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A Multi Degree of Freedom Actuation System for Robot and Machine Vision Industrial Applications

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Abstract. This paper presents the ongoing research to develop an actuation system with multi-degree of freedom, for robot and machine vision industrial applications. This is mainly aiming to overcome the current teething issues with digital visual transducer spot angle and enhance the relevant industrial applications performance and accuracy, at low cost. This paper is focused on the actuation system design and development. It covers the actuation system design optimisation, structure, and working principles. Finite element analysis has been used in the design optimisation process. This has been utilised to test the actuation system structure, investigate the dynamic behaviour and the deformation of the stator (active piezo-ceramic electrodes). The initial analysis and experimental results of the work is also presented in this paper and this is showed the potential of the current development.

Keywords. USM Actuator, Machine Vision, Robot Eyes.

1. Introduction

As the human eyes are one of the most important organs of the human body. Our abilities and talents are greatly depend on our ability to see, recognize, distinguish objects and 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 autonomous and manufacture technologies more and more often broaden well beyond the limits of human visual capacities. This is where artificial machine and robot vision 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]. These process and analysis are the key stages of decision making for some of the autonomous industrial applications and manufacturing process.

The principal aim of this research is to develop technology that has the ability to perceive, reason, move in 3-dimensional (3D) and learn from experiences, at lower cost. The research presented in this paper is particularly focused on the development of an actuation system.

The digital visual transducer as shown in Figure 1 has a teething issue with the normal spot angle as the viewing angle is restricted to the in-focus area. This could be improved by integrating the visual transducer to an actuation system. However, most of

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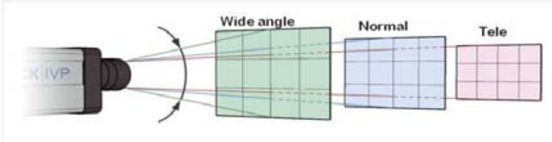
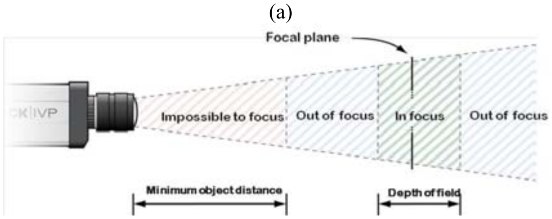
the available ones can provide movement in 1 or 2D and there is a need to develop an innovative system with multi degree of freedom that could move in 3D. Investigation into the state of the art of emerging cutting edge actuators technology and possible approaches to develop a creative, sustainable and simple design structure that meets the 3D motions and machine vision requirements, at lower cost was a challenge. However with the potential structure, characteristics and working mechanism that piezoelectric ultrasonic actuators/motors (USM) technology offer and that could bring to this area of applied research industrial applications. There is a strong believes that this technology will fulfil the requirements and this is where this research programme has started.



(a)

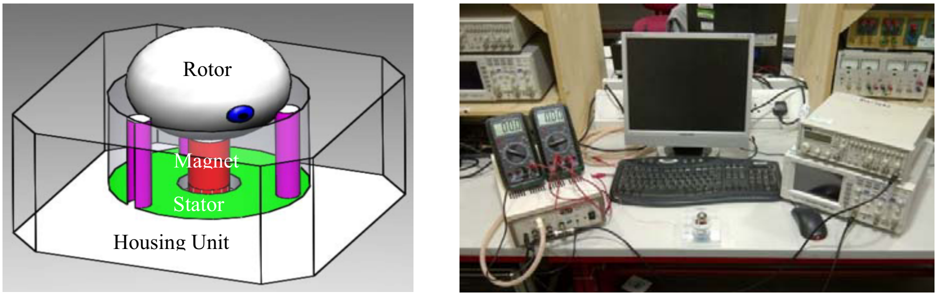


(b)

Figure 1. The digital visual transducer (Camera) (a) Field of View in 2D showing the wide, Normal and Tele angle (b) Depth of field and minimum object distance [4]

2. Actuation System Design and Structure

Figure 2 shows the actuator design, structure and CAD sold model. The proposed actuator consists of three main parts, the rotor, stator and housing unit. The stator is a piezoelectric transducer ring made of Piezoelectric Lead Zirconate Titanate (PZT) - 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 which is 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) USM Design and structure & (b) Actual fabricated prototype under testing

3. Actuation System Working Principles

The proposed actuator is designed using bending and longitudinal vibration modes 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. One mode of 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. The longitudinal and bending vibration modes are coupled by asymmetry of the piezoelectric ceramic vibration ring [5-14]. By attaching three perpendicular rods named 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. Obtaining the trajectory of these points across the sphere rotor will help to control the actuator movements. Figure 2 shows the arrangement of the three rods and the rotor of the actuator.

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.

$$X_A = W_1 \cos(2\pi f\ t + \alpha_1) \qquad (1)$$

$$Y_A = W_2 \cos(2\pi f t + \alpha_2) \qquad (2)$$

$$Z_A = W_3 \cos(2\pi f t + \alpha_3) \qquad (3)$$

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.

4. Modelling and Analysis of Actuation System

There are two methods of analysis can be used to model such USM's since they have a number of complex non-linear characteristics [6-7, 14]. These methods are: the Analytical Analysis and the Finite Element Analysis (FEA) methods. FEA has been used in the design and development process lifecycle of this actuation system. This is aiming to evaluate the actuator structure, by performing an algebraic solution of a set of equations that describing an ideal model structure, with a finite number of variables. 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 [11-12, 15-20]. Figure 3 shows the FEA variations of the displacement of the PZT Transducer ring versus the exciting frequency, for the USM actuator structure. This shows the natural frequency of the actuator structure is close to 40 KHz. It also shows the possible displacement and vibration amplitude that can be generated in the three dimensions due to the piezoelectric materials deformation.

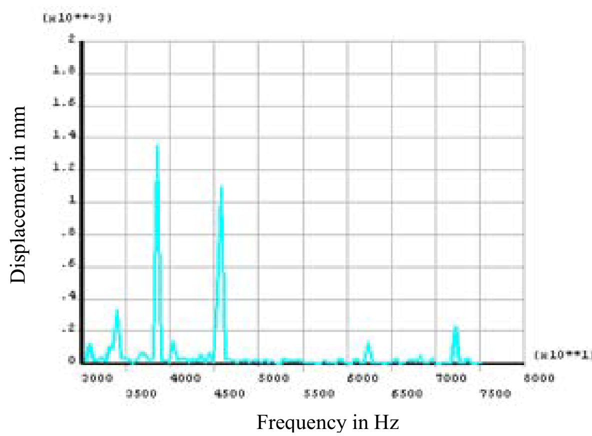


Figure 3. The variations of displacement vs. frequency of the proposed USM actuator using single flexural vibration transducer, at 40 volt

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 actuator, which can be determined using the following relationship [16-17]:

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

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.

A prototype of the actuator was fabricated. A series of experimental tests and measurements were carried out, to examine the characteristics of the developed prototype. A constant voltage has been chosen, varying the frequency up and down between 38 kHz to 42 kHz, the movement trajectory of the rotor shown a movement 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. 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 4). These measurements showed the potential of using the voltage and or the frequency to control the 3D motions of the developed actuator. The variation of the actuator speed of movement against the increase of the load attached incrementally to the sphere and this is shown in Figure 5.

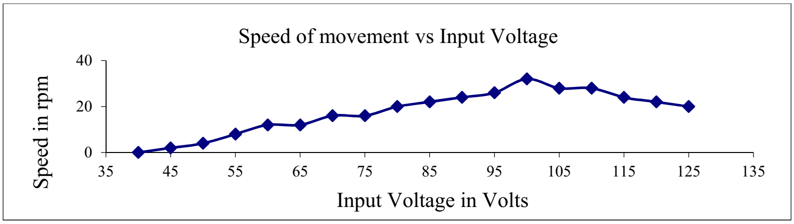


Figure 4. The variation of the speed of the 3D movement vs. input voltage for the fabricated USM prototype using single flexural vibration transducer

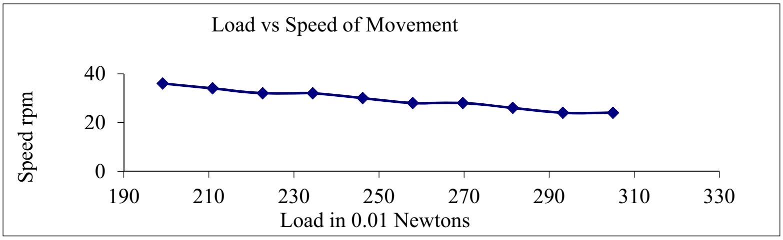


Figure 5. The variation of the speed of the 3D movement vs. load for the fabricated USM prototype using single flexural vibration transducer

For robot and machine vision industrial applications, 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 wireless sensors that could be integrated into the rotor. Therefore, the maximum load that the developed actuator can carry out was measured. This shows that the maximum load the USM prototype can carry out is equal to 3.5-Newton. The resolution of the rotor was measured and was found less than 5 micro-meters, at nominal operating parameters of voltage of 100VAC, current of 50 mA and frequency of 39.53 KHz.

5. Conclusion

This paper has presented the initial outcomes of the ongoing research to develop an actuation system with multi degree of freedom. The paper has focused on the actuator development life cycle. Finite element analysis has been utilised during the design process and has helped in design structure optimisation. It has also helped to define the actuator working principles. A prototype of the actuator fabricated and its characteristics were measured. The initial experimental tests showed the ability of the developed actuator to provide 3D-motion, typical operating parameters are: frequency: 39.2 KHz, voltage: 100 volt and current: 50 m-amperes. The developed prototype has a speed of movement equal to 35 rpm and a resolution of less than 5μm. It can handle maximum load of 3.5-Newton. Research still undertaken to optimise the actuator design and obtain 3D movement trajectory mathematical model. This will be followed by an integration of the necessary sensors and develop the relevant control algorithm.

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