INTEGRATION OF SHAPE MEMORY ALLOY FOR MICROACTUATION

ALAA A. H. ABUZAITER

UNIVERSITI TEKNOLOGI MALAYSIA

INTEGRATION OF SHAPE MEMORY ALLOY FOR MICROACTUATION

ALAA A. H. ABUZAITER

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Electrical Engineering)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

SEPTEMBER 2016

I dedicate this thesis to my beloved family;

my dear father and my merciful mother, those who sacrificed their life for me

To my brothers, sisters and my fiancee Hanan

Whose love, kindness, patience and prayer have brought me this far

ACKNOWLEDGEMENT

First and foremost, my unlimited and sincere appreciation goes to the Lord of the seven heavens and earth ALLAH (SWT) for His endless mercies, blessings and guidance through from birth till now and forever. Alhamdullahi Robi Alamin.

I would like to express my deepest gratitude and thanks to Dr. Mohamed Sultan Mohamed Ali, my honourable supervisor, for giving me the opportunity to work in his wonderful research group. His continuous guidance, committed support and invaluable advice throughout my studies have made the completion of this work possible. His enthusiasm and hard work caused me to awake every day with enthusiasm for what I was to do next. I have learned a great deal from him on every aspect of academics including teaching, research, manuscript writing, grant applications and management skills and I hope to learn much more from him.

I sincerely thank all the professors and lecturers who have taught me for their invaluable lessons. In addition, I would also like to thank all of my friends: Omer Faris, Marwan Nafea, Salma, Noor Dzulaikha, Aqilah, Amirah 'Aisha and Krishna Veni: Thank you for sharing with me your useful ideas and information and offering moral support during the course of my studies.

Last but not least, I owe more than I can express to my mother Wedad, for the greatest support and love I have received. Sincere and deep gratitude goes to my father Abed Allah, my brothers (Mohamed and Ahamed), my sisters (Ola and Abeer) and my fiancee Hanan for their support and encouragement throughout the years of my Ph.D. They have been my source of dedication, inspiration and motivation, without them I would have never been able to accomplish this thesis.

ABSTRACT

Shape memory alloy (SMA) actuators in microelectromechanical system (MEMS) have a broad range of applications. The alloy material has unique properties underlying its high working density, simple structures, large displacement and excellent biocompatibility. These features have led to its commercialization in several applications such as micro-robotics and biomedical areas. However, full utilization of SMA is yet to be exploited as it faces various practical issues. In the area of microactuators in particular, fabricated devices suffer from low degrees of freedom (DoF), complex fabrication processes, larger sizes and limited displacement range. This thesis presents novel techniques of developing bulk-micromachined SMA microdevices by applying integration of multiple SMA microactuators, and monolithic methods using standard and unconventional MEMS fabrication processes. The thermomechanical behavior of the developed bimorph SMA microactuator is analyzed by studying the parameters such as thickness of SMA sheet, type and thickness of stress layer and the deposition temperature that affect the displacement. The microactuators are then integrated to form a novel SMA micromanipulator that consists of two links and a gripper at its end to provide three-DoF manipulation of small objects with overall actuation *x*- and *y*- axes displacement of 7.1 mm and 5.2 mm, respectively. To simplify the fabrication and improve the structure robustness, a monolithic approach was utilized in the development of a micro-positioning stage using bulk-micromachined SMA sheet that was fabricated in a single machining step. The design consisted of six spring actuators that provided large stage displacement range of 1.2 mm and 1.6 mm in *x*- and *y*-axes, respectively, and a rotation of 20° around the *z*-axis. To embed a self-sensing functionality in SMA microactuators, a novel wireless displacement sensing method based on integration of an SMA spiral-coil actuator in a resonant circuit is developed. These devices have the potential to promote the application of bulk-micromachined SMA actuator in MEMS area.

ABSTRAK

Penggerak aloi yang memiliki memori bentuk (SMA) telah digunakan secara meluas untuk pelbagai aplikasi di dalam sistem elektromekanikal-mikro (MEMS). Bahan ini telah terbukti mempunyai ciri-ciri asas yang unik seperti kepadatan kerja yang tinggi, struktur yang ringkas, sesaran yang besar dan kesesuaian-bio yang baik. Ciri-ciri ini telah membawa kepada pengkomersialan aloi ini dalam beberapa aplikasi seperti mikro-robotik dan bidang bioperubatan. Walau bagaimanapun, penggunaan bahan ini masih belum dieksploitasi sepenuhnya disebabkan pelbagai isu praktikal. Dalam bidang penggerak-mikro khususnya, peranti yang difabrikasi mempunyai pelbagai masalah seperti darjah kebebasan (DoF) yang rendah, proses fabrikasi yang kompleks, saiz yang besar dan jarak sesaran yang terhad. Tesis ini membentangkan teknik baharu untuk membentuk peranti-mikro daripada SMA dengan menggunakan integrasi beberapa penggerak-mikro SMA dan kaedah monolitik dengan menggunakan proses piawaian MEMS dan fabrikasi MEMS yang tidak konvensional. Ciri-ciri termomekanikal penggerak-mikro dwi-lapisan SMA yang dibangunkan dianalisis dengan mengkaji parameter yang mempengaruhi sesaran seperti ketebalan kepingan SMA, jenis dan ketebalan lapisan ketegangan dan juga suhu pendepositan. Penggerak-mikro kemudiannya diintegrasi untuk membina satu penggerak-mikro SMA baharu yang terdiri daripada dua pautan dan satu penggenggam pada penghujungnya untuk memberikan manipulasi tiga DoF untuk suatu objek kecil dengan jumlah sesaran di paksi *x* dan *y* masing-masing sebanyak 7.1 mm dan 5.2 mm. Satu pendekatan monolitik telah digunakan dalam pembangunan penentu kedudukan-mikro menggunakan helaian SMA pukal yang difabrikasi melalui satu langkah pemesinan bagi mempermudahkan proses fabrikasi dan memperbaiki keteguhan struktur. Reka bentuk ini terdiri daripada enam penggerak berbentuk spring yang mengawal pergerakan dalam paksi *x* dan *y* sebanyak 1.2 mm dan 1.6 mm, dan juga putaran sebanyak 20° di paksi *z*. Kaedah pengesanan tanpa-wayar yang baharu berdasarkan integrasi SMA lingkaran gegelung dalam litar salunan telah dibangunkan bagi fungsi pengesanan sesaran dalam mikroakuator SMA. Teknik-teknik yang dibangunkan dijangka menggalakkan penggunaan penggerak SMA pukal yang dimesin dalam bidang MEMS.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

Ag	-	Silver
Al	-	Aluminium
Au	-	Gold
BCB	-	Benzocyclobutene
CABG	-	Coronary artery bypass graft
CAD	-	Computer-aided design
Cd	-	Cadmium
CTE	-	Coefficient of thermal expansion
Cu	-	Copper
CVD	-	Chemical vapor deposition
DC	-	Direct current
DOF	-	Degrees of freedom
DSC	-	Differential scanning calorimetry
Fe	-	Iron
FEA	-	Finite element analysis
FESEM	-	Field emission scanning electron microscope
g	-	Gram
H_2O	-	DI water
HF	-	Hydrofluoric acid
Hf	-	Hafnium
HNO_3	-	Nitric acid
Hz	-	Hertz
In	-	Indium
IR	-	Infrared
K	-	Kelvin
kg	-	Kilogram
LC	-	Inductor-capacitor

m^3	-	Cubic metre
mA	-	Milliampere
MEMS	-	Microelectromechanical systems
MHz	-	Mega hertz
mm	-	Millimetre
mm^2	-	Square millimetre
Mn	-	Manganese
Ni	-	Nickel
NiTi	-	Nickel-titanium
nm	-	Nanometer
NOL	-	Naval ordnance laboratory
OWSME	-	One-way shape memory effect
Pa	-	Pascal
PE	-	Pseudoelasticity
PECVD	-	Pplasma enhanced chemical vapor deposition
PI	-	Polyimide
Poly-Si	-	Polysilicon
Pt	-	Platinum
PVD	-	Physical vapor deposition
PWM	-	Pulse-width modulation
RF	-	Radiofrequency
S	-	Second
SE	-	Superelasticity
Si	-	Silicon
Si_3N_4	-	Silicon nitride
SiO_2	-	Silicon dioxide
SMA	-	Shape memory alloy
SME	-	Shape memory effect
SMM	-	Shape memory material
Sn	-	Tin
Ti	-	titanium
Tl	-	Thallium
TME	-	Temperature memory effect

TWSME	-	Two-way shape memory effect
W	-	Watt
Zn	-	Zinc
Zr	-	Zirconium
°C	-	Degrees celsius
μEDM	-	Micro electric discharge machining
μm	-	Micrometre

LIST OF SYMBOLS

A_f	-	Finish temperature of austenite phase transformation
A_s	-	Start temperature of austenite phase transformation
B_{max}	-	Maximum bending
B_{sma}	-	Phase transformation bending
c_{SiO_2}	-	Thermal capacity of SiO_2
c_{sma}	-	Thermal capacity of SMA
E	-	Young's modulus
E_{Cu}	-	Heat energy loss resulting from the copper wires' resistance
E_{Lh}	-	Energy of latent heat difference resulted from phase transformation
E_{con}	-	Convection energy from the SMA sheet to the surrounding air
E_{in}	-	Inner energy from electrical current
E_{sio_2}	-	Energy of the heat change of the SiO_2
E_{sma}	-	Energy of the heat change of the SMA
h	-	Sheet height
h_h	-	Equivalent convective heat transfer coefficient during heating process
h_C	-	Equivalent convective heat transfer coefficient during cooling process
h_{SiO_2}	-	Thickness of SiO_2
h_{sma}	-	SMA thickness
i	-	Electrical current
l	-	Sheet length

l_{cu}	-	Length of the Cu wire
M_f	-	Finish temperature of martensite phase transformation
M_s	-	Start temperature of martensite phase transformation
t	-	Time
T_0	-	Initial temperature
T_{0_h}	-	Initial temperature of the sheet during heating process
T_{0_c}	-	Initial temperature of the sheet during cooling process
T_{f_h}	-	Final temperature of the sheet during heating process
T_{f_c}	-	Final temperature of the sheet during cooling process
t_{0_h}	-	Time moment at the beginning of the heating process
t_{0_c}	-	Time moment at the beginning of the cooling process
t_{f_h}	-	Time moment at the finishing of the heating process
t_{f_c}	-	Time moment at the finishing of the cooling process
w	-	Width of the sheet
$Y(\xi)$	-	Young's modulus
Y_A	-	Young's modulus of SMA's modulus at 100% austenite
Y_M	-	Young's modulus of SMA's modulus at 100% martensite
ε_{max}	-	Maximum SMA residual strain
ξ_{s_0}	-	Initial stress induced
ξ_0	-	Initial martensite fraction
ξ_0	-	Initial strain
ξ_T	-	Temperature-induced
ξ_s	-	Stress-induced
σ_0	-	Initial stress
ΔT	-	Temperature difference between the initial flat condition and the deformed state
α	-	Coefficient of thermal expansion
θ	-	Theta
$\Omega(\xi)$	-	Transformation tensor
β	-	Coefficient of thermo-elasticity
ξ	-	Martensite volume fraction

σ	-	Electrical resistivity
ρ_{SiO_2}	-	Densities of SiO_2
ρ_{cu}	-	Densities of Cu
ρ_{sma}	-	Densities of SMA

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

Microelectromechanical systems (MEMS) is a technology that has paved the way for achieving a variety of microactuators, which are mainly utilized to manipulate small objects in micro-scale. Their rapid advancements offer many benefits to various applications, especially in biomedical [1, 2] and microrobotics [3] fields. Microactuators can be classified based on their actuation principles to electrostatic, electromagnetic, piezoelectric, thermal and shape memory alloy (SMA) actuators [4]. These actuators have their own properties and advantages that allow them to be used in various applications depending on their requirements.

Electrostatic microactuators have been applied in many applications such as hard disc drives and aeronautical fields [5, 6]. These actuators provide fast response, small energy loss and reversible motion. However, they often suffer from a limited displacement range, short lifetime and high voltage requirements for their operation [1, 3]. Electromagnetic microactuators have been utilized in several devices, such as micropumps and optical switches [7, 8]. Yet, this type of actuator requires complicated control systems, due to its magnetic nature [9]. Piezoelectric microactuators are applied extensively in printers and digital cameras [10], due to their fast response, high accuracy and large stress tolerance [11]. Despite their advantages, piezoelectric actuators require high actuation voltages and involve a complicated fabrication process, which make them uncomplimentary [12]. Thermal microactuators have limited applications compared to other types of actuators, due to their slow response, high power consumption and the high temperature requirement for actuation [13]. One of the most popular types of thermal microactuators is the bimorph type, which actuates using the difference in the coefficient of thermal expansion (CTE) of two different materials. SMA microactuators is a type of thermal actuators that overcome the major drawbacks of conventional thermal microactuators.

SMA microactuators offer various advantages over other actuation techniques, such as high work density, large actuation force, simple mechanical structures, resistance to corrosion, low cost, biocompatibility and large actuation range [14]. Although this material was discovered in the mid-twentieth century, it has received a great deal of attention from researchers and, thus, it has been deployed in many application in various fields, such as microrobotics [3], micropumps [15], medical tools and biomedical applications [16]. Nonetheless, there is still room for improvement in terms of the design and fabrication of SMA microactuators in order to grasp better performance, simpler fabrication and a more rigid structure.

1.2 Problem Statement

Despite the significant work by many researchers on the bulk-micromachined SMA microactuators, the exploitation of this material has not been pushed to its boundaries in the area of microrobotics. There has not been a satisfactory advancement in SMA actuation mechanisms and integration techniques in order to improve the performance of SMA microactuators. These issues stand in the way of the implementation of SMA in many microactuators. Nonetheless, many SMA-based devices have been presented in recent years. However, there are several limiting issues that need to be highlighted and resolved to enhance the performance and allow further miniaturization of the overall size of these devices. One of these concerns is device fabrication process itself, which usually comprises several long steps that result in complex design and fabrication, high cost and low-resulted integrity [17-20]. Moreover, in order to assemble SMA-based devices, it often involves the assembly of multiple parts along with the SMA actuator such as heating circuit, couplings, bias spring, feedback sensor and joints [21-23]. This practice brought about bulky design, limited actuation, low degree of freedom, less actuation force and prosaic robustness. These issues can be addressed by adopting the integration of multiple SMA microactuators and a monolithic approach to form the device structure.

Another issue associated with microactuators is in cases where their movement tracking is required. The conventional approaches that have tackled this matter adopted the integration of sensors with actuators, which resulted in bulkier and costlier devices whose fabrication is rather complex. Therefore, this has limited the utilization of such actuators in implantable devices, where compactness is necessary to minimize their medical invasiveness. Consequently, more advanced actuators have incorporated a self-sensing mechanism that provides real-time movement feedback without the need for additional sensors or readout circuitry. However, these attempts were limited to piezoelectric actuators [24, 25] that involve complex implementation of the sensing process. A potential solution that allows both compactness and a passive device can be implemented by integration of an SMA actuator with a self-sensing element.

1.3 Research Objectives

The main objectives of this research are to develop bulk-micromachined SMA micromanipulators and an integrated wireless displacement sensing element. The specific objectives are:

1. To investigate the bulk-micromachined SMA bimorph actuation methods and the associated parameters that govern the actuation performance such as types and thickness of the stress layer as well as the depositing temperature.

2. To develop a multi-link integrated bulk-micromachined SMA micromanipulator with three degrees of freedom (DoF) and a gripper mechanism.

3. To design and fabricate a novel monolithic SMA micro-positioning stage that offers a three DoF.

4. To develop an SMA wireless displacement sensing method based on integration of an SMA spiral-coil actuator in a resonant circuit.

5. To characterize the performance of the developed actuators, including their temporal and thermal responses.

1.4 Scope of Research

The scope of this research focuses on the development of SMA devices using the integration of multiple SMA microactuators and monolithic approaches. Furthermore, this research studies SMA bimorph actuation methods, which uses internal Joule heating to actuate the SMA microactuators. In addition, using finite element analysis (FEA), the thermomechanical behavior and the thermal responses of SMA micromanipulators were simulated. The current flow distribution of the monolithic micro-positioning stage is also simulated. In term of the fabrication process, this study follows the standard and unconventional of MEMS fabrication techniques including conventional lithography, electroplating, etching processes, as well as the use of micro electrical discharged machining (μEDM) and plasma enhanced chemical vapor deposition (PECVD). In addition, the research examines the integration of a sensing element in an SMA actuator by utilizing a resonant circuit to develop a wireless displacement sensing device. The software that were used in the design and simulation are SolidWorks and COMSOL Multiphysics, respectively. For characterization purposes, different apparatus such as laser displacement sensor, force sensor, impedance analyzer, thermal camera, and microscope were used for displacement sensing, force measurement, resonant frequency tracking, thermal analysis, and microscopic imaging, respectively.

1.5 Research Contributions

The research proposes four significant contributions by developing SMA microactuators. These contributions can be highlighted as follows:

1. Simulation and characterization of SMA bimorph actuators in order to determine the optimal thickness of SMA and the stress layer as well as the depositing temperature. Based on these simulation results, an optimized design was fabricated using bulk-micromachined SMA bimorph actuators.

2. Development of a novel SMA micromanipulator structure by the integration of a sequence of SMA bimorph microactuators. The SMA micromanipulator has three DoF with a large actuation range and simple fabrication steps with a gripping mechanism.

3. A novel monolithic micro-positioning stage driven by six SMA microactuators. The device was fabricated in a single fabrication step and provided large displacement ranges.

4. A novel wireless displacement sensing method using resonant-based SMA actuators has been studied and experimentally demonstrated with a spiral-coil SMA actuator.

1.6 Potential Impact of the Research

The applications of MEMS-based actuators in robotics and biomedical areas are currently limited due to the factors of low actuation force, limited displacement range, bulky size, actuation mechanism and biocompatibility. The use of SMA bulk-micromachined actuators overcomes these weaknesses exceptionally well. It also paves the way for a variety of potential applications such as micro surgical tools and active catheters; for these applications, the SMA biomedical devices require compactness and biocompatibility that is essential for minimally invasive surgery. Therefore, the precise control as well as the high DoF of the developed SMA microactuators that form the final micromanipulator would be greatly beneficial [26-28].

Furthermore, this research introduces a monolithic SMA micro-positioning stage that has a three DoF movement. This monolithic approach has improved the fabrication process at a lower cost, it has also helped in maintaining structure robustness and reliable actuation. These features would potentially promote the application of SMA-based actuators in highly precise mechanisms. In addition, by using SMA and its shape memory effect, a spiral-coil actuator that has a self-sensing function has been developed. The utilization of this actuator in the form of a resonance circuit has allowed the implementation of a wireless displacement sensing that is passive and very compact in size. This method also eliminates the need for a wired interface, which is an important criterion for many biomedical devices such as implantable devices. The successful outcomes of this research are expected to promote advances in these device technologies in biomedical fields and beyond.

1.7 Thesis Outline

This thesis is divided into seven chapters. Chapter 1 is a general overview of MEMS microactuators applications followed by the problem statement, objectives and scope of the research. Chapter 2 presents the literature review of this research, which covers an overview of MEMS actuation mechanisms, SMA material properties and actuation methods, MEMS micromanipulators, micro-positioning stage and wireless displacement sensing. Chapter 3 presents the thermomechanical behavior analysis of the bimorph SMA structure and studies the parameters that affect the displacement of the microactuator. Chapter 4 proposes a new structure for an SMA micromanipulator by integrating a sequence of SMA bimorph microactuators with three DoF and a gripping mechanism. Chapter 5 reports the development of a novel three-DoF monolithic SMA micro-positioning stage capable of linear movements along *x*- and *y*-axes as well as rotational movements provided by six SMA actuated springs. Chapter 6 demonstrates a method that enables real-time displacement monitoring and control of micromachined resonant-type actuators using wireless radio frequency. Finally, the thesis concludes with chapter 7, where the key results and directions for future work are discussed. A list of publications arising from the thesis is given.

REFERENCES

[1] Nisar, A., N. Afzulpurkar, B. Mahaisavariya, and A. Tuantranont. 2008. MEMS-based micropumps in drug delivery and biomedical applications. *Sensors and Actuators B: Chemical*. 130(2): 917-942.

[2] Erismis, M. A., H. P. Neves, P. De Moor, R. Puers, and C. Van Hoof. 2010. A water-tight packaging of MEMS electrostatic actuators for biomedical applications. *Microsystem technologies*. 16(12): 2109-2113.

[3] Donald, B. R., C. G. Levey, C. D. McGray, I. Paprotny, and D. Rus. 2006. An untethered, electrostatic, globally controllable MEMS micro-robot. *Microelectromechanical Systems*. 15(1): 1-15.

[4] Bell, D., T. Lu, N. Fleck, and S. Spearing. 2005. MEMS actuators and sensors: observations on their performance and selection for purpose. *Journal of Micromechanics and Microengineering*. 15(7): S153-S164.

[5] Fan, L.-S., T. Hirano, J. Hong, P. Webb, W. Juan, W. Lee, *et al.* 1999. Electrostatic microactuator and design considerations for HDD applications. *IEEE Transactions on Magnetics*. 35(2): 1000-1005.

[6] Rashedin, R., T. Meydan, and F. Borza. 2006. Electromagnetic micro-actuator array for loudspeaker application. *Sensors and Actuators A: Physical*. 129(1): 118-120.

[7] Su, Y. and W. Chen. 2007. Investigation on electromagnetic microactuator and its application in micro-electro-mechanical system (MEMS). *International Conference on Mechanical and Automotive Engineering (ICMA 2007)*. Kagawa, Japan. 5-8 August. 3250-3254.

[8] Chang, H.-T., C.-Y. Lee, and C.-Y. Wen. 2007. Design and modeling of electromagnetic actuator in mems-based valveless impedance pump. *Microsystem Technologies*. 13(11-12): 1615-1622.

[9] Braun, S., N. Sandstrom, G. Stemme, and W. van der Wijngaart. 2009. Wafer-scale manufacturing of bulk shape-memory-alloy microactuators based on adhesive bonding of titanium–nickel sheets to structured silicon wafers. *Microelectromechanical Systems*. 18(6): 1309-1317.

[10] Uchino, K. 2008. Piezoelectric actuators 2006. *Journal of Electroceramics*. 20(3-4): 301-311.

[11] Nafea, M., Z. Mohamed, A. M. Abdullahi, M. A. Ahmad, and A. R. Husain. 2014. Dynamic hysteresis based modeling of piezoelectric actuators. *Jurnal Teknologi (Sciences and Engineering)*. 67(5): 9-13.

[12] Liu, G., Z. Yang, J. Liu, X. Li, H. Wang, T. Zhao, *et al.* 2014. A low cost, high performance insulin delivery system based on PZT actuation. *Microsystem Technologies*. 20(12): 2287-2294.

[13] Iamoni, S. and A. Somà. 2014. Design of an electro-thermally actuated cell microgripper. *Microsystem technologies*. 20(4-5): 869-877.

[14] Stirling, L., C.-H. Yu, J. Miller, E. Hawkes, R. Wood, E. Goldfield, *et al.* 2011. Applicability of shape memory alloy wire for an active, soft orthotic. *Journal of materials engineering and performance*. 20(4-5): 658-662.

[15] Xuesong, S., H. Yanling, G. Shuxiang, Y. Xiufen, and Y. Xiaonan. 2009. The development of a new type of compound peristaltic micropump. *IEEE International Conference on Robotics and Biomimetics (ROBIO 2009)*. Bangkok, Thailand. 22-25 February, 2009. 698-702.

[16] Fu, Y., H. Du, W. Huang, S. Zhang, and M. Hu. 2004. TiNi-based thin films in MEMS applications: a review. *Sensors and Actuators A: Physical*. 112(2): 395-408.

[17] De Sars, V., S. Haliyo, and J. Szewczyk. 2010. A practical approach to the design and control of active endoscopes. *Mechatronics*. 20(2): 251-264.

[18] Tzorakoleftherakis, E., A. Mavrommati, and A. Tzes. 2016. Design and Implementation of a Binary Redundant Manipulator with Cascaded Modules. *Journal of Mechanisms and Robotics*. 8(1): 011002-10.

[19] Giataganas, P., N. Iou, Y. Koveos, E. Kelasidi, and A. Tzes. 2011. Design and experimental evaluation of an innovative SMA-based tendon-driven redundant

endoscopic robotic surgical tool. *19th Mediterranean Conference on Control & Automation (MED)*. Corfu, Greece. 20 - 23 June. 1071-1075.

[20] Tung, A. T., B.-H. Park, D. H. Liang, and G. Niemeyer. 2008. Laser-machined shape memory alloy sensors for position feedback in active catheters. *Sensors and Actuators A: Physical*. 147(1): 83-92.

[21] Xu, K. and N. Simaan. 2010. Analytic formulation for kinematics, statics, and shape restoration of multibackbone continuum robots via elliptic integrals. *Journal of Mechanisms and Robotics*. 2(1): 011006-13.

[22] Ye, X., C. Hasson, W. J. Yoon, and J.-J. Cabibihan. 2015. Design of a steering mechanism for a Tethered Capsule Endoscope. *7th IEEE International Conference on Cybernetics and Intelligent Systems (CIS) and IEEE Conference on Robotics, Automation and Mechatronics (RAM)*. Angkor Wat, Cambodia. 15-17 July. 234-238.

[23] Colorado, J., A. Barrientos, C. Rossi, and K. Breuer. 2012. Biomechanics of smart wings in a bat robot: morphing wings using SMA actuators. *Bioinspiration & biomimetics*. 7(3): 036006.

[24] Law, W. W., W. Liao, and J. Huang. 2003. Vibration control of structures with self-sensing piezoelectric actuators incorporating adaptive mechanisms. *Smart Materials and Structures*. 12(5): 720.

[25] Moheimani, S. R. and Y. K. Yong. 2008. Simultaneous sensing and actuation with a piezoelectric tube scanner. *Review of Scientific Instruments*. 79(7): 073702.

[26] Crews, J. H. and G. D. Buckner. 2012. Design optimization of a shape memory alloy–actuated robotic catheter. *Journal of Intelligent Material Systems and Structures*. 23(5): 545-562.

[27] Kourambas, J., F. C. Delvecchio, R. Munver, and G. M. Preminger. 2000. Nitinol stone retrieval-assisted ureteroscopic management of lower pole renal calculi. *Urology*. 56(6): 935-939.

[28] Petrini, L. and F. Migliavacca. 2011. Biomedical applications of shape memory alloys. *Journal of Metallurgy*. 2011(501483): 1-15.

[29] Judy, J. W. 2001. Microelectromechanical systems (MEMS): fabrication, design and applications. *Smart materials and Structures*. 10(6): 1115.

[30] Maluf, N. and K. Williams. 2004. *Introduction to microelectromechanical systems engineering*. Boston, London: Artech House.

[31] Choudhary, N. and D. Kaur. 2016. Shape memory alloy thin films and heterostructures for MEMS applications: A review. *Sensors and Actuators A: Physical*. 242(3): 162-181.

[32] Chuang, W.-C., H.-L. Lee, P.-Z. Chang, and Y.-C. Hu. 2010. Review on the Modeling of Electrostatic MEMS. *Sensors*. 10(6): 6149-6171.

[33] Thielicke, E. and E. Obermeier. 2000. Microactuators and their technologies. *Mechatronics*. 10(4–5): 431-455.

[34] Chunchieh, H., C. Christophorou, K. Najafi, A. Naguib, and H. M. Nagib. 2002. An electrostatic microactuator system for application in high-speed jets. *Microelectromechanical Systems*. 11(3): 222-235.

[35] Poddar, A. and K. Pandey. 2000. Microwave switch using MEMS-technology. *8th IEEE International Symposium on High Performance Electron Devices for Microwave and Optoelectronic Applications*. Glasgow, Scotland. 13-14 November. 134-139.

[36] Ziaei, A., T. Dean, and Y. Mancuso. 2005. Lifetime characterization of capacitive RF MEMS switches. *Smart Materials and Structures*. San Diego, California. 20-22 May. 388-396.

[37] Watson, B., J. Friend, and L. Yeo. 2009. Piezoelectric ultrasonic micro/milli-scale actuators. *Sensors and Actuators A: Physical*. 152(2): 219-233.

[38] Conway, N. J., Z. J. Traina, and S.-G. Kim. 2007. A strain amplifying piezoelectric MEMS actuator. *Journal of Micromechanics and Microengineering*. 17(4): 781.

[39] Ölander, A. 1932. An electrochemical investigation of solid cadmium-gold alloys. *Journal of the American Chemical Society*. 54(10): 3819-3833.

[40] Greninger, A. B. and V. G. Mooradian. 1938. Strain Transformation in Metastable Beta Copper-Zinc and Beta Copper-Ti Alloys. *AIME TRANS*. 128(337-369.

[41] Kurdjumov, G. and L. Khandros. 1949. First reports of the thermoelastic behaviour of the martensitic phase of Au-Cd alloys. *Doklady Akademii Nauk SSSR*. 66(1): 211-213.

[42] Chang, L. and T. Read. 1951. Behavior of the elastic properties of AuCd. *Trans. Met. Soc. AIME*. 189(1): 47.

[43] Buehler, W. J., J. Gilfrich, and R. Wiley. 1963. Effect of low-temperature phase changes on the mechanical properties of alloys near composition TiNi. *Journal of applied physics*. 34(5): 1475-1477.

[44] Stoeckel, D. 1990. *Shape memory actuators for automotive applications*. London: Butterworth-Heinemann

[45] Bil, C., K. Massey, and E. J. Abdullah. 2013. Wing morphing control with shape memory alloy actuators. *Journal of Intelligent Material Systems and Structures*. 24(7): 879-898.

[46] Hartl, D. J. and D. C. Lagoudas. 2007. Aerospace applications of shape memory alloys. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*. 221(4): 535-552.

[47] Kheirikhah, M. M., S. Rabiee, and M. E. Edalat. 2011. A review of shape memory alloy actuators in robotics. *RoboCup 2010: Robot Soccer World Cup XIV*. ed: Springer. 206-217.

[48] Hwang, D. and T. Higuchi. 2014. A rotary actuator using shape memory alloy (SMA) wires. *IEEE/ASME Transactions on Mechatronics*. 19(5): 1625-1635.

[49] Morgan, N. B. 2004. Medical shape memory alloy applications—the market and its products. *Materials Science and Engineering: A*. 378(1–2): 16-23.

[50] Li, H., Y. Zheng, Y. Pei, and J. T. M. De Hosson. 2014. TiNi shape memory alloy coated with tungsten: a novel approach for biomedical applications. *Journal of Materials Science: Materials in Medicine*. 25(5): 1249-1255.

[51] Mohd Jani, J., M. Leary, A. Subic, and M. A. Gibson. 2014. A review of shape memory alloy research, applications and opportunities. *Materials & Design*. 56(4): 1078-1113.

[52] Sun, L. and W. Huang. 2009. Nature of the multistage transformation in shape memory alloys upon heating. *Metal Science and Heat Treatment*. 51(11): 573-578.

[53] Otsuka, K. and C. M. Wayman. 1999. *Shape memory materials*. Cambridge university press.

[54] Evirgen, A., I. Karaman, R. Santamarta, J. Pons, and R. Noebe. 2015. Microstructural characterization and shape memory characteristics of the Ni 50.3 Ti 34.7 Hf 15 shape memory alloy. *Acta Materialia*. 83(3): 48-60.

[55] Pruski, A. and H. Kihl. 1993. Shape memory alloy hysteresis. *Sensors and Actuators A: Physical*. 36(1): 29-35.

[56] Luo, H., E. Abel, X. Liu, Y. Liao, and Z. Wang. 2010. *Hysteresis behaviour and modeling of SMA actuators*. INTECH Open Access Publisher.

[57] Frenzel, J., E. P. George, A. Dlouhy, C. Somsen, M.-X. Wagner, and G. Eggeler. 2010. Influence of Ni on martensitic phase transformations in NiTi shape memory alloys. *Acta Materialia*. 58(9): 3444-3458.

[58] Tadaki, T., K. Otsuka, and K. Shimizu. 1988. Shape memory alloys. *Annual Review of Materials Science*. 18(1): 25-45.

[59] Kim, H. Y., S. Hashimoto, J. I. Kim, H. Hosoda, and S. Miyazaki. 2004. Mechanical properties and shape memory behavior of Ti-Nb alloys. *Materials Transactions*. 45(7): 2443-2448.

[60] Pemble, C. M. and B. C. Towe. 1999. A miniature shape memory alloy pinch valve. *Sensors and Actuators A: Physical*. 77(2): 145-148.

[61] Nespoli, A., S. Besseghini, S. Pittaccio, E. Villa, and S. Viscuso. 2010. The high potential of shape memory alloys in developing miniature mechanical devices: A review on shape memory alloy mini-actuators. *Sensors and Actuators A: Physical*. 158(1): 149-160.

[62] Miller, D. A. and D. C. Lagoudas. 2001. Influence of cold work and heat treatment on the shape memory effect and plastic strain development of NiTi. *Materials Science and Engineering: A*. 308(1): 161-175.

[63] Zhang, N., P. B. Khosrovabadi, J. Lindenhovius, and B. Kolster. 1992. TiNi shape memory alloys prepared by normal sintering. *Materials Science and Engineering: A*. 150(2): 263-270.

[64] Virgala, I., A. Gmiterko, and M. Kelemen. 2013. Motion Analysis of In-pipe Robot Based on SMA Spring Actuator. *Journal of Automation and Control*. 1(1): 21-25.

[65] Huitao, Y., M. Peisun, and C. Chongzhen. 2005. A novel in-pipe worming robot based on SMA. *IEEE International Conference Mechatronics and Automation*. Ontario, Canada. 29 July-1 August. 923-927.

[66] Mahvash, M. and P. E. Dupont. 2011. Stiffness control of surgical continuum manipulators. *IEEE Transactions on Robotics*. 27(2): 334-345.

[67] Mohamed Ali, M. S. and K. Takahata. 2010. Frequency-controlled wireless shape-memory-alloy microactuators integrated using an electroplating bonding process. *Sensors and Actuators A: Physical*. 163(1): 363-372.

[68] Luo, H. Y. and E. W. Abel. 2007. A comparison of methods for the training of NiTi two-way shape memory alloy. *Smart Materials and Structures*. 16(6): 2543.

[69] Yoo, Y. I., J. W. Jeong, J. J. Lee, and C. H. Lee. 2012. Effect of heat treatment on the two-way recovery stress of tube-shaped NiTi. *Journal of Intelligent Material Systems and Structures*. 23(10): 1161-1168.

[70] Huang, W. and H. B. Goh. 2001. On the long-term stability of two-way shape memory alloy trained by reheat treatment. *Journal of Materials Science Letters*. 20(19): 1795-1797.

[71] Huang, W. and W. Toh. 2000. Training two-way shape memory alloy by reheat treatment. *Journal of Materials Science Letters*. 19(17): 1549-1550.

[72] Liu, Y. and P. McCormick. 1990. Factors influencing the development of two-way shape memory in NiTi. *Acta Metallurgica et Materialia*. 38(7): 1321-1326.

[73] Urbina, C., S. De La Flor, F. Gispert, and F. Ferrando. 2013. Two-way shape memory efficiency of the Ti-Ni 54.4 wt. (%) enhanced by thermal treatments. *Functional Materials Letters*. 06(06): 1350057.

[74] Özgen, C., "Effect of stress assisted aging on superelastic behavior of a hot-rolled TiNi shape memory alloy," Middle East Technical University, 2011.

[75] Huang, W. M., H. B. Goh, and C. Li. 2002. Effects of reheat treatment conditions on two-way shape memory. *Journal of Materials Science Letters*. 21(13): 991-993.

[76] Wang, Z. G., X. T. Zu, X. D. Feng, L. B. Lin, S. Zhu, L. P. You, *et al.* 2003. Design of TiNi alloy two-way shape memory coil extension spring. *Materials Science and Engineering: A*. 345(1–2): 249-254.

[77] Duerig, T. W., K. Melton, and D. Stöckel. 2013. *Engineering aspects of shape memory alloys*. Butterworth-Heinemann.

[78] Tang, C., W. M. Huang, C. C. Wang, and H. Purnawali. 2012. The triple-shape memory effect in NiTi shape memory alloys. *Smart Materials and Structures*. 21(8): 085022.

[79] Tang, C., W. M. Huang, and C. C. Wang. 2013. From dual-shape/temperature memory effect to triple-shape memory effect in NiTi shape memory alloys. *Advances in Science and Technology*. 78(2): 1-6.

[80] Auricchio, F., R. L. Taylor, and J. Lubliner. 1997. Shape-memory alloys: macromodelling and numerical simulations of the superelastic behavior. *Computer methods in applied mechanics and engineering*. 146(3): 281-312.

[81] Poncin, P., C. Millet, J. Chevy, and J. Proft. 2004. The materials and processes for medical devices conference. *the materials and processes for medical devices conference*. Saint Paul, Minnesota. 25–27 August 279-283.

[82] Airoldi, G., G. Riva, and M. Vanelli. 1995. Superelasticity and shape memory effect in NiTi orthodontic wires. *Journal de Physique IV*. 5(C8): C8-1205-C8-1210.

[83] Idelsohn, S., J. Pena, D. Lacroix, J. Planell, F. Gil, and A. Arcas. 2004. Continuous mandibular distraction osteogenesis using superelastic shape

memory alloy (SMA). *Journal of Materials Science: Materials in Medicine*. 15(4): 541-546.

[84] Menna, C., F. Auricchio, and D. Asprone. 2015. *Applications of Shape Memory Alloys in Structural Engineering*. Elsevier Amsterdam.

[85] Kaya, A., I. Kaya, and H. E. Karaca. 2015. U-Shape Slot Antenna Design with High-Strength Ni54Ti46 Alloy. *Arabian Journal for Science and Engineering*. 40(9): 1-11.

[86] Benard, W. L., H. Kahn, A. H. Heuer, and M. A. Huff. 1998. Thin-film shape-memory alloy actuated micropumps. *Microelectromechanical Systems*. 7(2): 245-251.

[87] Fu, Y., W. Huang, H. Du, X. Huang, J. Tan, and X. Gao. 2001. Characterization of TiNi shape-memory alloy thin films for MEMS applications. *Surface and Coatings Technology*. 145(1): 107-112.

[88] Ishida, A. and V. Martynov. 2002. Sputter-deposited shape-memory alloy thin films: properties and applications. *Mrs Bulletin*. 27(02): 111-114.

[89] Krulevitch, P., A. P. Lee, P. B. Ramsey, J. C. Trevino, J. Hamilton, and M. A. Northrup. 1996. Thin film shape memory alloy microactuators. *Microelectromechanical Systems*. 5(4): 270-282.

[90] Paik, J. K., E. Hawkes, and R. J. Wood. 2010. A novel low-profile shape memory alloy torsional actuator. *Smart Materials and Structures*. 19(12): 125014.

[91] Mohamed Ali, M. S., B. Bycraft, A. Bsoul, and K. Takahata. 2013. Radio-Controlled Microactuator Based on Shape-Memory-Alloy Spiral-Coil Inductor. *Microelectromechanical Systems*. 22(2): 331-338.

[92] Mohamed Ali, M. S. and K. Takahata. 2011. Wireless microfluidic control with integrated shape-memory-alloy actuators operated by field frequency modulation. *Journal of Micromechanics and Microengineering*. 21(7): 075005.

[93] Seguin, J.-L., M. Bendahan, A. Isalgue, V. Esteve-Cano, H. Carchano, and V. Torra. 1999. Low temperature crystallised Ti-rich NiTi shape memory alloy films for microactuators. *Sensors and Actuators A: Physical*. 74(1): 65-69.

[94] König, D., R. Zarnetta, A. Savan, H. Brunken, and A. Ludwig. 2011. Phase transformation, structural and functional fatigue properties of Ti–Ni–Hf shape memory thin films. *Acta Materialia*. 59(8): 3267-3275.

[95] Kahn, H., M. A. Huff, and A. H. Heuer. 1998. The TiNi shape-memory alloy and its applications for MEMS. *Journal of Micromechanics and Microengineering*. 8(3): 213.

[96] Zhigang, W., J. Hewit, E. Abel, A. Slade, and B. Steele. 2005. Development of A Shape Memory Alloy Actuator for Transanal Endoscopic Microsurgery. *27th IEEE Annual International Conference of the Engineering in Medicine and Biology Society (EMBS 2005)*. 17-18 Jan. 2006. 4341-4344.

[97] Reynaerts, D., J. Peirs, and H. Van Brussel. 1997. An implantable drug-delivery system based on shape memory alloy micro-actuation. *Sensors and Actuators A: Physical*. 61(1–3): 455-462.

[98] Sugawara, T., K.-i. Hirota, M. Watanabe, T. Mineta, E. Makino, S. Toh, *et al*. 2006. Shape memory thin film actuator for holding a fine blood vessel. *Sensors and Actuators A: Physical*. 130(8): 461-467.

[99] Paik, J. K. and R. J. Wood. 2012. A bidirectional shape memory alloy folding actuator. *Smart Materials and Structures*. 21(6): 065013.

[100] Mineta, T., S. Kudoh, E. Makino, T. Kawashima, and T. Shibata. 2011. Accurate and simple assembly process of shape memory alloy tubular micro manipulator with a bias mechanism. *Microelectronic Engineering*. 88(8): 2683-2686.

[101] Pieczyska, E., M. Staszczak, V. Dunić, R. Slavković, H. Tobushi, and K. Takeda. 2014. Development of Stress-Induced Martensitic Transformation in TiNi Shape Memory Alloy. *Journal of Materials Engineering and Performance*. 23(7): 2505-2514.

[102] Bellouard, Y., T. Lehnert, J.-E. Bidaux, T. Sidler, R. Clavel, and R. Gotthardt. 1999. Local annealing of complex mechanical devices: a new approach for developing monolithic micro-devices. *Materials Science and Engineering: A*. 273(0): 795-798.

[103] Clausi, D., H. Gradin, S. Braun, J. Peirs, G. Stemme, D. Reynaerts, *et al.* 2009. Microactuation utilizing wafer-level integrated SMA wires. *22nd International Conference on Micro Electro Mechanical Systems (MEMS 2009)* Sorrento, Italy. 25-29 January. 1067-1070.

[104] Noh, H.-s., K.-s. Moon, A. Cannon, P. J. Hesketh, and C. Wong. 2004. Wafer bonding using microwave heating of parylene intermediate layers. *Journal of Micromechanics and Microengineering*. 14(4): 625.

[105] Kim, Y.-K., E.-K. Kim, S.-W. Kim, and B.-K. Ju. 2008. Low temperature epoxy bonding for wafer level MEMS packaging. *Sensors and Actuators A: Physical*. 143(2): 323-328.

[106] Niklaus, F., P. Enoksson, E. Kälvesten, and G. Stemme. 2001. Low-temperature full wafer adhesive bonding. *Journal of Micromechanics and Microengineering*. 11(2): 100.

[107] Yeun-Ho, J. and M. G. Allen. 2008. A Micromachined Chip-to-Board Interconnect System Using Electroplating Bonding Technology. *IEEE Transactions on Advanced Packaging*. 31(2): 357-366.

[108] Stevens, J. M. and G. D. Buckner. 2004. Actuation and Control Strategies for Miniature Robotic Surgical Systems. *Journal of Dynamic Systems, Measurement, and Control*. 127(4): 537-549.

[109] Shih-An, L., W. Chung-Wei, C. Yi-Hong, L. Chia-Hung, Y. Min-Hao, L. Yi-Chun, *et al.* 2012. Servo motor controller design for robotic manipulator. *International Symposium on Intelligent Signal Processing and Communication Systems (ISPACS 2012)*. New Taipei, Taiwan. 4-7 Nov. 2012. 254-257.

[110] Xie, Y., Y. Tan, and R. Dong. 2013. Nonlinear modeling and decoupling control of XY micropositioning stages with piezoelectric actuators. *IEEE/ASME Transactions on Mechatronics*. 18(3): 821-832.

[111] de Jong, B. R., D. M. Brouwer, M. J. de Boer, H. V. Jansen, H. M. Soemers, and G. J. Krijnen. 2010. Design and fabrication of a planar three-DOFs MEMS-based manipulator. *Microelectromechanical Systems*. 19(5): 1116-1130.

[112] Lin, S., S. Chang, and B. Li. 2014. Gearshift control system development for direct-drive automated manual transmission based on a novel electromagnetic actuator. *Mechatronics*. 24(8): 1214-1222.

[113] Liang, Q., D. Zhang, Z. Chi, Q. Song, Y. Ge, and Y. Ge. 2011. Six-DOF micro-manipulator based on compliant parallel mechanism with integrated force sensor. *Robotics and Computer-Integrated Manufacturing*. 27(1): 124-134.

[114] Davis, B. A. October, 2005. 2005. Investigation of the thermomechanical response of shape memory alloy hybrid composite beams. *North Carolina State University, Raleigh, NC, USA*. Raleigh, NC. NASA/CR-2005-213929.

[115] Du, Y., B. Liu, M. Xu, E. Dong, S. Zhang, and J. Yang. 2015. Dynamic characteristics of planar bending actuator embedded with shape memory alloy. *Mechatronics*. 25(0): 18-26.

[116] Kaneko, S., S. Aramaki, K. Arai, Y. Takahashi, H. Adachi, and K. Yanagisawa. 1996. Multi-Freedom Tube Type Manipulator with SMA Plate. *Journal of Intelligent Material Systems and Structures*. 7(3): 331-335.

[117] Nicolas Chaillet, Moustapha Hafez, and P. Lambert. 2013. Actuators for Microrobotics. *Microrobotics for micromanipulation*. N. Chaillet and S. Régnier. Eds. ed Hoboken, NJ: John Wiley & Sons, Inc.

[118] Abadie, J., N. Chaillet, and C. Lexcellent. 2009. Modeling of a new SMA micro-actuator for active endoscopy applications. *Mechatronics*. 19(4): 437-442.

[119] Yoon, H.-S., H.-J. Cha, J. Chung, and B.-J. Yi. 2013. Compact design of a dual master-slave system for maxillary sinus surgery. *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2013)*. 5027-5032.

[120] Li, Z., R. Du, M. C. Lei, and S. M. Yuan. 2011. Design and analysis of a biomimetic wire-driven robot arm. *International Mechanical Engineering Congress and Exposition (ASME 2011)*. Colorado, USA. 11-17 November. 191-198.

[121] Ho, M., Y. Kim, S. S. Cheng, R. Gullapalli, and J. P. Desai. 2015. Design, development, and evaluation of an MRI-guided SMA spring-actuated

neurosurgical robot. *The International journal of robotics research*. 34(8): 1147-1163.

[122] Lim, G., K. Park, M. Sugihara, K. Minami, and M. Esashi. 1996. Future of active catheters. *Sensors and Actuators A: Physical*. 56(1–2): 113-121.

[123] Mineta, T., T. Mitsui, Y. Watanabe, S. Kobayashi, Y. Haga, and M. Esashi. 2002. An active guide wire with shape memory alloy bending actuator fabricated by room temperature process. *Sensors and Actuators A: Physical*. 97–98(1): 632-637.

[124] Lan, C.-C., J.-H. Wang, and C.-H. Fan. 2009. Optimal design of rotary manipulators using shape memory alloy wire actuated flexures. *Sensors and Actuators A: Physical*. 153(2): 258-266.

[125] Bellouard, Y., R. Clavel, J.-E. Bidaux, R. Gotthardt, and T. Sidler. 1997. A concept for monolithic shape memory alloy micro-devices. *Le Journal de Physique IV*. 7(C5): C5-603-C5-608.

[126] Bellouard, Y., R. Clavel, R. Gotthardt, J. Bidaux, and T. Sidler. 1998. A New Concept of Monolithic Shape Memory Alloy Micro-Devices Used in Micro-Robotics. *6th International Conference in Actuator*. Bremen, Germany. 17-19 June. 499-502.

[127] Zhang, H., Y. Bellouard, T. C. Sidler, E. Burdet, A.-N. Poo, and R. Clavel. 2001. Monolithic Shape Memory Alloy microgripper for 3D assembly of tissue engineering scaffolds. *Intelligent Systems and Advanced Manufacturing*. 50-60.

[128] Bellouard, Y., A. Sulzmann, J. Jacot, and R. Clavel. 1998. Design and highly accurate 3D displacement characterization of monolithic SMA microgripper using computer vision. *Intelligent Systems & Advanced Manufacturing*. Pittsburgh, Pennsylvania. 1-2 January. 2-11.

[129] Bellouard, Y., T. Lehnert, R. Clavel, T. Sidler, and R. Gotthardt. 2001. Laser annealing of shape memory alloys: A versatile tool for developing smart micro-devices. *Le Journal de Physique IV*. 11(PR8): 571-576.

[130] Malukhin, K. and K. Ehmann. 2008. Development of A Monolithic Shape Memory Alloy Manipulator. *Micro-Assembly Technologies and Applications*. ed: Springer. 243-250.

[131] Kwon, J., J. Hong, Y.-S. Kim, D.-Y. Lee, K. Lee, S.-m. Lee, *et al.* 2003. Atomic force microscope with improved scan accuracy, scan speed, and optical vision. *Review of Scientific Instruments*. 74(10): 4378-4383.

[132] Dai, R., T.-b. Xie, W. Gong, and S.-p. Chang. 2008. A high precision profilometer based on vertical scanning microscopic interferometry. *Journal of Shanghai University (English Edition)*. 12(3): 255-260.

[133] Wang, J. and S. Guo. 2008. Development of a precision parallel micro-mechanism for nano tele-operation. *International Journal of Robotics and Automation*. 23(1): 56-63.

[134] Ihn, Y., S.-H. Ji, H. Moon, H. Choi, and J. Koo. 2012. A dual step precision multi-DOF stage for maskless digital lithography. *Microsystem Technologies*. 18(9-10): 1741-1750.

[135] Fleming, A. J. 2011. Dual-Stage Vertical Feedback for High-Speed Scanning Probe Microscopy. *IEEE Transactions on Control Systems Technology*. 19(1): 156-165.

[136] Gozen, B. A. and O. B. Ozdoganlar. 2012. Design and evaluation of a mechanical nanomanufacturing system for nanomilling. *Precision Engineering*. 36(1): 19-30.

[137] Stilson, S., A. McClellan, and S. Devasia. 2001. High-speed solution switching using piezo-based micropositioning stages. *IEEE Transactions on Biomedical Engineering*. 48(7): 806-814.

[138] Yao, Q., J. Dong, and P. M. Ferreira. 2007. Design, analysis, fabrication and testing of a parallel-kinematic micropositioning XY stage. *International Journal of Machine Tools and Manufacture*. 47(6): 946-961.

[139] Cai, K., Y. Tian, F. Wang, D. Zhang, and B. Shirinzadeh. 2016. Development of a piezo-driven 3-DOF stage with T-shape flexible hinge mechanism. *Robotics and Computer-Integrated Manufacturing*. 37(C): 125-138.

[140] Guo, Z., Y. Tian, C. Liu, F. Wang, X. Liu, B. Shirinzadeh, *et al*. 2015. Design and control methodology of a 3-DOF flexure-based mechanism for micro/nano-positioning. *Robotics and Computer-Integrated Manufacturing*. 32(4): 93-105.

[141] Tian, Y., B. Shirinzadeh, and D. Zhang. 2010. Design and dynamics of a 3-DOF flexure-based parallel mechanism for micro/nano manipulation. *Microelectronic engineering*. 87(2): 230-241.

[142] Dong, W., J. Tang, and Y. ElDeeb. 2009. Design of a linear-motion dual-stage actuation system for precision control. *Smart materials and structures*. 18(9): 095035.

[143] Sasaki, M., F. Bono, and K. Hane. 2008. Large-displacement micro-XY-stage with paired moving plates. *Japanese Journal of Applied Physics*. 47(4S): 3226.

[144] Olfatnia, M., L. Cui, P. Chopra, and S. Awtar. 2013. Large range dual-axis micro-stage driven by electrostatic comb-drive actuators. *Journal of Micromechanics and Microengineering*. 23(10): 105008.

[145] Xiao, S. and Y. Li. 2013. Optimal design, fabrication, and control of an micropositioning stage driven by electromagnetic actuators. *IEEE Transactions on Industrial Electronics*. 60(10): 4613-4626.

[146] Petit, L., A. Hassine, J. Terrien, F. Lamarque, and C. Prelle. 2014. Development of a Control Module for a Digital Electromagnetic Actuators Array. *IEEE Transactions on Industrial Electronics*. 61(9): 4788-4796.

[147] Kim, M., J.-h. Jeong, H. Kim, and D. Gweon. 2015. A six-degree-of-freedom magnetic levitation fine stage for a high-precision and high-acceleration dual-servo stage. *Smart Materials and Structures*. 24(10): 105022.

[148] Wang, N., X. Liang, and X. Zhang. 2014. Design and Analysis of a Novel XY Micro-positioning Stage Used Corrugated Flexure Beams. *Intelligent Robotics and Applications*. X. Zhang, H. Liu, Z. Chen, and N. Wang. Eds. ed Switzerland: Springer. 586-595.

[149] Izhar, U., A. Izhar, and S. Tatic-Lucic. 2011. A multi-axis electrothermal micromirror for a miniaturized OCT system. *Sensors and Actuators A: Physical*. 167(2): 152-161.

[150] Espinosa, A., K. Rabenorosoa, C. CLevy, B. Komati, P. Lutz, X. Zhang, *et al.* 2014. Piston motion performance analysis of a 3dof electrothermal mems scanner for medical applications. *International Journal of Optomechatronics*. 8(3): 179-194.

[151] Dahmardeh, M., M. Ali, M. Sultan, T. Saleh, T. M. Hian, M. V. Moghaddam, *et al.* 2013. High-power MEMS switch enabled by carbon-nanotube contact and shape-memory-alloy actuator. *physica status solidi (a)*. 210(4): 631-638.

[152] Buchaillot, L., Y. Nakamura, S. Nakamura, and H. Fujita. 1999. Thin Film of Titanium/Nickel Shape Memory Alloy for Multi-Degree of Freedom Microactuators. *Production research*. 51(8): 642-643.

[153] Hubert, A., N. Calchand, Y. Le Gorrec, and J.-Y. Gauthier. 2012. Magnetic Shape Memory Alloys as smart materials for micro-positioning devices. *Advanced electromagnetics*. 1(2): 75-84.

[154] Bassiuny, A., M. Ismail, and E. Bakr. 2014. Fuzzy Incremental Controller for SMA Smart Actuator With Application to Micro-Positioning. *Journal of Control Engineering and Technology*. 4(1): 58-65.

[155] Hiroki, C., T. Yamamoto, Y. Takeda, A. Suzuki, and T. Sakuma. 2010. Exploitation of shape memory alloy actuator using resistance feedback control and its development. *Progress in Natural Science: Materials International*. 20(11): 97-103.

[156] Moilanen, H. and S. Leppävuori. 2001. Laser interferometric measurement of displacement-field characteristics of piezoelectric actuators and actuator materials. *Sensors and Actuators A: Physical*. 92(1): 326-334.

[157] Horsley, D. A., N. Wongkomet, R. Horowitz, and A. P. Pisano. 1999. Precision positioning using a microfabricated electrostatic actuator. *IEEE Transactions on Magnetics*. 35(2): 993-999.

[158] Chu, L. L. and Y. B. Gianchandani. 2003. A micromachined 2D positioner with electrothermal actuation and sub-nanometer capacitive sensing. *Journal of Micromechanics and Microengineering*. 13(2): 279.

[159] Ozbey, B., E. Unal, H. Ertugrul, O. Kurc, C. M. Puttlitz, V. B. Erturk, *et al*. 2014. Wireless Displacement Sensing Enabled by Metamaterial Probes for Remote Structural Health Monitoring. *Sensors*. 14(1): 1691-1704.

[160] Shan, Y., J. E. Speich, and K. K. Leang. 2008. Low-cost IR reflective sensors for submicrolevel position measurement and control. *IEEE/ASME Transactions on Mechatronics*. 13(6): 700-709.

[161] Xiong, J., F. Li, N. Zhao, and N. Jiang. 2014. Tracking and Recognition of Multiple Human Targets Moving in a Wireless Pyroelectric Infrared Sensor Network. *Sensors*. 14(4): 7209-7228.

[162] Jia, P. and D. Wang. 2012. Self-calibrated non-contact fibre-optic Fabry–Perot interferometric vibration displacement sensor system using laser emission frequency modulated phase generated carrier demodulation scheme. *Measurement Science and Technology*. 23(11): 115201.

[163] de Jesus Rangel-Magdaleno, J., R. de Jesus Romero-Troncoso, R. A. Osornio-Rios, E. Cabal-Yepez, and A. Dominguez-Gonzalez. 2010. FPGA-based vibration analyzer for continuous CNC machinery monitoring with fused FFT-DWT signal processing. *IEEE Transactions on Instrumentation and Measurement*. 59(12): 3184-3194.

[164] Pan, B., K. Qian, H. Xie, and A. Asundi. 2009. Two-dimensional digital image correlation for in-plane displacement and strain measurement: a review. *Measurement science and technology*. 20(6): 062001.

[165] Koshimizu, C., "Resonant circuit for measuring temperature profile of a semiconductor substrate," USA Patent, 2004.

[166] Wang, Y., Y. Jia, Q. Chen, and Y. Wang. 2008. A passive wireless temperature sensor for harsh environment applications. *Sensors*. 8(12): 7982-7995.

[167] DeHennis, A. and K. D. Wise. 2002. A double-sided single-chip wireless pressure sensor. *15th IEEE International Conference on Micro Electro Mechanical Systems*. Las Vegas, USA. 20-24 January. 252-255.

[168] Tan, Q., H. Kang, J. Xiong, L. Qin, W. Zhang, C. Li, *et al*. 2013. A Wireless Passive Pressure Microsensor Fabricated in HTCC MEMS Technology for Harsh Environments. *Sensors*. 13(8): 9896-9908.

[169] Butler, J. C., A. J. Vigliotti, F. W. Verdi, and S. M. Walsh. 2002. Wireless, passive, resonant-circuit, inductively coupled, inductive strain sensor. *Sensors and Actuators A: Physical*. 102(1): 61-66.

[170] Wen, Y., P. Li, J. Yang, and M. Zheng. 2004. Detecting and evaluating the signals of wirelessly interrogational passive SAW resonator sensors. *IEEE Sensors Journal*. 4(6): 828-836.

[171] Bhadra, S., D. S. Tan, D. J. Thomson, M. S. Freund, and G. E. Bridges. 2013. A wireless passive sensor for temperature compensated remote pH monitoring. *IEEE Sensors Journal*. 13(6): 2428 - 2436.

[172] Hamsch, M., R. Hoffmann, W. Buff, M. Binhack, and S. Klett. 2004. An interrogation unit for passive wireless SAW sensors based on Fourier transform. *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*. 51(11): 1449-1456.

[173] Kaiser, T. 2006. Passive telemetric readout system. *IEEE Sensors Journal*. 6(5): 1340-1345.

[174] Tan, E. L., W. N. Ng, R. Shao, B. D. Pereles, and K. G. Ong. 2007. A wireless, passive sensor for quantifying packaged food quality. *Sensors*. 7(9): 1747-1756.

[175] Sridhar, V. and K. Takahata. 2009. A hydrogel-based passive wireless sensor using a flex-circuit inductive transducer. *Sensors and Actuators A: Physical*. 155(1): 58-65.

[176] Peterson, B. J., A. V. Olson, and T. J. Kaiser. 2010. A Wireless Sensor Interrogator Design for Passive Resonant Frequency Sensors Using Frequency Modulation Spectroscopy. *IEEE Sensors Journal*. 10(12): 1884-1890.

[177] Viswanath, A., S. R. Green, J. Kosel, and Y. B. Gianchandani. 2013. Metglas–Elgiloy bi-layer, stent cell resonators for wireless monitoring of viscosity and mass loading. *Journal of Micromechanics and Microengineering*. 23(2): 025010.

[178] Sivaramakrishnan, S. and R. Rajamani. 2007. Estimators for Inductive-Coupling Based Batteryless Wireless High-Frequency Sensing. *American Control Conference (ACC 2007)*. New York, USA. 9-13 July. 3642-3647.

[179] Cazeca, M. J., J. Mead, J. Chen, and R. Nagarajan. 2013. Passive wireless displacement sensor based on RFID technology. *Sensors and Actuators A: Physical*. 190(2): 197-202.

[180] Johnson, S. M. and D. J. Rowcliffe. 1985. Mechanical properties of joined silicon nitride. *Journal of the American Ceramic Society*. 68(9): 468-472.

[181] Tada, H., A. E. Kumpel, R. E. Lathrop, J. B. Slanina, P. Nieva, P. Zavracky, *et al*. 2000. Thermal expansion coefficient of polycrystalline silicon and silicon dioxide thin films at high temperatures. *Journal of applied physics*. 87(9): 4189-4193.

[182] Fu, Y., H. Du, S. Zhang, and S. E. Ong. 2005. Effects of silicon nitride interlayer on phase transformation and adhesion of TiNi films. *Thin Solid Films*. 476(2): 352-357.

[183] Romano, R. and E. A. Tannuri. 2009. Modeling, control and experimental validation of a novel actuator based on shape memory alloys. *Mechatronics*. 19(7): 1169-1177.

[184] Lott, C. D., T. W. McLain, J. N. Harb, and L. L. Howell. 2002. Modeling the thermal behavior of a surface-micromachined linear-displacement thermomechanical microactuator. *Sensors and Actuators A: Physical*. 101(1–2): 239-250.

[185] Yan, Q., L. Wang, B. Liu, J. Yang, and S. Zhang. 2012. A novel implementation of a flexible robotic fin actuated by shape memory alloy. *Journal of Bionic Engineering*. 9(2): 156-165.

[186] Tanaka, K. 1986. A thermomechanical sketch of shape memory effect: one-dimensional tensile behavior. *Res Mechanica*. 18(1): 251-263.

[187] Liang, C. and C. A. Rogers. 1990. One-dimensional thermomechanical constitutive relations for shape memory materials. *Journal of intelligent material systems and structures*. 1(2): 207-234.

[188] Flores, E. S. and M. Friswell. 2012. Multi-scale finite element model for a new material inspired by the mechanics and structure of wood cell-walls. *Journal of the Mechanics and Physics of Solids*. 60(7): 1296-1309.

[189] Yang, K. and C. Gu. 2008. Modelling, simulation and experiments of novel planar bending embedded SMA actuators. *Mechatronics*. 18(7): 323-329.

[190] Barbarino, S., E. S. Flores, R. Ajaj, I. Dayyani, and M. Friswell. 2014. A review on shape memory alloys with applications to morphing aircraft. *Smart materials and structures*. 23(6): 063001.

[191] Sun, L., W. M. Huang, Z. Ding, Y. Zhao, C. C. Wang, H. Purnawali, *et al*. 2012. Stimulus-responsive shape memory materials: A review. *Materials & Design*. 33(0): 577-640.

[192] Brinson, L. C. 1993. One-dimensional constitutive behavior of shape memory alloys: thermomechanical derivation with non-constant material functions and redefined martensite internal variable. *Journal of intelligent material systems and structures*. 4(2): 229-242.

[193] Miller, D. A. and D. C. Lagoudas. 2000. Thermomechanical characterization of NiTiCu and NiTi SMA actuators: influence of plastic strains. *Smart Materials and Structures*. 9(5): 640.

[194] Tobushi, H., T. Hachisuka, S. Yamada, and P.-H. Lin. 1997. Rotating-bending fatigue of a TiNi shape-memory alloy wire. *Mechanics of Materials*. 26(1): 35-42.

[195] AbuZaiter, A., M. Nafea, A. A. M. Faudzi, S. Kazi, and M. S. Mohamed Ali. 2015. Thermomechanical behavior of bulk NiTi shape-memory-alloy microactuators based on bimorph actuation. *Microsystem Technologies*. 22(8): 1-7.

[196] AbuZaiter, A., E. L. Ng, S. Kazi, and M. S. Mohamed Ali. 2015. Development of Miniature Stewart Platform Using TiNiCu Shape-Memory-Alloy Actuators. *Advances in Materials Science and Engineering*. 2015(9).

[197] Mohamed Ali, M. S., A. AbuZaiter, C. Schlosser, B. Bycraft, and K. Takahata. 2014. Wireless displacement sensing of micromachined spiral-coil actuator using resonant frequency tracking. *Sensors*. 14(7): 12399-12409.

[198] AbuZaiter, A. and M. S. M. Ali. 2014. Analysis of Thermomechanical Behavior of Shape-Memory-Alloy Bimorph Microactuator. *5th International*

Conference on Intelligent Systems Modelling and Simulation. Langkawi, Malaysia. 27-29 January. 390-393.

[199] AbuZaiter, A., E. L. Ng, M. S. M. Ali, and S. Kazi. 2015. Miniature parallel manipulator using TiNiCu shape-memory-alloy microactuators. *10th Asian Control Conference (ASCC2015)*. Kota Kinabalu, Malaysia. 31 May -3 June. 1-4.

[200] Abuzaiter, A., M. Nafea, A. A. M. Faudzi, S. Kazi, and M. S. M. Ali. 2014. Micromanipulator Based on Integrated Shape-Memory-Alloy Bimorph Actuators. *40th Micro & Nano Engineering (MNE 2014)*. Lausanne, Switzerland. 22-26 September. 70-72.

[201] AbuZaiter, A., M. Nafea, and M. S. M. Ali. 2016. Development of a Shape-Memory-Alloy Micromanipulator Based on Integrated Bimorph Microactuators. *Mechatronics*. *38*: 16-28.

[202] AbuZaiter, A., O. Faris, M. Nafea, and M. S. M. Ali. 2016. Design and Fabrication of a Novel XYθz Monolithic Micro-Positioning Stage Driven by NiTi Shape-Memory-Alloy Actuators. *Smart Materials and Structures*. (Submitted).