A Smart Ultrasonic Actuator with Multidegree of Freedom for Unmanned Vehicle Guidance Industrial Applications

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Abstract

A smart piezoelectric ultrasonic actuator with multidegree of freedom for unmanned vehicle guidance industrial applications is presented in this paper. The proposed actuator is aiming to increase the visual spotlight angle of digital visual data capture transducer. Furthermore research are still undertaken to integrate the actuator with an infrared sensor, visual data capture digital transducers and obtain the trajectory of motion control algorithm.

The actuator consists of three main parts, the stator, rotor and housing unit. The stator is a piezoelectric ring made from S42 piezoelectric material, bonded to three electrodes made from a material that has a close Characteristics to the S42. The rotor is a ball made from steel material. The actuator working principles is based on creating micro elliptical motions of surface points, generated by superposition of longitudinal and bending vibration modes, of oscillating structures. Transferring this motion from flexible ring transducer through the three electrodes, to the attached rotor, create 3D motions.

The actuator Design, structures, working principles and finite element analysis are discussed in this paper. A prototype of the actuator was fabricated and its characteristics measured. Experimental tests showed the ability of the developed prototype to provide multidegree of freedom with typical speed of movement equal to 35 rpm, a resolution of less than 5μm and maximum load of 3.5 Newton. These characteristics illustrated the potential of the developed smart actuator, to gear the spotlight angle of digital visual data capture transducers and possible improvement that such micro-actuator technology could bring to the unmanned vehicle guidance and machine vision industrial applications.

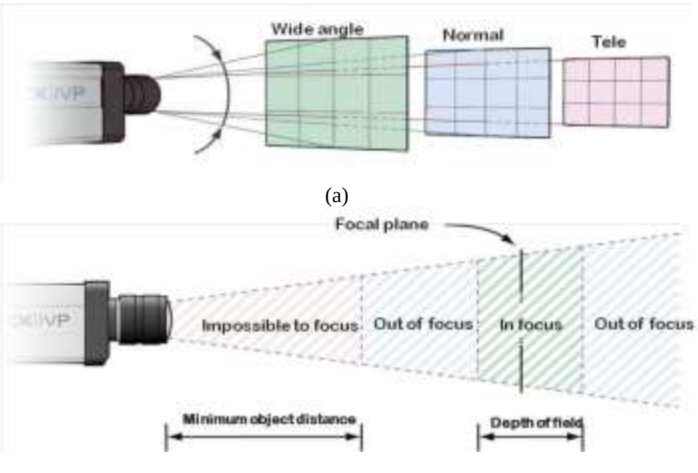
Keywords - *3D Ultrasonic Actuator, Machine Vision, Robot Guidance, Mechatronics*

I. INTRODUCTION

Human eyes are one of the most important organs of the human body. Our abilities and talents are greatly depending on our ability to see, recognise, distinguish objects and to estimate distances. Most jobs depend on our ability of visual perception. As amazing as the human sense of vision may be, we must admit that today's manufacture technologies more and more often broaden well beyond the limits of human visual capacities. This is where machine vision and robot guidance technology comes in. It is one of the constantly growing areas of research and development that dealing with processing and analysing of visual digital data capture [1-3]. It plays a key role in the development of intelligent systems and enables decision making for some of the industrial process and manufacturing. The primary objectives of this research is to develop technology that has the ability to perceive, reason, move and learn from experiences, at lower cost. We are particularly focus on developing of an actuator system that could provide 3D motions with multidegree of freedom to overcome the visual data capture transducer focus angle (Figure 1) and enhance the machine vision system ability to perceive and move in 3D. Investigation into the state of the art of actuators technology and possible approaches to develop a creative, sustainable and simple design structure that meets the 3D motions and machine vision requirements, at lower cost was a challenge. However with the potential characteristics and working mechanism that ultrasonic actuator technology offers and that could bring to this area of applied research industrial applications. There is a strong believes that this technology will fulfill the requirements and this is where this research programme has started.

Ultrasonic actuators (USM) principles of operations are based mainly on the concept of driving the rotor by a mechanical vibration force generated on the stator (Lead Zirconate Titanate (PZT) Transducer), via piezoelectric effect. USM can be classified into two main categories, based on the PZT working mode, bonded type [5-9] and bolt-clamped type actuators [10-12]. USM's have compact size, high force density, simple mechanical structure, slow speed without additional gear or spindle, high torque, non-magnetic operation, freedom for constructional design, very low inertia, fast dynamic time responses, direct drive, fine position resolution, miniaturization and noiseless operation. These criteria gave them the potential to be used in a number of industrial applications [13-25].

Demanding and careful examination for piezoelectric ultrasonic motors industrial applications reveals that there are apparent teething issues. The first is in regard to the dynamic time response of the USM actuator and its transfer function. While a piezo-ceramic elements, typically PZT, expands in direct proportion to the magnitude of the applied voltage, the USM on the other hand accumulates those displacements over time. Therefore the transfer function of the actuator, relating to the magnitude of the driving signal to the displacement is an integrator [18, 21-26] and this showed a delay in the dynamic time response of the USM, but it is not nearly significant as that in an electromagnetic DC and or AC actuators. The second issue is that because motion is generated through a friction force between actuator elements therefore it has a dead band. Often USM does not move until the input signal is greater than 10% of the maximum allowed voltage, to overcome the friction, such a dead band limits the ability of USM to accelerate quickly [5, 21-26].



(a)

(b)

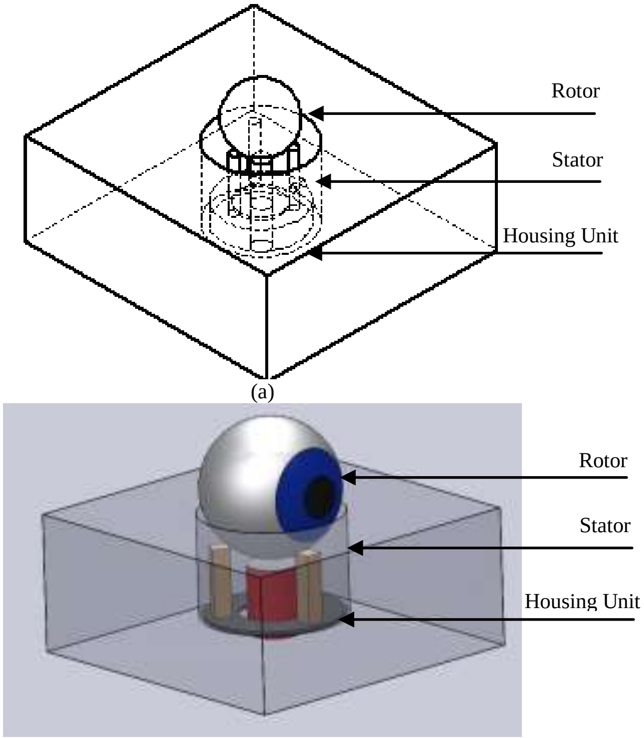
Figure 1: The Camera (a) Field of View in 2D showing the wide, Normal and Tele angle (b) Depth of Field and Minimum object distance [4]

The development of the new 3D piezoelectric actuator with multidegree of freedom presented in this paper have passed through three main phases, phase one focused on the actuator design and structure, phase two focused on finite element analysis, to test the actuator design structure and material micro deformation. The final stage focused on material selection, prototype fabrication, test and measurements.

II. 3D USM WITH MULTIDGREE OF FREEDOM DESIGN AND DEVELOPMENT

Figure 2 (a) and (b) shows the 3D actuator design, structure and CAD sold model. Figure 3 shows side view cross section of the actuator structure. The proposed actuator consists of three main parts, the rotor, stator and housing unit. The stator is a piezoelectric transducer ring made of Lead Zirconate Titanate - S42 piezoelectric material. Three titanium rods and a magnet were designed and attached to the stator, to support the rotor at three tips. The three rods has been detached at 120- degree and located at the transducer driving tips, to transfer the micro elliptical motion to the rotor. The rotor is a sphere of steel of size 28mm that rests on the stator intersecting at the tips of the rods. The structure is housed by Perspex, a transparent thermoplastic material.

The shape of three titanium rods is circular. This is to make sure that each rod is intersected with the sphere rotor in one single point. This is to minimise the friction force and avoid any possible loss of the stator thrust driving force. The three rods are fastened to the ring and the transducer ring is bonded to the housing using silicon rubber. This is to avoid any interference with the stator modes of vibration and provide the necessary degree of freedom, to transfer the micro elliptical force from the PZT ring to the rotor, through the three titanium rods. The magnet was design and its force has been determined carefully to keep the rotor attached to the rods and ensure efficient transfer of the stator vibration force.



(a)

(b)

Figure 2: Design and structure of the proposed 3D USM for machine vision industrial applications (a.) Design & structure & (b) CAD Solid Model

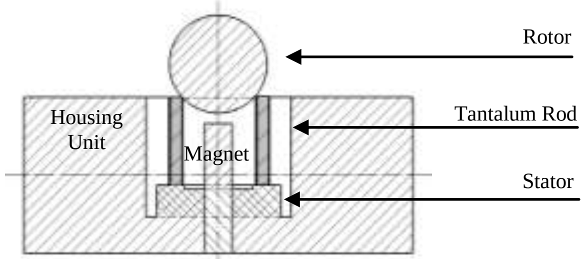


Figure 3: Cross section side view of the proposed 3D USM for machine vision and robot guidance industrial applications

The proposed design has many advantageous over any other 3D actuator technology. It presents a very creative, sustainable and simple design that is easy to manufacturer and maintained. The principles of motion is based on material deformation and friction force, therefore there is no much risk of interference and influences by any other system in the same working environment. This is in addition to the parts can be replaced if its performance deteriorated. It is also presents a very good example of empowering and sustainable innovation design approach since it is presents a new 3D actuator and at the same time overcome one of the most teething issues with 3D digital visual data capture technology. The design structure and working mechanism also presents for the first time a new approach that allows transferring the piezoelectric phenomena through titanium material and performing the same efficiency of creating motion using friction between sold parts.

III. 3D USM WITH MULTIDEGREE OF FREEDOM WORKING PRINCIPLES

The proposed actuator is designed using bending and longitudinal vibrations in a single ring transducer, which has a fixed wavelength. The concept is to utilise two modes of vibrations, to obtain the desired motion of the piezoelectric element, bending and longitudinal vibrations. One vibration produces a normal force while the other vibration generates thrust force, which is perpendicular to the normal force, resulting in an elliptical trajectory of micro elliptical motions, at a number of the rig surface tips. However, to create a strong second bending vibration mode, the polarisation direction of the piezoelectric vibrator is perpendicular to the titanium rods; the piezoelectric ceramic vibrator was arranged as shown in Figure 4. The longitudinal and bending vibration modes are coupled by asymmetry of the piezoelectric ceramic vibration ring [8, 18-24]. By attaching three perpendicular rods A, B and C, with 120^0 separation angle, to the piezoelectric ceramic ring surface, the micro elliptical motions are transferred to the rods tips, causing the rotor to move in 3D. The rotor movement is caused by the sequential frictional force generated at the tips of each rod.

The following equations (1), (2) and (3), represent the vibrations of the displacement in the parallel and perpendicular direction of the travelling wave generated by the flexural vibration ring transducer that transferred through the three rods, respectively.

$$X_A = W_1 \cos\left(2\pi f\ t + \alpha_1\right) \quad \ldots (1)$$

$$Y_A = W_2 \cos\left(2\pi f t + \alpha_2\right) \quad \ldots (2)$$

$$Z_A = W_3 \cos\left(2\pi f t + \alpha_3\right) \quad \ldots (3)$$

Where; X_A, Y_A and Z_A are the possible displacements in parallel and perpendicular direction, respectively. W_1, W_2 and W_3 are the maximum vibration amplitudes in the X, Y and Z directions, respectively, f is the resonant frequency, t is the time and α is the phase difference.

IV. 3D USM FINITE ELEMENT ANALYSIS AND MODELLING

USM's have many complex non-linear characteristics. Commonly two methods of analysis can be used to simulate and model such types of motors [6, 8, 10, 16-17, 24]. These methods are the Analytical Analysis and the Finite Element Analysis (FEA) methods. FEA has been used in the proposed 3D actuator design and development process lifecycle, to evaluate the motor structure by performing an algebraic solution of a set of equations, describing an ideal model structure, with a finite number of variables. Samples of the data used in the proposed actuator modelling are illustrated in tables 1 and 2.

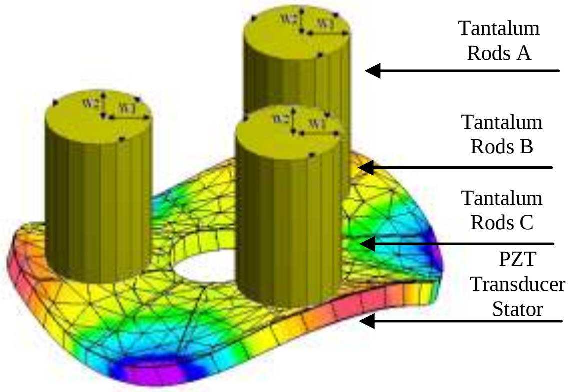


Figure 4: 3D Actuator stator arrangements including the PZT ring transducer and three titanium rods and principles used to generate 3D motions

Table 1 PZT-S42 piezo-ceramic material, titanium solid rods material, and the steel ball material used in the proposed USM

Material	Coefficient (Unit)	Value
PZT-S42	Relative permittivity (Ωm)	1450
	Dissipation Constant (%)	0.4
	Mechanical Quality factor	600
	Density (g/ cm^3)	7.6
Titanium Rod	Poisson's ratio	0.32
	Young`s Modulus of elasticity (Gpa)	116
	Density (g/ m^3)	16.69
steel Ball	Poisson's ratio	0.3
	Young`s Modulus of elasticity (Gpa)	70
	Density (g/ m^3)	2.7

Table 2 transformation of e-coefficient to D-coefficient for Piezoceramic material used in usm modelling

Material	Coefficient	Value (m/v)
Piezo-ceramics	$D_{31} \text{ x } 10^{-12}$	-155
	$D_{33} \text{ x } 10^{-12}$	320

The solid structure is divided into small portions named finite elements; an approximate solution for each finite element is generated. A summation of all the approximate solutions of the finite elements is obtained. The ring has been defined as made of piezoelectric Ceramic PZT-S42 material and the three rods have been selected as made of titanium material. ANSYS FEA CAD simulation software tools have been used in this analysis and simulation.

As stated in Table 2, the piezoelectric charge constant D_{31} rated as -150 is the working mode of the piezoelectric ring used to excite the bending vibrations of the ring. The D_{31} mode has a lower electromagnetic coupling efficiency compared to the D_{33} (320). The design dimensions of the stator for such actuator are mainly based on the vibration modes, capacitance ratio, and direction of vibratory displacement obtained using FEA [21, 22, 29-30].

Figure 5 shows the FEA variations of the displacement of the PZT Transducer ring versus the exciting frequency, for the proposed USM actuator structure. This shows the natural frequency of the proposed structure is equal to 39.7 KHz. It shows also the possible displacement and vibration amplitude that can be generated in the three dimensions due to the material deformation.

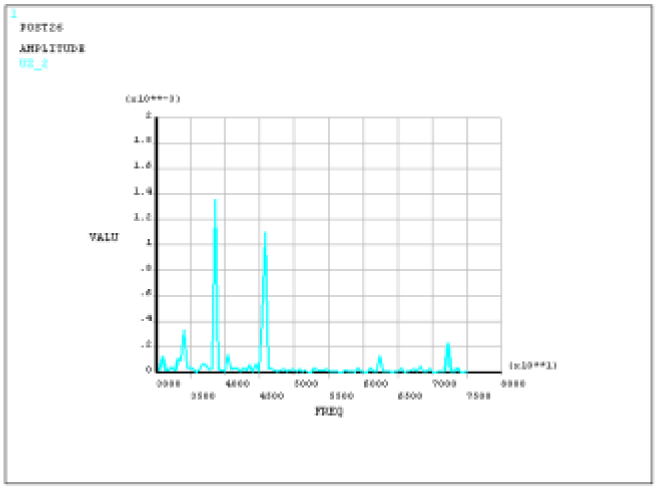


Figure 5: The variations of the PZT vibration ring displacement vs. frequency at 40 volt of the proposed 3D USM actuator

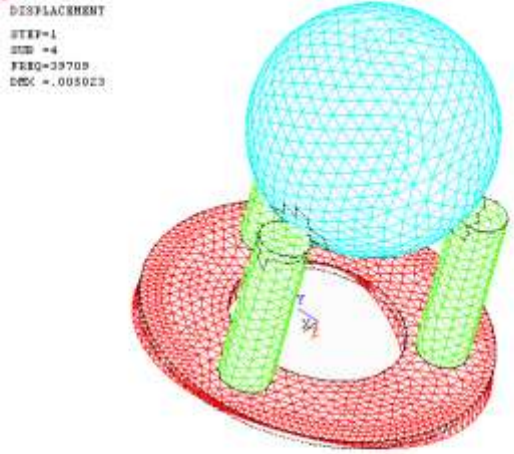


Figure 6: 3D USM FEA model at drawn frequency of 39.709 kHz of the proposed 3D USM actuator using single flexural vibration transducer

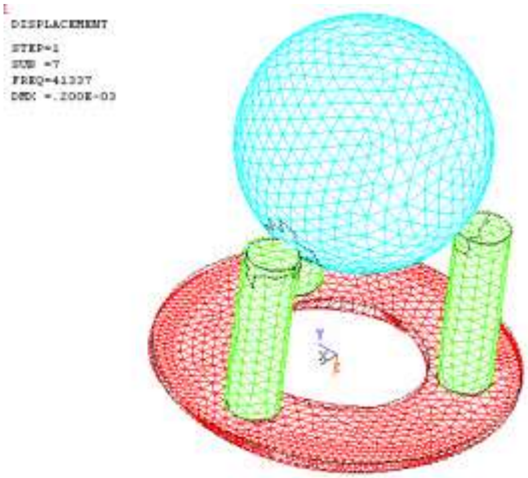


Figure 7: 3D USM FEA model at drawn frequency of 39.709 kHz of the proposed 3D USM actuator using single flexural vibration transducer

The natural frequency of the actuator stator indicates the dynamic time response of the USM and in this case it is on the order of microseconds. This can be calculated roughly as Q times the vibration period. Where Q is the quality factor of the motor, which can be determined using the following relationship [17-18]:

$$Q = \frac{R_m}{\sqrt{\frac{L}{C_{\Sigma}}}} \qquad (4)$$

Where; R_m is the equivalent resistor of the vibrating transducer, at a fixed operating frequency, L is the inductance of the LC-driving circuit and C_{Σ} is the total capacitance which is not constant and depends on the vibrating transducer internal capacitance, cable internal capacitance and LC-driving circuit capacitance. Figures 6 and 7 show the 3D USM FEA model at drawn frequency of 39.709 kHz for bending & longitudinal vibration mode. It shows also the material deformation, actuator structure and intersection between the actuator parts

The FEA simulation and modelling enabled to test actuator structure, investigate material modes of vibration, material deformation, and select the PZT material of the flexural transducer ring, defining the operating parameters for the actuator, determining the principles of motion and possible technique to control the trajectory of motions, by controlling the phase between the modes of vibrations.

A prototype of the 3D USM actuator was fabricated. The elements of the manufactured prototype were integrated successfully into the housing of the actuator and a series of experimental tests and measurements were carried out, to examine the potential characteristics of the developed prototype. Figure 8 shows the fabricated prototype and Figure 9 shows the arrangement used for testing. The arrangement shown in Figure 10 has been used to test and measure the actuator main characteristics. A piezoelectric driver was used to provide the Piezo-ceramic vibrating transducer ring with the alternative driving voltage and current. A function generator was used to provide various shapes of signal including sinusoidal, saw-tooth and square wave. A display unit, which consists of a digital oscilloscope and PC computer, was used to trace the signal and determine the actuator operating parameters.

A measurement of the operating parameters is carried out using the same arrangement used in the modelling of the actuator, as shown in Figures 4 and 5. The PZT ring transducer is connected to a single phase AC power source with a wide range of amplitude and frequency. A switching unit has been used to regulate the AC input power to the PZT ring transducer. Then a measurement of both the amplitude and frequency of the AC input signal is carried out. A sine wave input signal is obtained from a signal generator with the frequency sited to 100 kHz range. The input signal is monitored using the digital oscilloscope and the current is monitored using a digital Multi-meter. A gain of-25-amplification factor was obtained by changing the load range of the piezo driver model 603. The high voltage output is connected to the positive side of the piezoelectric ring and the ground of the piezo driver is connected to the negative one. The input signal from the signal generator is monitored on the oscilloscope. Voltage ranges of 1V -5V are selected. The voltage was increased in 1Volt intervals by adjusting the amplitude of the signal generator. The frequency of the input signal is adjusted on the signal generator, by gradually increasing it in 3-5 kHz intervals. The voltage and frequency is sequentially increased until the resonance frequency of the piezoelectric ring transducer is reached. The voltage is kept constant, and the frequency is adjusted until a trajectory is obtained. The trajectory is controlled by varying the frequency on the signal generator until a 3D rotational motion is obtained.

Figure 8: Fabricated Prototype of the proposed 3D USM using a single piezo-ceramic flexural vibrating ring transducer

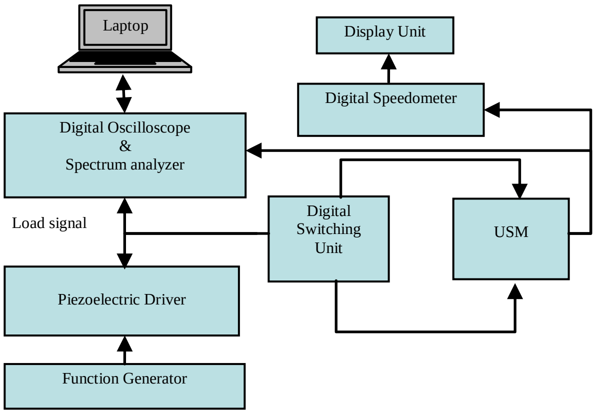


Figure 9: Block diagram of the test rig arrangement used to measure characteristics of the fabricated 3D USM prototype using single vibration ring

Figure 10: Practical test rig arrangement used to measure the characteristics of the fabricated 3D USM actuator prototype using single flexural vibration transducer

The frequency fixed at 39.53 KHz and the input voltage increased in sequential steps until reached 45Volt that when the rotor start move. The current and movement has been measured in revolution per minute (rpm) and the voltage has been recorded. Figure 11 shows the variation of the current vs. input voltage for the fabricated 3D USM prototype. This shows that the actuator is a capacitive load and the relationship graph can be used to determine its actuator internal impedance.

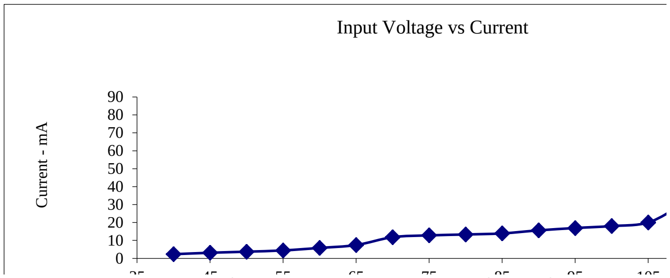


Figure 11: The variation of the current vs. input voltage for the fabricated 3D USM prototype using single flexural vibration transducer

A constant voltage has been chosen of 100VAC, varying the frequency up and down between 38 kHz to 42 kHz, the movement trajectory of the rotor was moving in 3D. The frequency of USM driver has been altered incrementally. The speed of the actuator has been measured for each increment. It was noticed during this process that the speed of the actuator increases as the frequency of the actuator driver increased. These measurements show the potential of using the voltage and or the frequency to control the 3D motions of the developed actuator. These measurements shows that the overall power consumption is in order of 5-watts. The resolution of the actuator was also measured and this found less than 5 micrometer.

A constant frequency has been chosen of 39.2 kHz, the voltage of USM driver has been altered incrementally. The speed of the actuator has been measured for each increment. Figure 12 shows the relationship between the input voltage and the speed on rpm. For machine vision industrial application, there is no much load will be carried out by the actuator. The maximum load that could be expected is the load of lenses and any other sensors that could be integrated into the rotor. Therefore, the maximum load that the developed 3D actuator can carry out was measured. This shows that the maximum load the prototype can carry out is equal to 3.5-Newton.

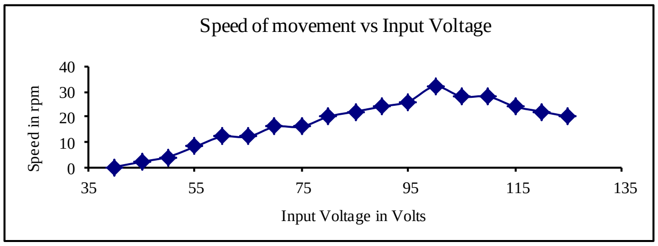


Figure 12: The variation of the 3D movement speed vs. input voltage for the fabricated 3D USM prototype using single flexural vibration transducer

V. CONCLUSIONS

A 3D piezoelectric ultrasonic actuator with multi degree of freedom actuator for unmanned vehicle guidance and machine vision industrial applications has been developed. The actuator design, structures, working principles and finite element analysis are discussed. A prototype of the actuator fabricated and its characteristics were measured. Experimental tests showed the ability of the developed actuator to provide 3D motions with typical operating parameters of: frequency: 39.2 KHz, voltage: 100 volt and current: 50 m-amperes. This has indicated a close agreement with FEA results. The prototype typical speed of movement is equal to 35 rpm, and has a resolution of less than 5µm and can handle maximum load of 3.5-Newton. These shows the potential of the developed actuator to meet the essential requirements for machine vision digital visual data capture transducer and increase the visual spotlight angle of digital visual data capture transducer.

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BIOGRAPHICAL NOTES:

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