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Review

A review of shape memory alloy research, applications and opportunities

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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.

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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

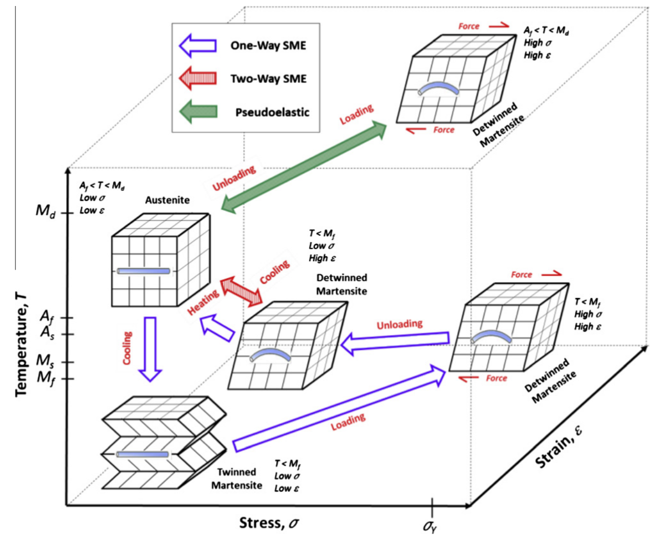


Fig. 1. SMA phases and crystal structures [36–38].

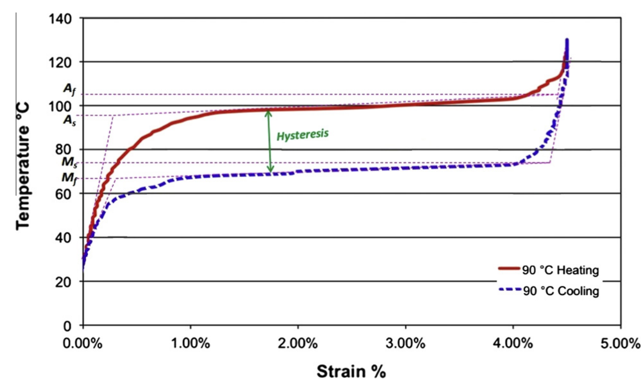


Fig. 2. Flexinol NiTi SMA (HT) phase transformation [57].

[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.

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

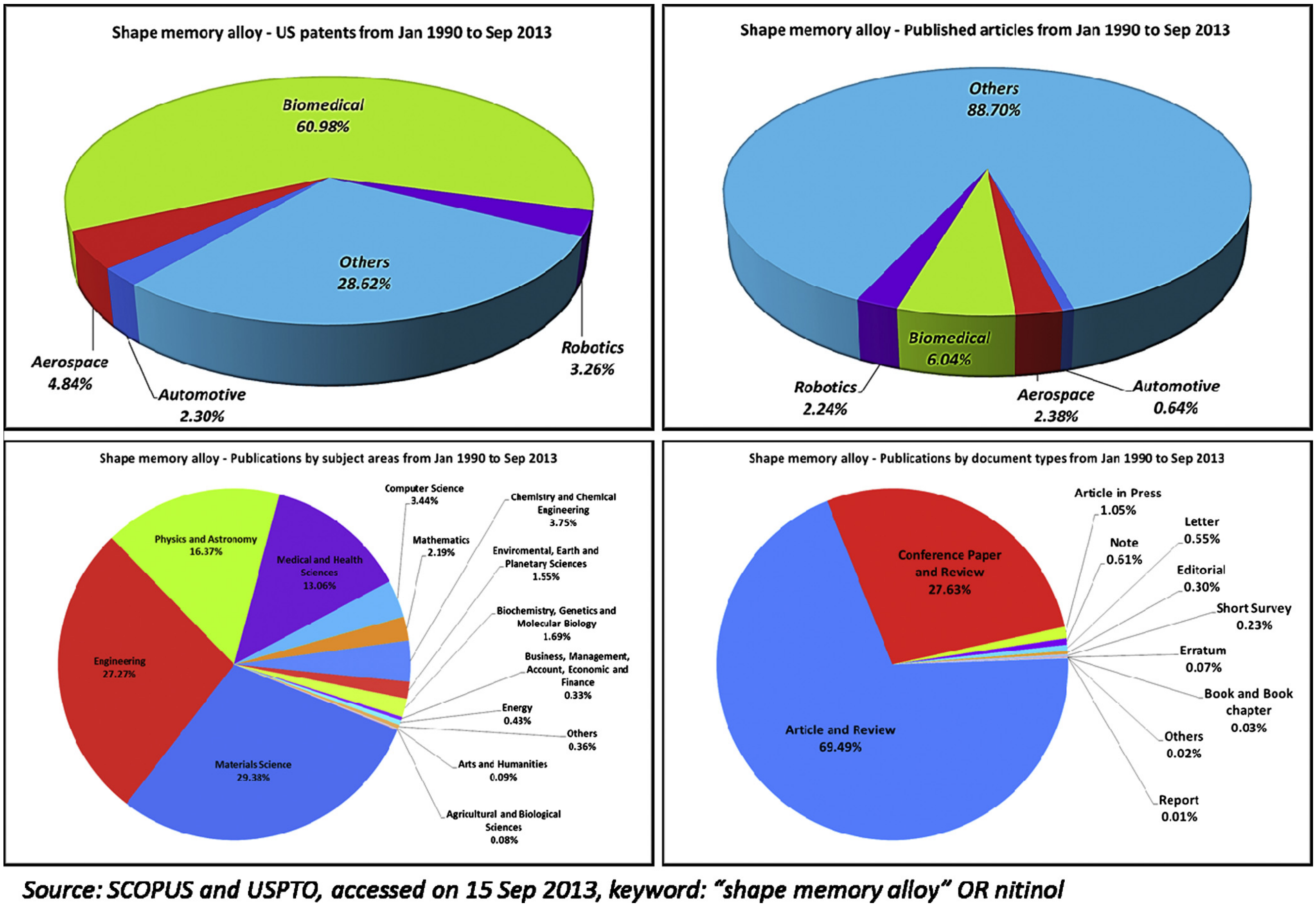


Fig. 3. SMA publications and US patents from January 1990 to June 2013.

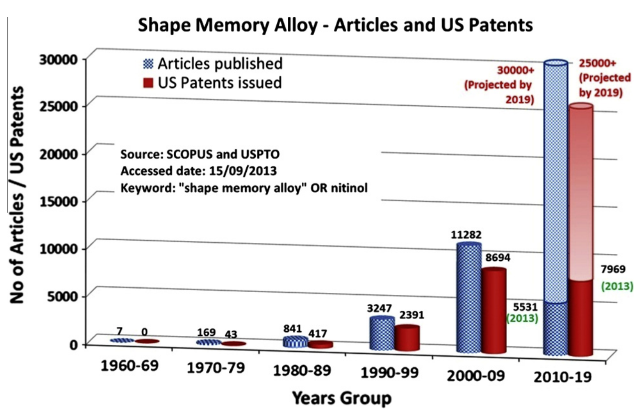


Fig. 4. Number of "Shape Memory Alloy" articles and patents by years-group.

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

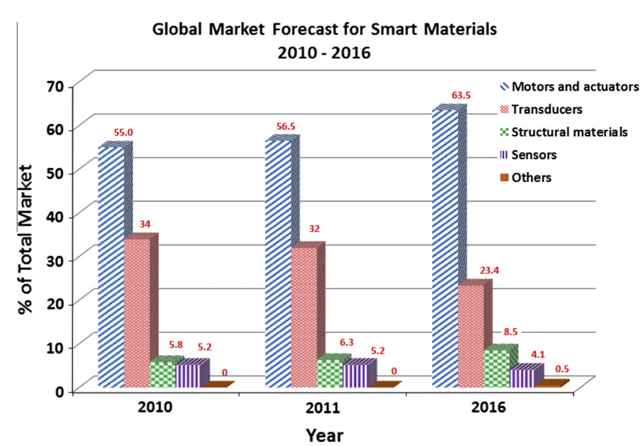


Fig. 5. Global market forecast for smart materials for 2010–2016 [79].

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

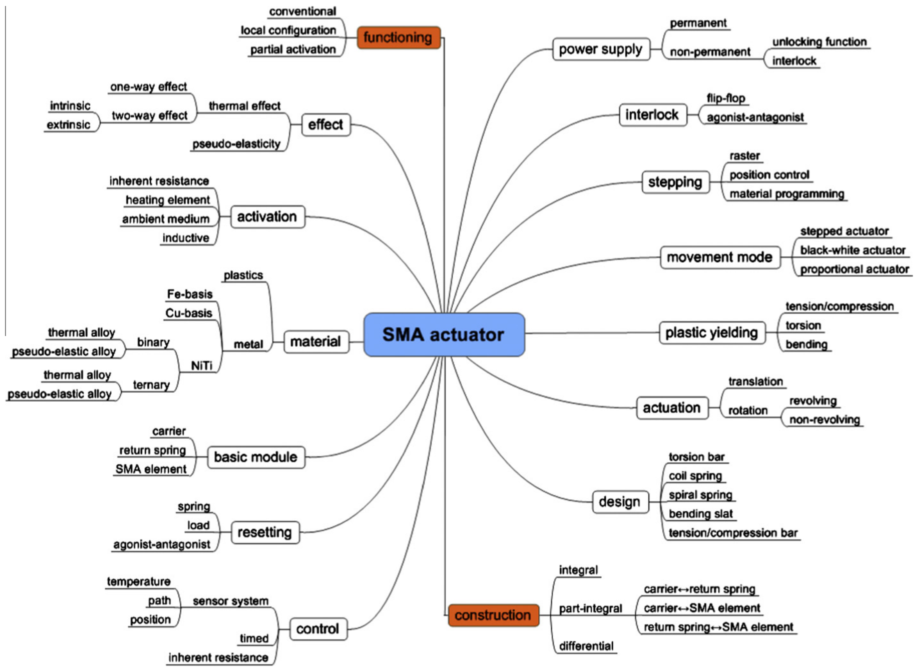


Fig. 6. SMA actuator element features [99].

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.

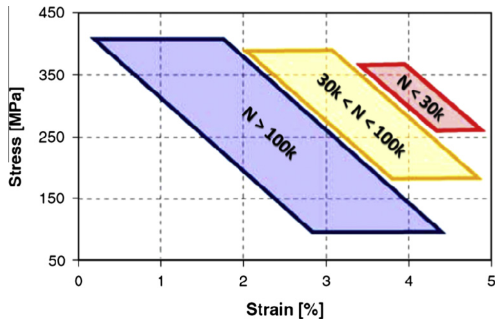


Fig. 7. Fatigue lifetime for Smartflex 76 under different stress–strain [140].

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

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

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.

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

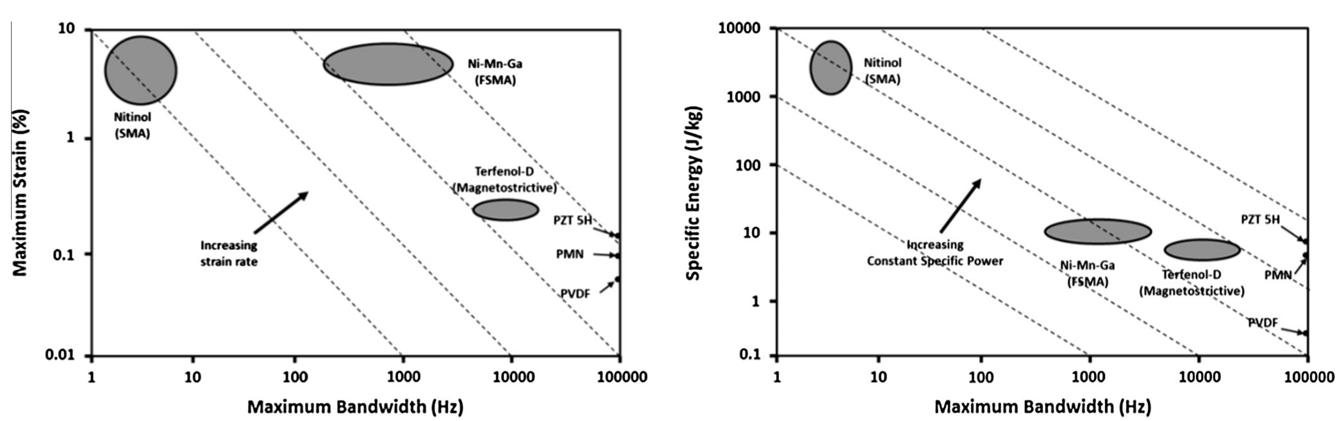


Fig. 8. Maximum strain and specific energy versus maximum bandwidth for different classes of active materials [43].

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) × 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].

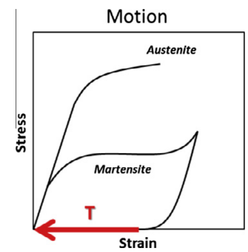
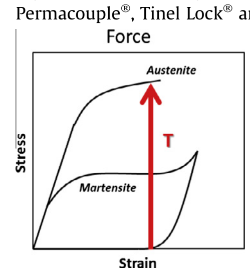
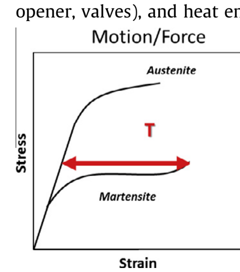
5.2. Aerospace applications

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

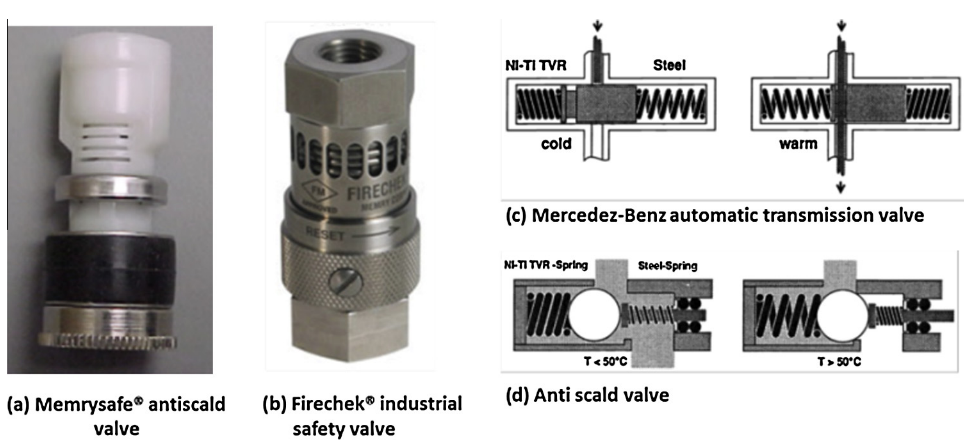
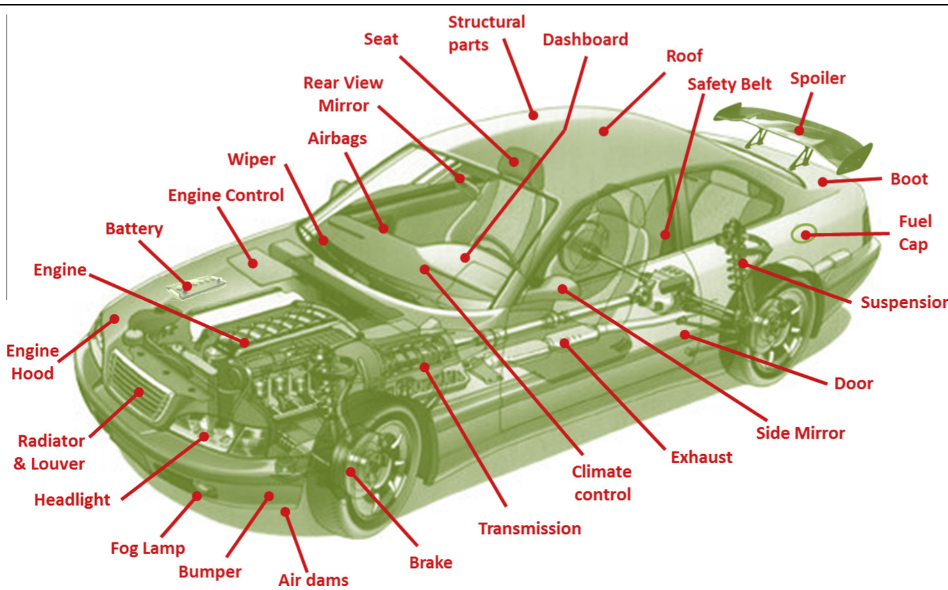


Fig. 9. NiTi thermovariable rate (TVR) springs applications [202,203].

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.

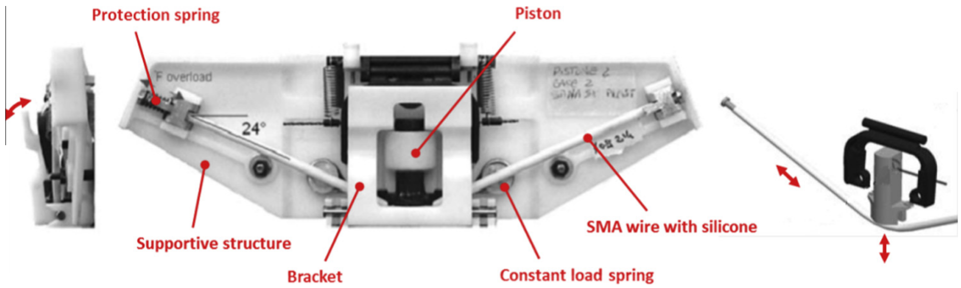


Fig. 10. EAGLE mirror prototype [207].

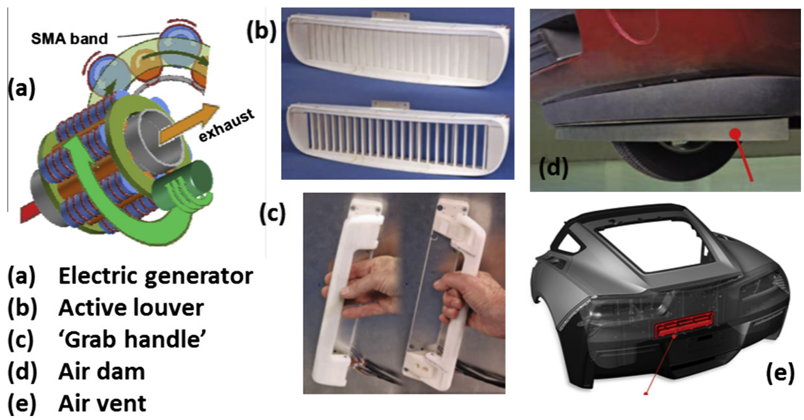


Fig. 11. Emerging General Motors' SMA applications [3,209,210].

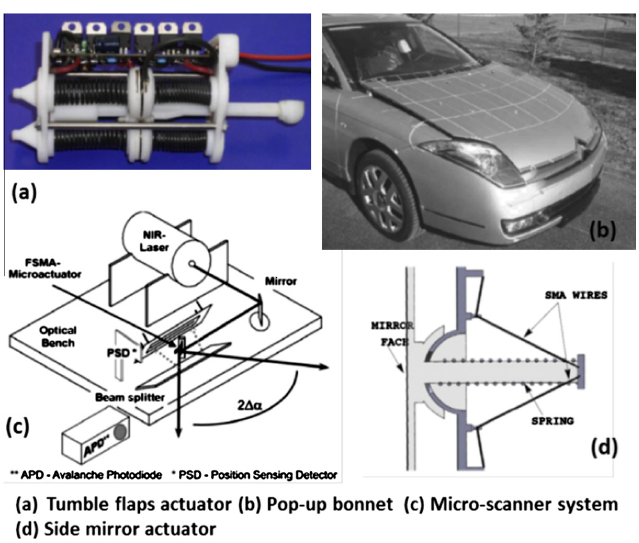


Fig. 12. Other SMA application in the automotive domain [211–213,217].

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	

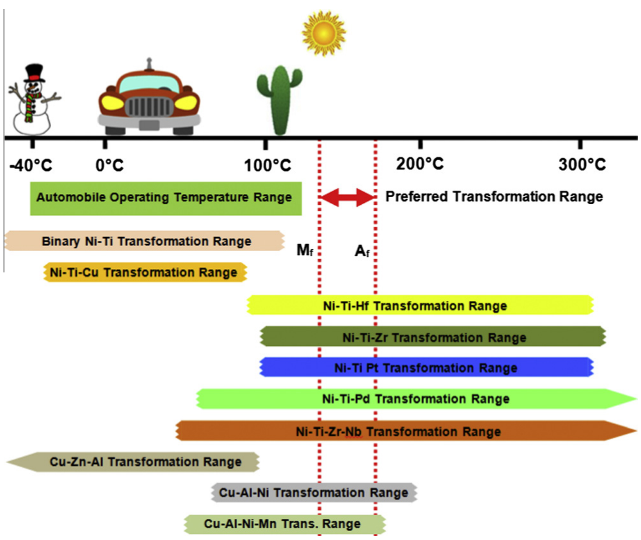


Fig. 13. Operating temperature range for automobiles applications and the transformation temperatures for selected commercially available and developed SMAs [13,34,161,218].

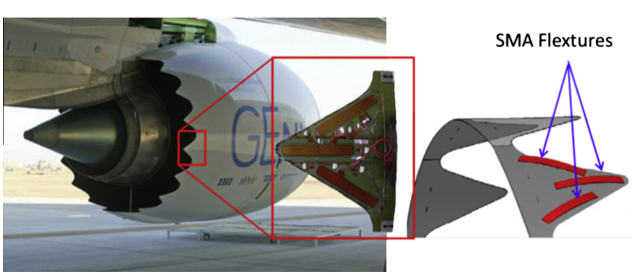


Fig. 14. Boeing's variable geometry chevron (VGC) [238].

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.

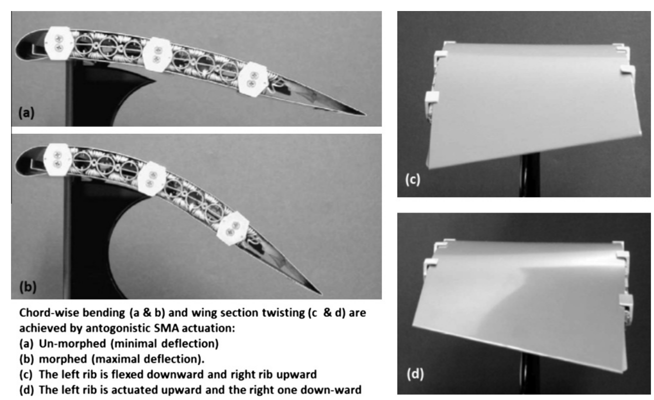
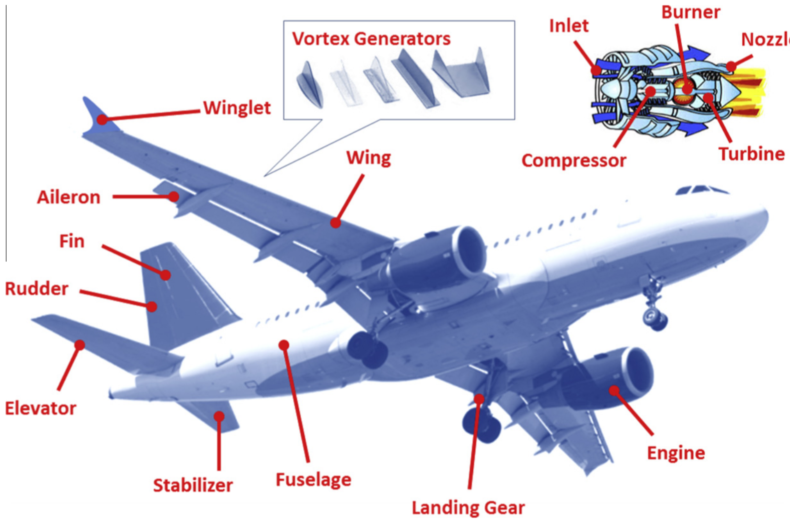


Fig. 15. Wing morphing with antagonistic SMA actuators [235,249].

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]		

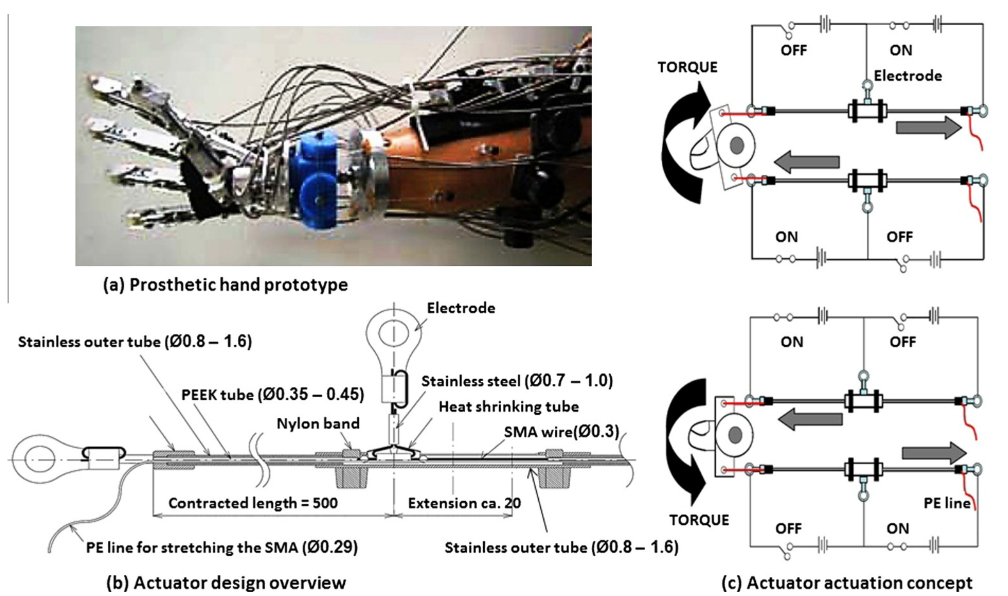
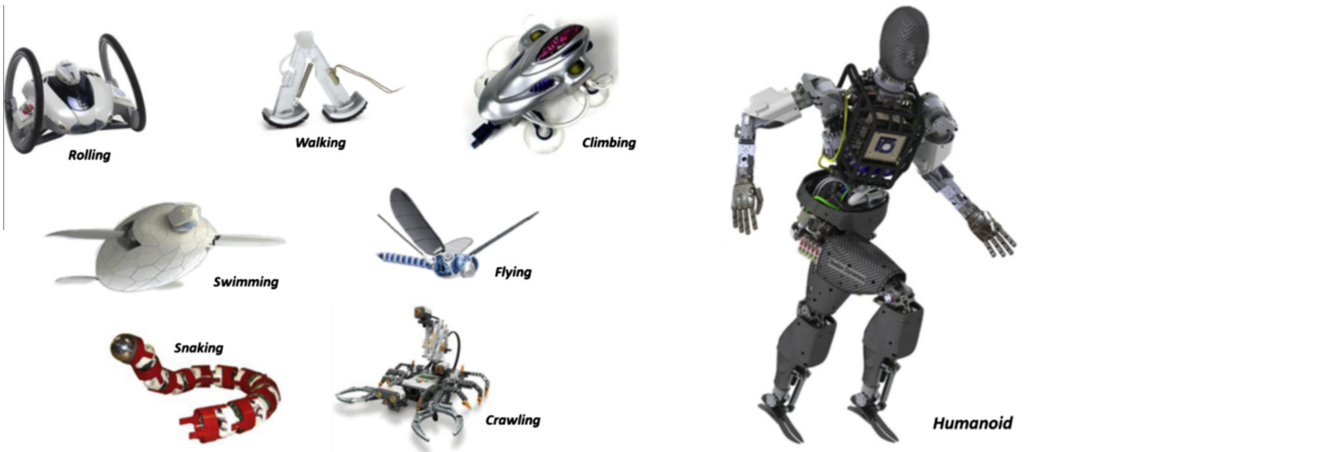


Fig. 16. Prosthetic hand powered by SMA actuators [103].

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]

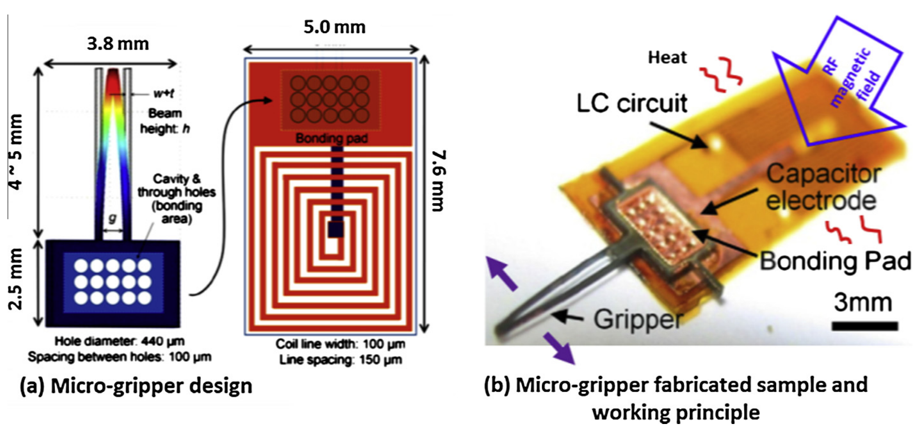


Fig. 17. Micro-gripper with SMA actuator [281].

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

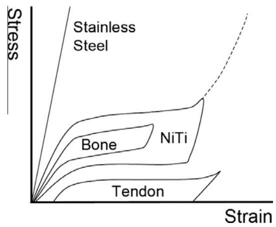
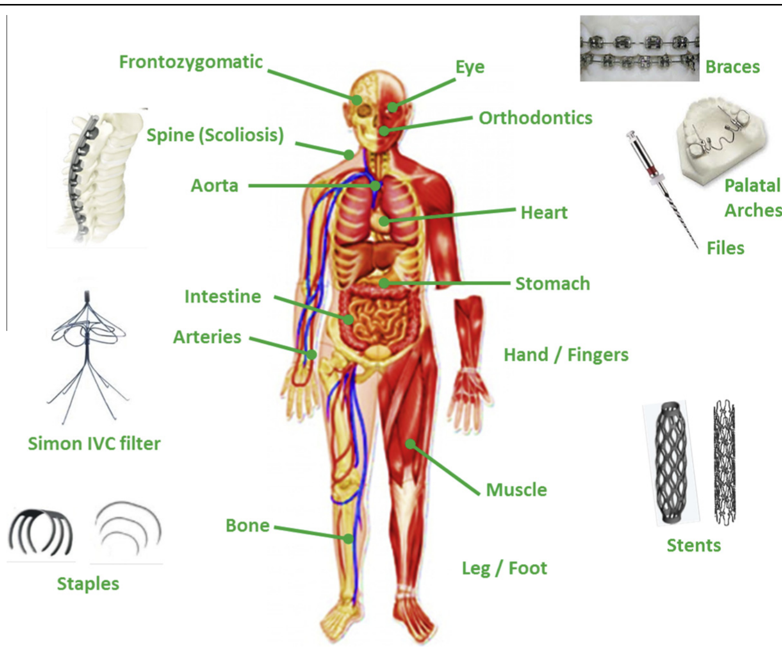


Fig. 19. The stress versus strain relationship for superelastic nitinol, stainless steel, bone and tendon tissues [27].

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]

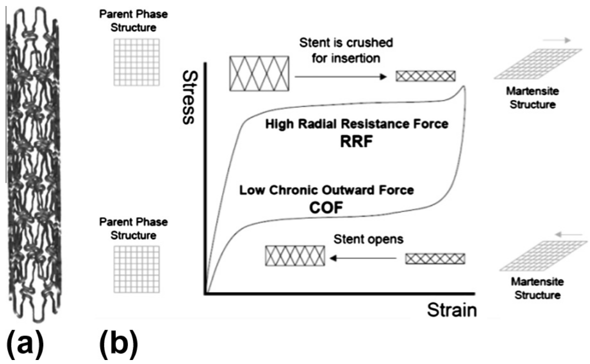


Fig. 20. (a) Model of stent laser cut from nitinol tubing. (b) The radial resistance force and chronic outward force as a function of superelastic hysteresis loop [27].

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.

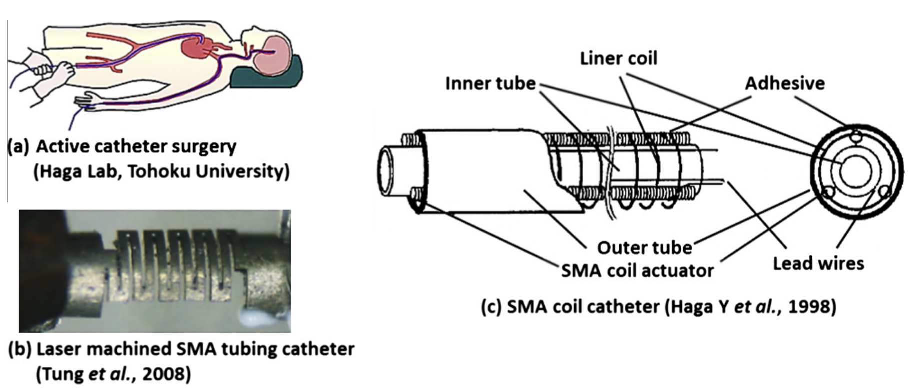


Fig. 21. SMA active catheter [297,298].

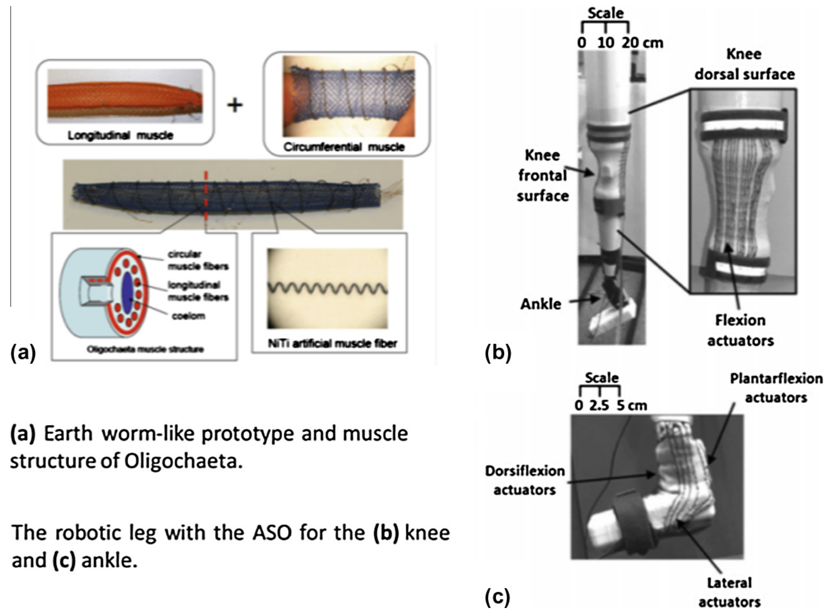


Fig. 22. Muscle like NiTi SMA [299,300].

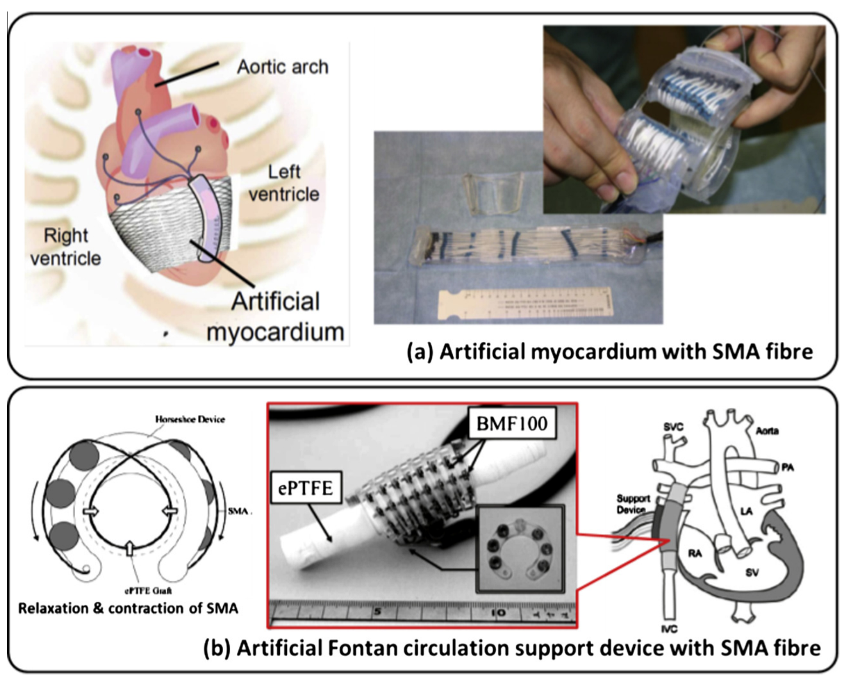


Fig. 23. Artificial heart support devices with SMA fibre [301].

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

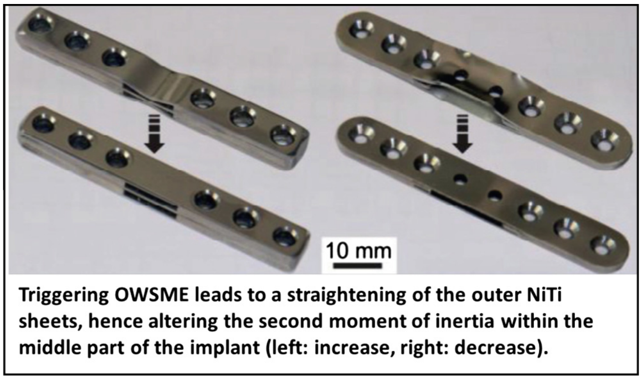


Fig. 24. An 'alterable stiffness' implant [291].

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

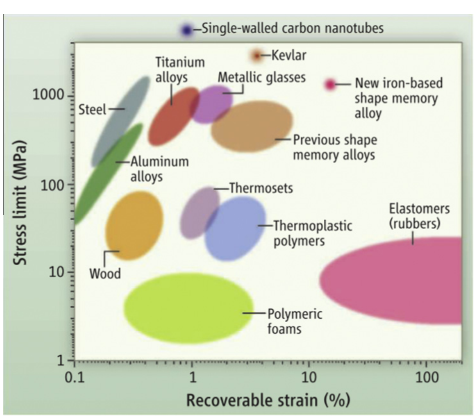


Fig. 25. Comparison stress and strain of new developed SMA with other materials [100,317].

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-

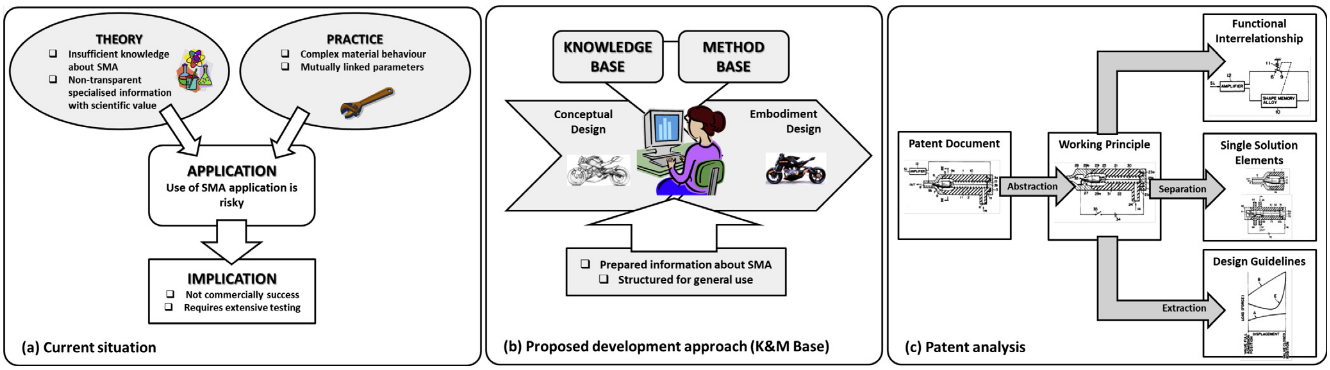


Fig. 26. Current situation and proposed approach for SMA in product design [80].

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]

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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	Control	2013	Gao et al.

SMA actuators (*continued*)

Actuators and motors Description	Remarks	Year	Inventor/ researcher
controlling a phase transformation temperature of a shape memory alloy. Developed by Dynalloy and GM	system		[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]
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]

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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.

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