Chapter

The Roles of Piezoelectric Ultrasonic Motors in Industry 4.0 Era: Opportunities & Challenges

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Abstract

Piezoelectric Ultrasonic motors (USM) are based on the principle of converse piezoelectric effect i.e., vibrations occur when an electrical field is applied to piezoelectric materials. USMs have been studied several decades for their advantages over traditional electromagnetic motors. Despite having many advantages, they have several challenges too. Recently many researchers have started focusing on Industry 4.0 or Fourth Industrial revolution phase of the industry which mostly emphasis on digitization & interconnection of the entities throughout the life cycle of the product in an industrial network to get the best possible output. Industry 4.0 utilizes various advanced tools for carrying out the nexus between the entities & bringing up them on digital platform. The studies of the role of USMs in Industry 4.0 scenario has never been done till now & this article fills that gap by analyzing the piezoelectric ultrasonic motors in depth & breadth in the background of Industry 4.0. This article delivers the novel working principle, illustrates examples for effective utilization of USMs, so that it can buttress the growth of Industry 4.0 Era & on the other hand it also analyses the key Industry 4.0 enabling technologies to improve the performance of the USMs.

Keywords: piezoelectric ultrasonic motors, industry 4.0

1. Introduction

Increasing functionalities and weights/sizes reductions are critical issues for future aircrafts, space exploration vehicles, space instrumentations and industrial application etc. One challenge is the miniaturization of motors, wherein the efficiency of commonly used electromagnetic coil-based motors is dramatically reduced when their size less than centimeters scales. On the other hands, the rapid developments on piezoelectric ultrasonic motors (USMs) may fill the technical gap. Piezoelectric ultrasonic motors have been used in various technological fields from past decade in the gadgets, which we are using in our daily life i.e., a mobile phone to most advanced applications in aerospace. Recent advanced sciences & technologies developments on complex & tech-savvy products like satellites, mobile phones, camera lens, spaceships, automotive, robotics, biomedical instruments, manufacturing, etc., makes our life more convenient. These new products have raised new demands on modern motors like micro scale, light weight, high torque, no electromagnetic interference, low noise etc., which cannot be met by traditional motors. To make bridge for this gap, many scientists developed specialized motors, such as electrostatic motors, USMs, bionic motors, photo-thermal motors, shape memory alloy motors, microwave motors, etc. Among them, USMs have more advantages [1].

Although the first concept of USMs was invented in 1948, when just after the World War II, USMs have been used for practical applications in 1980s. It works on the principle of converse piezo electric effect *i.e.*, vibrations occur when an electrical field is applied to some piezoelectric structures. Similar to traditional electromagnetic motors this kind of motors comprises of stator & rotor, however, the difference is that a USM consists of piezoelectric structure, which is bonded to stator instead of coil and magnet pairs to make simpler and compact in size. In USMs, the piezoelectric structure is first vibrated in ultrasonic frequency band (>20 kHz), which in turn vibrates the stator when a driving voltage is applied in matched frequency. Thus, the frictional contact force between the stator & rotor or slider leads to the mechanical movement & torque. USMs can obtain high torque/weight ratio (torque density) in comparison with traditional electromagnetic motors because they are compact in structure & flexible in design. They are capable to drive the payloads directly without connecting to gear or gear train mechanism for some special applications. Most important that USMs quickly response commends in less than a few microseconds due to the advantages of piezoelectric materials and small inertia of rotors. Furthermore, they have capability of self-locking, high holding torque, precision motion control which can be utilized for application areas requiring high degree of precise motion for, e.g., medical operations & manufacturing or inspection of intricate products. In addition, USMs have zero electromagnetic interference which is one of the prominent applications in magnetic resonance imaging (MRI). USMs can also be operated in extreme temperature conditions which makes them first choice to use in aerospace application for e.g., space mission. Apart from above, they are silent during their operating cycle which makes them suitable for low noise applications [1].

Although USMs has many advantages, there are still several challenges remaining to achieve them in key areas like new design, motion control, piezoelectric material, friction & wear, thermal performance, modeling & optimization and advanced manufacturing technologies [2]. These challenges needed to be addressed in order to make USMs to be broadly utilized with its full potential in modern day industrial settings & diverse field of applications.

Fourth Industrial revolution or Industry 4.0 is the current phase of the industry wherein its emphasis on the digitization & interconnection of the products & services throughout the product life cycle i.e., from the birth of the product to the end of the life of product/services. Industry 4.0 relies mainly on various technological tools, which include but not limited to Big Data & AI analytics, Augmented reality (AR) Additive Manufacturing, Cyber Security, Industrial Internet of Things (IIoT), Autonomous Robots, Digital Twins, Horizontal & Vertical integrations & Cloud computing for carrying out the process of digitization & interconnection. Therefore, in this article, we not only take advantage of Industry 4.0 tools to improve the performance of the USMs but also promote the applications of USMs that can make them best fit into Industry 4.0 settings.

This chapter is divided into five sections. In the first section, we will introduce the history of development of USMs, types of USMs, structure & operating mechanism of USMs, and piezoelectric materials used. In the second section, the reviews of various articles, especially the publications in the last 5 years on ultrasonic motors from eclectic sources i.e., conference proceedings, journals, US patents & doctoral thesis. It analyses them & gives a brief bibliographic summary comprising of publication year, journal of publication, country of origin of research. The classification of USM technologies in different categories, which include mainly new design, motion control, piezoelectric material, friction & wear, thermal performance, modeling & optimization & provide comprehensive summary of the articles describing achievements, challenges & opportunities, will be presented in the third section. The fourth Section of this chapter will briefly introduce industry 4.0 & key enabling technologies, i.e., Big Data & Artificial Intelligence analytics, Augmented Reality, Additive manufacturing, Industrial internet of things (IIoT), Digital Twins & simulation. In the Fifth section, it will be addressed that the approaches to improve the overall performance of piezoelectric motors by effective utilizing key enabling technologies offered in Industry 4.0 settings. It further elaborates on the various types & applications of piezoelectric motors that can be utilized effectively to foster Industry 4.0 expectations.

2. Piezoelectric ultrasonic motors

Development of Piezoelectric USMs has been in progress since 1980. Piezoelectric motors worked on the principle of reverse piezoelectric effect i.e., electrical energy applied to piezoelectric substrate is converted into mechanical actuation or motion in this case it refers to vibration. These motors are known as "Ultrasonic Motors" since the frequency of vibration of the piezoelectric element inside the motor is in the range of ultrasonic frequency band i.e., greater than 20 kHz. The chronology of events in the development of ultrasonic motors is summarized in **Table 1** [1].

2.1 Classification

Ultrasonic Motors do not have a uniform methodology for classification because of the design flexibility & structural diversity [1]. For application point of view, USMs can be classified as rotary and linear type motors; from vibration shape, USMs can be classified as rod shape, π-shape, ring shape, and cylinder shape, from vibration characteristics, USMs can be classified as standing wave and propagating wave types; etc. More details of classification are done by viewing angle as illustrated in **Table 2** [1]. Classification is also done based upon the vibration type i.e., Longitudinal Vibration, Longitudinal Bending Vibration, Longitudinal-torsional vibration, Bending Vibrations & In-Plane vibrations [1].

2.2 Operating mechanism of USM

The most common USMs is the Traveling Wave Ultrasonic Motors (TRUMs) because of their simple constructions and broad applications. One typical TRUM is mainly composed with a stator, rotor, shell, bearing, spring, friction linear, PZT, base, etc. Piezoelectric ceramic is affixed to stator while rotor is affixed by friction liner [1]. Friction liner is bonded to a rotor, which contacts with stator through axial pressure. The traveling wave is formed by superposition of two mode responses with equal amplitude and phase difference $\pi/2$ both in time and space. If pre-pressure is applied to the rotor, then the vibration with micro amplitude of points on stator surface will be transformed to rotary motion of the rotor through frictional force. A structural diagram of TRUM is shown in **Figure 1** and the working principle of traveling wave, which is formed inside of the USM leading to the motion of the rotor, is presented in **Figure 2**. For successful development of the traveling wave, it is necessary that the two resonant modes with an identical frequency and mode shapes (standing waves) in an elastic body have $\pi/2$ phase difference both in

Year	Name of Scientist/ organization	Chronology of Events in the development of USM
1948	Williams and Brown	First patent of "piezo motor" was applied.
1965	Lavrinenko	Patent invention was granted for using piezoelectric plate to drive rotor.
1973	Barth from IBM	Two piezoelectric actuators to produce longitudinal vibration of horns was used. The rotor is driven by the contact friction between the rotor surface and end of the horns.
1975	Vishnevsky	The edge of a rectangular piezoelectric composite stator was pressed by the spring, which excited a longitudinal vibration mode to drive the rotor
1981	Lithuanian Vasiliev	An ultrasonic motor with the ability of driving larger loads of gramophone wheel. It became the first practical application of piezoelectric actuator.
1982	Sashida	A standing wave USM was designed. Piezoelectric ultrasonic motor met the performance requirements for actual applications for the first time.
1983	Sashida	Traveling wave USM was designed.
1985	Kumada	A longitudinal-torsional hybrid ultrasonic motor driven by single phase signal.
1987	Ishc from Panasonic, Inc	A ring type traveling wave ultrasonic motor based on Sashida's traveling wave motor.
1987	Canon Co.Ltd	The ring-type ultrasonic motor in the zoom lens of EOS camera was used first time in Engineering application
1995	Zhao, Chunsheng	A disk-type traveling wave ultrasonic motor

Table 1.
Summary of the development of ultrasonic motors [1].

Viewing Angle	Type
Wave propagation method	Traveling Wave, Standing Wave
Movement Output way	Rotational, Linear
Contact State between the stator & rotor	Contact, Non-contact
Excitation conditions of stator by piezoelectric components	Resonant, Non-Resonant
Number of degrees of freedom of the rotor	Single degree of freedom, multi-degree of freedom
Displacement of operating mode in direction	Out plane, In-plane
Geometric shape of stators	Disks, Ring, Bar & Shell
Rotary directions	Unidirectional, Bidirectional

Table 2.
The classification of UTM methodologies [1].

space and time [1] & quarter wavelength difference i.e., λ/4 [2]. Consider a point P on the stator the traveling process of point P is illustrated in **Figure 2a**–**d**. At time t = 0 point P is at initial position as shown in **Figure 2a**, at t = T/4, **Figure 2b** the wave propagates right the wave peak reaches point P further at t = T/2, **Figure 2c** wave & Point P moves λ/4 forward then at t = 3 T/4 **Figure 2d** wave valley reaches point P & at t = T point P reaches initial position [1].

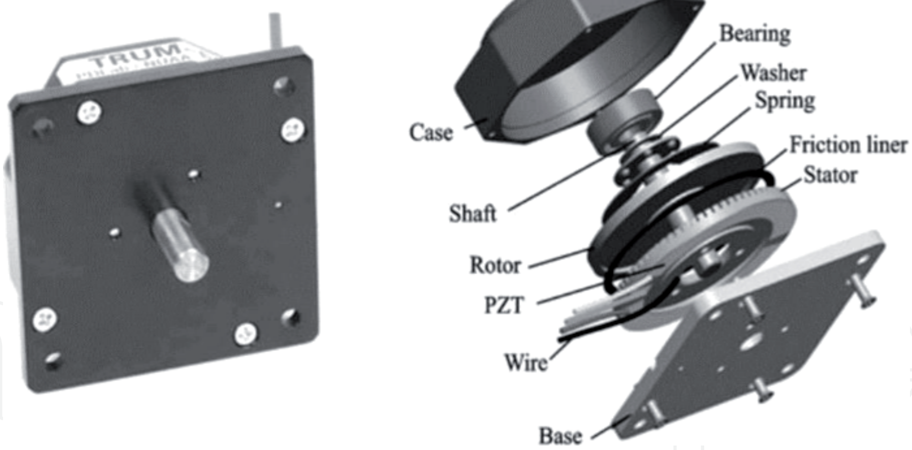

Figure 1.
Structural diagram of TRUM [1].

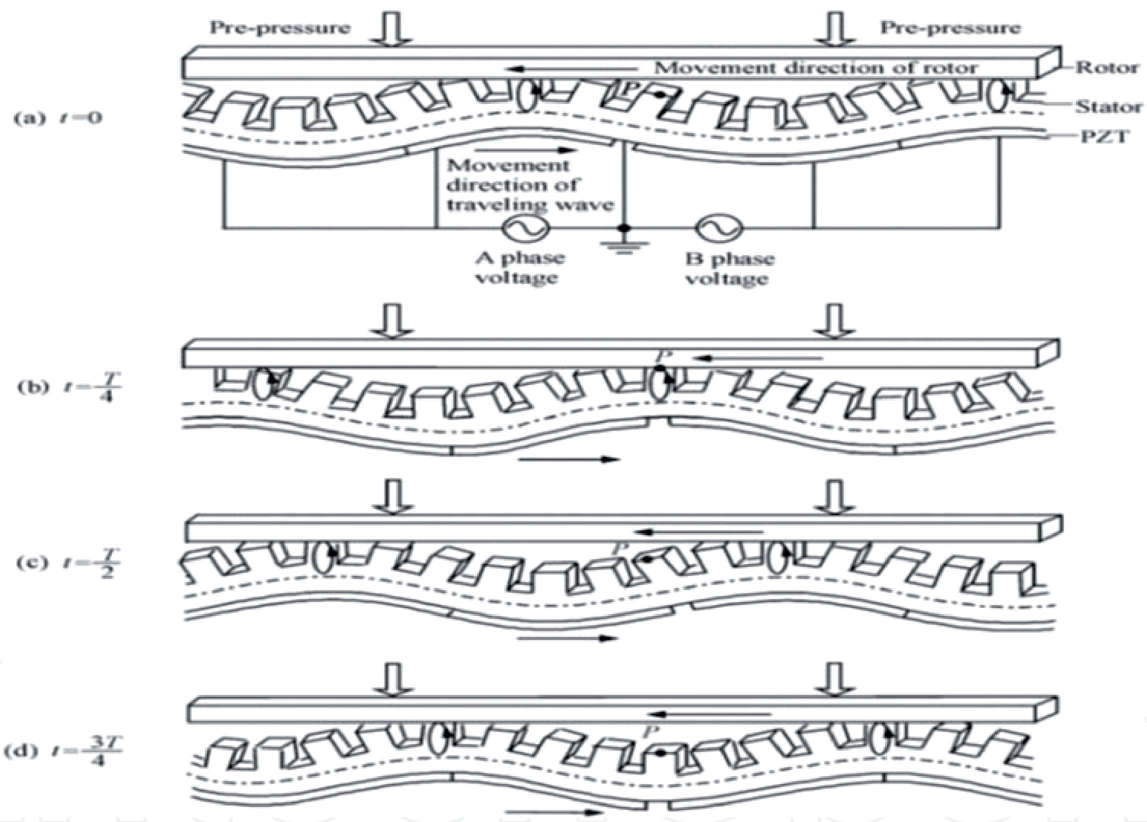

Figure 2.
Traveling wave mechanism of TRUM [1].

In order to achieve traveling wave, selection of right piezoelectric materials is required. Most commonly used piezoelectric materials are Barium Titanate BaTiO3, Lead Zirconate-lead titanate (PZT), relaxor ferroelectrics of $Pb(Mg_xNb_{1-x}O_3)$-$PbTiO_3$(PMN-PT) and $Pb(Zn_xNb_{1-x})O_3$-$PbTiO_3$(PZN-PT) single crystals [1].

3. Review on piezoelectric ultrasonic motors

This section provides a brief summary of the articles published since last 5 years since 2015 [2–298]. The articles are taken from eclectic resources like conference proceedings, high impact journals, patents & masters, Ph.D. thesis from reputed universities. After reviewing the articles, we found that most of the articles on ultrasonic motors found were stressing upon research areas like new design, modeling & optimization, motion control, friction & wear, piezoelectric materials used in USM, thermal performance, applications of USM & review papers. [2] We carried out statistical analysis for the research articles published on USM during this period. We plotted graph for number of publications with research areas (**Figure 3**), with year of publication (**Figure 4**), by country of research (**Figure 5**) & journal publication (**Figure 6**). From **Figure 3** one can see that majority of the articles published on USM stressed upon new design & modeling & optimization. **Figure 4** shows that gradual increase in the trend of number of publications. **Figure 5** indicates that countries like China & Japan are the leaders in doing research on USM. **Figure 6** shows journal "Ultrasonics" & "Sensors & Actuators A: Physical are the favorite among researchers & publishers for publishing articles on USM. In the following section, we are going

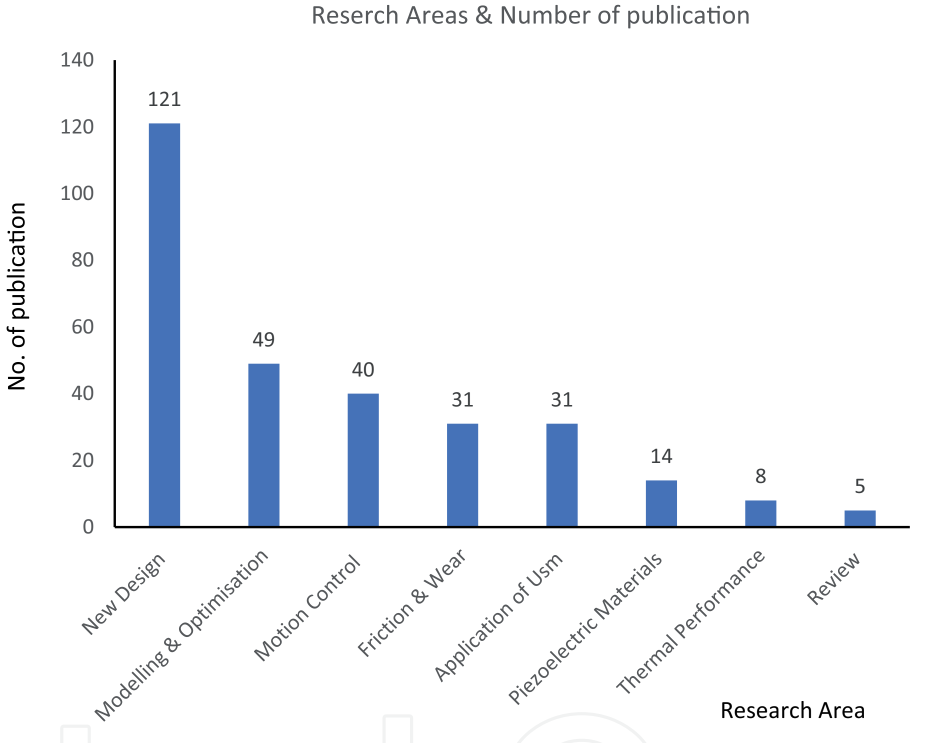

Figure 3.
Summary of number of publications in each research areas of USM in the years of 2015–2020.

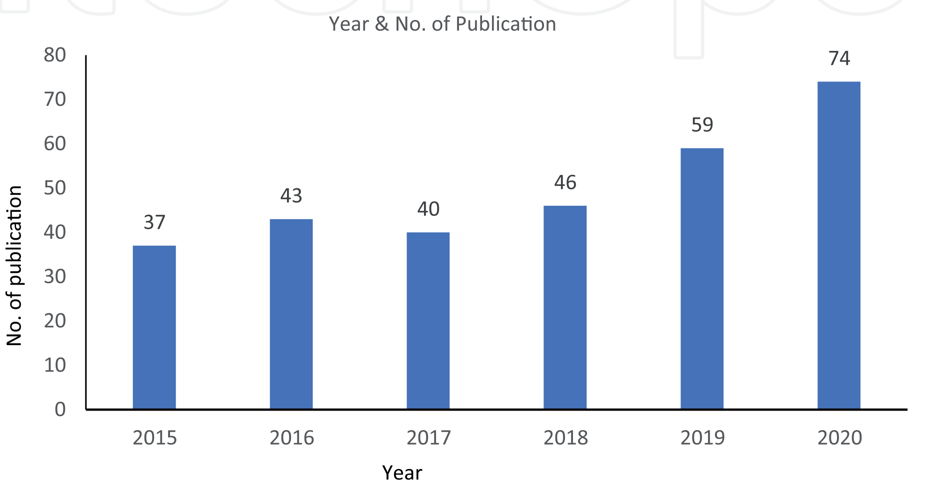

Figure 4.
Summary of number publications per year on USM from 2015 to 2020.

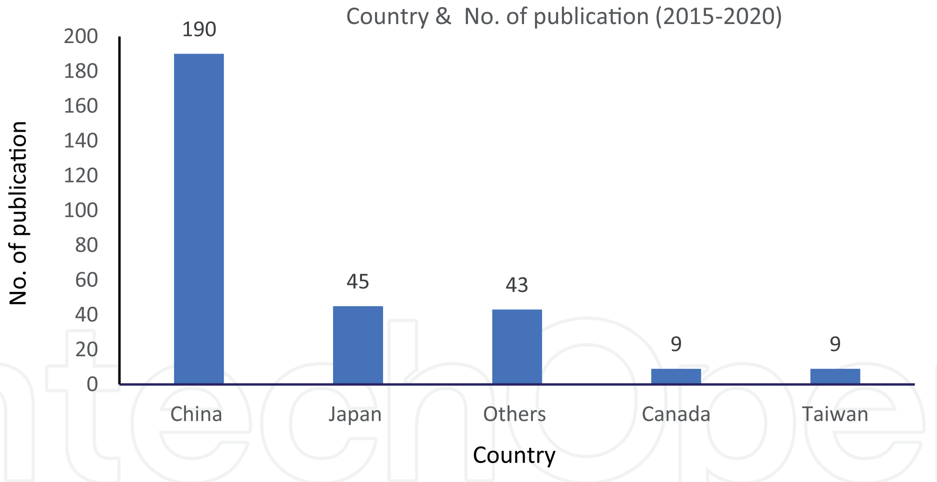

Figure 5.
Summary of USM publication numbers of author's country and region distribution.

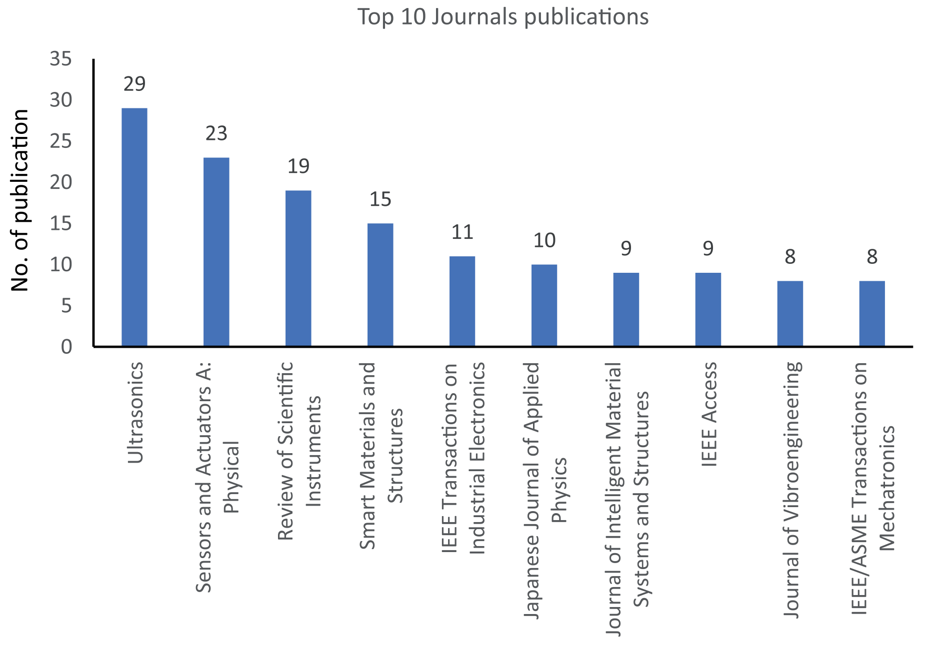

Figure 6.
Summary of USM publication numbers in the top ten journals.

to briefly discuss the achievements, challenges, & opportunities about those publications made in the areas identified above.

3.1 New design

In this section, we summarize the novel ideas proposed by the researchers for designing & developing ultrasonic motors as well as optimizing their designs in order to improve their efficiency & performance. The major objectives are to make UTMs with small size, high torque, and high-power density. Among them, miniaturization of the motor is the key challenge to achieve.

3.1.1 New developments for miniaturization

Since 2015 various research articles emphasized upon miniaturization, micro USM, scaling to sub millimeter range. Tomoaki Mashimo et al., a research group at Japan, develop serial of micro ultrasonic motor (μ-UTMs) with volume scale of a few cubic millimeters to submillimeter [3–10]. Those μ-UTMs include rotary and linear types for different applications. Don L. DeVoe et al. developed one of the smallest bulk PZT TRUMs capable of bidirectional motion with PZT stator of diameter 4.12 mmand 323 mN preload force. The motor stator was fabricated using micro powder blasting of homogeneous PZT sheet. It achieved a maximum speed of 30 rpm & stall torque of 501 mN-mm [11]. Yingxiang Liu et al. carried out an overall weight of 8.5 g longitudinal–bending hybrid linear USM, whichis able to achieve 487 mm/s no-load speed, the maximum output force of 2.3 N, and & weight of the prototype obtained, and respectively [12]. Qiquan Quan et al. developed U shaped piezoelectric ultrasonic motor that mainly focused on miniaturization and high-power density [13]. Fulin Wang et al. developed a miniature spherical ultrasonic motor using wire stators for directional adjustment of a vascular endoscopic camera [14]. Ho et al., proposed a miniaturized simple shear vibration piezoelectric screw-driven structure USM to drive the high precision linear motor [15]. Zhou et al., developed a novel a radius of 2 mm three-dimensional contact model of piezoelectric TRUM utilizing MEMS fabrication technology [16].

3.1.2 New developments for high power densities

In addition to miniaturization some researchers focused on high torque and power density aspects of piezo motors, Mizuno et al., developed a hybrid torsional/bending (T/B) modes USM to provide high driving force, large driving distance, and low weight, resulting into high torque density and high-power density [17]. It is constructured with rod-shaped transducer operating in torsional/bending (T/B) modes and excited two elliptical motions on its bilateral ends to drive the rotor orthogonally pressed onto the transducer. Chang et al., developed a ring-shaped traveling wave ultrasonic motor with a suspension stator for improving output power density [17]. The maximum stator vibration amplitude of 4.25 μm, which is nearly 4.7 times of that without suspension, with speed of 62 rpm and a stall torque of 49.5 mNm was observed, under a driving signal of 30 V_{pp} when the mass block was 0.30 g. Fan et al. developed a miniaturized ultrasonic motor with a high thrust–weight ratio by using the first order bending vibration mode (B1 mode) and second order bending vibration mode (B2 mode) to realize bidirectional movement through a single-phase driving signal [19]. Li et al., constructed screw-type USM with a three-wavelength exciting mode to achieve a high-output thrust [20].

In order to meet the requirement of large thrust & maximum output few research articles on the ultrasonic motors were based upon typical shapes, such as U-shape, V-shape, L-shaped, and Π-type. For instance, the structure of the linear ultrasonic motor with a laminated stator, which was made of two identically single U-shaped stators, was proposed by Sun et al., [36]. The testing results showed that the maximum output force of the laminated motors increases by 40% than that of single layer U-shaped motor, while the maximum velocity increased by 38%. Yao et al. proposed a novel large thrust-weight ratio V-shaped linear USM with a flexible joint operated in the coupled longitudinal-bending mode. The motor had a compact size and a simple structure with a large thrust-weight ratio (0.75 N/g) [37]. Furthermore, they also proposed a novel large thrust L-shaped linear USM utilizing the antisymmetric and symmetric modes of the L-shaped stator operating in a single resonance mode to realize the bidirectional motion of the slider [38]. In order to meet the demand of a linear ultrasonic motor with large thrust in narrow space, a novel Π-type linear ultrasonic motor with double driving feet was constructed [39]. The motor had structural stability and high dynamic performance, such as a no-load speed of 273 mm/s and 238 mm/s in two directions, corresponding to a maximal thrust of 80 N and 110 N. Wang et al., constructed a V-type motor having two driving feet and a simple structure, which torque applied to the motor was converted into a normal preload between the driving feet and the mover to avoid the use of a large preloading mechanism [40]. The maximum no-load velocities of the motor moving to the right and left are 85.2 mm/s and 76 mm/s, respectively, and the maximum output force is 1.96 N.

Light weight, high torque & desired output performance are some of the important features required in USMs. Niu et al., developed a light arch shaped, four legged linear & hollow USMs, which a light arc-shaped USM with the first-order longitudinal vibration mode and the second order bending vibration mode were superimposed in the stator plane, in order to meet the requirements [45]. The output torque of the USM under the single-stator configuration reached up to 2.6×10^{-2} N·m, and the double-stator which was 1.5 times greater than that under of single stator configuration.

To realize applications involving low speed and high torque in the high-performance actuator industry, especially in the aerospace field, a novel 70H (Hollow) TRUM with an outer diameter of 70 mm and an aperture ratio of 53% (the ratio between the aperture and outer diameter) with a mass of 210 g was developed [46]. The TRUM, The torque density of 11.43 N·m/kg, maximum no-load speed of 50 rpm, and the maximum stall torque 2.4 N·m were achieved.

The influence of the vibration mode of the stator and the structural dimensions of the metal elastomer and piezoelectric ceramic ring on the effective electromechanical coupling coefficient (EMCC) was analyzed by Niu et al. [47]. The efficiency of a hollow USM was improved by optimizing the stator's effective electromechanical coupling coefficient. In addition, a four-legged linear ultrasonic motor with a new structure which is the in-plane first-order longitudinal vibration mode and the out-of-plane anti-symmetric vibration mode superimposed to produce linear motion [48]. The USM consists of a stator and four groups of eight piezoelectric ceramic sheets. The experimental results for a prototype 600 × 160 mm showed the maximum translational speed could reach 135 mm/s and the maximum thrust of 3.6 N with a 200 V driving voltage. The USM had the advantages of simple structure and high output efficiency, which made it suitable for precision systems and industrial applications.

Izuhara et al. proposed a linear piezoelectric motor using a hollow rectangular stator that can translate a load placed inside it by a direct drive [49]. This stator structure enabled a quick response and high resolution by few components for controlling autofocus and zoom mechanisms in imaging devices.

3.1.3 Multiple degrees of freedom piezoelectric ultrasonic motor (multi-DOF-USM)

Shi et al., constructed a new type of multiple-degree-of-freedom (Multi-DOF) compact structure USM to achieve high output torque [33]. It consisted of a ring type composite stator with four driving feet uniformly arranged in the inner circumference of the ring stator. The stator employs two orthogonal axial bending modes and a radial bending mode, by exciting two of them simultaneously, to generate elliptic trajectories on driving feet tips and to push sphere rotor around x, y and z axis respectively. Su et al. improved the performance of a non-resonant piezoelectric motor, which is a symmetric piezoelectric linear motor driven by three-phase square-triangular waves signal and four-phase sine waves signal of peak to peak value 100 V at 100 Hz with 50 V offset [34]. The speeds of prototype reached 733 μm/s and 667 μm/s and the maximum thrust is 8.34 N and 6.31 N respectively. Similarly, a non-resonant linear ultrasonic motor utilizing longitudinal traveling waves was proposed by Liang Wang et al. [35]. The stator system was modeled by utilizing the transfer matrix method (TMM). The motor prototype achieved a maximum mean velocity of 115 mm/s and a maximum load of 0.25 N.

Li et al. proposed electromagnetic-piezoelectric hybrid driven three-degree-of-Freedom USM which is hybrid driven electromagnetic filed and electrical field [41]. In one of their design, a novel ball-type spherical multi-DOF USM, composed of three built-in stators and a hollow spherical rotor was developed and tested for the design of a compact multi-degree-of-freedom (multi-DOF) piezoelectric driven actuator [42]. The rotational speeds of X-axis, Y-axis and Z-axis can reach 29 r/min, 17 r/min and 16 r/min, respectively, when the frequency matches, which verifies the feasibility and rationality of the multi-DOF movement of the motor. They also proposed a multi-DOF spherical USM with built-in traveling wave stators, in which each traveling wave stator could be controlled independently and the spatial arrangement of the support structures [42]. The maximum speed achieved 45.6 rad/min with output torque of 1.265 Nm when an excitation voltage of 400 V with the preload of 100 N. The motor had the advantages of large output force and adjustable preload.

Kazokaitis et al., developed a novel design of a multi-DOF USM, which is combined the magnetic sphere type rotor and two oppositely placed ring-shaped piezoelectric actuators into one mechanism [44]. Such a structure increases impact force and allows rotation of the sphere with higher torque useful for attitude control systems used in small satellites.

3.1.4 Preload effect study

Contact mechanism between the stator & rotor is one of the important factors responsible for the efficient performance of the USMs. The studies of contact surface, contact mechanism, preloading method of USMs has been one of the prominent topics in the USM research field. Zhang et al., proposed a solution to reduce the radial sliding by optimizing the stator comb-teeth of a TRUM [50]. They further developed a 3D finite element model for longitudinal torsional USM by ADINA in order to study the mechanical simulation and contact analyses [51]. A novel hollow type USM, which the preload was applied from the bottom of the stator through a wave spring, was proposed, [52] It could not only enhance the anti-overload ability but also extended the working life of the motor.

Wang et al., analyzed the characteristics of a TRUM with considering the structural stiffness of the preload structure [53]. It demonstrated that the pre-pressure on the rotor was not a constant value because of the structural stiffness of the preload structure. In addition, it explained the driving mechanism of the TRUM under unsteady pre-pressure and deduced a dynamic model considering the stiffness of the preload structure.

In addition, contact force analysis by Hertz contact theory popped up in few research articles. Dong et al., carried out design and performance analysis of a TRUM with double vibrators [54]. The analytical model of double-vibrator motor was established based on elliptical distribution rule of surface point velocity, linear superposition of motions and contact force analysis under Hertz contact theory. Pan et al., focused on the coupling relationship between the flywheel vibration and the gimbal rotation through the variable stiffness of the bearing [54].

3.1.5 Multivibrators

Some research articles emphasized on novel idea of constructing USMs by using multivibrators. Yang et al. illustrated that TRUM with double vibrators can improve the output performance effectively [56]. Inheriting the concept of two traveling waves propagating in the stator and rotor, a dual traveling wave rotary ultrasonic motor (DTRUM) energized only in the stator was proposed. The experimental results showed that the performance of dual traveling wave TRUM was superior to the TRUM with single traveling wave. The no load speed was 60 rpm and the stalling torque was 0.85 Nm. They further presented, an optimal design of a double-vibrator USM using combination methods of finite element method, sensitivity analysis and adaptive genetic algorithm [57]. The measured results showed that this method was effective for the optimal design of ultrasonic motors. Lu et al. proposed a new idea for constructing the motor with the stator containing several vibrators fabricated by bonding piezoelectric ceramics (PZTs) to a metal base [58]. The longitudinal and bending modes were excited in the vibrators by two alternating current (AC) voltages with a 90° phase difference were applied. The bending vibrations of the vibrators were stacked to form the torsional vibration of the stator, ultimately generating longitudinal-torsional composite vibration. Mohammed & Zakariyya proposed an idea on the development of a new type of a linear USM with double cantilever vibrators [59]. The resonance frequencies of the vibrators were 21.33 kHz, and this was also the frequency in which the two vibrators were driven to determine the output parameter such as driving force and velocity.

Multi-vibration mode USMs and sandwich type USMs were designed & analyzed in some of the research articles. Zhou et al., developed a novel multi-mode differential USM with two sandwich-type transducers, which utilized the diverse combination of four vibration modes: symmetrical and anti-symmetrical first longitudinal modes, symmetrical and antisymmetric second bending modes, which it could realize three-step speed regulation with different speed-thrust force characteristics by switching the operation mode [65]. They also presented a novel 2-DOF planar linear USM which the stator of the motor was divided as two transducers and two isosceles triangular beams [66]. The operating principle of the USM and the formation of the elliptical trajectory of the driving foot were analyzed, and the variable mode excitation method was illustrated. This motor can gain a maximum speed of 211.3 mm/s with thrust force of 3.15 N under an exciting voltage of 400 V_{P-P}. A new sandwich type ultrasonic motor using combination of the first symmetrical and anti-symmetrical longitudinal modes was presented by them [67]. The working principle of the motor and the elliptical trajectory formation of the driving foot were analyzed. A new linear USM using hybrid mode of the first symmetric and anti-symmetric longitudinal modes was described [68]. The stator was constructed by two Langevin transducers in combination with two isosceles triangular beams. Zhou et al., constructed a rotary USM with rotationally symmetrical structure, which the stator consists of four connected sandwich-type transducers and eight driving feet [69]. With the driving frequency of 50.93 kHz and voltage 300 V_{P-P}, the motor gave a maximal no-load speed of 157.9 r/min and a maximal output torque of 11.76 mNm.

Lu et al., proposed a single-modal linear motor based on multi vibration modes which contained two kinds of PZT ceramics [70]. The linear motor works by exciting the transverse vibration mode of the PZT ceramic on the upper surface of stator elastomer and the shear vibration mode of PZT ceramics at two ends simultaneously. The no-load velocity and the maximum output force reach 169.4 mm/s and 1.1 N, respectively. Mizuno et al., developed a high-torque sandwich-type MDOF-Spherical USM using a new annular vibrating stator with a strong excitation structure [70]. The maximum torques of rotation around the X(Y)-axis and Z-axis were measured as 1.48 N·m and 2.05 N·m respectively. Moreover, the values for torque per unit weight of the stator were obtained as 0.87 N·m/kg for the X(Y)-axis and 1.20 N·m/kg for the Z-axis, separately. Ma et al., developed a compact motor in which the stator composed of two piezoelectric plates attached to a T-shaped steel body [72]. Two orthogonal bending modes were excited by driving one piezoelectric plate and the reversed motion of the rotor could be obtained by driving the piezoelectric plate on the opposite side. Maximum power of 2.3 mW and efficiency of 9% with a load of 0.8 mN m at a rotation speed of 27 rpm were obtained for a prototype stator with a size of 15 mm × 2.44 mm × 2 mm, operated at 44.8 kHz.

Ceponis et al., presented a numerical and experimental investigations of a multimodal TRUM, which is driven by four electric signals with phase difference of π/2., being able to generate up to 115 RPM rotation speed at constant preload force [81]. They further proposed a new flat cross-shaped USM, which operation principle based on the first in-plane bending mode of the cross-shaped stators driven by four harmonic signals with phase difference of π/2 [82]. The advantages of the motor were high rotation speed, simple and scalable design, and the small space required for motor mounting wherein it can be directly mounted on the printed circuit board. Prototype achieved a maximum rotation speed of 972.62 RPM at 200 Vp-p when the preload force of 22.65 mN was applied.

Tanoue et al., designed a novel ultrasonic linear motor equipped with a quadruped stator that used the first longitudinal mode and the first and second bending modes [85]. A maximum driving speed of 148 mm/s and a maximum thrust of 294 mN were achieved for a device with a total length of 20 mm and a weight of 5 g. One more linear USM that drives a slider rod inside the quadruped stator to realize a compact linear motion system was proposed by them [86]. Maximum no-load speed of 258 mm s-1 and maximum thrust of 490 mN were obtained with total length of the stator transducer of 20 mm and its weight of 4.9 g. Cheon et al., proposed a new type of ultrasonic rotary motor that could replace existing ultrasonic motors for driving camera zoom lenses and investigated experimentally [87]. Peng et al., presented a new kind of the rotary USM with a longitudinal vibration model of the Langevin transducer acting as the stator, while the rotor consisted of a shaft and spiral fins, the spiral fins working as an elastic coupling component by which it cannot change its direction because the spiral fins' incline direction was fixed [88]. This motor can be used when one directional motion was required. Romlay et al., proposed an improved stator design of TWUSM using the comb-teeth structure which was expected to increase the overall efficiency [89]. Le et al., proposed a novel design methodology to optimize actuator configuration for linear USMs by considering the dynamic behavior of the stator in its operating environment, where it interacts mechanically with the moving stage and other peripheral components [90]. This helped to evaluate the actuator output performance parameters for design optimization. Pan et al., developed a novel low-friction type piezoelectric rotary motor based on centrifugal force with high speed, high power, and high efficiency output, novel low-friction type piezoelectric rotary motor [91]. Yang et al., proposed a dual-rotor hybrid USM with four side panels without using the torsional piezoelectric ceramics, which was indirectly excited by four uniformly distributed side panels along the circumference of stator cylinder [92]. The stalling torque of the prototype is 8 mNm and the no-load speed is 140 r/min was obtained at 44.7 kHz for a prototype with the size 27.2 mm x 27.2 mm x 70 mm, while the outer diameter of the stator cylinder was 20 mm. The experimental results indicate that the motor could operate in the first longitudinal and the second torsional coupled vibration modes transformed from the first longitudinal and the first bending vibration modes of four side panels.

Jiu et al., proposed a modal independent USM with dual stator based on optimizing the location of a rotor and two stators which excited at the same mode [93]. Modal test showed the disparity between the modal frequencies of the stators was 0.78%. The rotary speed of the USM is 75 revolutions per minute (clockwise) and 65.8 revolutions per minute (anti-clockwise) with the maximum torque of 8.4 N. mm at the voltage of 400 $V_{p\text{-}p}$. Li et al., proposed a traveling wave ultrasonic motor with a metal/polymer-matrix material compound stator which the stator was composed of a metal ring and polymer-matrix teeth [94]. The main merits of the proposed ultrasonic motor were low cost, light weight, high processing efficiency and long life. Sanikhani proposed a new linear ultrasonic motor based on the orthogonal vibration modes of an elliptical shaped [94]. Based on the experimental results, the prototype has a no-load speed of 40 mm/s and maximum thrust force of 1.55 N under excitation voltage of 70 Vp and preload of 12 N. Sun et al., developed a novel cylindrical ultrasonic motor easy to be fixed [96]. Two orthogonal B_{03} bending vibration modes of the stator were generated with temporal shift of 90 to produce elliptical movement on the driving surface. The weight of the proposed stator and motor was only 2.56 and 4.1 g, respectively & it achieved a maximum speed of 170 r/min under working frequency of 31.6 kHz [96].

In order to reduce the driving voltage and gain better output characteristics of piezoelectric actuators, an eight-zonal piezoelectric tube-type threaded ultrasonic motor based on two second order bending modes was analyzed by Chu et al. [97]. The USM could output a stall force of about 5.0 N and a linear velocity of 4.9 mm/s with no load at the driving voltage of 40 V_{pp}. This USM with a compact structure and screw drive mechanism showed fine velocity controllability and had great application in micro-positioning systems. Borodinas et al., described a USM that used the radial mode of excitation of the double ring's stator [98]. The main goal of the proposed design was to increase motor performance using d_{33} ceramic polarization working in the radial mode. The motor could be driven by a simple harmonic signal and used for standard piezoceramic rings [98]. An ultrasonic linear motor with dual piezoelectric (PZT) actuators which a traveling wave motion was generated on the stator by a double-sided excitation of the stator of the USM, was developed by Yang et al. [99]. The simulation results showed the differences to the characteristics that are achieved by adjusting the critical parameters, such as the PZT boned positions, the excitation frequency and the preload, in order to derive the best design [99]. Aoyagi et al., analyzed an application of noncontact transportation utilizing the near-field acoustic levitation phenomenon, which is a rotary-type noncontact-synchronous ultrasonic motor using acoustic viscous force [100]. Xu et al., proposed a novel rotary ultrasonic motor with two longitudinal transducers [101]. Only first order longitudinal vibration mode was used in the ultrasonic motor, which avoided the frequency degeneration of modal coupling ultrasonic motors. Mechanical performances showed that the motor can obtain rotary speed of 350 r/min and the maximum torque is 186 N·mm under the voltage of 300 Vp – p. Wu et al., fabricated & investigated a ring-shaped alumina/PZT vibrator to form a traveling-wave USM. The rotation speed of the alumina/PZT motor was larger than that of the stainless-steel/PZT motor, meanwhile, it exhibited superior maximal-torque-to-voltage and maximal-output-power-to voltage ratios [102].

Stable operation is one of the most crucial requirements for resonators in vibratory gyroscopes and ultrasonic motors, but eigenvalue splitting can deteriorate operation stability. Wang et al., proposed the estimation and elimination of eigenvalue splitting and vibration instability of resonators arranged in a fashion of ring-shaped periodic structures [103]. To simplify the driving power of the inertia drive USM, a low-frequency USM driven by a 50 Hz sine wave was proposed. Wang et al., proposed a standing-wave trapezoidal ultrasonic linear motor, which consisted of a trapezoidal piezoceramic plate with slanted sidewalls and a clip fastener to achieve bidirectional linear motion [105]. A trapezoidal piezoceramic plate sized 22 x 8 x 1.5 mm^3 and provided a travel distance of 10.10 mm and an output force of 12.151 g at a driving voltage of 10 V was useful for compact products.

Patents were filed on by various inventors. For instance, 1) YANG et al., files a patent which described a multi-spoke-type ultrasonic motor, to increase output performance of the ultrasonic motor, prolong service life, and reduce manufacturing costs; [106] 2) Rosenkranz et al., for U -shaped piezo motors; [107] 3) YANG et al., for ultrasonic linear actuation device includes a mover and a plurality of stator sets; [108].

Shi et al., proposed a deep-sea linear ultrasonic motor, which took in-plane expansion mode as the working mode [109]. The influences of static seal and the pressures of water on the performance of the ultrasonic motor were studied. Performance of prototype whose velocity was measured at 214 mm/s while the water pressure was 8 MPa and the voltage signal with a frequency of 72 kHz and a voltage magnitude of 200 V. Nakajima et al., proposed a MDOF-USM consisting of a spherical stator and a rotor of various shapes [110]. Chen et al., presented a hollow, linear, nut-type USM based on two degenerate, 3rd-order bending modes in the section plane of cylinders [111]. The motor with four PZT plates reached an upward speed of 0.95 mm/s when the load force was 3 g, and the maximum thrust force was 0.35 N.

3.1.6 Improvements on linear USMs

Linear USMs are one of the most commonly used USMs among all because of the less complex design & effective driving method. Zheng et al. proposed a novel single-phase standing wave linear ultrasonic motor, which was made of a single PZT ceramic square plate with a circular hole in the center [60]. The driving mechanism of the motor was based on the combining the in plane expanding and bending modes to generate bidirectional linear motion [60]. They also proposed a miniature, ring-shaped, linear piezoelectric ultrasonic motor based on multimodal coupling operating in a single, in-plane mode [61]. This motor can produce a maximum driving force of 2.7 N, a no-load moving speed of 56 mm/s, and a high positioning resolution of 0.1 μm in open-loop control. It had advantages of simple structure, controllable micrometer-scale displacement, and large bidirectional working stroke indicated that the proposed linear motor had great potential for industrial applications for precise actuations [61]. Further a novel ring-shaped linear ultrasonic motor operating in orthogonal mode was proposed by them [62]. The motor was fabricated using a self-made high-performance PSN-PMS-PZT ceramic with the optimal composition, which had a high vibration velocity of 0.86 m/s. It exhibited a faster moving speed of 248 mm/s, a relatively large driving force of 2.6 N, and a high positioning precision of 0.2 m in open-loop control, indicating that the proposed linear motor based on self-made PSN-PMS-PZT ceramic had a great potential application for precise actuations [62].

Bai et al., proposed a two-way self-moving linear USM, which composed of a diamond-shaped metal elastic body, a piezoelectric ceramic piece and a parallel guide rail [63]. By exciting the piezoelectric ceramic sheets on both sides of the elastic body, the first order bending vibration mode was excited to realize the bidirectional movement of the motor. Under the excitation of 200Vpp, the forward and reverse frequency of the ultrasonic motor is 18.18KHz and 18.07KHz, and the forward and reverse no-load speed was 43.76 mm/s and 43.14 mm/s, respectfully. Takemura et al., developed a prototype of linear ultrasonic motor with an embedded preload mechanism [64]. The motor was driven bidirectionally by selective excitation of the second and third resonant vibration modes of the stator. The maximum velocity, thrust and power of the motor are 62.5 mm/s, 0.12 N and 1.01 mW respectively [63].

3.1.7 Energy harvesting type USMs

Wang et al., proposed an energy harvesting type ultrasonic motor in which two PZT rings were adopted in the new motor, one was bonded on the bottom surface of the stator metal body to generate the traveling wave in the stator, and the other one was bonded on the outside top surface of the stator metal body to harvest and convert into the vibration-induced energy of the stator into electric energy [83]. They further developed a novel multifunctional composite device by using one single PZT ring, in which a piezoelectric actuator, a sensor and an energy harvester are embedded [84]. The piezoelectric ceramic ring was polarized into three regions to produce the actuating, sensing and energy harvesting functions.

3.1.8 Comprehensive approaches

Liu's research group made a remarkable contribution in the development of novel ultrasonic motors in last 5 years [21–32]. their research manly focused on bonded type structure, USM with nanometer resolutions, symmetric & asymmetric structure, multi degree of freedom motors & hybrid excitation. Some of his work from year 2015 to 2020 are described below: 1) A cylindrical traveling wave ultrasonic motor using bonded-type composite beam was proposed, a new exciting mode for L-B (longitudinal-bending) hybrid vibrations using bonded-type was adopted, which requires only two pieces of PZT ceramic plates and a single metal beam; [21] 2) A crossbeam ultrasonic motor with miniature size was developed, which used a bonded PZT ceramics to excite two first bending vibration modes that are orthogonal in space. The symmetrical crossbeam assured that two vibrations have the same resonance frequency, which solved the problem of mode frequencies degeneracy; [22] 3) A new-type linear ultrasonic motor which combined two orthogonal bending vibration modes & eight pieces of PZT ceramic plates and a metal beam that includes two cone-shaped horns and a cylindrical driving foot was developed & the maximal velocity of the achieved by this motor was 735 mm/s and the maximal thrust 1.1 N; [23] 4) A ultrasonic motors having three degree of freedom using four piezoelectric ceramic plates in bonded-type structure was proposed. It took advantage of a longitudinal mode and two bending modes, different hybrids of which can realize three-DOF actuation [24]. Because of symmetric structure the resonance frequencies of the two bending modes were identical; 5) A novel single-mode linear piezoelectric ultrasonic motor based on asymmetric structure was proposed [25]. The motor adopts the combination of the first longitudinal vibration and the asymmetric mechanical structure to produce the oblique movement on the driving foot which resulted in linear output motion under the friction coupling between the driving foot and the runner; 6) A two-degrees-of-freedom ultrasonic motor, which could generate linear motions with two DOF by using only one longitudinal–bending hybrid sandwich transducer, was proposed [26]. The results indicate that the maximum no-load velocities of the motor in horizontal and vertical directions are 572 and 543 mm/s under the preload of 100 N and the voltage of 300Vp − p respectively. The maximum output forces in horizontal and vertical directions are 24 and 22 N when the preload was 200 N; 7) A cantilever ultrasonic motor with nanometer resolution was designed, fabricated and tested, & it achieved an output speed of 344.35 mm/s when the frequency and voltage were 22.7 kHz and 200 $V_{p\text{-}p}$ respectively [27]. The maximum output force was 8 N under the voltage and preload of 100 $V_{p\text{-}p}$ and 50 N & high displacement resolution of 48 nm under the resonant working state was achieved; [8] a novel spherical stator multi-DOF ultrasonic motor using in-plane non-axisymmetric mode was proposed [28]. The mechanical output characteristics around X, Y and Z axes were measured under different excitations, pre-tightening forces and loading conditions. The no-load rotary velocities of the prototype were 200 r/min, 198 r/min and 250 r/min and the maximum load torques were 10.8 Nm, 11.0 Nm and 12.3 Nm around X, Y and Z axes, respectively was achieved; [28] 9) a novel rotary stack having advantages of high precision, high stiffness, high dynamic range, and simple structure, which was not only suitable for generating the precise rotary motion, but also for exciting high-frequency rotary vibration was proposed this was required in the applications of micro–nano manipulations; [29] 10) A novel bending-bending piezoelectric actuator driven by a single-phase signal was proposed, in which the two-dimensional 8-shaped trajectory of the driving tip moved the runner [30]. This prototype could rotate a pulley (22 mm in diameter) at the maximum speed of 1373 rpm forward and 1350 rpm backward under a preload of 9 N, respectively; 11) A new method to reduce the volume of the traveling wave USM with ring-shape stator and improve its output speed, torque density, efficiency, and power density [31]. The USM obtained an output speed of 53.86 rpm under a preload of 0.69 N when the frequency and voltage were 24.86 kHz and 250 V_{p-p}, the maximum stall torque was tested as about 0.11 Nm. under the preload of 3.14 N. 12) A sandwich-type multi-degree-of-freedom (MDOF) ultrasonic motor with hybrid excitation was proposed [32]. The prototype achieves no-load speeds of 109.8 r/min, 107.9 r/min, and 290.8 r/min in the YOZ, XOZ, and XOY driving modes, respectively. The proposed motor employs only four pieces of lead zirconate titanate ceramics to achieve the MDOF rotations of a spherical rotor.

USMs are known for their precise motion & position control. Fen, et al., developed a novel integral terminal sliding-mode-based adaptive integral backstepping control (ITSMAIBC) to accommodate the impacts of inherent friction, hysteresis nonlinearity, model uncertainties and retain high tracking precision [73]. Chen et al., presented a new butterfly-shaped linear piezoelectric motor for linear motion [74]. In the closed loop condition the positioning accuracy of plus or minus <0.5 μm was experimentally obtained for the stage propelled by the piezoelectric motor. Xu et al., presented a novel standing wave ultrasonic stepping motor operated in radial vibration mode [75]. Metal blades of the stator and grooves of the rotor were designed for precise positioning. In order to improve the torque, the rotor was pushed by blades of the stator directly without any friction material.

Sarhan et al., proposed a tubular USM operating in single phase, with rectangular plate having in plane out of plane vibration [79]. The maximum speed and torque of the tubular USM motor was 59 rpm and 0.28 mNm at 80 V_{pp} of applied voltage. It can be used where accurate control and high resolution at low speed is required. [They further proposed a motor working with coupled in-plane and out-of-plane vibration modes of rectangular plate provided a large contact area between stator and rotor of motor which can reduce wear and enhance motor lifetime [80]. Overall dimension of prototype was 49x14 x2 mm, working frequency of motor was 49.6 kHz, no-load speed and stall force of motor are 122 rpm and 0.32 mN m at 50 V, respectively.

Mustafa et al., proposed extremum seeking control (ESC) as an adaptive seeking technique with fast convergence and high robustness to optimize the USM performance by tracking maximum efficiency states [243]. The application of a non-sinusoidal periodic excitation voltage to induce a near-square-wave driving tip trajectory in linear ultrasonic motors (LUSMs) was proposed by Le et al. [244]. This would reduce lost power in the periodic driving tip motion, thereby, increasing the output force and power of the LUSM. A high-efficiency Pseudo-Full-Bridge inverter with the aid of the soft-switching technology, which was accomplished by the resonance of the in-series inductance with the snubber capacitance was presented by shi et al. [245]. The efficiency of the whole drive increases by a factor of 1.25 after replacing the traditional inverter with the proposed one. A method for adjusting difference between the longitudinal and bending mode frequencies of the laminated composite stator was proposed by Li et al. [246]. The frequency adjustment method was realized by changing the applied magnetic field which affected the effective elastic modulus of the composite stator. The sensitivities of motor performances on the pre-pressure were analyzed and a targeted optimization method was discussed by Chen et al. [247]. A simulation model with power dissipation and an integrated experimental facility with the preload adjustment device was adopted to analyze the laws from multiple perspectives. Peng et al., presented a new kind of the rotary ultrasonic motor with a longitudinal vibration model of the Langevin transducer acting as the stator, while the rotor consisted of a shaft and spiral fins [248]. A high-efficiency compensation method of the dead zone with the aid of the adaptive dither for the ultrasonic motor was proposed by Shi et al. [249]. The method not only could effectively compensate the dead zone and conveniently control the velocity, but also superior to the existing phase-difference-based method in terms of improving the efficiency of the ultrasonic motor. Zhu, et al., presented a novel linear piezoelectric motor suitable for rapid ultra-precision positioning [251]. By changing the input signal, the motor could work in the fast-driving mode as well as in the precision positioning mode. In the fast-driving mode, the motor achieved maximum no-load speed of 181.2 mm/s and maximum thrust of 1.7 N at 200 $V_{p\text{-}p}$. & in precision positioning mode, the motor acted as a flexible hinge piezoelectric actuator producing motion in the range of 8 μm. Li et al., proposed a novel dual-frequency asymmetric excitation method for motors which can operate under traditional single-phase asymmetric or two-phase symmetric excitation modes [252]. The motor demonstrated acceptable temperature characteristics and operating stability under the proposed excitation method with calculated optimal frequencies. Zhou et al., presented a novel linear ultrasonic motor with two operation modes wherein the stator of the motor was divided into two transducers and two isosceles triangular beams [253]. Dong et al., proposed a new equivalent circuit of a piezoelectric ring in radial vibration mode considering three types of fundamental losses, i.e., dielectric, elastic, and piezoelectric. Prototype achieved a maximum torque of 270 Nm [254].

3.2 Piezoelectric materials in USM

Piezoelectric materials used in USM, plays an important role in determining its performance. In the following table we tabulated some prominently used material & their properties (**Table 3**).

Wu et al. explored how elliptical shapes and force factors of the polymer-based vibrators vary as several key structural parameters were changed [229]. Subsequently, attempt to improve the maximum torques of the polymer-based USMs by adjusting several key dimensions, and the reason for their relatively low output torques and power compared to the metal-based USMs were done. Further he employed a high-order bending mode in the polymer-based cylindrical ultrasonic motor, because this mode yields a relatively high electromechanical coupling factor, which may lead to high output power of the motor. Additionally, in contrast with the low-order modes with only vertical nodal lines, the high-order mode has both horizontal and vertical nodal lines on the circumferential outer surface of the polymer-based vibrator [230]. Similarly Wu et al. also researched on, polyphenylene sulfide (PPS)-based bimodal piezoelectric motor. Considering the viscoelasticity of PPS, the electromechanical coupling analytical model was established to describe the dynamics of the PPS-based motor by using the Kelvin-Voigt viscoelastic model. Based on the proposed model, the Taguchi method was adopted to match the resonance frequencies of the longitudinal and bending vibration. The performance test demonstrates that the PPS-based motor could yield the maximal torque of 2 mNm with the stator weight of 5.4 g [232]. Wang et al., fabricated a lead zirconate titanate (PZT) thick-film piezoelectric micro stator based on a

Sr. No.	Material	Properties	Description	Ref.
1	Poly(phenylene sulfide) (PPS)	low density, low elastic modulus, & low mechanical loss	It was used to fabricate an annular elastomer with teeth and was glued a piece of piezoelectric-ceramic annular disk to the bottom of the elastomer to form a vibrator.	[229]
2	Poly phenylene sulfide/alumina/PZT triple-layered	low density, low elastic modulus, & low mechanical loss	A thin alumina disk sandwiched between the PPS vibrating body and PZT disk to compensate the stiffness was constructed. The maximum output torque and power of the triple-layered motors were 5 and 13 times the values of the double-layered motors, respectively, due to the enhanced force factor and electromechanical coupling factor.	[232]
3	Lead-free CH doped $(K_{0.5}Na_{0.5})NbO_3$ (KNN) ceramics	kp:34.1% (±2%); kt:45.3% (±2%); Qm:3170 (±2%); Rz:8.6 Ω (± 3%); and tanδ:0.1%.	Piezoelectric motors fabricated using these ceramics achieved a velocity of 4.5 mm/s, vertical velocity of 3.02 mm/s, and output power of 2.93 mW with a negligible increase in temperature and high stability while driven.	[234]
4	c-axis crystal-oriented $(Sr,Ca)_2NaNb_5O_{15}$ (SCNN) plate	mechanical coupling coefficient of k_{31} = 7%, a mechanical quality factor of Q_m = 3200	The mechanical nonlinearity behavior was not observed, and the temperature dependences of the quality factor and the equivalent stiffness decreased. Motor shown the revolution speed 100 rpm in torque from 150 μN·m to 900 μN·m, the output power 7.5 mW, efficiency 3.5% at 657 μN·m and 109 rpm.	[240]
5	polyimide (PI) composite (1.41 g/cm^3) reinforced with carbon fibers (CF)	high elastic modulus, wear resistance, and suitable friction coefficient.	To reduce the weight without decreasing the mechanical output performance this material was used for making Stator. Output Stall Torque = 0.22 Nm, Wear Resistance 1.38×10^{-5} mm/N·m, reduce the weight over 83.6%	[237]
6	Mn doped 0.27PIN-0.46PMN-0.27PT single crystal	lower excitation frequency, lower driving voltage, and less power loss. Mechanical quality factors (Q_m ~ 600)	USM using this material in single-mode was made. Motor speed up to 42.3 cm/s, a driving torque of 0.42 N cm, and an output power density of 0.45 W/cm^3, under the driving voltage of 21 V was obtained. Used for making miniaturized and high-power motors.	[238]

Sr. No.	Material	Properties	Description	Ref.
7	single crystal lead magnoniobate titanate (PMNT)	excellent piezoelectric properties and temperature stability	The criterions of crystal orientation for ring type USM proposed. Cutting orientation for the crystal poled along $[001]_c$ direction has better electromechanical properties and process compatibility. This orientation improves the lateral piezoelectric coefficient from ~90 pC/N to ~1201 pC/N and electromechanical coupling factor to 0.92.	[239]
8	Surface textured polyimide composites	High friction coefficient and high elastic modulus	To enhance conversion efficiency & tribological performance. The surface texture is capable of storing abrasive debris to protect the friction interface. Meanwhile, boundary effect of texture can increase friction coefficient. After the combination of the advanced PI friction material and the surface texture, the conversion efficiency of the USM increased by 82.8%.	[241]

Table 3.
The list of piezoelectric materials for USM.

high-performance PZT thick film by electrohydrodynamic jet (E-jet) printing in order to simplify the manufacturing process and enhanced the performance of the piezoelectric stator. The thick-film micro stator produced a traveling wave with an amplitude of 345 nm, and the mechanical quality factor was found to be 736 [236]. Zhao et al., proposed an oblate-type ultrasonic micro-motor with multilayer piezoelectric ceramic with chamfered driving tips. The micro-motor works based on the standing-wave principle and has a higher rotary speed than the traditional standing-wave. The experimental results showed that the rotary speed was around 2000 r/min at the voltage of 20 V_{p-p} [242].

3.3 Thermal performance of USM

Performance of Ultrasonic motors in extreme temperature setting is the key challenge faced by various researchers. Thus, Nishizawa et al. developed spherical ultrasonic motor for space application & investigated for the durability to the radiant heat from the sun [256]. Drive performance was conducted for estimated duration more than 70 mins for higher than +120°C conditions. In order to maintain its drive performance, selection of piezoelectric elements & adhesive materials were significantly discussed. [256], further spherical USM was investigated in low temperature environment of −80°C, & approximately 60 minutes cumulative drive time was achieved by applying the same piezoelectric element and the adhesive materials utilized for high temperature conditions [257]. Shi et al., presented a general optimum frequency tracking scheme for an ultrasonic motor, which no longer required the amplitudes of the applied voltages to keep identical [258]. The mechanical quality factor of an ultrasonic motor was initially derived to describe

Applications	Description
Magnetic Resonance Imaging	To determine the effects of a USM on MR images in the high field MRI scanner (3 T) using signal-to-noise ratio (SNR) [268].
Magnetic Resonance Imaging	To evaluate the temperature increase caused by a 3.0-T magnetic resonance imaging (MRI) system on an ultrasonic motor (USM) used to actuate surgical robots in the MRI environment [269].
Magnetic Resonance Imaging	To quantify and compensate the geometric distortion of MR images as generated by the presence of USMs [270]
Magnetic Resonance Imaging	To investigate displacement force and torque applied to an ultrasonic motor at various bore locations using the designed apparatus presented in the Materials and Methods [271]
Magnetic Resonance Imaging	to study the types of image artifacts generated by the USM, provide comparison between them, introduce their sources, and provide compensation methods [272].
Magnetic Resonance Imaging	To demonstrate that image distortion related issues can be partly addressed by replacing metallic nonactive motor components from a resonant ultrasonic motor for non-metallic equivalents [273].
Magnetic Resonance Imaging	A new cable-driven robot for MRI-guided breast biopsy. A compact three degree-of-freedom (DOF) semi-automated robot driven by ultrasonic motors was designed with non-magnetic materials [274].
Wearable Walking assist device	The fundamental study for understanding and quantifying the muscle fatigue reduction effect of walking assist system which is applicable to individual characteristic using ultrasonic motors [275].
Wearable Walking assist device	A hip-joint support ambient walking assistive system consider a timing and amplitude of assist for effective and individual-oriented assist was investigated [276].
Medical Endoscope	A spiral motion hollow micromotor operating in E02-mode traveling wave with outer diameter (3.6 mm) and length (3 mm), applied to an endoscope imaging system for driving optical lens, and a high quality image has been obtained due to its autofocus & autozoom function [277].
Low-frequency Sonophoresis system of transdermal drug delivery.	A new sonophoresis system of transdermal drug delivery, which involves the combination of an ultrasonic transducer and a linear ultrasonic motor, is designed to control permeability in in vitro LFS (Low frequency sonophoresis) [278]
Surgical Instrument with Torque Assist	To an ultrasonic surgical instrument including a torque assist feature to facilitate connection of the waveguide with an ultrasonic transducer [279].
Humanoid eyeball orientation system	A compact ring type 3-DOF USM fabricated to meet the specification of requirements for humanoid eyeball orientation system [280].
Underwater Robots	A dual-rotor ultrasonic motor with double output shafts, compact size, and no electromagnetic interference, characterized, and applied for actuating underwater robots [281].
Deep Sea Drones	A prototype of deep-sea drone by use of spherical ultrasonic motors for sensing marine bottom and make maps of the 4,000 m depth grades [282].
Single-gimbal control moment gyroscope	A structure-compacted single-gimbal control moment gyroscope, directly driven by an ultrasonic motor obtained wide-range closed-loop speed control of the gimbal from 0.2 mrad/s to 1.6 rad/s, which is the base of the high stability and high precision of the control moment gyroscope [283].
Continuously variable beam expander	An automatic continuously variable beam expander with two hollow ultrasonic motors as its actuators was used to expand a laser beam by between threefold and fivefold, and nanoscale positioning and high-precision beam shaping was achieved [284].
Two-axis Nonmagnetic Turntable	Non-magnetic technology to carry out research on the pointing accuracy and motion control of the turntable [285].

Applications	Description
Morphing carbon fiber composite airfoil	A morphing carbon fiber composite airfoil concept with an active trailing edge enabled by an innovative structure driven by an electrical actuation system that uses linear ultrasonic motors (LUSM) with compliant runners, providing full control of multiple degrees of freedom [286].
Bio-Inspired Flapping Wing Rotor	To vary the flapping frequency rapidly during a stroke, an ultrasonic motor (USM) was used to drive the FWR.(Flapping Wing Rotor) [287].
Blade Free Drone	A “Blade-Free drone” is a blimp style drone for safe indoor flying without the use of propellers or flapping wings. It uses micro blowers which can eject air through ultrasonic vibrations generated by piezoelectric device as an actuator [288].
LiDAR Systems	A novel design of a compact standing-wave rotary USM based on a coupled axial-tangential mode, one power source, and a bulk piezoelectric actuator of a tube form was developed for autonomous vehicle [289].
An Optical Image Stabilization of Portable Digital Camcorders	A sensor-shift optical image stabilization (OIS) using a novel ultrasonic linear motors (ULMs) and a fuzzy sliding-mode controller (FSMC) was used to compensates the optical path deviation that was caused by user’s hand-tremor for avoiding image blurring [290].
Dual piezoelectric beam robot	To study the effect of the piezoelectric patches’ positions on the performance of the robot [291]
Haptic grippers	Two piezometers, walking and traveling-Wave Piezoelectric Motors used as Actuator in haptic grippers were compared. Walking quasi-static motor was superior at low velocities & traveling wave ultrasonic motors were suitable when high velocity is required [292].
Microgripper	3-DOF microgripper driven by Linear Ultrasonic Motors (LUMs), with nanometer positional accuracy and an operational space in the millimeter scale was presented [293].
Variable Aperture	A new type of piezoelectric actuator with a screw-coupled stator and rotor was developed to operate an aperture. The actuator and the aperture are integrated to control the luminous flux. This actuator is having high resolution, high speed, simple structure and compact size [294].
Coiled stator ultrasound motor (CS-USM)	The propagation velocity of elastic waves from the simulated the vibration displacement mode profile along a straight line acoustic waveguide was analyzed via three-dimensional finite element method [295]
Scanning probe microscopy	One coordinate piezoelectric stepping motor of the scanning probe microscopy (SPM) nanomanipulator, allocated to the positioning was designed [296].
Gravimeter	A novel absolute gravimeter based on an ultrasonic motor was proposed in order to resolve the limitations related to free-fall absolute gravimeter, such as the complex structure and its large site [297].
photoacoustic microscopy	A PAM (photoacoustic microscopy) system was designed with a miniature ultrasonic actuator to significantly downsize the scanning probe (61 mm × 50 mm × 47 mm) [298]

Table 4.
Listed of the research articles (2015–2020) on the applications of USM.

the loss, which further was also in proportion to the temperature rise. The optimum frequency from the loss reduction viewpoint was then obtained, at which frequency the ultrasonic motor maintained the minimum loss and subsequently the minimum temperature rise. Sunif et al., presented heat energy modeling method for determining and characterizing of a piezoelectric stator profile that applied in a piezoceramic ultrasonic motor with the consideration of heat generated [259]. A thermal analysis was conducted in order to analyze the heat distribution on the stator & results showed different longitudinal deflection with the increment of the temperature. Liu et al. studied the temperature variations of different components under different driving voltages for a high-power longitudinal-longitudinal hybrid type T shaped ultrasonic motor [260]. Cheng et al. described about hypothesis that a temperature gradient transverse to the wave propagating direction could significantly increase the working velocity of acoustic streaming-driven motors which was then investigated by numerically solving the hydrodynamic equations & it was found that the velocity of the rotor only weakly depends on the transverse temperature gradient, the velocity increased by only ~8.8% for temperature difference of 40°C between the rotor and the stator [261]. Nakazono et al., studied temperature dependence of USM in cryogenic conditions [262]. Ultrasonic transducer comprising of a body & nut made of SUS304 & bolt made of titanium was fabricated & evaluated in the temperature range of 45 to 293 K. It was proved that when titanium was used for clamping bolt of the transducer, the motor can be driven without the regulation of the preload.] Lv et al., developed a novel theoretical model to investigate the temperature field and output characteristics of a standing wave ultrasonic motor [263]. The results showed that the developed model can not only predict the temperature variation of motor in continuous operation but also evaluate the influence of surface roughness and various input parameters on output characteristics of motor.

We reviewed some literature review papers published on ultrasonic motors. We found author Peng et al. reviewed literature & provided summary on precision piezoelectric motors over long ranges based on the principle of repeating a series of small periodic step motions, named "frequency leveraged motors" [264]. Work was classified into three categories by different frequency driving methods, including ultrasonic motors, quasi-static motors, and motors combined resonant and quasistatic operations. A comprehensive summary of piezoelectric motors, with their classification from initial idea to recent progress, was presented by Spanner and Koc [265]. This review also includes some of the industrial and commercial applications of piezoelectric motors that are presently available in the market as actuators. Peled et al., reviewed & provided summary of the design of high precision motion solutions based on L1B2 (first longitudinal and second bending modes) ultrasonic motors—from the basic motor structure to the complete motion solution architecture, including motor drive and control, material considerations and performance envelope [266]. Gao et al., presented recent progress in non-resonance piezoelectric actuators with the working principles and properties of actuators and the piezoelectric materials and configurations, fabrication, and applications [267].

3.4 Ultrasonic motors applications

The **Table 4** illustrates about various research articles published on the ultrasonic motor applications.

4. Industry 4.0

Kagermann in 2011 first published the main ideas of Industry 4.0 [299] and built the foundation for the Industry 4.0 manifesto published in 2013 by the German National Academy of Science and Engineering (acatech) [300, 301]. The concept of Industry 4.0 is based on the integration of information and communication technologies and industrial technology and is mainly dependent on building a Cyber-Physical System (CPS) to realize a digital and intelligent factory, in order to promote manufacturing to become more digital, information-led, customized, and green. The purpose of Industry 4.0 is to build a highly flexible production model of personalized and digital products and services, with real-time interactions between people, products and devices during the production process [302]. Industry 4.0 is a complex and flexible system involving digital manufacturing technology, network communication technology, computer technology, automation technology and many other areas [302]. There are many technologies used to implement Industry 4.0 like Internet of things, cybersecurity, augmented reality, big data & AI Analytics, Autonomous robot, additive manufacturing, Simulation & Digital twin, System integration & cloud computing [303]. Among all this we will be considering a few of them for improving the performance of the USM & we will also predict, how USM can best fit into industry 4.0 scenario.

Digital twin plays a role of a bridge between cyber world & physical world [304]. A digital twin of USM can be made to monitor its development from design phase to end user. It can be further extended up to recycling & remanufacturing & complete cyber physical system can be implemented [305]. Number of components used, CAD drawing of mechanical & electrical component, materials & their properties can be embedded in the 3D model, this will be the first step in formation of the digital twin of USM [305]. Results of simulation of the motor in various environment to validate its performance & product design can also be embedded in the digital twin to enhance it further. Additionally, the environmental performance and impact can be simulated at this phase via life cycle assessment (LCA) module too, e.g., design for recycling, design for disassembly and design for remanufacturing. The simulation results and disassembly are maintained in the product archive for future remanufacturing operations [305]. When the USM will be sold to an end user, he or she can update the product status via various Industry 4.0 enablers, e.g., mobile apps, smart tags, QR code, websites, and so forth. At this phase, the changes of product, e.g., location, ownership, upgrading, repairing and maintenance, can be updated and maintained inside the mirrored digital twin [305]. When the USM stops service, the users can update the digital status via mobile app or web service. He or she can contact a professional collector who has the expertise in this specific device. Failed USM can be evaluated, and testing can be applied to the individual component. Based on the examination results, the digital twin can be updated, and the proper operation can be planned accordingly, e.g., recovery at the component level, material level [305]. Developing a holistic digital twin of USM which captures data from the real world will be highly useful for tackling many challenges encountered during the design, modeling & optimization phase of the motor. Thus, action can be taken accordingly during the design phase in order to enhance the performance of the motor. So that, fully developed digital twin model of USM can be further utilized to simulate it for various types of application i.e., space exploration, medical devices, manufacturing industries etc [1].

Large amount of the data is generated during simulation & validation or collected from the digital twin of the USM or from the end user. This data can be used for analyzing & enhancing the performance of the USM. Further this data can be used to create algorithm which can be used for precise motion & drive control of the motors thus improving its overall performance. Depending on the application, a variety of algorithms can be used such as artificial neural networks (ANN) [306, 307]. ML offers great potential for intelligent data analyses and is a key technology for autonomous robots, image and signal analysis as well as complex controls for sensor-actuator systems [306, 308]. ML techniques can e.g., contribute to condition monitoring, predictive maintenance, or process control of the motor [306–308]. Consequently, data generated during operation of USM can be effectively utilized as important information for various sensors installed in Industry 4.0 setup [300].

Additive manufacturing can play a vital role in designing the complex shapes & size of the USM for different application. In AM components are manufactured by layer-by-layer deposition of the material [306, 309]. The possibility of materializing a complex digital model directly into a physical component without the need for shaping, maintaining and warehousing tools as well as manual intervention ideally reflects the idea of digital production [306]. AM allows the production of geometrically complex, function-optimized and customer-specific products at any location equipped with a suitable AM machine and thus contributes to the flexibilization and globalization of production processes [306]. Further, AM offers potential business for making spare parts [306, 310]. By using AM, designer can create physical prototype of the components used in USM using different combination of materials to analyze its fit, form & function for desired application.

Using IoT (internet of things) and CPSs (cyber physical system) it is possible to monitor the motors in real time. Interconnection of motors & the data obtained while its running during real time makes it possible to react quickly, effectively to every instance. Sensors embedded in the motors can give real time feedback of the parameters for instance, temperature rise which can be further analyzed for improving the design & performance of the motor. These sensors can also provide data for the whole life cycle of the motor which can be thus utilized by the researchers & manufacturers to incorporate into the motors which will ultimately result into overall improvement of the motor thus saving time & energy [300].

Augmented reality is the key technology of Industry 4.0 [311]. It enables human to access digital information and overlay that information with the physical world [312]. Ultrasonic motors are used in various engineering application areas i.e., from medical field to aerospace. They are manufactured in various size & shapes [1]. Use of augmented reality (AR) will make the USM designer aware of the fit, form & function of the motor suitable for different types of application w.r.t volume & space availability in real world environment. Thus, by using AR technology they can effectively design the USM based upon the requirement.

5. Conclusions

This book chapter gives a brief summarization of the research articles from eclectic sources like journal, patents and masters-PhD thesis published in last 5 years on piezoelectric ultrasonic motors. This article gives us the statistical analysis of number of publications on ultrasonic motors with respect to year of publication, country of origin & list of top 10 research journal. It divides all the articles into different categories and highlights the challenges, opportunities & research carried out. It broadly classifies the research article in areas like new design, modeling & simulation, friction & wear, piezoelectric materials, thermal performance & USM applications. Further it introduces with concept of Industry 4.0 & its key enabling technologies. It explains how to apply industry 4.0 technologies like digital twins & simulations, big data & machine learning, Industrial internet of things, additive manufacturing & augmented reality to improve the design & performance of the USM and how USM can best fit in Industry 4.0 era. Ultrasonic motors have tremendous potential for the improvement & Industry 4.0 technologies has tremendous potential to improve its design & performance on the other hand USM has many advantages & wide application areas which can be best suited for industry 4.0 settings. Thus, both USM & industry 4.0 if amalgamated together can give us a remarkable output in future.

Conflict of interest

NA

Notes/Thanks/Other declarations

NA

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