMEDICAL/SURGICAL INSTRUMENTS	
Braces/brackets	[288,506,507]	Catheters/snares	[508,509]
Palatal arches	[510]	Scopes (Ureteroscopy, endoscopy, laparoscopy)	[511–515]
Files	[516]		
		Suture	[517]
ORTHOPAEDIC		MISCELLANEOUS	
Head	[518]	Cardiology (Heart)	[301,302]
Spine	[519–523]	Hepatology (Liver, gallbladder, biliary tree and pancreas)	[524,525]
Bone	[291,526,527]		
Muscles	[28]	Otorhinolaryngology (Ear, nose and throat)	[528–531]
Hands/fingers	[103,532]		
Legs	[300,533]	Gastroenterology (Gullet, stomach and intestine)	[534–540]
VASCULAR			
Aorta	[541,542]	Urology (Kidneys, adrenal glands, ureters, urinary bladder, urethra and the male reproductive organs)	[543–548]
Arteries	[549]		
Vena cava filter	[550–554]		
Ventricular Septal Defect (VSD)	[555–557]	Plastic, reconstructive and aesthetic surgery	[558]
Vessels	[559–561]		
Valves	[562–564]	Ophthalmology (Eye)	[565]

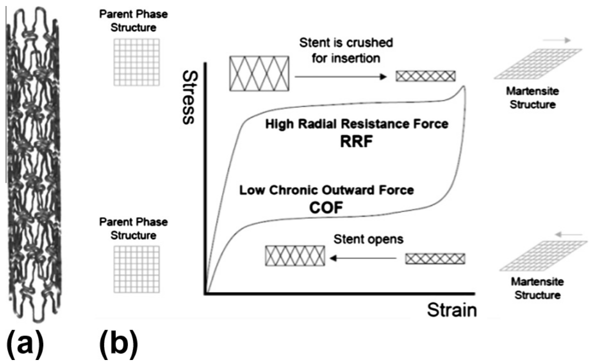


Fig. 20. (a) Model of stent laser cut from nitinol tubing. (b) The radial resistance force and chronic outward force as a function of superelastic hysteresis loop [27].

Today, catheter-based surgeries have become increasingly popular due to the demand for MIS treatment, which will further minimise operation trauma. The application of SMAs has improved the active catheter capability to move accurately with larger bending angles, which enables novel diagnosis and therapy to be treated [293,296,297]. A laser machined SMA actuator from NiTi tubing as proposed by Tung et al. [298], allows for the creation of custom-tailored SMA actuators with force, elongation and size characteristics, which are not achievable with common straight wire or coil spring actuators, leading to another viable option for developing actuators for steerable catheters (see Fig. 21).

A micro-muscle fibre crafted from NiTi SMA coiled springs was presented by Kim et al. [299], utilising many of the SMAs attributes (resilience, high energy density, flexibility and scalability) to produce a novel mesh-worm prototype that employs a bio-inspired antagonistic actuation for its body deformation and locomotion, and this could make an excellent actuator candidate for meso-scale applications. Similar work has also been done by Stirling et al. [300], to develop an active, soft orthotic for the knee. They concluded that even though SMA springs could provide the soft characteristics as required and produce a large energy density; it was not appropriate for this application due to the poor response time and would be difficult to operate if not tethered to an external power supply. However, it could be appropriate for applications with a slower time scales or reduced forces requirements (see Fig. 22).

An artificial myocardium was developed by Shiraishi et al. [301] using a nanotech covalent type SMA fibre with a parallel-link structured myocardial assist device, which is capable of supporting natural contractile functions from the outside of the ventricle without blood contacting the surface. The researchers concluded that their system might be applied in patients with exertional heart stroke, as well as cardiac massage during a lifesaving emergency for recovery from ventricular fibrillation. Recently, they have developed another mechanical circulation support device using SMA fibres for Fontan circulation to assist pulmonary circulation in patients with congenital heart diseases (see Fig. 23) [302].

An 'alterable stiffness' implant might help the bone to heal faster, thus able to bear weight earlier and avoid a follow-on operation. Currently, this alteration is only possible with a biodegradable implant, 'fixateur externe' or a second surgery. Therefore, an 'alterable stiffness' implant made of NiTi-SMA has been developed to alter the stiffness of the implant with contactless heat induction [291] (see Fig. 24).

In the last few years, there have been concerns from medical practitioners and researchers about the fatigue and fracture behaviour of SMA materials, and several observations and follow-up procedures were conducted to understand these behaviours and to design better biomedical applications in the future [27,303,304]. The concern of biocompatibility of the NiTi SMAs has also been raised due to the known toxic, allergenic and carcinogenic properties of nickel, and an alternative material composition has been considered [291,305,306]; such as the new ideas of shaping the tissues with SMPs and SMHs [457].

6. Opportunities and future direction of SMA applications

The commercial and research interest in SMMs, particularly in SMAs are rapidly increasing, and many potential new applications have been proposed, such as listed in Table 17 [307]. The chance of success of a new idea can be evaluated and ranked into three different categories of applications, i.e. substitution, simplification and novel applications [218]. Applications with higher novelty and good competitive price are more interesting and have a better chance to penetrate the market. A few successful mass produced SMA applications in the market are the underwire brassiere, the mobile-phone antenna, eyeglass frames, the SMA pneumatic valves developed by Alfmeier Präzision AG (now Actuator Solutions GmbH) for the lumbar support device in car seats and the Xlinea™ autofocus (AF) module for smart phones [201,308,309]. However, the percentages of commercially successful SMA applications are still considered to be low [61,80,81].

6.1. Future trends in SMAs

The future trends in SMAs can be expected at three different levels [218]: (1) development of new or improved SMAs, (2) combination of the functional properties of SMAs with the structural properties of other materials (e.g. hybrid or composite SMMs), and (3) search for new markets.

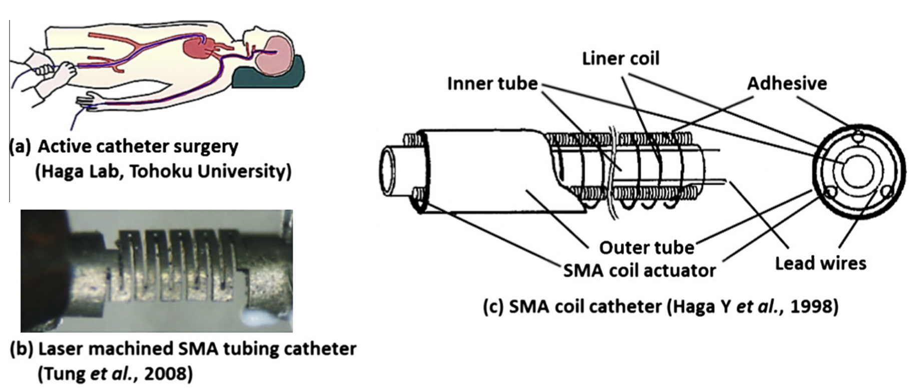


Fig. 21. SMA active catheter [297,298].

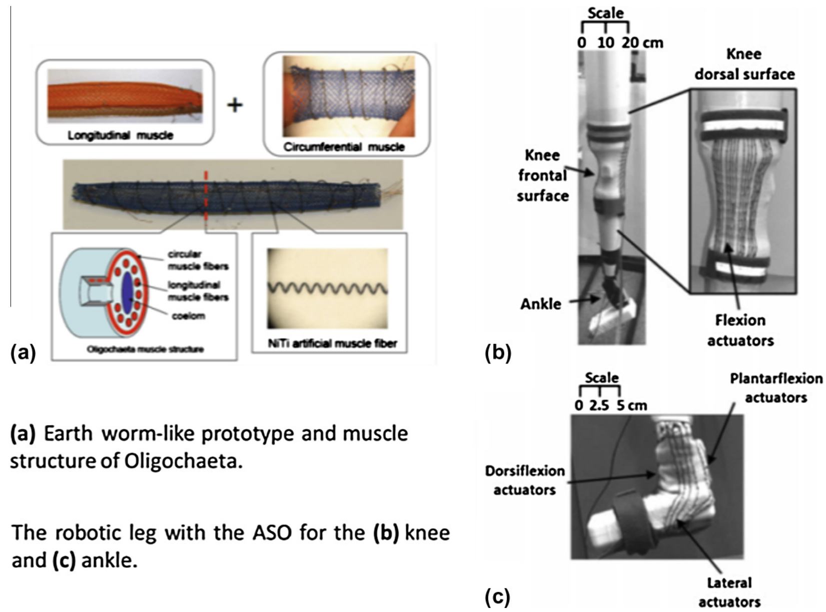


Fig. 22. Muscle like NiTi SMA [299,300].

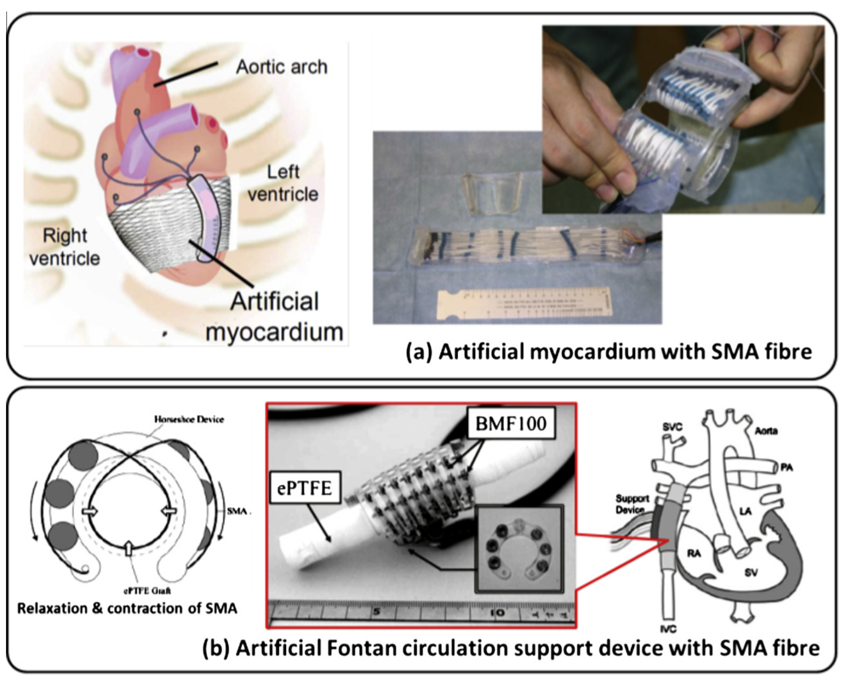


Fig. 23. Artificial heart support devices with SMA fibre [301].

The developments of new or improved SMAs have significantly enhanced SMAs attributes and performances (see Fig. 25). Many researchers are recently interested in 'programming' the SMMs by locally embedding multiple shape memories into SMMs with various techniques to set the temporary shapes without permanently changing the material properties, instead of utilising the traditional 'training' method [310,311]. For example, a new process known as multiple memory material technology (MMMT) developed by researchers at University of Waterloo, Canada has transformed SMAs into multiple shapes at various temperatures [310]. A new single-crystal SMA (SCSMA) made of copper–aluminium–nickel (CuAlNi) developed by TiNi Aerospace has exhibited better performance over NiTi SMA, i.e. higher operation temperature (>200 °C), fully resettable (repeatable with 100% recovery), up to one million of cycles operation, greater strain recovery (9%), wider tranformation temperature range (−270 °C to +250 °C) and very narrow loading hysteresis (<25 °C) [312]. Another new developed ferrous-based SMA known as NCATB alloy has exhibited maximum superelastic strain of about 13.5% and a very high tensile strength of 1200 MPa [313]; and a new developed FSMA made from NiMn alloy has also been used for actuation, sensing, magnetic refrigeration, active tissue scaffolding and energy harvesting [314–316].

Recently, the performances and functionality of SMAs has been augmented by integrating SMAs with other materials to form shape memory hybrids (SMHs) or shape memory composites (SMCs). Various combinations of SMAs and other materials have improved the material performance such as higher damping capacity and toughness [318,319], active stiffening [320], triple-state

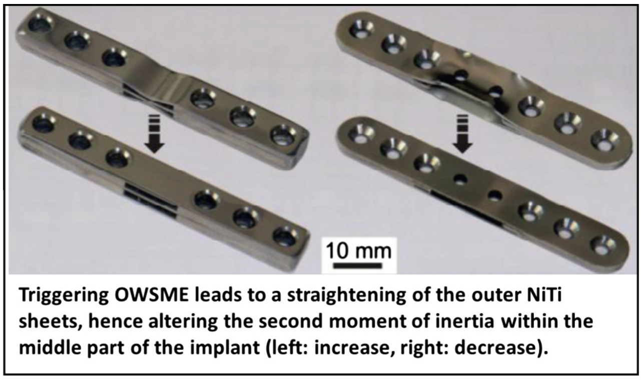


Fig. 24. An 'alterable stiffness' implant [291].

Table 17
Potential SMA applications [307].

Configuration	Potential applications
SMA tendons, wires and cylinders	Adaptive control and actuation of aircraft flight surfaces
Embedded SMA wires	Shape-adaptive composite materials
SMA actuators	Transmission line sag control and ice removal from overhead power lines
SMA energy absorbers and tendons	Earthquake-resistant building and bridges, bridge and structural repairs
SMA dampers	Engine mountings, structural supports
SMA wires, wings, legs, actuators, etc.	Mobile micro-robots, robot arms and grippers
SMA wires, composites, etc.	Prosthetics, artificial muscles

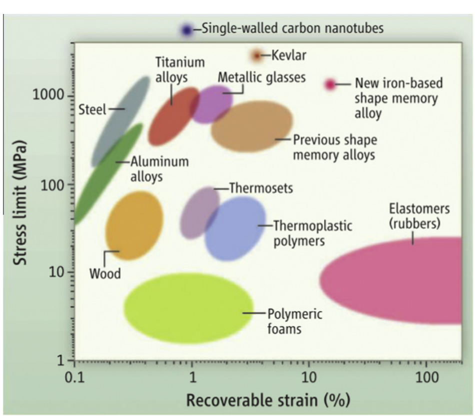


Fig. 25. Comparison stress and strain of new developed SMA with other materials [100,317].

changing [321] and self-healing capability [196]. An advanced composite structure constructed from CFRP composites with embedded SMA wires has also been employed as a structural health monitoring (SHM) system (i.e. for sensing and damage detection) with structural ice protection capacity [322].

The unique properties of SMAs result in high damping, combined with the capability to resist extreme, repetitive and various loading conditions (e.g. earthquake), substantially make SMAs highly compatible with for civil engineering applications, especially in damping and vibration control [323,324]. Several potential SMA applications in bridge and building structures are bearings, columns, beams, and connecting elements between beams and columns [325]. However, there are still limitations such as greater cost compared to structural steel, much slower response time and larger power consumption requirement for activation due to the larger cross-section of the structure, and difficulties in both machining and welding [326]. Other new potential industries for SMA applications are oil and gas industry [310,327], industrial and manufacturing [8], sports [328–330] and arts [331] (see appendices).

The future of SMAs is full of potential as SMAs becoming more multifunctional and capable to perform more active roles in complex systems [317].

6.2. Future directions of SMA applications

Many potential areas and topics of research have been proposed [332], but most of the research on SMAs that has been conducted has focused mainly on the metallurgical properties, and less on the design perspective. It was concluded that to utilise the SMA applications, closer collaboration between material scientists and engineering designers is essential, due to the available information offered by material scientists is not transparent and difficult to digest directly (i.e. too specialised in material science and technology) by the design engineers [80,82,332]. Therefore, the challenges in designing SMA actuators are not mainly the SMA limitations, but also how to convey the information effectively. As example, Spaggiari et al. [333] described that the three main challenges for SMA actuator design are: (1) obtaining a simple and reliable material model, (2) increasing the stroke of the actuator, and (3) finding design equations to guide the engineer in dimensioning the actuator.

For this reason, the development of an effective information platform or database for SMA applications is important to reduce the development time and cost, to minimise the risk of failure products and to identify potential applications effectively with patents screening and analysis (see Fig. 26) [80]. An optimum design of SMA actuators could be realised by providing design engineers with appropriate design procedures and guidelines [13,80,82,332,333].

Actually, there is no lack in vision or ideas for creating the SMA applications, but there is a serious problem in making it marketable [334]. Involvement of marketing personnel in SMM communities is also essential in shaping SMA applications to adapt to the commercial market with different approaches and strategies, where 'smart marketing' is the key to an unconditional breakthrough [218]. A few standards and requirements for SMMs have been drafted by several SMM communities as guidelines in various fields and applications, such as for terminology, testings, fabrications and treatments [335].

Furthermore, the importance of incorporating modern computer design and analysis tools such as CAD and FEA into developing innovative and reliable SMA applications has led to an interest in more accurate 3D constitutive models, which are calibrated from carefully obtained material characterisation and experimental data. These are considered essential to speed up the development process, especially for preliminary studies and validation of high risk and/or expensive projects.

7. Discussion

Although, more than 10,000 US SMA related patents have been proposed in many sectors [61,81,336] (see Fig. 4), only the four major sectors are presented in this work, due to the huge classification of sectors and applications. The most recent developments of SMMs, others than SMAs are also omitted; due to the objective of this review is to focus on SMAs. After the first commercially success SMA application as pipe coupler in 1969 [7], the demand for SMAs are increasing after 1980s, especially in the biomedical sec-

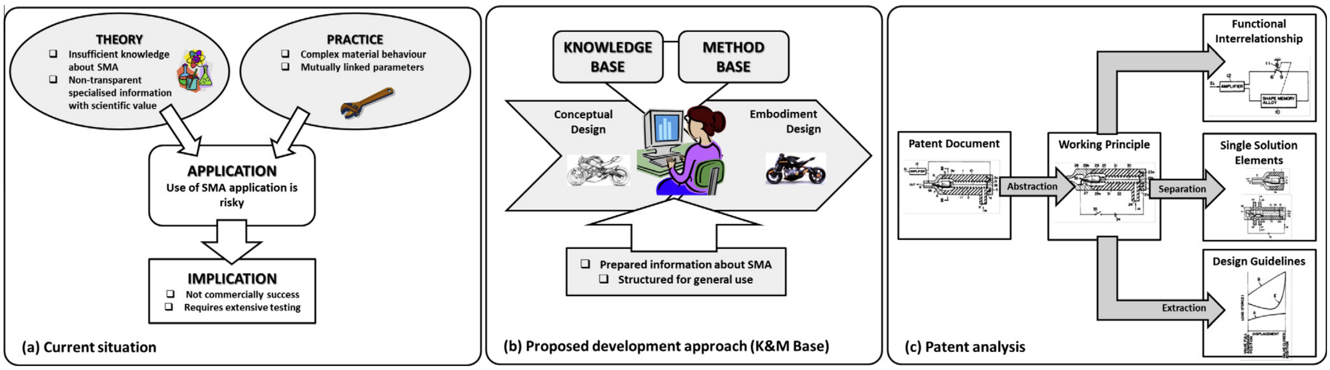


Fig. 26. Current situation and proposed approach for SMA in product design [80].

tor (see Fig. 3). Consequently, major manufacturers such as ATI Wah Chang Corporation, Dynalloy Inc., Johnson-Mattheys, Memory-Metalle GmbH, Memry Corporation, SAES Group and Toki Corporation have continued to grow in both size and knowledge base.

The advancement in the process and manufacturing technologies (see Appendix D) has led to an increase in production quantity and quality, and at the same time reduced the material price. New SMA materials (e.g. MSMAs and HTSMAs) or forms (e.g. NiTi thin films, composites or hybrids) have been researched, and more promising attributes and enhancements are being offered (see Section 6), and further outweigh their challenges (see Section 3.2).

The current research or development trends of SMAs, in the selected sectors are (see Section 5):

(a) Automotive and aerospace:
- Self-healing and sensing structures/components (e.g. smart tyre and airbags).
- Morphing capability for aerodynamic and aesthetic features.
- High temperature actuators.
- Noise, vibration and harshness (NVH) dampers/isolators.
- Rotary actuators.

(b) Robotics:
- Micro and fast actuators.
- Efficient, stable and accurate actuators.
- Rotary actuators.

(c) Biomedical:
- Artificial muscles.
- Shape memory implants.
- Toxic (i.e. Nickel) free SMAs.

The self-healing capability of SMHs (i.e. combination of SMAs and SMMs, particularly SMPs) [196,337–339] has potentially created new applications, such as healable composites, coatings and brake pads. The potential of SMAs to work as both sensor and actuator simultaneously is favourable for miniature actuators. The fabrication of mini- and micro-actuators such as NiTi thin films (see Section 4.3) is possible, with the new fabrication technologies, which further enhanced SMAs attributes and functionality.

8. Conclusions

In general, the important designing factors to be considered for SMA applications are as listed below:

- Operating temperature range for the actuator: Selection of SMA material and heat transfer technique to be considered.
- Force required for deforming the actuator: Selection of SMA shape, size, loading configuration and design technique to be considered.
- The required speed of the actuator: Selection of SMA material, shape, size and cooling technique.
- The stroke required: Selection of SMA material, shape, size, loading configuration and design technique to be considered.
- Type of sensors and controller to incorporate with the actuator (e.g. position, temperature, force or resistance) to ensure long life and stability.
- Durability and reliability of the actuator: Selection of SMA material, size, loading configuration and number of cycles to be considered.

Proposed actions to be taken to increase the commercialisation of SMA applications:

- Good collaboration within the SMM community (i.e. between material scientists, engineering designers and marketing personnel) and utilisation of information platform or database to share the knowledge of SMAs and designing SMA applications.
- Utilisation of new SMA materials, including hybrid or composite SMMs to enhance its performance and functionality.
- Exploration of new markets for SMA applications.
- Incorporation of modern computer design and analysis tools such as CAD and FEA into the design and development process.

Future development

The identified future development for SMA applications:

- Development of more efficient and effective information platform or base for knowledge sharing within SMM communities.
- Development of new materials (including composites and hybrid SMMs), fabrication technologies and treatment processes for SMAs, which are more stable, more durable and can be utilised in a broad range of industries.
- Development of new design approaches or guidelines for creation of novel SMA applications, in existing and new markets.
- Development of robust computational models of SMA behaviour.

- Development of integrated actuator systems (with compact, fast and intelligent controllers).

Appendix A. SMA actuators

Actuators and motors Description	Remarks	Year	Inventor/ researcher
Self-regulating actuator that cut-off the power when reach its stroke. Also protect actuator and connected mechanism from damage due to jam or malfunction	Linear type. Self-regulated	1985	Morgan and Yaeger [340]
An actuator with multiple SMA wires arranged around a resilient member (such as spring) to increase bandwidth	Linear type	1986	Hosoda et al. [341]
A temperature traction device suited to closing doors automatically following a short delay after opening	Linear type	1987	Sampson [342]
An actuator comprising of a SMA wire and control element rotate to different section by applying various selective voltage. Aimed primarily for robotics but is deemed more widely applicable	Rotary type	1987	Gabriel et al. [343]
An actuator consisting of two concentric tubes of SMA, torsional along their longitudinal axis, with the ends constrained relative to one another to provide two stable positions and smooth motion between the two with more describes uniform heating, thus deliver maximum work output per unit volume with minimal power consumption for activation	Rotary type. Bi-directional	1992	Swenson [344]
A micro-actuation system in which able to move freely with a stroke in the range of 1–500 μm	Linear type. Folding	1994	Komatsu et al. [345]
An invention for increasing the life of a SMA actuator by maintaining a martensite strain on the SMA element at <3%	Linear/ Rotary type. Control strain	1995	Thoma et al. [146]
An actuation system to control multiple SMA elements in a matrix configuration that reduces the electrical connections by 50%	Control system	1998	Mukerjee and Christian [346]
A linear actuator to translate an object from one position to another by the action of a SMA flat spring attached at one end to a heating device and to the object at the other end	Linear type	1999	Foss and Siebrecht [347]
An actuator consists of SMA strips (coiled into springs) and SMA springs that produce a constant force from applied heat. Can rotate either a clockwise or anti-clockwise depending on which spring is activated	Rotary type	2000	Weems [348]
A rotary actuator which can provide either small or large amounts of torque and is able to operate in both directions using a single SMA member	Rotary type	2000	Jacot et al. [349]
A rotary drive system that incorporates SMA elements for use in a motorised camera	Rotary type	2001	Williams [350]
A method of designing a SMA actuator to enhance service life (more than 100 k cycles), with limited tensile stress (100 MPa)	Enhance life cycle	2004	Homma [351]
An actuator with two stable working positions that will switch between these positions upon sequential activation of a SMA element, and maintained until the next activation cycle	Two states switch	2005	Biasiotto et al. [352]
A rotary actuator composed of a SMA	Rotary type	2006	Jacot et al. [245]

(continued on next page)

SMA actuators (*continued*)

Actuators and motors Description	Remarks	Year	Inventor/ researcher
torque tube connected with a bias superelastic return spring			
Several linear and rotational actuators with combination of SMA elements to create a long output stroke from as compact unit	Linear and Rotary types	2006, 2007	Gummin et al. [353,354]
An actuator assembly with several protection mechanisms and variable return force to impart motion in an output shaft	Linear type	2006	Von Behrens [355]
A linear actuator with several SMA members in tubular shape and are set coaxially to provide a telescopic extension	Linear type	2008	Yson et al. [356]
A turn-actuator with a tensile element made of three SMA elements, which are fixed to a rotational element in such a way it can rotates in both direction	Rotary type	2008	Garscha et al. [357]
A SMA linear actuator with a SMA wire, two moving bodies and two bias springs positioned in a cylinder	Linear type	2009	Takahashi [358]
A torque actuator incorporating SMA and MSMA composites	Rotary type	2010	Taya et al. [359]
A linear actuator design based on MSMA composites (A hybrid electromagnet and a permanent magnet to activate FSMA spring)	Linear type	2010	Taya et al. [360]
An SMA wire actuator made in a series to increase applied load	Linear type	2010	Butera [361]
A solar tracking mechanism driven by SMA motor	Linear type	2010	Altali and Benjamin [362]
An actuator device with sliding elements and thermal conduction to base to improve response time	Linear type	2010	Yang [363]
A device and method for controlling a phase transformation temperature of a shape memory alloy. Developed by Dynalloy and GM	Control system	2013	Gao et al. [364]

Appendix B. Bonding and joining

Fasteners, seals, connectors and clamps Description	Remarks	Year	Inventor/ researcher
A pre-tensioned SMA actuator for high loads and long period idling applications (e.g. clamping mechanism for space station)	Clamps	1990	Romanelli and Otterstedt [365]
A device for the non-explosive separation of coupled components with SMA element in a controlled fashion	Release mech	1992	Johson [253]
A metal to metal seal for use in a wellbore that incorporates a SMA element	Seals	1993	Ross [366]
A method to enhance fatigue lifetime around holes formed in structural members through cold working using a tool or an interference fit fastener fabricated from SMA material	Fasteners	1993	Kennedy and Larson [367]
A heat operated release mechanism with SMA element that is controllable to allow a heat exchanger (on PCB Board) to be held firmly in place and to be withdrawn when so desired	Release mech. PCB application	1996	Porter [368]
A novel clamping device incorporating a SMA element for the easy clamping and release of a work piece	Release/ clamp mech	1998	Schron and Summers [369]
An effective connection between two components by simple relative motion, with one of the components being a super-elastic material	Fasteners	2001	White [370]
A sealing assembly that	Seals	2002	White [371]

Bonding and joining (*continued*)

Fasteners, seals, connectors and clamps			
Description	Remarks	Year	Inventor/ researcher
incorporates a flat washer gasket made of a super-elastic alloy that deforms elastically to seal between two connecting members when the sealing surfaces are fully engaged			
A releasable fastener system comprising a series of loops (composed of a fibre that has a non-axisymmetric coating of a SMA) that when pressed together they interlock to form a releasable engagement	Fasteners	2004	Cheng et al. [372]
A system consists of two release mechanism of different structure states (pseudoelastic and martensite-austenite)	Release mech	2004	Carman et al. [373]
To improve adhesion between two dissimilar metals (such as a hard CrN coating and aluminium) with interlayer of SMA material between them by compensating the mismatches of mechanical	Fasteners	2006	Cheng et al. [374]
Devices and methods for fasteners (such as bolts) made of single crystal SMA capable of adjusting the tension in the assembly	Fasteners	2006	Johnson et al. [375]
SMA as fastening system for instrument panels, e.g. in a motor vehicle which can improve the fixing or releasing of trim panel and can change the approach to dashboard design	Fasteners	2007	Rudduck et al. [376]
A torque transmitting coupling assembly incorporates an elongated shaft member made of a super-elastic alloy, which lock two members together in a fixed relative position upon activation	Fasteners	2008	White [377]

Bonding and joining (*continued*)

Fasteners, seals, connectors and clamps			
Description	Remarks	Year	Inventor/ researcher
A device and method for holding components together and permanently deforms a bolt to adjust the components to a pre-determined distance without being fully detached fully by selective activation of SMA element	Fasteners	2008	Johnson et al. [378]
Several types of fastener, fastener systems and fastener assemblies using SMA elements	Fasteners	2009	Rudduck et al. [379]
A ratchet mechanism with SMA	Clamps	2011	Johnson et al. [380]

Appendix C. Industrial and manufacturing

Industrial and manufacturing			
Description	Remarks	Year	Inventor/ researcher
A SMA wire as its driving source to open or close the linear valve	Valve	1990	Homma [381]
A linearly actuated valve with SMA wire that is inexpensive, lightweight and constructed from as few parts as possible	Valve	1993	Coffee [382]
A fluid control valves with SMA element	Valve	2001	Hines et al. [383]
An invention for a press brake tool holder with SMA actuator for the clamping force	Press brake tool	2007	Morehead and Harrington [384]
Same tool/die to form different geometries with changeable SMA surface	Tool and Die	2007	Browne et al. [385]
A resettable thermal valve for fluid flow control using a SMA actuator that permits the valve to move from an open to a closed position when heated to a predetermined temperature	Valve	2008	Vasques and Garrod [386]
To control the gas flow rate (flow controller) with SMA by varying aperture size (rotary motion) of the frame	Valve	2008	MacGregor et al. [387]
Adjusting the nozzle tip height and hot runner seals in an injection	Injection moulding	2009	Jenko [388]

(*continued on next page*)

Industrial and manufacturing (*continued*)

Industrial and manufacturing Description	Remarks	Year	Inventor/ researcher
moulding machine effectively and efficiently with SMA element			

Appendix D. SMA material and process and material improvements

SMA process and material improvements Description	Remarks	Year	Inventor/ researcher
Producing a two-way SME from one-way memory material by deforming the material into a predetermined shape and then work hardening, such as through shot peening	Transform OWSME to TWSME	1998	Ingram [389]
A process ("training") for conditioning a SMA by cold working and annealing prior to force application/ release cycling at a temperature above the martensitic-austenitic transformation finish temperature, but below the maximum temperature at which the austenitic-martensitic transformation will be effected by the force application, to yields greater control over the forward and reverse transformation temperatures and therefore produces a reduction in the hysteresis variability	Reduce hysteresis variability	2000	Carpenter and Draper [390]
A novel SMA (Ti50Ni47Fe3) which responds to changes in ambient temperature over a narrower temperature range (~2 °C) by taking advantage of a transition to the R-phase rather than the martensite phase to reduce hysteresis effects. A specific application for such an actuator is to control an anti-freeze plug for opening a drainage hole in a condensate collector pan of an air conditioner when the ambient temperature approaches freezing	SMA material with narrow temperature range	2002	Ashurst [391]
An apparatus to improve the control and operating efficiency of a SMA device by using a thermoelectric (TEC) material to pump heat between the SMA and a heat sink	SMA improvement with TEC	2006	Jacot et al. [245]
A method of preparing nitinol for use in manufacturing instruments with improved fatigue resistance by subjecting the nitinol to a strain and thermal cycling process (between a cold bath of about 0–10 °C and a hot bath of about 100–180 °C for a minimum of about five cycles)	Improve fatigue resistance	2007	Berendt [392]
A system of a multitude SMA segments, which are linked together but controlled	SMA controller system	2007	Asada et al. [393]

SMA material and process and material improvements (*continued*)

SMA process and material improvements			
Description	Remarks	Year	Inventor/ researcher
separately to generate co-ordinated gross movement as well as independent fine movements with a minimum of complexity			
SMA actuator manufacturing system	Manufacture SMA	2009	Hamaguchi et al. [394]
A range of compositions in the Ni–Ti–Pt SMA for high temperature (above 100 °C), high force, narrow hysteresis and produce a high specific work output	HTSMA	2009	Noebe et al. [242]
A method of forming single crystal thin film SMA by the specific heat treatment of an amorphous sputter deposits. The single crystal SMA exhibits greater recovery, constant force deflection, wider transition temperature range and a narrow loading hysteresis	Thin film SMA forming	2009	Johnson [171]
Shape-setting methods for the fabrication of devices made from single crystal Cu–Ni–Al SMA	Cu–Ni–Al SMA shape-setting method	2009	Johnson et al. [395]
“Hyperelastic” SMA single crystal material which is capable of a recoverable strain of 9% (and in exceptional circumstances as large as 22%). These SMAs exhibit no creep or gradual change during repeated cycling because there are no grain boundaries (Cu–Al–X, where X may be Ni, Fe, Co or Mn)	Hyperelastic SMA	2010	Johnson et al. [396]
A ferrous-based SMA known as NCATB alloy has exhibited maximum superelastic strain of about 13.5% and a very high tensile strength of 1200 MPa	Fe-based SMA. Higher strain and strength	2010	Tanaka et al. [313]
Adding cobalt (Co) as ternary elements into NiTi alloys has proven to increase the plateau stress (i.e. ‘stiffness’) of NiTi alloys by 35%, which is important for medical applications	NiTiCo SMA. Increase stiffness of material	2011	Fasching et al. [397]
‘Programming’ process to enable NiTi SMA to perform Triple-SME	Transform OWSME to Triple-SME	2012	Tang et al. [311]
Researchers from University of Western Australia and Gyeongsang National University developed novel methods of preparing single material NiTi SMA to exhibit “four-way” SME via laser annealing and thermal diffusion annealing	Four ways SME NiTi SMA	2012	Meng et al. [398]
NiMn FSMA can be used for actuation, sensing, magnetic refrigeration, active tissue scaffolding and energy harvesting	FSMA	2013	CRDF Global [314]
Multiple shapes of SMA at various temperatures could be achieved by using a new process, namely Multiple Memory Material Technology (MMMT). These	Multiple Shapes SMA	2013	Khan et al. [310]

(continued on next page)

SMA material and process and material improvements (*continued*)

SMA process and material improvements Description	Remarks	Year	Inventor/ researcher
new breeds of smart materials are called Multiple Memory Materials (MMMs)			
A single-crystal SMA (SCSMA) made of CuAlNi that exhibits significantly better performance over NiTi SMA. This new alloy is capable to operate at more than 200 °C, fully resettable (repeatable with 100% recovery), may be operable for up to one million of cycles, provide significantly greater strain recovery (9%), wider transition temperature range (−270 °C to +250 °C), and very narrow loading hysteresis (<25 °C)	CuAlNi SCSMA. Better performance than NiTi SMA	2013	TiNi Aerospace [312]

Appendix E. Miscellaneous SMA applications

Miscellaneous Description	Remarks	Year	Inventor/ researcher
An invention for a subterranean wellbore tool with SMA actuator	Wellbore tool	1993	Ross [399,400]
A refreshable braille cell display uses a single moving part per tactile element (with SMA actuators) gives users access to full computer generated screens of text and graphical information in real time	Braille	1997	Decker [401]
A golf ball with SMA layer to provide an effect of tightening the core, thus improving the ball's resiliency, resulting an increased travel distance	Golf ball	1999	Maehara et al. [328]
A control tab installed at the trailing edge of the stern planes of a submarine, by a remote control actuator system with two SMA cables	Submarine	2000	Goldstein and Nguyen [402]
A striking face for golf clubs with SMA material with capability to change patterns to create a sweet spot on the striking face of the club	Golf club	2001	Krumme and Frank [330]
Application of SMA as ejecting drops mechanism	Ink jet printer	2003	Siverbrook [403]
To recover surface damage from mechanical contact by activating a SMA surface either as a complete entity or as a protective coating	Material surface	2006	Cheng et al. [404]
SMA actuator to vary the exit nozzle fan flaps of a gas turbine engine to improve performance and efficiency	Gas turbine	2006	Rey et al. [405]
The invention of a two-way actuated shape memory composite material (SMA is bonded to another elastic metal)	SMA composites	2007	Walak [406]
A cold-launch system with one or more stages of SMA actuators to accelerate material to a required launch velocity	Cold-launcher	2008	Shah et al. [407]
SMA underwire assembly for use in a brassiere	Fashion/ brassiere	2009	Fan et al. [408]
SMA elements to modify blade surface of wind turbines to improve aerodynamics	Wind turbine	2012	Smith et al. [409]
SMA to automatically adjust the jet nozzle of an air-condition system	Air-condition jet nozzle	2013	TROX [410]

Appendix F. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.matdes.2013.11.084.

References

[1] Borroni-Bird CE. Smarter vehicles. Smart structures and materials 1997: industrial and commercial applications of smart structures technologies. San Diego, CA; 1997.

[2] Butera F, Coda A, Vergani G. Shape memory actuators for automotive applications. In: Nanotec IT newsletter. Roma: AIRI/nanotec IT; 2007. p. 12–6.

[3] GM. Chevrolet Debuts Lightweight 'Smart Material' on corvette. General Motors News; 2013.

[4] Ölander A. An electrochemical investigation of solid cadmium-gold alloys. Am Chem Soc 1932;54:3819–33.

[5] Vernon LB, Vernon HM. Process of manufacturing articles of thermoplastic synthetic resins. In: US Patent 2234993; 1941.
[6] Buehler WJ, Gilfrich JV, Wiley RC. Effect of low-temperature phase changes on the mechanical properties of alloys near composition TiNi. Appl Phys 1963;34:1475–7.
[7] Kauffman G, Mayo I. The story of Nitinol: the serendipitous discovery of the memory metal and its applications. Chem Educator 1997;2:1–21.
[8] Wu MH, Schetky LM. Industrial applications for shape memory alloys. In: International conference on shape memory and superelastic technologies. Pacific Grove, California, USA; 2000. p. 171–82.
[9] Zider RB, Krumme JF. Eyeglass frame including shape-memory elements. In: US Patents 4772112. Menlo Park, California, USA: CVI/Beta Ventures, Inc.; 1988.
[10] Hautcoeur A, Eberthardt A. Eyeglass frame with very high recoverable deformability. In: US Patents 5640217. Fergaflex, Inc., Montreal, Canada; 1997.
[11] Furuya Y. Design and material evaluation of shape memory composites. Intell Mater Syst Struct 1996;7:321–30.
[12] Leo DJ, Weddle C, Naganathan G, Buckley SJ. Vehicular applications of smart material systems. 1998:106–16.
[13] Stoeckel D. Shape memory actuators for automotive applications. Mater Des 1990;11:302–7.
[14] Bil C, Massey K, Abdullah EJ. Wing morphing control with shape memory alloy actuators. J Intell Mater Syst Struct 2013;24:879–98.
[15] Hartl DJ, Lagoudas DC. Aerospace applications of shape memory alloys. Proc Inst Mech Eng, Part G: J Aerospace Eng. 2007;221:535–52.
[16] Humbeeck JV. Non-medical applications of shape memory alloys. Mater Sci Eng, A 1999:134–48.
[17] McDonald Schetky L. Shape memory alloy applications in space systems. Mater Des 1991;12:29–32.
[18] Sun L, Huang WM, Ding Z, Zhao Y, Wang CC, Purnawali H, et al. Stimulus-responsive shape memory materials: a review. Mater Des 2012;33:577–640.
[19] Kohl M. Shape memory microactuators (microtechnology and MEMS). 1 ed. Heidelberg: Springer-Verlag Berlin; 2010.
[20] Kahny H, Huff MA, Heuer AH. The TiNi shape-memory alloy and its applications for MEMS. Micromech Microeng 1998;8:213–21.
[21] Fujita H, Toshiyoshi H. Micro actuators and their applications. Microelectron J 1998;29:637–40.
[22] Kheirikhah M, Rabiee S, Edalat M. A review of shape memory alloy actuators in robotics. In: Ruiz-del-Solar J, Chown E, Plöger P, editors. RoboCup 2010: Robot Soccer World Cup XIV. Berlin Heidelberg: Springer; 2011. p. 206–17.
[23] Sreekumar M, Nagarajan T, Singaperumal M, Zoppi M, Molfino R. Critical review of current trends in shape memory alloy actuators for intelligent robots. Ind Rob.: Int J 2007;34:285–94.
[24] Furuya Y, Shimada H. Shape memory actuators for robotic applications. Mater Des 1991;12:21–8.
[25] Petrini L, Migliavacca F. Biomedical applications of shape memory alloys. J Metall 2011;2011.
[26] Song C. History and current situation of shape memory alloys devices for minimally invasive surgery. Open Med Dev J 2010;2:24–31.
[27] Morgan NB. Medical shape memory alloy applications – the market and its products. Mater Sci Eng, A 2004;378:16–23.
[28] Machado LG, Savi MA. Medical applications of shape memory alloys. Braz J Med Biol Res 2003;36:683–91.
[29] Mantovani D. Shape memory alloys: properties and biomedical applications. JOM 2000;52:36–44.
[30] Duerig T, Pelton A, Stöckel D. An overview of nitinol medical applications. Mater Sci Eng, A 1999;273–275:149–60.
[31] Langenhove LV, Hertleer C. Smart clothing: a new life. Int J Clothing Sci Technol 2004;16:63–72.
[32] Wilkes K, Liaw P, Wilkes K. The fatigue behavior of shape-memory alloys. JOM 2000;52:45–51.
[33] Cederström J, Van Humbeeck J. Relationship between shape memory material properties and applications. J Phys IV France 1995;05. C2-335-C2-41.
[34] Hodgson DE, Wu MH, Biermann RJ. Shape memory alloys. ASM Handbook: ASM International 1990:897–902.
[35] Huang W. On the selection of shape memory alloys for actuators. Mater Des 2002;23:11–9.
[36] Sun L, Huang WM. Nature of the multistage transformation in shape memory alloys upon heating. Met Sci Heat Treat 2009;51:573–8.
[37] Mihálcz I. Fundamental characteristics and design method for nickel-titanium shape memory alloy. Periodica Polytechnica Ser Mech Eng 2001;45:75–86.
[38] Lagoudas DC. Shape memory alloys: modeling and engineering applications. 1st ed. New York: Springer; 2010.
[39] Duerig TW, Pelton AR. Ti–Ni shape memory alloys. Materials Properties Handbook, Titanium Alloys, Materials Park, OH: American Society for Metals; 1994. p. 1035–48.
[40] Huang W, Toh W. Training two-way shape memory alloy by reheat treatment. Mater Sci Lett 2000;19:1549–50.
[41] Perkins J, Hodgson D. The two-way shape memory effect. Butterworth-Heinemann, Engineering Aspects of Shape, Memory Alloys(UK), 1990; 1990. p. 195–206.
[42] Schroeder TA, Wayman CM. The two-way shape memory effect and other "training" phenomena in Cu–Zn single crystals. Scr Metall 1977;11:225–30.
[43] Ma J, Karaman I, Noebe RD. High temperature shape memory alloys. Int Mater Rev 2010;55:257–315.
[44] Stöckel D. The shape memory effect: phenomenon, alloys, applications. In: Shape memory alloys for power systems (EPRI); 1995. p. 1–13.
[45] Huang W. Two-way behaviour of a nitinol torsion bar. Smart structures and materials 1999: 3–4 March, 1999, Newport Beach, California Smart materials technologies, vol. 3675. 1999. p. 284.
[46] Otsuka K, Wayman C. Shape memory materials. Cambridge: Cambridge University Press; 1998.
[47] Perkins J, Hodgson D, Duerig TW, Melton KN, Stockel D, Wayman CM. Engineering aspects of shape memory alloys. British Library; 1990. 195.
[48] Stalmans R, Van Humbeeck J, Delaey L. Training and the 2 way memory effect in copper based shape memory alloys. J Phys IV 1991;1:403–8.
[49] Funakubo H, Kennedy JB. Shape memory alloys. In: Gordon and breach, xii+ 275, 15 × 22 cm, illustrated; 1987.
[50] Brailovski V, Prokoshkin S, Terriault P, Trochu F. Shape memory alloys: fundamentals, modeling and applications: Universtié du Québec. École de Technologie Supérieure; 2003.
[51] Delaey L. Diffusionless transformations. Materials Science and Technology: Wiley-VCH Verlag GmbH & Co. KGaA; 2006. p. 587–654.
[52] Otsuka K, Wayman C. Mechanism of shape memory effect and superelasticity. In: Otsuka K, Wayman C, editors. Shape memory materials. Cambridge: Cambridge University Press; 1998. p. 27–48.
[53] Buehler WJ, Wang FE. A summary of recent research on the nitinol alloys and their potential application in ocean engineering. Ocean Eng 1968;1:105–8.
[54] Tadaki T, Otsuka K, Shimizu K. Shape memory alloys. Annu Rev Mater Sci 1988;18:25–45.
[55] Ren X, Otsuka K. Origin of rubber-like behaviour in metal alloys. Nature 1997;389:579–82.
[56] Otsuka K, Ren X. Mechanism of martensite aging effects and new aspects. Mater Sci Eng, A 2001;312:207–18.
[57] Dynalloy Inc., Technical characteristics of Flexinol actuator wires. In: Dynalloy Inc. U, editor. Costa Mesa (CA); 2007. p. 12.
[58] Liu Y. Some factors affecting the transformation hysteresis in shape memory alloys. In: Chen HR, editor. Shape memory alloys: manufacture, properties and applications. Nova Science Publishers; 2010. p. 361–9.
[59] Sreekumar M, Nagarajan T, Singaperumal M. Application of trained NiTi SMA actuators in a spatial compliant mechanism: experimental investigations. Mater Des 2009;30:3020–9.
[60] Mertmann M, Vergani G. Design and application of shape memory actuators. Eur Phys J: Spec Top 2008;158:221–30.
[61] Vaidyanathan R. Shape-memory alloys. Kirk-Othmer Encyclopedia of Chemical Technology: John Wiley & Sons, Inc.; 2000.
[62] Greninger AB, Mooradian VG. Strain Transformation in metastable beta copper–zinc and beta copper–Ti alloys. AIME TRANS 1938;128:337–69.
[63] Kurdjumov GV, Khandros LG. First reports of the thermoelastic behaviour of the martensitic phase of Au–Cd alloys. Doklady Akademii Nauk SSSR 1949;66:211–3.
[64] Chang LC, Read TA. Behavior of the elastic properties of AuCd. Trans Met Soc AIME 1951;191:47.
[65] Abrahamsson P, Bjiimemo R. The need for product design tools in shape memory technology. In: 3rd IUMRS international conference on advanced materials. Sunshine City, Ikebukuro, Tokyo, Japan; 1994. p. 1171–4.
[66] Strittmatter J, Gümpel P. Long-time stability of Ni–Ti-shape memory alloys for automotive safety systems. J Mater Eng Perform 2011;20:506–10.
[67] Butera F. Shape memory actuators for automotive applications. Adv Mater Processes 2008;166:37.
[68] Kumar PK, Lagoudas DC. Introduction to shape memory alloys. In: Shape memory alloys. US: Springer; 2008. p. 1–51.
[69] Johnson AD. State-of-the-art of shape memory actuators. In: 6th international conference on new actuators. Bremen, Germany; 1998.
[70] Baz A, Imam K, McCoy J. Active vibration control of flexible beams using shape memory actuators. J Sound Vib 1990;140:437–56.
[71] Duerig TW, Stockel D, Keeley A. Actuator and work production devices. In: Engineering aspects of shape memory alloys. UK: Butterworth-Heinemann; 1990. p. 181–94.
[72] Hirose S, Ikuta K, Umetani Y. Development of shape-memory alloy actuators. Performance assessment and introduction of a new composing approach. Adv Rob 1988;3:3–16.
[73] Karhu M, Lindroos T. Long-term behaviour of binary Ti–49.7 Ni (at.%) SMA actuators – the fatigue lives and evolution of strains on thermal cycling. Smart Mater Struct 2010;19:115019.
[74] Choon TW, Salleh AS, Jamian S, Ghazai MI. Phase transformation temperatures for shape memory alloy wire. ENFORMATIKA 2007;19:304–7.
[75] Ren J, Liew KM. Meshfree modelling and characterisation of thermomechanical behaviour of NiTi alloys. Eng Anal Boundary Elem 2005;29:29–40.
[76] Wada K, Liu Y. Shape recovery of NiTi shape memory alloy under various pre-strain and constraint conditions. Smart Mater Struct 2005;14:S273.
[77] Wang ZG, Zu XT, Feng XD, Zhu S, Bao JW, Wang LM. Characteristics of two-way shape memory TiNi springs driven by electrical current. Mater Des 2004;25:699–703.
[78] Wang ZG, Zu XT, Feng XD, Lin LB, Zhu S, You LP, et al. Design of TiNi alloy two-way shape memory coil extension spring. Mater Sci Eng: A. 2003;345.
[79] McWilliams A. Smart materials and their applications: technologies and global markets. BCC Research Advanced Materials Report; 2011. p. 161.

[80] Welp EG, Breidert J. Knowledge and method base for shape memory alloys. Materialwiss Werkstofftech 2004;35:294–9.
[81] Zhang C, Zee RH, Thoma PE. Development of Ni-Ti based shape memory alloys for actuation and control. In: Energy Conversion Engineering Conference 1996 (IECEC 96). IEEE; 1996. p. 239–44.
[82] Abrahamsson P, Møster E. Demands on shape memory alloys from the application designer's point of view. J Phys IV France 1997;07. C5-667-C5-72.
[83] Langbein S, Czechowicz A. Adaptive resetting of SMA actuators. J Intell Mater Syst Struct 2012;23:127–34.
[84] Reynaerts D, Brussel HV. Design aspect of shape memory actuators. Mechatronics 1998;8:635–56.
[85] Leary M, Schiavone F, Subic A. Lagging for control of shape memory alloy actuator response time. Mater Des 2010;31:2124–8.
[86] Winzek B, Schmitz S, Rumpf H, Sterzl T, Ralf Hassdorf, Thienhaus S, et al. Recent developments in shape memory thin film technology. Mater Sci Eng: A. 2004;378:40–6.
[87] Ryhänen J, Kallioinen M, Tuukkanen J, Junila J, Niemelä E, Sandvik P, et al. In vivo biocompatibility evaluation of nickel-titanium shape memory metal alloy: muscle and perineural tissue responses and encapsule membrane thickness. Biomed Mater Res 1998;41:481–8.
[88] Richman RH, Rao AS, Kung D. Cavitation erosion of NiTi explosively welded to steel. Wear 1995:181–3 [Part 1:80-5].
[89] Singh JK, Alpas AT. Dry sliding wear mechanisms in a Ti50Ni47Fe3 intermetallic alloy. Wear 1995;181–183:302–11.
[90] Clayton P. Tribological behavior of a titanium-nickel alloy. Wear 1993:162–4 [Part A:202-10].
[91] Lederlé S. Issues in the design of shape memory alloy actuators. USA: Massachusetts Institute of Technology; 2002.
[92] Hunter IW, Hollerbach JM, Ballantyne J. A comparative analysis of actuator technologies for robotics. Rob Rev 1991;2.
[93] Tadesse Y. Electroactive polymer and shape memory alloy actuators in biomimetics and humanoids; 2013. p. 868709–12.
[94] Angioni SL, Meo M, Foreman A. Impact damage resistance and damage suppression properties of shape memory alloys in hybrid composites—a review. Smart Mater Struct 2011;20:013001.
[95] Smith C, Villanueva A, Joshi K, Tadesse Y, Priya S. Working principle of bio-inspired shape memory alloy composite actuators. Smart Mater Struct 2011;20:012001.
[96] Godard OJ, Lagoudas MZ, Lagoudas DC. Design of space systems using shape memory alloys. In: Smart structures and materials: international society for optics and photonics; 2003. p. 545–58.
[97] Saadat S, Salichs J, Noori M, Hou Z, Davoodi H, Bar-on I, et al. An overview of vibration and seismic applications of NiTi shape memory alloy. Smart Mater Struct 2002;11:218.
[98] Waram T. Actuator design using shape memory alloys. 2nd (metric) ed. Hamilton, Ont.: TC Waram; 1993.
[99] Langbein S. Development of standardised and integrated shape memory components in "one-module"-design. In: 8th European symposium on martensitic transformations (ESOMAT 2009). Prague, Czech Republic: EDP Sciences; 2009. p. 1–9.
[100] Ashby F. Materials selection in mechanical design. Elsevier/Butterworth-Heinemann; 2011.
[101] Qiu J, Tani J, Osanai D, Urushiyama Y. High-speed actuation of shape memory alloy. Smart Mater MEMS: Int Soc Opt Photonics 2001:188–97.
[102] Featherstone R, Teh Y. Improving the speed of shape memory alloy actuators by faster electrical heating. In: Ang Jr M, Khatib O, editors. Experimental robotics IX. Berlin Heidelberg: Springer; 2006. p. 67–76.
[103] Chee Siong L, Yokoi H, Arai T. New shape memory alloy actuator: design and application in the prosthetic hand. in: 27th Annual International Conference of the Engineering in Medicine and Biology Society (IEEE-EMBS 2005). Shanghai, China; 2005. p. 6900–3.
[104] An L, Huang WM, Fu YQ, Guo NQ. A note on size effect in actuating NiTi shape memory alloys by electrical current. Mater Des 2008;29:1432–7.
[105] Tadesse Y, Thayer N, Priya S. Tailoring the response time of shape memory alloy wires through active cooling and pre-stress. J Intell Mater Syst Struct 2010;21:19–40.
[106] Gorbet RB, Morris KA, Chau RCC. Mechanism of bandwidth improvement in passively cooled SMA position actuators. Smart Mater Struct 2009;18:095013.
[107] Hisaaki T, Kimio K, Hiroyuki I, Cahoon J. Basic research on shape memory alloy heat engine (output power characteristics and problems in development). JSME Int J 1990;33-I:263–8.
[108] Howe RD, Kontarinis DA, Peine WJ. Shape memory alloy actuator controller design for tactile displays. In: Proceedings of the 34th IEEE Conference on Decision and Control, 1995, vol. 4. 1995. p. 3540–4.
[109] Mascaro SA, Asada HH. Wet shape memory alloy actuators for active vasculated robotic flesh. In: 2003 Proceedings ICRA '03 IEEE International Conference on Robotics and Automation, vol. 1. 2003. p. 282–7.
[110] Wellman PS, Peine WJ, Favalora G, Howe RD. Mechanical design and control of a high-bandwidth shape memory alloy tactile display. In: 1997 International symposium on experimental robotics. Barcelona, Spain; 1997.
[111] Bergamasco M, Salsedo F, Dario P. A linear SMA motor as direct-drive robotic actuator. In: 1989 Proceedings, 1989 IEEE International Conference on Robotics and Automation, vol. 1. 1989. p. 618–23.
[112] Romano R, Tannuri EA. Modeling, control and experimental validation of a novel actuator based on shape memory alloys. Mechatronics 2009;19:1169–77.
[113] Selden B, Cho K, Asada HH. Segmented shape memory alloy actuators using hysteresis loop control. Smart Mater Struct 2006;15:642.
[114] Brian S, Kyujin C, Asada HH. Segmented shape memory alloy actuators using hysteresis loop control. Smart Mater Struct 2006;15:642.
[115] Luo Y, Takagi T, Maruyama S, Yamada M. A shape memory alloy actuator using Peltier modules and R-phase transition. J Intell Mater Syst Struct 2000;11:503–11.
[116] Bhattacharyya A, Lagoudas DC, Wang Y, Kinra VK. On the role of thermoelectric heat transfer in the design of SMA actuators: theoretical modeling and experiment. Smart Mater Struct 1995;4:252.
[117] Shahin AR, Meckl PH, Jones JD, Thrasher MA. Enhanced cooling of shape memory alloy wires using semiconductor 'heat pump' modules. J Intell Mater Syst Struct 1994;5:95–104.
[118] Russell RA, Gorbet RB. Improving the response of SMA actuators. In: 1995 Proceedings, 1995 IEEE International Conference on Robotics and Automation, vol. 3. 1995. p. 2299–304.
[119] Chee Siong L, Yokoi H, Arai T. Improving heat sinking in ambient environment for the shape memory alloy (SMA). In: 2005 (IROS 2005) 2005 IEEE/RSJ international conference on intelligent robots and systems; 2005. p. 3560–5.
[120] Huang S, Leary M, Ataalla T, Probst K, Subic A. Optimisation of Ni-Ti shape memory alloy response time by transient heat transfer analysis. Mater Des 2012;35:655–63.
[121] Ditman JB, Bergman LA, Tsao T-C. The design of extended bandwidth shape memory alloy actuators. J Intell Mater Syst Struct 1996;7:635–45.
[122] Huang S, Jani JM, Leary M, Subic A. The critical and crossover radii on transient heating. Appl Therm Eng 2013;60(1–2):325–34.
[123] Jackson CM, Wagner HM, Wasilewski RJ. 55-Nitinol-The Alloy with a Memory: it's physical metallurgy properties, and applications. NASA SP-5110. NASA Special, Publication; 1972. p. 5110.
[124] Jun HY, Rediniotis OK, Lagoudas DC. Development of a fuel-powered shape memory alloy actuator system: II. Fabrication and testing. Smart Mater Struct 2007;16:S95.
[125] Thrasher MA, Shahin AR, Meckl PH, Jones JD. Efficiency analysis of shape memory alloy actuators. Smart Mater Struct 1994;3:226.
[126] He YJ, Sun QP. Frequency-dependent temperature evolution in NiTi shape memory alloy under cyclic loading. Smart Mater Struct 2010;19:115014.
[127] Erbstoeszer B, Armstrong B, Taya M, Inoue K. Stabilization of the shape memory effect in NiTi: an experimental investigation. Scripta Mater 2000;42:1145–50.
[128] Tang W, Sandström R. Analysis of the influence of cycling on TiNi shape memory alloy properties. Mater Des 1993;14:103–13.
[129] Iadicola MA, Shaw JA. An experimental setup for measuring unstable thermo-mechanical behavior of shape memory alloy wire. J Intell Mater Syst Struct 2002;13:157–66.
[130] Carreras G, Casciati F, Casciati S, Isalgue A, Marzi A, Torra V. Fatigue laboratory tests toward the design of SMA portico-braces. Smart Struct Syst 2011;7:41–57.
[131] Torra V, Auguet C, Isalgue A, Lovey FC, Sepulveda A, Soul H. Metastable effects on martensitic transformation in SMA Part 8 – temperature effects on cycling. J Therm Anal Calorim 2010;102:671–80.
[132] Carreras G, Isalgue A, Torra V, Lovey FC, Soul H. Metastable effects on martensitic transformation in SMA part 5 – Fatigue-life and detailed hysteresis behavior in NiTi and Cu-based alloys. J Therm Anal Calorim 2008;91:575–9.
[133] Isalgue A, Torra V, Yawny A, Lovey FC. Metastable effects on martensitic transformation in SMA part 6 – The Clasius – Clapeyron relationship. J Therm Anal Calorim 2008;91:991–8.
[134] Auguet C, Isalgue A, Torra V, Lovey FC, Pelegrina JL. Metastable effects on martensitic transformation in SMA Part 7 – Aging problems in NiTi. J Therm Anal Calorim 2008;92:63–71.
[135] Auguet C, Isalgue A, Lovey FC, Pelegrina JL, Ruiz S, Torra V. Metastable effects on martensitic transformation in SMA Part 3 – Tentative temperature effects in a NiTi alloy. J Therm Anal Calorim 2007;89:537–42.
[136] Sepulveda A, Muñoz R, Lovey FC, Auguet C, Isalgue A, Torra V. Metastable effects on martensitic transformation in SMA Part 2 – the grain growth effects in Cu–Al–Be alloy. J Therm Anal Calorim 2007;89:101–7.
[137] Auguet C, Isalgué A, Lovey FC, Martorell F, Torra V. Metastable effects on martensitic transformation in SMA Part 4 – theromomechanical properties of CuAlBe and NiTi observations for dampers in family houses. J Therm Anal Calorim 2007;88:537–48.
[138] Torra V, Pelegrina JL, Isalgue A, Lovey FC. Metastable effects on martensitic transformation in SMA Part 1 – recoverable effects by the action of thermodynamic forces in parent phase. J Therm Anal Calorim 2005;81:131–5.
[139] Barnes B, Brei D, Luntz J, LaVigna C. Development of an antagonistic SMA actuator for instar rifle stabilization system. In: Aerospace Division ASoME, editor. International Mechanical Engineering Congress and Exposition 2005 (IMECE 2005). Orlando, FL, USA: American Society of Mechanical Engineers; 2007. p. 333–46.
[140] Fumagalli L, Butera F, Coda A. SmartFlex® NiTi wires for shape memory actuators. J Mater Eng Perform 2009;18:691–5.
[141] Pieczyska E, Tobushi H, Date K, Miyamoto K. Torsional deformation and fatigue properties of TiNi SMA thin strip for rotary driving element. J Solid Mech Mater Eng 2010;4:1306–14.

[142] Tobushi H, Kitamura K, Yoshimi Y, Miyamoto K, Mitsui K. Mechanical properties of cast shape memory alloy for brain spatula. Trans Tech Publ 2011:213–8.
[143] Kitamura K, Tobushi H, Yoshimi Y, Date K, Miyamoto K. Fatigue properties of cast TiNi shape-memory alloy brain spatula. J Solid Mech Mater Eng 2010;4:796–805.
[144] Tamura H, Mitose K, Suzuki Y. Fatigue properties of Ti–Ni shape memory alloy springs. J Phys IV 1995;5. C8-617.
[145] Michael AD. The effect of stress ageing on the properties of shape memory alloys. J Phys IV France 1995;05. C2-349-C2-54.
[146] Thoma PE, Kao M-Y, Schmitz DM. Extended life SMA actuator. US Patents 5419788. USA: Johson Service Co., Milwaukee, USA; 1995. p. 5.
[147] Kuribayashi K. Improvement of the response of an SMA actuator using a temperature sensor. The Int J Rob Res 1991;10:13–20.
[148] Ikuta K, Tsukamoto M, Hirose S. Shape memory alloy servo actuator system with electric resistance feedback and application for active endoscope. In: 1988 IEEE international conference on robotics and automation; 1988. p. 427–30.
[149] Schiedeck F, Mojrzisch S. Design of a robust control strategy for the heating power of shape memory alloy actuators at full contraction based on electric resistance feedback. Smart Mater Struct 2011;20:045002.
[150] Meier H, Czechowicz A, Haberland C, Langbein S. Smart control systems for smart materials. J Mater Eng Perform 2011;20:559–63.
[151] Bergamasco M, Dario P, Salsedo F. Shape memory alloy microactuators. Sens Actuators, A 1990;21:253–7.
[152] Miyazaki S, Mizukoshi K, Ueki T, Sakuma T, Liu Y. Fatigue life of Ti–50 at.% Ni and Ti–40Ni–10Cu (at.%) shape memory alloy wires. Mater Sci Eng, A 1999;273–275:658–63.
[153] Nam TH, Saburi T, Shimizu K. Cu-content dependence of shape memory characteristics in Ti–Ni–Cu alloys. Mater Trans 1990;31:959–67.
[154] Jee KK, Han JH, Kim YB, Lee DH, Jang WY. New method for improving properties of SMA coil springs. Eur Phys J Spec Top 2008;158:261–6.
[155] Porter GA, Liaw PK, Tiegs TN, Wu KH. Fatigue and fracture behavior of nickel–titanium shape-memory alloy reinforced aluminum composites. Mater Sci Eng, A 2001;314:186–93.
[156] Fernandes FMB, Mahesh KK, Paula AdS. Thermomechanical Treatments for Ni–Ti Alloys. In: Fernandes FMB, editor. Shape memory alloys – processing, characterization and applications. InTech; 2013.
[157] Lagoudas DC, Miller DA, Rong L, Kumar PK. Thermomechanical fatigue of shape memory alloys. Smart Mater Struct 2009;18:085021.
[158] Wagner MFX, Nayan N, Ramamurty U. Healing of fatigue damage in NiTi shape memory alloys. J Phys D Appl Phys 2008;41:185408.
[159] Hornbogen E. Review Thermo-mechanical fatigue of shape memory alloys. J Mater Sci 2004;39:385–99.
[160] Firstov GS, Van Humbeeck J, Koval YN. High temperature shape memory alloys problems and prospects. J Intell Mater Syst Struct 2006;17:1041–7.
[161] Beyer J, Mulder JH. Recent developments in high temperature shape memory alloys. In: MRS proceedings. Cambridge Univ Press; 1994.
[162] Kim HY, Satoru H, Kim JI, Hosoda H, Miyazaki S. Mechanical properties and shape memory behavior of Ti–Nb alloys. Mater Trans 2004;45:2443–8.
[163] Noebe R, Gaydosh D, Padula Ii S, Garg A, Biles T, Nathal M. Properties and potential of two (Ni, Pt)Ti alloys for use as high-temperature actuator materials. 2005. p. 364–75.
[164] Lelatko J, Morawiec H. High temperature Cu–Al–Nb – based shape memory alloys. J Phys IV France 2001;11. Pr8-487-Pr8-92.
[165] Tellinen J, Suorsa I, Jääskeläinen A, Aaltio I, Ullakko K. Basic properties of magnetic shape memory actuators. In: Proc of 8th int conf on actuator. Bremen, Germany; 2002. p. 566–9.
[166] Czimmek P. Characterization of magnetic shape memory material. Siemen VDO Automotive Engineering Report; 2004.
[167] Henry CP. Dynamic actuation properties of Ni–Mn–Ga ferromagnetic shape memory alloys. In: Massachusetts Institute of Technology. Massachusetts Institute of Technology; 2002.
[168] Lu J, Liang Z, Qu W. In: Optimal design of rotating actuators made by magnetically controlled shape memory alloy. IEEE; 2009. p. 95–8.
[169] Tsuchiya K, Tsutsumi A, Ohtsuka H, Umemoto M. Modification of Ni–Mn–Ga ferromagnetic shape memory alloy by addition of rare earth elements. Mater Sci Eng, A 2004;378:370–6.
[170] Heczko O, Straka L. Temperature dependence and temperature limits of magnetic shape memory effect. J Appl Phys 2003;94:7139–43.
[171] Johnson AD. Shape memory alloy thin film, method of fabrication, and articles of manufacture. US Patents 7540899B1. TiNi Alloy Company; 2009.
[172] Fu Y, Du H, Huang W, Zhang S, Hu M. TiNi-based thin films in MEMS applications: a review. Sens Actuators, A 2004;112:395–408.
[173] Miyazaki S, Ishida A. Martensitic transformation and shape memory behavior in sputter-deposited TiNi-base thin films. Mater Sci Eng, A 1999;273–275:106–33.
[174] Krulevitch P, Lee AP, Ramsey PB, Trevino JC, Hamilton J, Northrup MA. Thin film shape memory alloy microactuators. J f Microelectromech Syst 1996;5:270–82.
[175] Gabriel KJ, Mehregany M, Walker JA. Thin film shape memory alloy and method for producing. US Patents 4864824. AT&T Bell Laboratories, Murray Hill, NJ, USA; 1989.
[176] Voit W, Ware T, Dasari RR, Smith P, Danz L, Simon D, et al. High-strain shape-memory polymers. Adv Funct Mater 2010;20:162–71.
[177] Ochonski W. Application of shape memory materials in fluid sealing technology. Ind Lubr Tribology 2010;62:99–110.
[178] Liu C, Qin H, Mather PT. Review of progress in shape-memory polymers. J Mater Chem 2007;17:1543–58.
[179] Witold S, Annick M, Shunichi H, L'Hocine Y, Jean R. Medical applications of shape memory polymers. Biomed Mater 2007;2:S23.
[180] Lendlein A, Kelch S. Shape-memory polymers. Angew Chem Int Ed 2002;41:2034–57.
[181] Hu J, Zhu Y, Huang H, Lu J. Recent advances in shape–memory polymers: structure, mechanism, functionality, modeling and applications. Prog Polym Sci 2012;37:1720–63.
[182] Xie T. Tunable polymer multi-shape memory effect. Nature 2010;464:267–70.
[183] Bellin I, Kelch S, Langer R, Lendlein A. Polymeric triple-shape materials. Proc Nat Acad Sci 2006;103:18043–7.
[184] Huang WM, Zhao Y, Wang CC, Ding Z, Purnawali H, Tang C, et al. Thermo/chemo-responsive shape memory effect in polymers: a sketch of working mechanisms, fundamentals and optimization. J Polym Res 2012;19:1–34.
[185] Wang CC, Huang WM, Ding Z, Zhao Y, Purnawali H. Cooling-/water-responsive shape memory hybrids. Compos Sci Technol 2012;72:1178–82.
[186] Liu Y, Lv H, Lan X, Leng J, Du S. Review of electro-active shape-memory polymer composite. Compos Sci Technol 2009;69:2064–8.
[187] Mohr R, Kratz K, Weigel T, Lucka-Gabor M, Moneke M, Lendlein A. Initiation of shape-memory effect by inductive heating of magnetic nanoparticles in thermoplastic polymers. Proc Nat Acad Sci USA 2006;103:3540–5.
[188] Lendlein A, Jiang H, Jünger O, Langer R. Light-induced shape-memory polymers. Nature 2005;434:879–82.
[189] Lv H, Leng J, Liu Y, Du S. Shape-memory polymer in response to solution. Adv Eng Mater 2008;10:592–5.
[190] Leng J, Lv H, Liu Y, Du S. Comment on "Water-driven programable polyurethane shape memory polymer: Demonstration and mechanism" [Appl. Phys. Lett. 86, 114105 (2005)]. Appl Phys Lett 2008;92. 206105-.
[191] Huang WM, Yang B, An L, Li C, Chan YS. Water-driven programmable polyurethane shape memory polymer: demonstration and mechanism. Appl Phys Lett 2005;86. 114105-.
[192] Sun L, Huang WM, Wang CC, Ding Z, Zhao Y, Tang C, et al. Polymeric shape memory materials and actuators. Liq Cryst 2013:1–13.
[193] Ratna D, Karger-Kocsis J. Recent advances in shape memory polymers and composites: a review. J Mater Sci 2008;43:254–69.
[194] Behl M, Lendlein A. Shape-memory polymers. Mater Today 2007;10:20–8.
[195] Hu J. Shape memory polymers and textiles. Cambridge, England: Woodhead Publishing Ltd.; 2007.
[196] Wang CC, Huang WM, Ding Z, Zhao Y, Purnawali H, Zheng LX, et al. Rubber-like shape memory polymeric materials with repeatable thermal-assisted healing function. Smart Mater Struct 2012;21:115010.
[197] Campbell D, Lake MS, Scherbarth MR, Nelson E, Six RW. Elastic memory composite material: an enabling technology for future furlable space structures. In: 46th AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics and materials conference. Austin, TX, USA: AIAA; 2005. p. 6735–43.
[198] Baer G, Wilson TS, Matthews DL, Maitland DJ. Shape-memory behavior of thermally stimulated polyurethane for medical applications. J Appl Polym Sci 2007;103:3882–92.
[199] Gall K, Yakacki CM, Liu Y, Shandas R, Willett N, Anseth KS. Thermomechanics of the shape memory effect in polymers for biomedical applications. J Biomed Mater Res, Part A 2005;73A:339–48.
[200] Hayashi S. Properties and applications of polyurethane-series shape memory polymer. In: Ashida K, Frisch KC, editors. International progress in urethanes. CRC Press; 1993. p. 90–115.
[201] Duerig T. Applications of shape memory. In: Materials science forum. Switzerland: Trans Tech Publication; 1990. p. 679–92.
[202] Wu MH, Schetky LM. Industrial applications for shape memory alloys. In: International conference on shape memory and superelastic technologies, 1st ed. Pacific Grove, California, USA; 2000. p. 171–82.
[203] Stoeckel D, Waram T. Use of Ni–Ti shape memory alloys for thermal sensor-actuators. In: Active and adaptive optical components. San Diego, CA, USA: SPIE; 1992. p. 382–7.
[204] Stoeckel D, Tinschert F. Temperature compensation with thermovariable rate springs in automatic transmissions. SAE technical paper series: SAE; 1991.
[205] Johnson RW, Evans JL, Jacobsen P, Thompson JR, Christopher M. The changing automotive environment: high-temperature electronics. IEEE Trans Electron Pack Manuf 2004;27:164–76.
[206] Neugebauer R, Bucht A, Pagel K, Jung J. Numerical simulation of the activation behavior of thermal shape memory alloys. 2010:76450J-J.
[207] Luchetti T, Zanella A, Biasiotto M, Saccagno A. Electrically actuated antiglare rear-view mirror based on a shape memory alloy actuator. J Mater Eng Perform 2009;18:717–24.
[208] Weber A. Smart materials have a bright future. Adv Assembly Mater Trans Appl 2010.
[209] Browne AL, Alexander PW, Mankame N, Usoro P, Johnson NL, Aase J, et al. SMA heat engines: advancing from a scientific curiosity to a practical reality. In: Smart materials, structures and NDT in Aerospace. Montreal, Quebec, Canada: CANSMART CINDE IZFP; 2011.
[210] Gehm R. Smart materials spur additional design possibilities. In: Automotive engineering international. SAE; 2007. p. 46–7.

[211] Bellini A, Colli M, Dragoni E. Mechatronic design of a shape memory alloy actuator for automotive tumble flaps: a case study. IEEE Trans Industr Electron 2009;56:2644–56.
[212] Strittmatter J, Gümpel P, Zhigang H. Long-time stability of shape memory actuators for pedestrian safety system. J Achiev Mater Manuf Eng 2009;34:23–30.
[213] Williams EA, Shaw G, Elahinia M. Control of an automotive shape memory alloy mirror actuator. Mechatronics 2010;20:527–34.
[214] Zychowicz R. Exterior view mirror for a motor vehicle. US Patents 5166832. Britax (GECO) SA; 1992. p. 5.
[215] Leary M, Huang S, Ataalla T, Baxter A, Subic A. Design of shape memory alloy actuators for direct power by an automotive battery. Materials and Design 2013;43:460–6.
[216] Suzuki M. Rotatable door mirror for a motor vehicle. US Patents 4626085, G02B 7/18 ed. Kabushiki Kaisha Tokai Rika Denki Seisakusho, Aichi, Japan; 1986. p. 9.
[217] Brugger D, Kohl M, Hollenbach U, Kapp A, Stiller C. Ferromagnetic shape memory microscanner system for automotive applications. Int J Appl Electromagnet Mech 2006;23:107–12.
[218] Van Humbeeck J, Chandrasekaran M, Delaey L. Shape memory alloys: materials in action. Endeavour 1991;15:148–54.
[219] Melton KN. General applications of shape memory alloys and smart materials. In: Otsuka K, Wayman CM, editors. Shape memory materials. Cambridge University Press; 1999. p. 220–39.
[220] Singh K, Chopra I. Design of an improved shape memory alloy actuator for rotor blade tracking. In: Smart structures and materials. SPIE; 2002. p. 244–66.
[221] Baumbick RJ. Shape memory alloy actuator. In: US Patents 6151897. The USA as represented by the Administrator of NASA, Washington DC, USA; 2000. p. 7.
[222] Cleveland MA. Apparatus and method for releaseably joining elements. In: US Patent 7367738B2. The Boeing Co.; 2008.
[223] Carpenter B, Lyons J. EO-1 technology validation report. In: Lightweight flexible solar array experiment. NASA/GSFC Last updated: August; 2001. p. 8.
[224] Huettl B, Willey C. Design and development of miniature mechanisms for small spacecraft. In: 14th AIAA/USU small satellite conference. North Logan, UT, USA: Utah State University Research Foundation; 2000. p. 1–14.
[225] Long CFL, Vezain GAP. Single actuation pushing device driven by a material with form memory. In: US Patents 5829253: Societe Nationale Industrielle et Aerospatiale, Paris Cedex, France; 1998. p. 12.
[226] Lortz BK, Tang A. Separation device using a shape memory alloy retainer. In: US Patents 5722709. Hughes Electronics, LA, California, USA; 1998.
[227] Fujun P, Xin-Xiang J, Yan-Ru H, Ng A. Application of shape memory alloy actuators in active shape control of inflatable space structures. In: Aerospace conference, 2005. IEEE; 2005. p. 1–10.
[228] Roh J-H, Han J-H, Lee I. Finite element analysis of adaptive inflatable structures with SMA strip actuator. In: Smart structures and materials 2005: smart structures and integrated systems. SPIE; 2005. p. 460–71.
[229] Prahlad H, Chopra I. Design of a variable twist tilt-rotor blade using shape memory alloy (SMA) actuators. In: 8th Annual international symposium on smart structures and materials. International Society for Optics and Photonics; 2001. p. 46–59.
[230] Birman V. Review of mechanics of shape memory alloy structures. Appl Mech Rev 1997;50:629.
[231] Landis GA, Jenkins PP. Dust on mars: materials adherence experiment results from mars pathfinder. In: Conference record of the twenty-sixth photovoltaic specialists conference, 1997. IEEE; 1997. p. 865–9.
[232] Kudva JN. Overview of the DARPA smart wing project. J Intell Mater Syst Struct 2004;15:261–7.
[233] Pitt D, Dunne J, White E, Garcia E. SAMPSON smart inlet SMA powered adaptive lip design and static test. In: 42nd AIAA structures, structrual dynamics, and materials conference. Seattle, WA, USA; 2001. p. 1–11.
[234] Mieloszyk M, Krawczuk M, Zak A, Ostachowicz W. An adaptive wing for a small-aircraft application with a configuration of fibre Bragg grating sensors. Smart Mater Struct 2010;19:085009.
[235] Sofla AYN, Meguid SA, Tan KT, Yeo WK. Shape morphing of aircraft wing: status and challenges. Mater Des 2010;31:1284–92.
[236] Icardi U, Ferrero L. Preliminary study of an adaptive wing with shape memory alloy torsion actuators. Mater Des 2009;30:4200–10.
[237] Strelec JK, Lagoudas DC, Khan MA, Yen J. Design and implementation of a shape memory alloy actuated reconfigurable airfoil. J Intell Mater Syst Struct 2003;14:257–73.
[238] Oehler SD, Hartl DJ, Lopez R, Malak RJ, Lagoudas DC. Design optimization and uncertainty analysis of SMA morphing structures. Smart Mater Struct 2012;21:094016.
[239] Hartl DJ, Lagoudas DC, Calkins FT, Mabe JH. Use of a Ni60Ti shape memory alloy for active jet engine chevron application: I. Thermomechanical characterization. Smart Mater Struct 2010;19:015020.
[240] Hartl DJ, Mooney JT, Lagoudas DC, Calkins FT, Mabe JH. Use of a Ni60Ti shape memory alloy for active jet engine chevron application: II. Experimentally validated numerical analysis. Smart. Mater Struct 2010;19:015021.
[241] Noebe RD, Quackenbush TR, II SAP. Benchtop demonstration of an adaptive chevron completed using a new high-temperature shape-memory alloy; 2005. p. 140–1.
[242] Noebe RD, Draper SL, Nathal MV, Garg A. High work output Ni–Ti–Pt high temperature shape memory alloys and associated processing methods. In: US Patents 7501032B1. The United states of America, NASA Washington DC, USA; 2009.
[243] Calkins FT, Mabe JH. Shape memory alloy based morphing aerostructures. J Mech Des 2010;132:111012.
[244] Caldwell N, Gutmark E, Ruggeri R. Heat transfer model for blade twist actuator system. J Thermophys Heat Transfer 2007;21:352–60.
[245] Jacot AD, Ruggeri RT, Clingman DJ. Shape memory alloy device and control method. In: US Patents 7037076B2. The Boeing Co.; 2006.
[246] Kennedy DK, Straub FK, Schetky LM, Chaudhry ZA, Roznoy R. Development of an SMA actuator for in-flight rotor blade tracking. 2000:62–75.
[247] Robert GL. Recent developments in smart structures with aeronautical applications. Smart Mater Struct 1997;6:R11.
[248] Testa C, Leone S, Ameduri S, Concilio A. Feasibility study on rotorcraft blade morphing in hovering. 2005:171–82.
[249] Elzey DM, Sofla AYN, Wadley HNG. A bio-inspired high-authority actuator for shape morphing structures. In: Smart structures and materials 2003 – active materials: behavior and mechanics. International Society for Optics and Photonics; 2003. p. 92–100.
[250] Huettl B, Willey CE. Design and development of miniature mechanisms for small spacecraft.
[251] Johnson AD. Non-explosive separation device. In: US Patents 5119555; 1992.
[252] Peffer A, Denoyer K, Fosness E, Sciulli D. Development and transition of low-shock spacecraft release devices. Aerospace conference proceedings, 2000, vol. 4. IEEE; 2000. p. 277–84.
[253] Johnson AD. Non-explosive separation device. In: US Patents 5119555: TiNI Alloy Co., California, USA; 1992. p. 14.
[254] Willey CE, Huettl B, Hill SW. Design and development of a miniature mechanisms tool-kit for micro spacecraft. In: 35th Aerospace mechanisms symposium; 2001.
[255] Lagoudas DC, Machado LG, Lagoudas M. Nonlinear vibration of a one-degree of freedom shape memory alloy oscillator: A numerical-experimental investigation. In: 46th AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics and materials conference. Austin, TX, USA; 2005. p. 1–18.
[256] Ngo E, Northwang WD, Cole MW, Hubbard C, Hirsch G, Mohanchandra KP, et al. Fabrication of active thin films for vibration damping in MEMS devices for the next generation army munition systems. DTIC Document; 2004.
[257] Williams KA, Chiu GT, Bernhard RJ. Controlled continuous tuning of an adaptively tunable vibration absorber incorporating shape memory alloys. 2000:564–75.
[258] Sherwin Y, Ulmer DG. Method for vibration damping using superelastic alloys. In: US Patent 6796408B2. The Boeing Co.; 2004.
[259] Grosskrueger DD, Carpenter BF, Easom BW, Draper JL. Apparatus and associated method for detuning from resonance a structure. In: US Patents 6024347. US006024347A ed: Lockheed Martin Corp., Bathesda, Md, USA; 2000. p. 14.
[260] Renz R, Kramer J. Metallic damping body. In: US Patents 5687958. Mercedes-Benz AG, Germany; 1997. p. 6.
[261] Knowles G, Bird RW. Telescopic wing system. In: US Patent 6834835B1. QorTek Inc.; 2004.
[262] Manzo J, Garcia E, Wickenheiser A, Horner GC. Design of a shape-memory alloy actuated macro-scale morphing aircraft mechanism. 2005:232–40.
[263] Kutlucinar I. Aircraft with shape memory alloys for retractable landing gear. In: US Patent 6938416B1. Emergency Warning Systems Inc.; 2005.
[264] Song G, Ma N. Shape memory alloy actuated adaptive exhaust nozzle for jet engine. In: US Patents 8245516. University of Houston; 2012.
[265] Core RA. Dilating fan duct nozzle. In: US Patent 7716932B2. Spirit AeroSystems Inc.; 2010.
[266] Shmilovich A, Yadlin Y, Smith DM, Clark RW. Integrated engine exhaust systems and methods for drag and thermal stress reduction. In: US Patent 7669785B2. Th Boeing Co.; 2010.
[267] Mons CM. Actuating device, bypass air bleed system equipped therewith, and turbojet engine comprising these. In: US Patents 2009/0056307A1. SNECMA; 2008.
[268] Wood JH. Shape changing structure in a jet engine nacelle nozzle and corresponding jet engine and operating method. In: EP Patent 1,817,489. The Boeing Co.; 2007.
[269] Wood JH, Dunne JP. Morphing structure. In: US Patent 7340883B2. The Boeing Co.; 2008.
[270] Larssen JV, Calkins FT. Deployable Flap Edge Fence. In: US Patents 2010/0219288A1. The Boeing Co.; 2010.
[271] Mabe JH, Calkins FT, Bushnell GS, Bieniawski SR. Aircraft systems with shape memory alloy (SMA) actuators, and associated methods. In: US Patent 7878459B2. The Boeing Co.; 2011.
[272] Widdle RD, Grimshaw MT, Crosson-Elturan KS, Mabe JH, Calkins FT, Gravatt LM, et al. High stiffness shape memory alloy actuated aerostructure. In: US Patent 2011/0030380A1. The Boeing Co.; 2009.
[273] Mani R, Lagoudas DC, Rediniotis OK. MEMS-based active skin for turbulent drag reduction. Smart Struct Mater 2003;2003(5056):9–20.
[274] Mohammad T, Jeng-Jong R, Chuh M. Thermal post-buckling and aeroelastic behaviour of shape memory alloy reinforced plates. Smart Mater Struct 2002;11:297.
[275] Fujita H. Studies of micro actuators in Japan. In: IEEE international conference on robotic automation. Institute of Industrial Science, Tokyo University; 1989. p. 1559–64.
[276] Kuribayashi K. Millimeter size joint actuator using shape memory alloy. In: Micro electro mechanical systems, 1989, proceedings, an investigation of

micro structures, sensors, actuators, machines and robots. IEEE; 1989. p. 139–44.
[277] Caldwell DG, Taylor PM. Artificial muscles as robotic actuators. In: IFAC Robot control conference (Syroc 88). Karlsruhe, Germany 1988. p. 401–6.
[278] Kuribayashi K. A new actuator of a joint mechanism using TiNi alloy wire. Int J Rob Res 1986;4:47–58.
[279] Honma D, Miwa Y, Iguchi. Micro robots and micro mechanisms using shape memory alloy to robotic actuators. Rob Syst 1985;2:3–25.
[280] Tao T, Liang Y-C, Taya M. Bio-inspired actuating system for swimming using shape memory alloy composites. Int J Automat Comput 2006;3:366–73.
[281] Mohamed Ali MS, Takahata K. Frequency-controlled wireless shape-memory-alloy microactuators integrated using an electroplating bonding process. Sens Actuators, A 2010;163:363–72.
[282] Tuna C, Solomon JH, Jones DL, Hartmann MJZ. Object shape recognition with artificial whiskers using tomographic reconstruction. In: 2012 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP); 2012. p. 2537–40.
[283] Stephen JF, George B, Stefan S. Design and fabrication of a bat-inspired flapping-flight platform using shape memory alloy muscles and joints. Smart Mater Struct 2013;22:014011.
[284] Bunget G, Seelecke S. Actuator placement for a bio-inspired bone-joint system based on SMA; 2009. p. 72880L-L-12.
[285] Colorado J, Barrientos A, Rossi C, Breuer KS. Biomechanics of smart wings in a bat robot: morphing wings using SMA actuators. Bioinspiration Biomimetics 2012;7:036006.
[286] Festo. BionicOpter – Inspired by dragonfly flight. Festo; 2013.
[287] Andreasen GF. Method and system for orthodontic moving of teeth. In: US Patents 4037324. A61G 7/00 ed. USA: University of Iowa Research Foundation; 1977. p. 8.
[288] Andreasen GF, Hilleman TB. An evaluation of 55 cobalt substituted Nitinol wire for use in orthodontics. J Am Dental Assoc 1971;82:1373–5.
[289] Oh S-R, Chang S-W, Lee Y, Gu Y, Son W-J, Lee W, et al. A comparison of nickel-titanium rotary instruments manufactured using different methods and cross-sectional areas: ability to resist cyclic fatigue. Oral Sur Oral Med Oral Path Oral Radiol Endodontology 2010;109:622–8.
[290] Dahlgren JM, Gelbart D. System for mechanical adjustment of medical implants. In: US Patent 2009/0076597A12009.
[291] Pfeifer R, Müller CW, Hurschler C, Kaierle S, Wesling V, Haferkamp H. Adaptable orthopedic shape memory implants. Procedia CIRP 2013;5:253–8.
[292] Maynard RS. Distributed activator for a two-dimensional shape memory alloy. In: US Patents 59412491999.
[293] Lim G, Park K, Sugihara M, Minami K, Esashi M. Future of active catheters. Sens Actuators, A 1996;56:113–21.
[294] Dotter CT, Buschmann RW, McKinney MK, Rösch J. Transluminal expandable nitinol coil stent grafting: preliminary report. Radiology 1983;147:259–60.
[295] Terzo G. Taking the pulse of the stent market. in: Investment dealers' digest 2006. p. 12.
[296] Haga Y, Esashi M, Maeda S. Bending, torsional and extending active catheter assembled using electroplating. In: MEMS 2000 the thirteenth annual international conference on 2000 Micro electro mechanical systems; 2000. p. 181–6.
[297] Haga Y, Tanahashi Y, Esashi M. Small diameter active catheter using shape memory alloy. In: The eleventh annual international, workshop on Micro Electro Mechanical Systems, 1998 MEMS 98 Proceedings; 1998. p. 419–24.
[298] Tung AT, Park B-H, Liang DH, Niemeyer G. Laser-machined shape memory alloy sensors for position feedback in active catheters. Sens Actuators, A 2008;147:83–92.
[299] Kim S, Hawkes E, Choy K, Joldaz M, Foleyz J, Wood R. Micro artificial muscle fiber using niti spring for soft robotics. In: IEEE/RSJ international conference on intelligent robots and systems, 2009 (IROS 2009). St. Louis, MO, USA: IEEE; 2009. p. 2228–34.
[300] Stirling L, Yu C-H, Miller J, Hawkes E, Wood R, Goldfield E, et al. Applicability of shape memory alloy wire for an active, soft orthotic. J Mater Eng Perform 2011;20:658–62.
[301] Shiraishi Y, Yambe T, Saijo Y, Sato F, Tanaka A, Yoshizawa M, et al. Morphological approach for the functional improvement of an artificial myocardial assist device using shape memory alloy fibres. In: 29th annual international conference of the IEEE engineering in medicine and biology society, 2007 (EMBS 2007); 2007. p. 3974–7.
[302] Yamada A, Shiraishi Y, Sugai TK, Miura H, Shiga T, Hashem MO, et al. Preliminary design of the mechanical circulation assist device for fontan circulation using shape memory alloy fibers. In: Long M, editor. World congress on medical physics and biomedical Engineering May 26–31, 2012. Beijing, China: Springer Berlin Heidelberg; 2013. p. 119–21.
[303] Pelton AR, Schroeder V, Mitchell MR, Gong X-Y, Barney M, Robertson SW. Fatigue and durability of Nitinol stents. J Mech Behav Biomed Mater 2008;1:153–64.
[304] Allie DE, Hebert CJ, Walker CM. Nitinol stent fractures in the SFA. In: Endovascular today 2004. p. 22–9.
[305] Biesiekierski A, Wang J, Abdel-Hady Gepreel M, Wen C. A new look at biomedical Ti-based shape memory alloys. Acta Biomater 2012;8:1661–9.
[306] Miyazaki S, Kim HY, Hosoda H. Development and characterization of Ni-free Ti-base shape memory and superelastic alloys. Mater Sci Eng, A 2006;438–440:18–24.
[307] Bogue R. Shape-memory materials: a review of technology and applications. Assembly Automation 2009;29:214–9.
[308] Dynalloy. Dynalloy Newsletters; 2007.
[309] Dynalloy. Dynalloy Newsletters; 2006.
[310] Khan MI, Pequegnat A, Zhou YN. Multiple memory shape memory alloys. Adv Eng Mater 2013;15:386–93.
[311] Tang C, Huang WM, Wang CC, Purnawali H. The triple-shape memory effect in NiTi shape memory alloys. Smart Mater Struct 2012;21:085022.
[312] Aerospace T. Single crystal shape memory alloys; 2013.
[313] Tanaka Y, Himuro Y, Kainuma R, Sutou Y, Omori T, Ishida K. Ferrous polycrystalline shape-memory alloy showing huge superelasticity. Science 2010;327:1488–90.
[314] Global C. New nickel manganese shape memory alloy developed. In: Success stories. CRDF Global; 2013.
[315] Niskanen AJ, Laitinen I. Design and simulation of a Magnetic Shape Memory (MSM) alloy energy harvester. Adv Sci Technol 2013;78:58–62.
[316] Ullakko K, Sasaki K, Müllner P. Sensor device. In: US Patent 2013/0091954A1. Boise State University; 2013.
[317] Ma J, Karaman I. Expanding the repertoire of shape memory alloys. Science 2010;327:1468–9.
[318] Raghavan J, Bartkiewicz T, Boyko S, Kupriyanov M, Rajapakse N, Yu B. Damping, tensile, and impact properties of superelastic shape memory alloy (SMA) fiber-reinforced polymer composites. Compos B Eng 2010;41:214–22.
[319] Furuya Y, Sasaki A, Taya M. Enhanced mechanical properties of TiNi shape memory fiber/Al matrix composite. JIM, Mater Trans 1993;34:224–7.
[320] Bidaux J-E, Månson J-A, Gotthardt R. Active stiffening of composite materials by embedded shape-memory-alloy fibres. In: MRS proceedings. Cambridge Univ Press; 1996. p. 107.
[321] Ghosh P, Rao A, Srinivasa AR. Design of multi-state and smart-bias components using Shape Memory Alloy and Shape Memory Polymer composites. Mater Des 2013;44:164–71.
[322] Fulvio P, Francesco C, Michele M, Umberto P. Multifunctional SMArt composite material for in situ NDT/SHM and de-icing. Smart Mater Struct 2012;21:105010.
[323] Qian H, Li H, Song G, Chen H, Ren W, Zhang S. Seismic vibration control of civil structures using shape memory alloys: a review. In: Earth and Space 2010@ sEngineering, science, construction, and operations in challenging environments. ASCE; 2010. p. 3377–95.
[324] Song G, Ma N, Li HN. Applications of shape memory alloys in civil structures. Eng Struct 2006;28:1266–74.
[325] Mirzaeifar R, DesRoches R, Yavari A, Gall K. Coupled thermo-mechanical analysis of shape memory alloy circular bars in pure torsion. Int J Non-Linear Mech 2012;47:118–28.
[326] Janke L, Czaderski C, Motavalli M, Ruth J. Applications of shape memory alloys in civil engineering structures—Overview, limits and new ideas. Mat Struct 2005;38:578–92.
[327] Song G, Patil D, Kocurek C, Bartos J. Applications of shape memory alloys in offshore oil and gas industry: a review. In: Proc earth and space 2010—engineering, science, construction, and operations in challenging environments (Honolulu, HI, USA, 14–17 March 2010); 2010. p. 366.
[328] Maehara K, Chikaraishi T. Golf ball. In: US Patents 5913736A. Bridgestone Sports Co. Ltd., Tokyo, Japan; 1999.
[329] Sahatjian RA. Sports racquet netting. In: US Patents 49095101990.
[330] Krumme JF, Dickinson FC. Golf club head or face. In: US Patents 6277033B1. Pixl Golf Technologies Inc., Palo Alto, CA, USA; 2001.
[331] Descamps O. The application of shape-memory alloys to sculpture. JOM 1991;43. 64–.
[332] Van Humbeeck J. Shape memory materials: state of the art and requirements for future applications. Le J de Phys IV 1997;7. C5-3.
[333] Spaggiari A, Mammano GS, Dragoni E. Optimum mechanical design of binary actuators based on shape memory alloys. In: Berselli G, Vertechy R, Vassura G, editors. Smart actuation and sensing systems – recent advances and future challenges. Croatia: InTech; 2012. p. 716.
[334] Breidert J, Welp E. Actuator development using a knowledge base. In: Proceedings of the 8th international conference on new actuators (ACTUATOR). Bremen, Germany 2002. p. 584–7.
[335] Testing ASf, Materials. In: Annual book of ASTM standards. American Society for Testing and Materials; 1983.
[336] Otsuka K, Ren X. Recent developments in the research of shape memory alloys. Intermetallics 1999;7:511–28.
[337] Kirkby EL, Rule JD, Michaud VJ, Sottos NR, White SR, Månson J-AE. Embedded shape-memory alloy wires for improved performance of self-healing polymers. Adv Funct Mater 2008;18:2253–60.
[338] Murphy EB, Wudl F. The world of smart healable materials. Prog Polym Sci 2010;35:223–51.
[339] Luo X, Mather PT. Shape memory assisted self-healing coating. ACS Macro Letters 2013;2:152–6.
[340] Morgan RK, Yaeger JR. Self-regulated actuator. In: US Patents 4524343, H01H 61/06 ed. Raychem Corporation, Menlo Park, California, USA; 1985. p. 7.
[341] Hosoda Y, Kojima Y, Fujie M, Honma K, Iwamoto T, Nakano Y, et al. Actuator. In: US Patents 4586335, F03G 7/06 ed. Hitachi Ltd., Tokyo, Japan; 1986. p. 5.
[342] Sampson R. Automatic closing activator. In: US Patent 47063301987.
[343] Gabriel KJ, Trimmer WSN, Walker JA. Shape memory alloy actuator. In: US Patents 4700541. American Telephone and Telegraph Company, AT&T Bell Laboratories, Murray Hill, NJ, USA; 1987. p. 6.
[344] Swenson SR. Shape memory bi-directional rotary actuator. In: US Patent 51272281992.

[345] Komatsu K, Mori T, Takinami M. Contraction-extension mechanism type actuator. In: US Patents 5335498, Terumo Kabushiki Kaisha, Tokyo, Japan; 1994.
[346] Mukherjee R, Christian TF. Actuation system for the control of multiple shape memory alloy elements. In: US Patents 5763979. The USA as represented by Secretary of Navy, Washington DC, USA; 1998. p. 7.
[347] Foss Jr RL, Siebrecht WA. Translational actuator. In: US Patents 6006522. Lockheed Martin Corp., Bethesda, Md.; 1999.
[348] Weems W. Constant force spring actuator. In: US Patent 6129181A2000.
[349] Jacot AD, Julien GJ, Clingman DJ. Shape memory rotary actuator. In: US Patent 6065934. The Boeing Co., Seattle, Washington, USA; 2000. p. 22.
[350] Williams PL. Stepper motor with shaped memory alloy rotary-driver. In: US Patents 6242841 B1: Eastman Kodak Co.; 2001.
[351] Homma D. Shape memory alloy actuator and method of designing the same. In: US Patent 6746552B2. Toki Corporation Kabushiki Kaisha; 2004.
[352] Biasiotto M, Butera F, Alacqua S. shape memory bistable actuator. In: US Patent 2005/0195064A1. CRF Societa Consortile per Azioni; 2005.
[353] Gummin MA, Donakowski W, Gaines G. Shape memory alloy actuators. In: US Patents 7256518B22007.
[354] Gummin MA, Donakowski W, Gaines GA. Shape memory alloy actuator. In: US Patents 7021055B22006.
[355] Von Behrens PE, Fairbanks DM. High stroke, highly integrated SMA actuators. In: US Patent 7017345 B2. Alfmeier Prazision AG.; 2006.
[356] Yson AP, Messinger RH. Shape memory alloy linear actuator. In: US Patent 7464548B2. The Boeing Co.; 2008.
[357] Garscha M, Auernhammer H, Engelhardt K. Turn-actuator with tensile element of shape memory alloy. In: US Patents 2008/0271559A1. Alfmeier Prazision AG.; 2008.
[358] Takahashi M. Shape memory alloys actuator. In: US Patent 2009/0302708A1. Olympus Co.; 2009.
[359] Taya M, Wada T, Chen H-h, Kusaka M, Cheng V, Wang C. Torque actuator incorporating shape memory alloy composites. In: US Patent 7810326B2. University of Washington; 2010.
[360] Taya M, Cheng V, Sugandi H, Liang Y, Chen H, Wang C-Y. Actuators based on ferromagnetic shape memory alloy composites. In: US Patent 7688168B2. University of Washington; 2010.
[361] Butera F. Actuator comprising elements made of SMA with broadened range of working temperatures. In: EP Patent 2,171,183. SAES GETTERS S.p.A.; 2010.
[362] Altaii K, Thomas B. Shape memory alloy motor as incorporated into solar tracking mechanism. In: US Patent 7692091B22010.
[363] Yang K. Actuation device having shape memory alloy component. In: US Patent 7795823B2. Chicony Electronics Co.; 2010.
[364] Gao X, Browne AL, Alexander PW, Johnson NL, Brown W. Apparatus and method of controlling phase transformation temperature of a shape memory alloy. In: US Patents 2013/0011806A1. Dynalloy Inc., GM Global Technology Operations LLC; 2013.
[365] Romanelli MJ, Otterstedt PJ. Pre-tensioned shape memory actuator. In: US Patents 4899543. Grumman Aerospace Corp., Bethpage, NY, USA; 1990. p. 15.
[366] Ross RJ. Wedge-set sealing flap for use in subterranean wellbores. In: US Patents 5215145. Baker Hughes Inc., Houston, Texas, USA; 1993. p. 13.
[367] Kennedy JR, Larson Jr DJ. Method of cold working holes using a shape memory alloy tool. In: US Patents 5265456. Grumman Aerospace Corp.; 1993. p. 7.
[368] Porter WW. Electrically-operated heat exchanger release mechanism. In: US Patents 5581441. AT&T Global Information Solutions Co., Dayton, Ohio, USA; 1996. p. 7.
[369] Schron JH, Summers JL. Clamping device. In: EP Patent 834,3801998.
[370] White PM. Stress induced interposed connector. In: US Patent 6257593B12001.
[371] White PM. Stress-induced gasket. In: US Patents 6435519B12002.
[372] Cheng Y-T, Ni W, Ulicny JC. Releasable fastener system. In: US Patent 6766566B2. General Motors Corp.; 2004.
[373] Carman GP, Mitrovic M, Pulliam WJ. Infinitely adjustable engagement system and method. In: US Patent 2006/0110211A12004.
[374] Cheng Y-T, Ni W, Lev LC, Lukitsch MJ, Grummon DS, Weiner AM. Metallic-based adhesion materials. In: US Patent 7005195B2. General Motors Corp.; 2006.
[375] Johnson AD, Bokaie M, Martynov V. Constant load bolt. In: US Patents 2008/0075557A12006.
[376] Rudduck D, Blattmann L, Brown S. Instrument panel. In: WO Patent 2,007,068,034. Telezygology Inc.; 2007.
[377] White PM. Drive shaft coupling. In: US Patents 7407440B2. Precimed S.A.; 2008.
[378] Johnson AD, Bokaie M, Martynov V. Non-explosive releasable coupling device. In: US Patents 7422403B12008.
[379] Rudduck D, Goldspink LR, Ng NA, Blattmann LD, Park JR, Kelliher CG, et al. Fasteners and other assemblies. In: US Patent 7610783B2. Telezygology Inc.; 2009.
[380] Johnson NL, Browne AL, Strom KA, Brei D, Barnes BM, Luntz JE. Ratchet reset mechanism. In: US Patents 7963360B2. GM Global Technology Operations, Inc.; 2011.
[381] Homma D. Valve driven by shape memory alloy. In: US Patent 4973024A. Toki Corporation Kabushiki Kaisha; 1990.
[382] Coffee CL. Linearly actuated valve. In: US Patents 5211371. Advanced Control Technologies, Inc., Indianapolis, Ind.; 1993. p. 10.
[383] Hines A, Gausman TJ, Glime WH, Hill SH, Rigsby BS. Shape memory alloy actuated fluid control valve. In: US Patents 6247678B1. Swagelok Co.; 2001.
[384] Morehead JH, Harrington HE. Thermally-actuated press brake tool holder technology. In: US Patent 7296457B2. Wilson Tool International Inc.; 2007.
[385] Browne AL, Buravalla VR, Johnson NL. Reconfigurable tools and/or dies, reconfigurable inserts for tools and/or dies, and methods of use. In: US Patent 7188498B2. GM Global Technology Operations, Inc.; 2007.
[386] Vasquez JA, Garrod TC. Resettable bi-stable thermal valve. In: US Patent 7424978B2. Honeywell International Inc.; 2008.
[387] MacGregor R, Szilagyi A, Von Behrens PE. Flow control assemblies having integrally formed shape memory alloy actuators. In: US Patent 7350762B2. Alfmeier Prazision AG.; 2008.
[388] Jenko EJ. Method adjustable hot runner assembly seals and tip height using active material elements. In: US Patent 7632450B2. Husky Injection Molding Systems Ltd.; 2009.
[389] Ingram RB. Process for the production of two-way shape memory alloys. In: US Patents 5836066. Innovative Dynamics, Inc., Ithaca, NY, USA; 1998. p. 23.
[390] Carpenter BF, Draper JL. Process for conditioning shape memory alloys. In: US Patents 6149742. Lockheed Martin Corp., Bethesda, Md.; 2000. p. 17.
[391] Ashurst GR. Ambient temperature shape memory alloy actuator. In: US Patent 6427712B1. Robertshaw Controls Co.; 2002.
[392] Berendt CJ. A method of preparing nitinol for use in manufacturing instruments with improved fatigue resistance. In: EP Patent 1,762,633. Sportswire LLC.; 2007.
[393] Asada HH, Cho K-J, Selden B. Shape memory alloy actuator system using segmented binary control. In: US Patents 7188473B1. Harry Haruriko Asada; 2007.
[394] Hamaguchi K, Tanii J, Kosaka A. System and method of manufacturing actuator. In: US Patent 7614228B2. Konica Minolta Holdings Inc.; 2009.
[395] Johnson AD, Bokaie M, Martynov V. Single crystal shape memory alloy devices and methods. In: US Patents 7544257B22009.
[396] Johnson AD, Martynov V, Bokaie MD, Gray GR. Hyperelastic shape setting devices and fabrication methods. In: US Patents 7842143B22010.
[397] Fasching A, Norwich D, Geiser T, Paul G. An Evaluation of a NiTiCo alloy and its suitability for medical device applications. J Mater Eng Perform 2011;20:641–5.
[398] Meng Q, Liu Y, Yang H, Shariat BS, Nam T-h. Functionally graded NiTi strips prepared by laser surface anneal. Acta Mater 2012;60:1658–68.
[399] Ross RJ. Shape-memory actuator for use in subterranean wells. In: US Patents 5199497. Baker Hughes Inc., Houston, Texas, USA; 1993. p. 13.
[400] Ross RJ. Firing mechanism for actuating wellbore tools. In: US Patents 5273116. Baker Hughes Inc., Houston, Texas, USA; 1993. p. 13.
[401] Decker LH. Refreshable braille-cell display implemented with shape memory alloys. In: US Patents 5685721A. American Research Corporation of Virginia; 1997.
[402] Goldstein D, Nguyen TD. Shape memory actuator system. In: US Patents 6041728. The USA as representaed by the Secretary of the Navy, Washington DC, USA; 2000.
[403] Silverbrook K. Shape memory alloy ink jet printing mechanism. In: US Patents 6557977. Silverbrook Research Pty Ltd; 2003.
[404] Cheng Y-T, Ni W, Lukitsch MJ, Weiner AM, Grummon DS. Self-healing tribological surfaces. In: US Patent 7060140B2. General Motors Corp.; 2006.
[405] Rey NM, Miller RM, Tillman TG, Rukus RM, Kettle JL. Variable area nozzle for gas turbine engines driven by shape memory alloy actuators. In: US Patents 7004047 B2. United Technology Corp.; 2006.
[406] Walak S. Two way composite nitinol actuator. In: US Patents 2007/0200656 A12007.
[407] Shah TK, Corboy GW, William Russell Kraft, II. Cold launch system comprising shape-memory alloy actuator. In: US Patents 7464634B1. Lockheed Martin Corp.; 2008.
[408] Fan J, Yu W, Zheng R. Underwire assembly for brassiere, brassiere using the same, and process for producing and wearing the brassiere. In: US Patents 7591707B2. The Hong Kong Polytechnic University; 2009.
[409] Smith JE, Pertl FA, Angle, II, Gerald M, Yarborough CN, Nawrocki AJ, et al. Airfoil for circulation controlled vertical axis wind turbines. In: US Patent 2012/0003090A1. West Virginia University; 2012.
[410] GmbH T. TROX TJN jet nozzles – acoustically and technically optimised. 2013. p. Self-adjusting variant with fast SMA actuator.
[411] Webster PJ, Ziebeck KRA, Town SL, Peak MS. Magnetic order and phase transformation in Ni2MnGa. Philoso Mag B 1984;49:295–310.
[412] Ullakko K, Huang JK, Kantner C, O'Handley RC, Kokorin VV. Large magnetic-field-induced strains in Ni2MnGa single crystals. Appl Phys Lett 1996;69:1966–8.
[413] Ullakko K, Huang JK, Kokorin VV, O'Handley RC. Magnetically controlled shape memory effect in Ni2MnGa intermetallics. Scripta Mater 1997;36:1133–8.
[414] Bigelow G, Padula II S, Garg A, Gaydosh D, Noebe R. Characterization of ternary NiTiPd high-temperature shape-memory alloys under load-biased thermal cycling. Metall Mat Trans A 2010;41:3065–79.
[415] Uchino K. Recent topics of ceramic actuators how to develop new ceramic devices. Ferroelectrics 1989;91:281–92.
[416] Swain MV. Shape memory behaviour in partially stabilized zirconia ceramics; 1986.
[417] Browne AL, Johnson NL. Reversibly opening and closing a grille using active materials. In: US Patents 7498926B2. GM Global Technology Operations Inc.; 2009.

[418] Mc Knight GP, Massey C, Herrera GA, Barvosa-Carter W, Johnson NL, Browne AL. Airflow control devices based on active materials. In: US Patents 7429074B2. General Motors Corp.; 2008.
[419] Aase JH, Browne AL, Johnson NL, Ulicny JC. Airflow control devices based on active materials. In: US Patents 7059664B2. General Motors Corp.; 2006.
[420] Macgregor R, Szilagyi A, Von Behrens P. Flow control assemblies having integrally formed shape memory alloy actuators. WO Patent 2004097218: Nanomuscle Inc.; 2004.
[421] Hashemi M, Schickel D. Actuator system for a lighting system. In: US Patent 8011813B2. Visteon Global Technologies Inc.; 2011.
[422] Browne AL, Aase JH, Johnson NL, Keefe AC. Adaptive head light and lens assemblies. In: US Patent 7275846B2. General Motors Corp.; 2007.
[423] Bohan SM. Shape memory alloy rotary actuator with capacitive position feedback. In: US Patent 7503444B2. BorgWarner Inc.; 2009.
[424] Kutlucinar I. Shape memory alloy actuators for use with repetitive motion devices. In: US Patent 6915633B2. Emergency Warning Systems Inc.; 2005.
[425] Buchanan HC, Victor KR. Windshield wiper with adjustable wiping pressure. In: US Patents 5062175. GM Corp., Ohio, USA; 1991. p. 6.
[426] Shaw G, Prince T, Snyder J, Willett M, Lisy F. Pressure sensor with integrated cooler and methods of using. In: US Patent 7587944B1. Orbital Research Inc.; 2009.
[427] Alacqua S, Capretti G, Biasiotto M, Zanella A. Sunshade device for motor-vehicles, with shape memory actuator. In: US Patent 7823955B2. CRF Societa Consortile per Azioni; 2010.
[428] Lane P. Wind deflector with actuating means for a slidable roof system. In: EP Patent 1,288,048. Prinz & Partner GbR; 2008.
[429] Butera F, Alacqua S, Zanella A. Sunshade unit for motor-vehicles with a shape memory actuator. In: EP Patent 1,726,467. CRF Societa Consortile per Azioni; 2006.
[430] Predki W, Bauer B. Concept of a start-up clutch with nickel-titanium shape memory alloys. Forsch Ingenieurwes 2010;74:41–7.
[431] Browne AL, Stauffer LE, Mathieu RJ, Szczerba JF, Johnson NL. Active material enabled self-actuated devices. In: US Patents 7631915B2. GM Global Technology Operations Inc.; 2009.
[432] Dominique CG. Lock Indicator. In: US Patent 2003/0177974A1. Ford Global Technologies Inc.; 2003.
[433] Dominique CG. Door handle device. In: EP Patent 1,347,131. Ford Global Technologies Inc.; 2003.
[434] Niskanen JD, Daniels AR, Mrkovic D. Vehicle lock controlled by a shape memory alloy actuator. In: US Patents 7364211B2. Intier Automotive Closures Inc.; 2008.
[435] Knebel AM, Salemi MR. Shape memory alloy fuel injector. In: US Patents 6691977B2. Delphi technologies, Inc.; 2004.
[436] Allston BK, Knebel AM, Salemi MR. Method and apparatus for controlling a shape memory alloy fuel injector. In: US Patents 6019113A. GM Corp., Detroit, Michigan, USA; 2000.
[437] Wu T. High pressure fluid passage sealing for internal combustion engine fuel injectors and method of making same. In: US Patents 5862995. Diesel Technology Co., Kentwood, Michigan, USA; 1999.
[438] Kilgore JT, Robinson BS. Fuel system containing a shape memory alloy. In: US Patents 6039030A. Siemens Automotive Corporation; 2000.
[439] Miyazaki S, Onoda M, Okada N, Fujii Y, Kim HY. Piston Ring. In: WO Patent 2,008,016,009. Nippon Piston Ring Co.; 2008.
[440] Brei D, Redmond J, Wilmot NA, Browne AL, Johnson NL, Jones GL. Hood lift mechanisms utilizing active materials and methods of use. In: US Patent 7063377B2. General Motors Corp.; 2006.
[441] Perry PD, Veinotte A. Automotive vapor purge valve using shape memory alloy wire. In: US Patents 7089919B2. Siemens Vdo Automotive Inc.; 2006.
[442] Browne AL, Johnson NL, Sears IG. On demand morphable automotive body moldings and surfaces. In: US Patents 7997632B2. GM Global Technology Operations, Inc.; 2011.
[443] Browne AL, Johnson NL, Kramarczyk MA. Tunable, healable vehicle impact devices. In: US Patent 7029044B2. General Motors Corp.; 2006.
[444] Browne AL, Johnson NL. Energy absorbing assembly and methods for operating the same. In: US Patents 6910714B2. General Motors Corp.; 2005.
[445] Choi JY. Exterior airbag cushion for vehicle and device having the same. In: US Patents. Hyundai Motor Company, Seoul (KR) Kia Motors Corp., Seoul (KR); 2011.
[446] Jones SD, Campbell JP, Janmey RM. Battery fluid manager using shape memory alloy components with different actuation temperatures. In: US Patents 7833649B2. Eveready Battery Company, Inc., St. Louis, MO (US); 2010.
[447] Rober KB, Browne AL, Johnson NL, Aase JH. Reversibly deployable air dam. In: US Patents 7686382B2. GM Global Technology Operations, Inc.; 2010.
[448] Mitteer DM. Shifter with actuator incorporating shape memory alloy. In: US Patent 7814810B2. Grand Haven Stamped Products, JSJ Corp.; 2010.
[449] Browne AL, Johnson NL, Mankame ND, Barvosa-carter W, Bucknor NK, Henry CP, et al. Active material based bodies for varying frictional force levels at the interface between two surfaces. In: US Patent 2009/0045042A1. GM Global Technology Operations Inc.; 2009.
[450] Browne AL, Johnson NL, Rober KB, Voss MA, Juechter TJ, Moss ED. Reversibly deployable spoiler. In: US Patents US007607717B2. GM Global Technology Operations Inc.; 2009.
[451] Browne AL, Johnson NL, Chernoff AB, Kramarczyk MA, Ukpai UI, Ulicny JC, et al. Active material based concealment assemblies. In: US Patent 7900986B2. GM Global Technology Operations Inc.; 2011.
[452] Browne AL, Mankame ND, Johnson NL, Keefe AC. Panels having active material based fold lines. In: US Patents 7284786B2. GM Global Technology Operations, Inc.; 2007.
[453] Yang R-J, Le JJ, Chou C, Tzou H-S. Automotive vehicle with structural panel having selectively deployable shape memory alloy elements. In: US Patent 7278679 B2. Ford Global Technologies LLC.; 2007.
[454] Browne AL, Johnson NL, Mankame ND, Ulicny JC, Jones GL, O'Kane JC. Customizable strut assemblies and articles that employ the same. In: US Patent 2005/0199455A1. General Motors Corp.; 2005.
[455] Zimmer G, Zimmer M. Frictional blocking device comprising an actuator. In: WO Patent 2006/063566A12006.
[456] Oku M. Pneumatic radial tire with belt cords having at least one shape-memory alloy filament. In: US Patent 5242002. Sumitomo Rubber Industries Ltd.; 1993.
[457] Alexander PW, Brown JH, Zolno A. Active material head restraint assembly. In: US Patents 7963600B2. GM Global Technology Operations LLC; 2011.
[458] Lawall JP, McQueen DK, Johnson NL, Browne AL, Alexander PW. Recliner release actuation through active materials. In: US Patent 7931337B2. GM Global Technology Operations Inc.; 2011.
[459] Browne AL, Johnson NL, Zavattieri PD, Ukpai UI, Ulicny JC, Cafeo JA, et al. Active material based conformable and reconfigurable seats. In: US Patent 7758121B2. GM Global Technology Operations, Inc.; 2010.
[460] Gandhi UN. Seat assemblies for vehicles. In: US Patent 7729828B2. Toyota Motor Engineering & Manufacturing North America Inc.; 2010.
[461] Kennedy KR, Nathan JF, Hanlon SR, Maue HW. Smartfold electronic actuation. In: US Patent 7775596B2. Lear Corp.; 2010.
[462] Browne AL, Johnson NL, Khoury JY, Alexander PW, Carpenter MG. Active material actuated headrest assemblies. In: US Patents 7556313B2. GM Global Technology Operations Inc.; 2009.
[463] Asada HH, Cho K-J, Roy B. Rapid heating, cooling and massaging for car seats using integrated shape memory alloy actuators and thermoelectric devices. In: US Patents 2005/0253425A1. Massachussets Institute of Technology; 2005.
[464] Gheorghita V, Gümpel P, Strittmatter J, Anghel C, Heitz T, Senn M. Using Shape memory alloys in automotive safety systems. In: Proceedings of the FISITA 2012 World Automotive Congress. Berlin Heidelberg: Springer; 2013. p. 909–17.
[465] Lawall JP, McQueen DK, Morris SE, Browne AL, Johnson NL, Thomas SD, et al. Airbag system. In: US Patents. GM Global Technology Operations, Inc., Detroit, MI (US); 2010.
[466] Melz T, Seipel B, Sielhorst B, Zimmerman E. Device for increasing occupant protection in a motor vehicle during a lateral impact. In: US Patent 7905517B2. Fraunhofer Gesellschaft; 2011.
[467] Balta JA, Simpson J, Michaud V, Månson JAE, Schrooten J. Embedded shape memory alloys confer aerodynamic profile adaptivity. Smart Mater Bull 2001;2001:8–12.
[468] Dunne JP, Hopkins MA, Baumann EW, Pitt DM, White EV. Overview of the SAMPSON smart inlet. In: 6th Annual International symposium on smart structures and materials conference 1999. p. 1–5.
[469] Geraci F, Cooper JE, Amprikidis M. Development of smart vortex generators. Smart Struct Mater 2003;2003(5056):1–8.
[470] Nam C, Chattopadhyay A, Kim Y. Application of shape memory alloy (SMA) spars for aircraft maneuver enhancement. p. 226–36.
[471] Kate M, Bettencourt G, Marquis J, Gerratt A, Fallon P, Kierstead B, et al. SoftBot: A soft-material flexible robot based on caterpillar biomechanics. Tufts University, Medford, MA; 2008.
[472] Lee S-K, Kim B. Design parametric study based fabrication and evaluation of in-pipe moving mechanism using shape memory alloy actuators. J Mech Sci Technol 2008;22:96–102.
[473] Menciassi A, Accoto D, Gorini S, Dario P. Development of a biomimetic miniature robotic crawler. Auton Rob 2006;21:155–63.
[474] Gambao E, Hernando M, Brunete A. Multiconfigurable inspection robots for low diameter canalizations. Bulletin22nd International Symposium on Automation and Robotics in Construction (ISARC 2005). Ferrara Italy; 2005.
[475] Huitao Y, Peisun M, Chongzhen C. A novel in-pipe worming robot based on SMA. In: 2005 IEEE International Conference Mechatronics and Automation, vol. 2. 2005. p. 923–7.
[476] Shiotsu A, Yamanaka M, Matsuyama Y, Nakanishi H, Hara Y, Tsuboi T, et al. Crawling and jumping soft robot KOHARO. In: 36th International Symposium on Robotics (ISR 2005). Tokyo, Japan; 2005.
[477] Liu CY, Liao WH. A snake robot using shape memory alloys. In: 2004 ROBIO 2004 IEEE International Conference on Robotics and Biomimetics; 2004. p. 601–5.
[478] Young Pyo L, Byungkyu K, Moon Gu L, Jong-Oh P. Locomotive mechanism design and fabrication of biomimetic micro robot using shape memory alloy. In: 2004 Proceedings ICRA '04 2004 IEEE international conference on robotics and automation, vol. 5. 2004. p. 5007–12.
[479] Menciassi A, Gorini S, Pernorio G, Dario P. A SMA actuated artificial earthworm. In: 2004 Proceedings ICRA '04 2004 IEEE international conference on robotics and automation, vol. 4. 2004. p. 3282–7
[480] Cepolina F, Michelini RC. Robots in medicine: a survey of in-body nursing aids – introductory overview and concept design hints. In: 35th international symposium on robotics 2004 (ISR2004). Paris, France; 2004.
[481] Z-n Mi, Z-b Gong, J-w Qian, Z-w Mi, L-y Shen. Study on moving principle of colonoscopic robot. J Shanghai Univ 2001;5:143–6.

[482] Reynaerts D, Peirs J, Van Brussel H. Design of a shape memory actuated gastro-intestinal intervention system. In: 5th International conference on new actuators. Breemen, Germany; 1996. p. 409–12.
[483] Berry M, Garcia E. Bio-inspired shape memory alloy actuated hexapod robot; 2008:69281M-M.
[484] Hoover AM, Steltz E, Fearing RS. RoACH: An autonomous 2.4 g crawling hexapod robot. In: IEEE/RSJ international conference on intelligent robots and systems 2008 (IROS 2008); 2008. p. 26–33.
[485] Sugiyama Y, Hirai S. Crawling and jumping by a deformable robot. Int J Rob Res 2006;25:603–20.
[486] Nishida M, Tanaka K, Wang HO. Development and control of a micro biped walking robot using shape memory alloys. In: 2006 ICRA 2006 proceedings 2006 IEEE international conference on robotics and automation; 2006. p. 1604–9.
[487] Chang-jun Q, Pei-sun M, Qin Y. A prototype micro-wheeled-robot using SMA actuator. Sens Actuators, A 2004;113:94–9.
[488] Bundhoo V, Haslam E, Birch B, Park EJ. A shape memory alloy-based tendon-driven actuation system for biomimetic artificial fingers, part I: design and evaluation. Robotica 2009;27:131–46.
[489] Andrianesis K, Tzes A. Design of an anthropomorphic prosthetic hand driven by Shape Memory Alloy actuators. In: 2008 BioRob 2008 2nd IEEE RAS & EMBS international conference on biomedical robotics and biomechatronics; 2008. p. 517–22.
[490] Price AD, Jnifene A, Naguib HE. Design and control of a shape memory alloy based dexterous robot hand. Smart Mater Struct 2007;16:1401.
[491] O'toole KT, McGrath MM. Mechanical design and theoretical analysis of a four fingered prosthetic hand incorporating embedded SMA bundle actuators. World Academy of Science, Engineering and Technology; 2007.
[492] Maeno T, Hino T. Miniature five-fingered robot hand driven by shape memory alloy actuators. In: 12th IASTED international conference on robotics and applications (IASTED) 2006. Honolulu, Hawaii, USA; 2006.
[493] Hino T, Maeno T. Development of a miniature robot finger with a variable stiffness mechanism using shape memory alloy. 2004.
[494] De Laurentis KJ, Mavroidis C. Mechanical design of a shape memory alloy actuated prosthetic hand. Technol Health Care 2002;10:91–106.
[495] Trimmer BA, Takesian A, Sweet B, Rogers CB, Hake DC, Rogers DJ. Caterpillar locomotion: a new model for soft-bodied climbing and burrowing robots. In: 7th international symposium on technology and mine problem. Monterey, California, USA; 2006.
[496] Menon C, Sitti M. Biologically inspired adhesion based surface climbing robots. In: 2005 ICRA 2005 Proceedings of the 2005 IEEE international conference on robotics and automation; 2005. p. 2715–20.
[497] Hong D, Priya S. Twelve degree of freedom baby humanoid head using shape memory alloy actuators. J Mech 2011;3. 011008-1.
[498] Hara F, Akazawa H, Kobayashi H. Realistic facial expressions by SMA driven face robot. In: 2001 Proceedings 10th IEEE international, workshop on robot and human interactive communication; 2001. p. 504–11.
[499] Alex V, Colin S, Shashank P. A biomimetic robotic jellyfish (Robojelly) actuated by shape memory alloy composite actuators. Bioinspiration Biomimetics. 2011;6:036004.
[500] Liwei S, Shuxiang G, Asaka K. A novel jellyfish-like biomimetic microrobot. In: 2010 IEEE/ICME International Conference on Complex Medical Engineering (CME); 2010. p. 277–81.
[501] Kyu-Jin C, Hawkes E, Quinn C, Wood RJ. Design, fabrication and analysis of a body-caudal fin propulsion system for a microrobotic fish. In: 2008 ICRA 2008 IEEE international conference on Robotics and Automation; 2008. p. 706–11.
[502] Zhenlong W, Guanrong H, Yangwei W, Jian L, Wei D. Embedded SMA wire actuated biomimetic fin: a module for biomimetic underwater propulsion. Smart Mater Struct 2008;17:025039.
[503] Ashrafiuon H, Eshraghi M, Elahinia MH. Position control of a three-link shape memory alloy actuated robot. J Intell Mater Syst Struct 2006;17:381–92.
[504] Terauchi M, Zenba K, Shimada A, Fujita M. Controller design on the fingerspelling robot hand using shape memory alloy. IN: 2006 international joint conference SICE-ICASE; 2006. p. 3480–3.
[505] Huang HL, Park S-H, Park J-O. Shape memory alloy based flower robot. In: 39th international symposium on robotics 2008. Seoul, Korea 2008.
[506] Torrisi L. The NiTi superelastic alloy application to the dentistry field. Bio-Med Mater Eng 1999;9:39–47.
[507] Airoldi G, Riva G, Vanelli M. Superelasticity and shape memory effect in NiTi orthodontic wires. J Phys IV 1995;5. C8-1205.
[508] Wang WY, Cooper SG, Eberhardt SC. Use of a nitinol gooseneck snare to open an incompletely expanded over-the-wire stainless steel Greenfield filter. AJR Am J Roentgenol 1999;172:499–500.
[509] Cekirge S, Weiss JP, Foster RG, Neiman HL, McLean GK. Percutaneous retrieval of foreign bodies: experience with the nitinol goose neck snare. J Vasc Interv Radiol 1993;4:805–10.
[510] Idelsohn S, Peña J, Lacroix D, Planell JA, Gil FJ, Arcas A. Continuous mandibular distraction osteogenesis using superelastic shape memory alloy (SMA). J Mater Sci – Mater Med 2004;15:541–6.
[511] Elisa B, Pietro V, Marco Q, Arianna M, Paolo D. Superelastic leg design optimization for an endoscopic capsule with active locomotion. Smart Mater Struct 2009;18:015001.
[512] Sunkil P, Kyo-in K, Seoung Min B, Jeong Youp P, Si Young S, Dongil 'Dan' C. A novel microactuator for microbiopsy in capsular endoscopes. J Micromech Microeng 2008;18:025032.
[513] Smith JM, Stein H. Endoscopic placement of multiple artificial chordae with robotic assistance and nitinol clip fixation. J Thorac Cardiovasc Surg 2008;135:610–4.
[514] Kourambas J, Delvecchio FC, Munver R, Preminger GM. Nitinol stone retrieval-assisted ureteroscopic management of lower pole renal calculi. Urology 2000;56:935–9.
[515] Cuschieri A. Variable curvature shape- memory spatula for laparoscopic surgery. Surg Endosc 1991;5:179–81.
[516] Sattapan B, Palamara JEA, Messer HH. Torque during canal instrumentation using rotary nickel-titanium files. J Endo 2000;26:156–60.
[517] Kujala S, Pajala A, Kallioinen M, Pramila A, Tuukkanen J, Ryhänen J. Biocompatibility and strength properties of nitinol shape memory alloy suture in rabbit tendon. Biomaterials 2004;25:353–8.
[518] Laster Z, MacBean AD, Ayliffe PR, Newlands LC. Fixation of a frontozygomatic fracture with a shape-memory staple. Br J Oral Maxillofac Surg 2001;39:324–5.
[519] Contra R, Dallolio V, Franzoso G, Gastaldi D, Vena P. Biomechanical study of a pathologic lumbar functional spinal unit and a possible surgical treatment through the implant of an interspinous device; 2005.
[520] Wever D, Elstrodt J, Veldhuizen A, v Horn J. Scoliosis correction with shape-memory metal: results of an experimental study. Eur Spine J. 2002;11:100–6.
[521] Sanders JO, Sanders AE, More R, Ashman RB. A preliminary investigation of shape memory alloys in the surgical correction of scoliosis. Spine 1993;18:1640–6.
[522] Sanders AE, Sanders JO, More RB. Nitinol spinal instrumentation and method for surgically treating scoliosis. In: US Patent 52902891994.
[523] Schmerling MA, Wilkov MA, Sanders AE, Woosley JE. Using the shape recovery of nitinol in the Harrington rod treatment of scoliosis. J Biomed Mater Res 1976;10:879–92.
[524] Rossi P, Bezzi M, Rossi M, Adam A, Chetty N, Roddie ME, et al. Metallic stents in malignant biliary obstruction: results of a multicenter European study of 240 patients. J Vasc Interv Radiol 1994;5:279–85.
[525] Davids PHP, Groen AK, Rauws EAJ, Tytgat GNJ, Huibregtse K. Randomised trial of self-expanding metal stents versus polyethylene stents for distal malignant biliary obstruction. Lancet 1992;340:1488–92.
[526] Coati M, Marazzi G, Marini G, Rossi G, Rossi L, Verturini D. Intramedullary nail comprising elements of shape-memory material. In: US Patent 8162942. Orthofix S.r.l.; 2012.
[527] Kujala S, Ryhänen J, Jämsä T, Danilov A, Saaranen J, Pramila A, et al. Bone modeling controlled by a nickel–titanium shape memory alloy intramedullary nail. Biomaterials 2002;23:2535–43.
[528] Kardas D, Rust W, Polley GA, Fabian T. Turning up the volume. ADVANTAGE. 2007:4.
[529] Rajan GP, Eikelboom RH, Anandacoomaraswamy KS, Atlas MD. In vivo performance of the Nitinol shape-memory stapes prosthesis during hearing restoration surgery in otosclerosis: a first report. J Biomed Mater Res B Appl Biomater 2005;72B:305–9.
[530] Yanagihara K, Mizuno H, Wada H, Hitomi S. Tracheal stenosis treated with self-expanding nitinol stent. Ann Thorac Surg 1997;63:1786–9.
[531] Vinograd I, Klin B, Brosh T, Weinberg M, Flomenblit Y, Nevo Z. A new intratracheal stent made from nitinol, an alloy with "shape memory effect". J Thorac Cardiovasc Surg 1994;107:1255–61.
[532] DeLaurentis KJ, Mavroidis C, Pfeiffer C. Development of a shape memory alloy actuated robotic hand. Neural Networks: Citeseer; 2000.
[533] Choudhary RK, Theruvil B, Taylor GR. First metatarsophalangeal joint arthrodesis: a new technique of internal fixation by using memory compression staples. J Foot Ankle Surg 2004;43:312–7.
[534] Song C, Frank T, Cuschieri A. Shape memory alloy clip for compression colonic anastomosis. J Biomech Eng 2005;127:351.
[535] Raju GS, Gajula L. Endoclips for GI endoscopy. Gastrointest Endosc 2004;59:267–79.
[536] Nudelman IL, Fuko V, Greif F, Lelcuk S. Colonic anastomosis with the nickel-titanium temperature-dependent memory-shape device. Am J Surg 2002;183:697–701.
[537] Tack J, Gevers A-M, Rutgeerts P. Self-expandable metallic stents in the palliation of rectosigmoidal carcinoma: a follow-up study. Gastrointest Endosc 1998;48:267–71.
[538] Angueira CE, Kadakia SC. Esophageal stents for inoperable esophageal cancer: which to use? Am J Gastroenterol 1997;92:373.
[539] Pocek M, Maspes F, Masala S, Squillaci E, Assegnati G, Moraldi A, et al. Palliative treatment of neoplastic strictures by self-expanding nitinol Strecker stent. Eur Radiol 1996;6:230–5.
[540] Cwikiel W, Willen R, Stridbeck H, Lillo-Gil R, Von Holstein CS. Self-expanding stent in the treatment of benign esophageal strictures: experimental study in pigs and presentation of clinical cases. Radiology 1993;187:667–71.
[541] Uflacker R, Robison J. Endovascular treatment of abdominal aortic aneurysms: a review. Eur Radiol 2001;11:739–53.
[542] Kaufman JA, Geller SC, Brewster DC, Fan C-M, Cambria RP, LaMuraglia GM, et al. Endovascular repair of abdominal aortic aneurysms. Am J Roentgenol 2000;175:289–302.
[543] Tanaka M, Hirano K, Goto H, Namima T, Uchi K, Jiang ZW, et al. Artificial SMA valve for treatment of urinary incontinence: upgrading of valve and introduction of transcutaneous transformer. Bio-Med Mater Eng 1999;9:97–112.

[544] Chonan S, Jiang ZW, Tani J, Orikasa S, Tanahashi Y, Takagi T, et al. Development of an artificial urethral valve using SMA actuators. Smart Mater Struct 1997;6:410.
[545] Gottfried HW, Gnann R, BrÄNdle E, Bachor R, Gschwend JE, Kleinschmidt K. Treatment of high-risk patients with subvesical obstruction from advanced prostatic carcinoma using a thermosensitive mesh stent. Br J Urol 1997;80:623–7.
[546] Mori K, Okamoto S, Akimoto M. Placement of the urethral stent made of shape memory alloy in management of benign prostatic hypertrophy for debilitated patients. J Urology 1995;154:1065–8.
[547] Yachia D. The use of urethral stents for the treatment of urethral strictures. Annales d'urologie. 4 ed1993. p. 245.
[548] Himpens J. Laparoscopic inguinal hernioplasty. Surg Endosc 1993;7:315–8.
[549] Hausegger KA, Cragg AH, Lammer J, Lafer M, Flückiger F, Klein GE, et al. Iliac artery stent placement: clinical experience with a nitinol stent. Radiology 1994;190:199–202.
[550] Bruckheimer E, Judelman AG, Bruckheimer SD, Tavori I, Naor G, Katzen BT. In vitro evaluation of a retrievable low-profile nitinol vena cava filter. J Vasc Interv Radiol 2003;14:469–74.
[551] Asch MR. Initial experience in humans with a new retrievable inferior vena cava filter1. Radiology 2002;225:835–44.
[552] Engmann E, Asch MR. Clinical experience with the antecubital simon nitinol IVC filter. J Vasc Interv Radiol 1998;9:774–8.
[553] Poletti PA, Becker CD, Prina L, Ruijs P, Bounameaux H, Didier D, et al. Long-term results of the Simon nitinol inferior vena cava filter. Eur Radiol 1998;8:289–94.
[554] Simon M, Kaplow R, Salzman E, Freiman D. A vena cava filter using thermal shape memory alloy experimental aspects. Radiology 1977;125:89–94.
[555] Walsh KP, Maadi IM. The Amplatzer septal occluder. Cardiol Young 2000;10:493–501. M3 - 10.1017/S1047951100008180.
[556] Chan KC, Godman MJ, Walsh K, Wilson N, Redington A, Gibbs JL. Transcatheter closure of atrial septal defect and interatrial communications with a new self expanding nitinol double disc device (Amplatzer septal occluder): multicentre UK experience. Heart 1999;82:300–6.
[557] Thanopoulos MDBD, Laskari MDCV, Tsaousis MDGS, Zarayelyan MDA, Vekiou MDA, Papadopoulos MDGS. Closure of atrial septal defects with the amplatzer occlusion device: preliminary results. J Am Coll Cardiol 1998;31:1110–6.
[558] Khouri RK. Method and apparatus for expanding soft tissue with shape memory alloys. In: US Patent 6478656. Brava LLC.; 2002.
[559] Lewis G. Materials, fluid dynamics, and solid mechanics aspects of coronary artery stents: a state-of-the-art review. J Biomed Mater Res B Appl Biomater 2008;86B:569–90.
[560] Tyagi S, Singh S, Mukhopadhyay S, Kaul UA. Self-and balloon-expandable stent implantation for severe native coarctation of aorta in adults. Am Heart J 2003;146:920–8.
[561] Carter AJ, Scott D, Laird JR, Bailey L, Kovach JA, Hoopes TG, et al. Progressive vascular remodeling and reduced neointimal formation after placement of a thermoelastic self-expanding nitinol stent in an experimental model. Cathet Cardiovasc Diagn 1998;44:193–201.
[562] Levi DS, Kusnezov N, Carman GP. Smart materials applications for pediatric cardiovascular devices. Pediatr Res 2008;63:552–8.
[563] Coats L, Bonhoeffer P. New percutaneous treatments for valve disease. Heart 2007;93:639–44.
[564] Laborde J, Borenstein N, Behr L, Farah B, Fajadet J. Percutaneous implantation of the corevalve aortic valve prosthesis for patients presenting high risk for surgical valve replacement. EuroIntervention: J EuroPCR Collaboration Working Group Interv Cardiol Eur Soc Cardiol 2006;1:472.
[565] Olsen TW, Loftness PE, Erdman AG. Surgical support structure. In: EP Patent 1,986,581B1. University of Minnesota; 2012.