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TOPICAL REVIEW

Review of MSM Actuators: Applications, Challenges, and Potential

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ABSTRACT Magnetic shape memory alloys (MSMAs) are a new and rapidly developing class of smart materials. These alloys demonstrate significant strain (from *6%* to *12%*) under an external magnetic field, which combined with their wide actuation frequency range, rapid accelerations, and high energy efficiency has resulted in MSMAs being used in a wide range of applications, for example, for energy harvesting, in measurement devices, flow control and pump applications, and as actuators and dampers. MSM actuators inherit the properties of MSMAs and MSM actuators can thus be extremely useful in many areas such as robotics, mobile machines, aerospace engineering and medicine, to name a few. Although the volume of research related to MSM actuators has increased in recent years, only a few types of these actuators exist, and the number of possible applications is currently rather limited. Nevertheless, MSM actuators clearly have great potential. Against this background, this paper reviews the current state of MSMA technology, examines different classes of MSM actuators and their current applications, and presents opportunities that have not yet been properly explored.

INDEX TERMS Actuator, ferromagnetic shape memory, magnetic shape memory, Ni-Mn-Ga.

I. INTRODUCTION

There is a constant need to make machine components smaller and more energy efficient. Yet, most currently available motors and actuators are heavy, bulky, and they have high inertia, which places limitations on the design of mobile machines, compact systems, and machines where high dynamics are required. For example, the use of traditional electro-mechanical systems increases the minimum size of wearable devices such as prosthetic limbs, and the complicated mechanical transmissions required increases the price of the devices. Additionally, mechanical transmissions cause additional frictional losses, resulting in increased battery consumption. Similar issues emerge with many other mobile devices and machines. Moreover, portable machines have space and weight limits, which sometimes makes conventional actuators unsuitable. Small actuators with high power density are extremely useful in areas such as surgical robotics, drones, exoskeletons, prosthetic limbs, manipulators, aerospace applications, and many more; and the development of new compact actuators with high power density will significantly benefit many industries.

One way to make actuators more compact and improve their power density could be utilization of smart materials. A potentially suitable group of smart materials for use in actuators are magnetic shape memory alloys (MSMAs), which were discovered in 1996 by K. Ullakko [1]. Oriented single crystals of these alloys can exhibit significantly large magnetic-field-induced strains (MFIS) ranging from 6% [2] to 10% [3], and even up to 12% in certain elementally doped alloys [4]. Additionally, MSMAs have high actuation frequency, and depending on the alloy, efficiency can be over 80% with a theoretical limit close to 95% [5].

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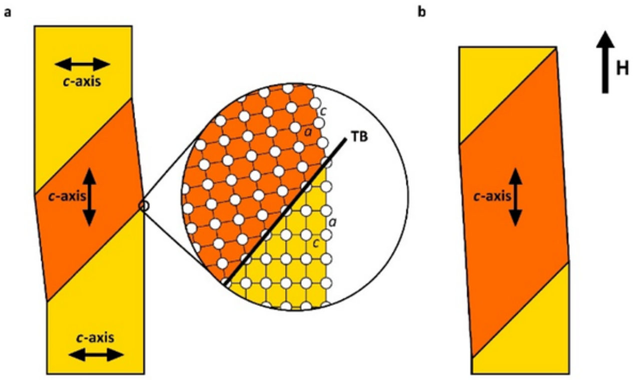

FIGURE 1. A schematic illustration of the magnetic shape memory effect in a single crystalline Ni-Mn-Ga sample (a) The sample before applying the magnetic field. (b) The same sample after magnetic field (H) application in the direction pointed by the arrow. Reprinted from [8] with permission of the author.

The magnetic shape memory effect (MSME) and the resultant large magnetic-field-induced stains (MFIS) observed in MSMAs occur when the easy magnetization axis (the shorter crystallographic c-axis) of the material's crystal lattice reorientates along an applied magnetic field [6], [7]. The MSME occurs through twin boundary motion. A sample exhibiting a microstructure with two parallel twin boundaries (TBs) is shown in [8, Fig. 1]: Yellow variants' c-axis is oriented in a horizontal direction, and an orange variants' c-axis is oriented in a vertical direction. The b-axis is oriented normal to the plane of view. The inset contains a magnified image showing the orientation of the unit cell on each side of the TB. When the field reaches the minimum value, the martensitic twin variants with the c-axis oriented along the applied magnetic field (H) grow at the expense of other variants with different orientations, which results in a physical contraction of the sample along the field direction. The sample retains its shape after the magnetic field is removed. A reverse transformation can be induced by applying a transverse magnetic field or by mechanical force. In order to exhibit large MFIS, an alloy must have high magnetic anisotropy compared to the energy needed to move the twin boundaries. The minimum field value depends on multiple factors, including chemical composition, crystal structure and quality, and twin boundary type.

Among MSMAs Ni-Mn-Ga with 10M structure is the most studied MSMA, mainly because it has relatively low twinning stress and high work output while still maintaining a large MFIS. Thus, the majority of the existing applications and devices based on MSM use alloy compositions exhibiting this crystal phase. An alloy with 10M structure has been shown to exhibit two primary types of twin boundaries, type 1 and type 2, that differ from each other crystallographically [9], [10]. These twin boundary types exhibit drastically different twinning stresses and mobilities. For example, in 10M martensite, type 1 twin boundaries have been shown to exhibit generally higher twinning stress of approximately 1 MPa in comparison to the twinning stress of approximately 0.05-0.3 MPa exhibited by type 2 boundaries [9], [10]. Type 1 twin boundaries are observed more often than type 2 boundaries, although samples with multiple boundaries can simultaneously exhibit both types of boundaries. How different twin boundary types are generated has received only limited study.

The maximum output stress generated by MSMAs can be calculated knowing the magnetic-field-induced stress and twinning stress (the stress required to move an existing twin boundary) [11]. Nucleation of the new twin boundaries may require several times higher stress than twinning stress of an existing boundary [12]. Magnetic field induced stress for 5M/10M Ni-Mn-Ga is approximately 3 MPA near austenite transformation start temperature [13]. According to [11] all the forces that act on MSM crystal, including external forces, should be in total balance. Force balance in general form can be written as equality between internal magnetic stress and the sum of the output stress and magnetic-field-induced stress. Thus, depending on twin boundary type and other parameters of a particular MSM crystal, the output stress for 5M/10M Ni-Mn-Ga can theoretically reach 2 MPa or a slightly higher value. Therefore, the cross-sectional area of MSM crystal along which actuation is made defining output force of that crystal. Up to a certain limit it is possible to increase the output force by increasing crystal's cross-sectional area. The maximum strain and output stress are only achieved in oriented single crystals cut perfectly along the {100} lattice planes of the austenitic parent phase.

Various internal or surface defects can result in the formation of pinning obstacles and residual twin variants that obstruct twin boundary motion, subsequently hindering large MFIS in such samples [14]. Hence, large MFIS in Ni-Mn-Ga is almost exclusively observed in oriented single crystals. Although some polycrystalline alloys have been shown to develop moderate MFIS [15], [16], [17], and the use of polymer hybrids has been suggested [18], application development in this area remains in its infancy, and this review therefore focuses exclusively on discussing the applications and devices basing on the use of single crystal MSMAs.

Irrespective of whether single or polycrystalline, materials with the MSM property are particularly promising due to their high-power density. Ni-Mn-Ga crystals have a magnetic cycle energy density 190 kJ/m^3, which can have power density of 114 MW/m^3 if actuated by frequency of 600 Hz [5]. This theoretical power density is much higher than that reported for the highest energy density actuator material so far, Terfenol-D [5]. Comparison of the energy densities and actuation frequencies of different smart materials is presented in [19]. It should be noted that recent research has demonstrated that the operating frequency of MSMAs can be even higher. For mm-sized MSMAs, the actuation frequency can reach kHz range [20], and μm-sized MSMAs may have a working frequency of 100 kHz [21]. The material properties of MSMAs are overviewed in detail by I. Aaltio and other authors [22], [23], [24], [25].

Beside MSMAs, there are many other smart materials with diverse properties which are also suitable for various applications. For example, actuators based on shape memory alloys (SMAs) is already a mature technology that has been broadly reviewed by many authors [26], [27], [28], [29]. MSMAs also have SMA properties, but the MSM effect occurs entirely in martensite and does not involve any phase transformations. SMA can generate higher output stress than MSMAs, but SMAs' actuation frequency is significantly lower. Likewise, actuators based on other materials can only be used in certain areas where the properties of a particular smart material will be most useful. However, there are application areas where several different smart materials can solve the same problem. Since if the applicability areas intersect, and SMA is already implemented there, then it may be worth trying to create MSM based solution as well, since it could be possible to achieve faster actuator response and higher energy efficiency as an example. This approach may work only in a limited number of applications, several examples will be given in the further sections.

The magneto-mechanical properties of MSMAs mean that MSM actuators can find a niche in small-scaled high frequency actuation applications where hydraulic, pneumatic, or electromechanical components are too big to be fit; and at the same time other technologies such as microelectromechanical systems (MEMS) are too small to be used. Additionally, MSM-based solutions can provide much better dynamics than conventional actuators, for instance, MSM element acceleration of 5×10^3 m/s^2 is reported in [5] and acceleration can theoretically reach 10^5 m/s^2. However, currently available MSM actuators have limited capabilities, for example, even though the actuators can provide fast response, the generated force and stroke are relatively low, which somewhat restricts usage of MSM actuators in many practical applications. Further development of MSM actuator technology to address some of its current weaknesses will enable more industries to benefit from MSM based solutions. This paper overviews MSM actuator types, their applications and challenges and suggests potential methods for improving MSM actuator design.

This paper reviews publications made during period from 1996 to April 2022. The paper focusses only on MSMA actuators driven by external magnetic field, and other applications were disregarded in this review. The MSMA applications presented in the paper include linear motion, revolute motion, complex motion, liquids and gas handling, and holding devices. The search was conducted using Scopus and Google Scholar databases using following search terms: Magnetic shape memory; ferromagnetic shape memory; magnetic shape memory review; magnetic shape memory actuator; magnetic shape memory control; magnetic shape memory model; MSM.

II. MSM ACTUATOR TYPES

Currently, there are not many cases where actuators based on MSMAs have found practical application and their use in mechatronics has been very limited. Several reviews have examined the current state of MSM based actuators: different MSM actuator concepts are described in [30]; linear actuator types are summarized in [31]; and the latest actuators and MSMAs are reported in [32].

Only a small number of different actuator concepts utilizing MSMAs have been proposed so far. A commonly used MSM actuator design is of linear type and is described in [30]: Linear actuators exploit the extension and contraction of the MSM element to generate linear cyclic motion of an end-effector (which is usually directly connected to a MSMA). This concept is popular due to its simplicity, and MSM linear actuators have found applications in pneumatic [33] and hydraulic [34] valves, and even as circuit breakers [35]. Moreover, due to the self-sensing properties of MSMAs, applications such as vibration damping are also possible [36].

MSMAs are, however, not limited to only linear deformations, it is also possible to create bending, twisting, and more complex shape changes in the crystals. The various heterogenous deformations possible in MSMAs have been described by [37]. These MSM deformations are utilized, for example, in micropumps [38]. Additionally, an approach to utilize the shear force generated by an MSM element is demonstrated in [39], where it is shown that a flapper made of an MSM element can generate a propulsion while submerged into a gas or liquid. An element of length, height, and width of 5 mm $\times$ 1 mm $\times$ 2 mm respectively generated force up to 40 mN with actuation frequency of 10 Hz. If the actuation frequency is increased to 50 Hz, the expected force outcome might be several orders larger compared with biological counterparts.

Complex MSMA deformation allows the creation of unique mechanisms with outstanding properties. However, these mechanisms are difficult to analyze and implement, and consequently, not very widespread. Rotational MSMA actuators have received scant attention.

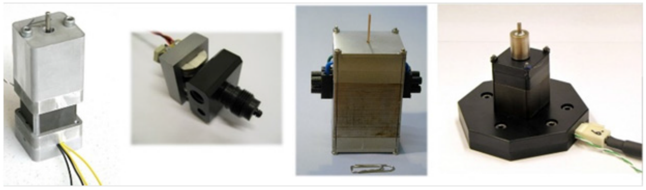

FIGURE 2. Various MSM actuators. Adapted from "K. Ullakko, private communication, 2022" with permission of the author.

A. LINEAR ACTUATORS

The majority of proposed linear MSM actuators utilize the linear motion of an MSMA directly without any additional force or torque transmission. In such design concepts MSM element pushes an end-effector and provides linear actuation. Several different linear MSM actuators are shown in Fig. 2.

The inherent hysteresis property of MSMAs makes MSM elements self-supporting, and MSM elements thus maintain their shape until an external force or a magnetic field is applied. Thus, if an actuator is extended under a magnetic

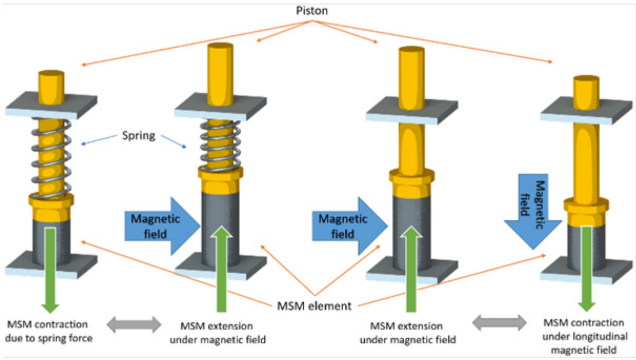

FIGURE 3. Spring returned and magnetic field returned MSM linear actuator types.

field, there must be an external force or a magnetic field of different orientation to return the actuator to the initial position.

There are several ways of implementing a reciprocating motion in MSMA actuators. Five different schemes which are called ''modes'' in the paper, are described in [31]. The modes division can be generalized as follows: MSM elements controlled only by force inputs (totally passive behavior); by a combination of a returning force (spring, gravity, external or other) and a magnetic field (provided by an electromagnet or permanent magnet); or by two or more magnetic fields with different orientations. Examples of two MSM linear actuator types are shown in Fig. 3.

A commonly used method to return the actuator to its original position is utilization of a spring. The spring contracts when the MSM element extends under a magnetic field and pushes the MSM element back when the magnetic field is disabled. An example of such a mechanism is described in [40]. This concept is simple in implementation, yet the spring counteracts the extension of MSM element and reduces the mechanism's force output. Research [41] investigates the properties of a spring actuator with various spring stiffnesses and measures work output under varying conditions.

Another design for an actuator is introduced in [42]. In the design, two MSM elements are located in opposite to each other. Thus, extension of one element causes contraction of the other. Since the two elements push each other, the concepted is called ''push-push''. Due to the hysteresis of MSMAs, it is possible to hold a ''stable position''. The position depends on the magnitude and duration of the current pulses applied. Since an infinite number of stable positions can be reached, the actuator is multistable, and it does not consume energy when it does not move. Article [43] suggests to use the push-push concept for a clamping device. Due to the multistability, the device does not consume energy while clamping an object. However, the clamping force is relatively low, only 3 N when the coils are not energized and 7 N when a clamping coil is energized.

Reference [40] demonstrates that it is possible to create a push-pull actuator that comprises only one MSM element, one coil and permanent magnets. The magnets hold the MSM element in the extended state. The coil, which is aligned perpendicularly to the magnets, is used to contract the element. Higher currents flowing through the coil cause higher MSM element contraction. If the current is returned to zero, the element is extended back by the magnetic field generated by the permanent magnets. Therefore, the actuator has only one stable position, namely, when it is fully extended. A high current of up to 30 A is needed to move the actuator. The current value can be reduced while the actuator is holding arbitrary position. The same principle is adopted in [44], which presents FEM simulation of a similar magnetic circuit.

The push-push concept has been complemented by introducing modularity. Research [45] suggests an actuator comprising a central gearbox module and two groups of MSM elements that push the end-effector in opposite directions. Each group consists of MSM modules that are mechanically interconnected. Consequently, the total strain of a group is summed up. The gearbox contains a knee lever that mediates the motion of one MSM group to another and provides variable gain ratio. The actuator utilizes a PI controller with a modified I component to make it energy efficient. Due to the multistability property of the actuator, the I component is minimized when the position error drops below a certain threshold, thus the integral part of the current is minimized. The controller behaves almost as a standard PI controller when the error is not below the threshold.

The size of MSM linear actuators can be significantly increased to reach higher force output. For example, an MSM actuator with a diameter of 260 mm and height of 90 mm capable of generating up to 1 kN of force at low frequencies is described in [46]. During tests, the actuator was not fully equipped with MSM elements and showed only 1.25 MPa of stress, whereas a higher stress output value is theoretically possible as mentioned in the introduction section. Thus, an optimized MSM actuator of the same size should be able to provide higher force output.

In addition to large actuators, micrometer-sized MSM elements have also been investigated. The paper [47] demonstrates that an MSMA pillar can be as small as approximately 108 μm $\times$ 50 μm $\times$ 50 μm. A system of such scale requires special manufacturing techniques and surface treatment, and some of the system's properties are different from those found at macroscale. A magnetic field below 0.4 T is sufficient to actuate the pillar and its actuation frequency may reach 100 kHz. These features enable the design of micro-magneto-mechanical devices based on MSMAs.

An alternative way of implementing an MSM-based linear actuator is suggested in [48, Fig. 4]. The proposed design uses coils and a thin bridge-like structure made of an MSMA. Deflection of the middle part of the MSM element can be controlled by magnetic fields applied similarly to the fifth operating mode described in [31]. The FEM analysis presented in the work indicated that the actuator can create forces in the order of one mN and generate out-of-place stroke of 17%. In this case, the stroke does not mean elongation of the

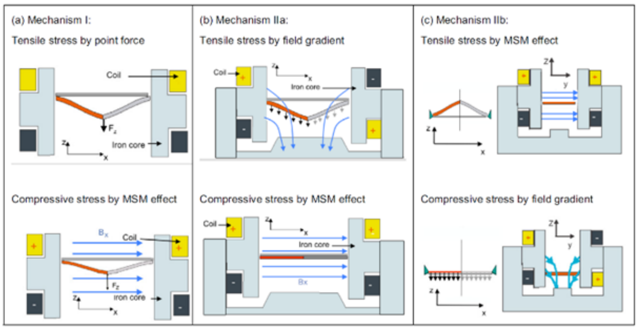

FIGURE 4. Bridge-like MSM actuator (a) actuation using mechanical loading and magnetic field-induced reorientation (b-c) loading by a magnetic field and MIR. Reprinted from [48].

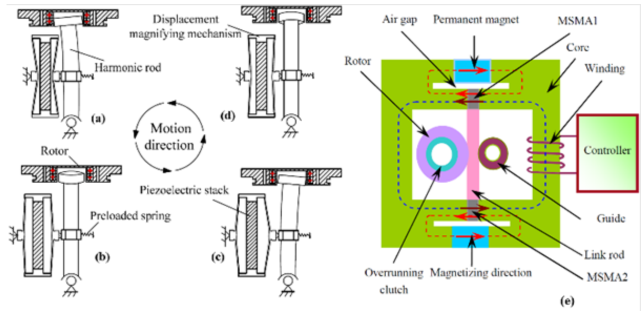

FIGURE 5. (a-d) Working principle of low-frequency harmonic rotating piezoelectric actuator; position of 0, 90, 180 and 270 degrees respectively. Adapted from [52] (e) Structure of Differential rotating MSMA. Adapted from [44] (©2009 IEEE).

MSM beam, but its deflection from an initial position. This concept could be suitable for applications that demand low force output, high deflections and low magnetic field.

In the examples described above, the magnetic circuits give different properties to relatively similar systems Depending on the topology of the magnetic circuit, MSM actuators can have different stable points or zones as well as varying efficiency during different parts of a working cycle. Permanent magnets can also affect the stable points of an MSM actuator and significantly increase the actuator's efficiency. Moreover, permanent magnets can allow the use of positive and negative current flows to extend and contract the actuator. The same reciprocating motion can be achieved by special coils alignments as demonstrated in "push-pull" and spring actuated actuator examples.

B. REVOLUTE ACTUATORS

The linear motion generated by MSM elements has been investigated in detail; however, there have been few attempts to create an actuator output of which would be a revolute motion. The proposal made in [44] utilizes a rod and an overrunning clutch to convert the linear motion of an MSMA into a rotational motion. The revolute motion is thus achieved by conversion of a reciprocating motion in the research. A more complex solution that outputs a revolute motion is precisely described in [49]. In the proposal, MSM elements are located spirally, and the spiral shape is limited by a fixed outer diameter. Extension of the elements results in rotation of a shaft in the center of the prototype with output torque of order N·m. Such an approach limits the revolute working range.

Some applications for MSM actuators may require high dynamics from the motion system. One way to achieve rotation is conversion of MSMA harmonic motion into revolute motion similarly to the working principle of modern harmonic gearboxes. This approach is utilized for a smart material alloy (SMA) actuator prototype reviewed in [50]. In earlier research, researchers had tried to implement harmonic drive based on the electrostatic effect [51]. The designed actuator had a high ratio between electric and mechanical frequencies, but it also had the major disadvantages that the output torque is of about 10^{-3} Nm and the actuator suffers from intense wear. Attempts to create revolute actuators using other smart materials are also described in [52]. The paper demonstrates a harmonic actuator prototype based on piezoelectricity. The piezoelectric material does not provide sufficient extension and the researchers thus had to implement an amplification mechanism to amplify the motion of the piezoelectric stack. MSMAs have a much higher extension ratio, higher acceleration and higher power density, and use of the same working principle but MSMAs rather than piezoelectric material could enable high-power density compact harmonic actuators. Comparison of two revolute actuators based on smart materials is shown in [52, 44, Fig. 5].

The various MSM deformation modes and the electric and magnetic circuits available could enable development of a new class of MSM revolute actuators. Paper [50] reviews in detail SMA actuators concepts and has a section dedicated to revolute SMA actuators. Several concepts described in the paper do not demand high torque input and require elongation of the same order as produced by MSMAs. Thus far, these concepts have however not been tested with MSMAs.

III. APPLICATIONS FOR MSMAs

MSMAs have found many applications in liquid and gas handling. The fast response of MSM elements is suitable for designing valves and the complex deformation of MSMAs can be utilized in micropump designs. These features allow parts conventionally used in hydraulic and pneumatic equipment to be replaced with MSM elements to increase overall energy-efficiency.

The possibility of using MSMAs for micropumps was first demonstrated by K. Ullakko [21, Fig. 6]. The pump uses an MSM element both ends of which are fixed with epoxy so that the MSM element maintains a constant length. The element is neither fully extended nor retracted when the ends are fixed. Consequently, the MSM element is deformed and has a shrinkage that can be moved by external magnetic field. A diametrically magnetized cylindrical magnet is used in

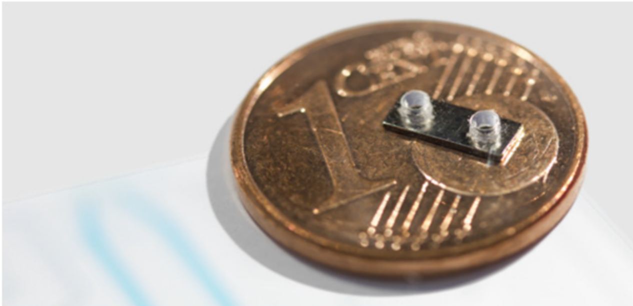

FIGURE 6. MSM based micropump size comparison with a 1 euro cent coin (a permanent magnet is not installed). Reprinted from "K. Ullakko, private communication, 2022" with permission of the author.

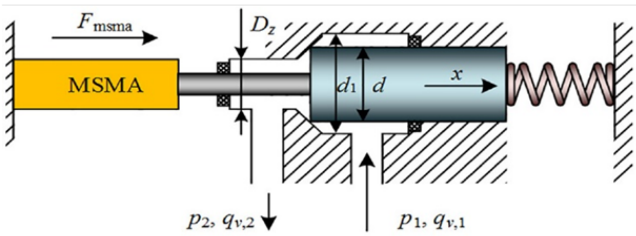

FIGURE 7. Schematic diagram of spool opening. Reprinted from [34].

[24] to create the necessary field. Rotation of a magnet by an electric motor or by hand changes magnetic field around MSM element. The shrinkage moves with the magnetic field and at the same time a liquid inside of the shrinkage moves from an inlet of the pump to an outlet. The paper compares MSM and piezoelectric micropumps and suggests that MSM-based solutions are theoretically more compact, can generate significantly higher pressure difference, and may have higher flow rate. An improved pump design by A. Saren *et al.* [53] increased the precision significantly. The pump works with gases and liquids, and the order of the transmitted volume is hundreds of nL per cycle with a pressure difference up to 4 bars and accuracy of ±5 nL for air and ±3 nL for water. The pump may be suitable for use with the lab on a chip concept.

An MSMA-based pneumatic valve is reported in [33]. The valve utilizes one MSM element that works as a linear actuator. The element moves a push rod, which opens and closes a gap for air flow. Actuation of the MSM element is done by two coils: one for extension and the second for contraction (mode 5 from [31]). Consequently, the valve is multistable and can maintain the set airflow without energy consumption as only switching to a different airflow value or valve closure consumes energy. It is demonstrated in the work that the energy efficiency of the valve can be improved by approximately 50% by utilization of a modified PI controller based on the concept presented in [45]. Another fast-switching pneumatic valve, which comprises an MSM element, coil for extension and a returning spring, is described in [54]. The design has a simpler coil arrangement than the valve in [33]. However, valves utilizing a spring and MSM element can overheat under continuous operation.

The rationale for utilization of MSM elements in fluid valves is discussed in [55]. Research describing two valve concepts with multistability is presented in [56]. The work investigates how electric current, switching time and other valve parameters affect the overall power consumption. A poppet-type hydraulic valve based on an MSM element is reported in [34, Fig. 7]. The valve utilizes a spring to contract the MSM element and a coil to elongate it. Valve opening time is 5 ms under 1 MPa pressure difference, and flow after opening reaches 0.88 L/min. If the pressure difference is 5 MPa, then the maximum flow rate is 18.17 L/min. Electric power consumption is about 120 W at the maximum valve opening, which is approximately equivalent to electromagnetic drives.

IV. CHALLENGES

A. TEMPERATURE

One challenge facing MSM alloys is their limited temperature range: currently available commercial MSM solutions can only work in the temperature range of −40 °C to 60 °C [23]. Some MSMAs have Curie temperature of 373 K and their efficiency drops to 45% if the temperature rises to 350 K [57]. MSMAs with these temperature properties are significantly inferior to other electromechanical actuators, and, they can thus be used only for a limited number of applications. Additionally, it is shown in [58] that there is a temperature dependance of strain and twinning stress in MSMAs. The type 1 twin boundaries of the most frequently used MSMA, Ni-Mn-Ga with 10M structure, exhibit a large increase in twinning stress when temperature is decreased, whereas this effect is much less pronounced in the type 2 twin boundaries [59], [60]. Consequently, most functional Ni-Mn-Ga compositions exhibit martensite to austenite transformation at ∼40–50 °C, that is, high enough to exhibit martensitic crystal structure at ambient temperature, but low enough to exhibit minimum twinning stress that allows movement of twin boundaries due to magnetic-field-induced stress. Recent work has investigated modified MSM alloys with high martensite transformation temperature over 373 K and high Curie temperature over 440 K [61], [62]. Such alloys could have considerable promise for future applications.

Despite the limited applicable temperature range, the thermal properties of commonly used MSMAs can be beneficial in certain applications. For example, it is shown in [35] that it is possible to create a circuit breaker for electrical and thermal protection based on a single MSM element. When an electric current in the circuit breaker exceeds a certain limit, the MSM element elongates due to magnetic field induced strain and disengages contact in the circuit. The same principal can be used for thermal protection due to the presence of thermo-mechanical strain property in the MSM element.

B. FATIGUE

MSMA based actuators can have higher actuation frequency than conventional actuators, and wear therefore should be considered carefully. Studies have estimated the fatigue life of MSMAs as being from 3.7×10^6 to over 2×10^9 cycles [63], [64]. It should also be noted that obtainable magnetic-field-induced strain reduces with cyclic load [63]. Longer fatigue life can be achieved by the use of high-quality single crystals and by avoidance of surface wear of the MSMA [23]. Important factors that can help to optimize fatigue performance are listed in [22]. The same work describes defects and other issues with MSMAs that could decrease fatigue life and increase twinning stress in crystals.

It is reported in [30] that MSM crystals with low twinning stress are much more brittle with a fatigue life of less than 10^7 cycles. Thus, crystals with type-1 twin boundaries have longer fatigue life than crystals with type-2 boundaries. On the other hand, the efficiency of MSM actuators decreases with increase in twinning stress value. The same publication reports that transition of the MSM element into single-variant state reduces the fatigue life, i.e., full elongation or contraction of the MSM crystal should be avoided and, the operational range of an actuator should hence be limited. Additionally, deformation of a crystal into a single state requires more stress and energy than deformation of a crystal with two or more variant states [22], [25]. Temperature change under cyclic load is shown in [63] to be insignificant: for the MSMA under study, the temperature increased by less than 2 K under load with 300 Hz frequency.

C. HYSTERESIS

Nonlinear behavior caused by hysteresis adds additional complexity to design of precise MSM-based actuators. Hysteresis is responsible for energy losses and can be observed in stress-strain and strain-input current curves [46]. Hysteresis is also the reason why an MSM based actuator can hold its position without power supply, which, as demonstrated in [65] for a push-pull actuator, can be exploited to reduce the energy consumption of MSM elements. Adjustments of a control algorithm can be made accordingly: as reported in [45] a modification of PI controller can take an advantage of hysteresis phenomena and increase energy efficiency of an MSM actuator. Even a simple PID controller can achieve nanometric resolution while maintaining a desired position in a spring returned MSM actuator, as shown in [66]. Additionally, efforts have been made to decrease position control error in MSM actuators using, for example, an observer-based inverse hysteresis approach [67] and a neural network-based iterative learning control [68]. Control based on multi-step numerical optimization is suggested in [69]. First, a model of a desired actuator is created, then the controller is optimized based on this model, and in the last step, the controller is optimized based on the real actuator. Since MSM actuators have nonlinear behavior due to hysteresis, use of a gradient descent approach for optimization may give unsatisfactory results. Additionally, the paper highlights that the control complexity of material with hysteresis is caused by fatigue wear, which changes the behavior of a particular crystal over time. Thus, control parameters should be updated periodically.

Even though MSMs exhibit hysteresis, MSM elements can be controlled precisely, as was demonstrated in [70], which adopts a Bouc-Wen model to describe the hysteresis of the MSMA actuator and uses Hopfield neural network online parameter identification to tune the model. The work reported maximum position error of the model was less than 0.4 μm when the experiment was run with actuation frequency of 1 Hz. Simulations of MSMAs behavior can also be carried out using the finite element method (FEM) [71], [72], [73].

D. MODELING

Various attempts are made to describe behavior of particular MSM elements after they have been manufactured as shown in Hysteresis section. Based on a series of experiments a model of an existing MSM crystal can be created. Nevertheless, under fatigue loads and due to temperature variations, crystal properties will change, making the model less accurate. A proper analytical model is needed to overcome these problems. The same model can help to predict properties of an arbitrary MSM crystal before it has been manufactured, eliminating the need in parameter identification after manufacturing. Analytical models have been proposed since the discovery of MSMAs; however, recent research [74] notes that several early models are somewhat contradictory as these models are related to early experimental data obtained on low quality MSM crystals and inadequate control of twin variant structure. At the same time [74] discusses various existing models and proposes an original method to describe twin boundary dynamics. A topological model of deformation twinning in 10M Ni-Mn-Ga crystals is proposed in [75] and a generalized approach for analyzing and modeling twin boundary dynamics is suggested in [76]. A practical application which utilizes MSM model is demonstrated in [77]. In this research MSM based energy harvester model is made, which comprises several minor models including MSM model, electrical and magnetic circuits. The resulting model have a good agreement with experimental data with maximum MSE of 2.6%.

V. CONCLUSION

The highly dynamic properties of magnetic shape memory alloys (MSMA) can be used to build very precise servo systems. Although such systems can implement complex motion, most research has thus far focused on linear motion, and linear actuators already find applications in precise positioning systems and in liquid and gas flow control devices. However, MSM actuators clearly have much untapped potential in other mechatronics systems.

When placed under a magnetic field, MSM material can show shape changes such as axial elongation, bending or twisting [46], and MSMAs can thus generate complex motion. Complex motion such as the swallow effect has only been implemented in micropumps [38]; however, it could be utilized to achieve a linear motion along a rod or a guiding rail. The torsional and bending behavior of the MSMAs also remains underexploited and no attempts have been made to produce pure revolute motion based on MSMAs. Development of MSM revolute actuators would be extremely beneficial to solve because the servo revolute actuators are in high demand in many industries.

Available MSMA actuators can achieve actuation frequencies up to several kHz. However, it might not be possible to utilize this large frequency range in many industries. Mechatronics solutions that utilize gearboxes and other mechanisms to reduce actuator output frequency already exist, and MSM actuators could be combined with additional mechanisms to convert high frequency motion into high force or high extension motion. Development of MSMA-based force or torque converters is an area worthy of exploration.

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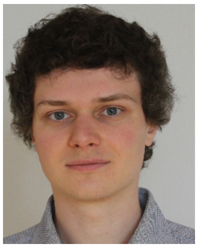

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