New actuators and their applications: from nano actuators to mega actuators

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-- From Nano Actuators to Mega Actuators --

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Abstract:
The present report describes R&D activities on new actuators undertaken at our laboratory at Okayama University for the past three years. These activities include various types of actuators, such as electromagnetic, electrostatic, piezoelectric, pneumatic, and hydraulic actuators, ranging in size and force from the nano to the mega range. These actuators are described in four categories: microactuators, power, intelligence, and novel principle.

1. Introduction

Figure 1 summarizes recent R&D trends in new actuators in the field of robotics and mechatronics [1]. The figure shows a diagram of R&D into extended robot applications, diversified actuator specifications, and basic technologies supporting new actuators. Actuators are expected to be very important in robotics and mechatronics. For example, a new type of actuator having a large power/weight ratio and high efficiency has become a break-through technology for the realization of human-friendly robots.

The number of fields in which actuators are applied has increased over the past few years, as shown in Fig. 1, and while conventional actuators were only required to rotate fast, strongly, efficiently, and precisely, the requirements for new actuators have become numerous and varied as well. For example, micro robots and active catheters require powerful microactuators, whereas nursing

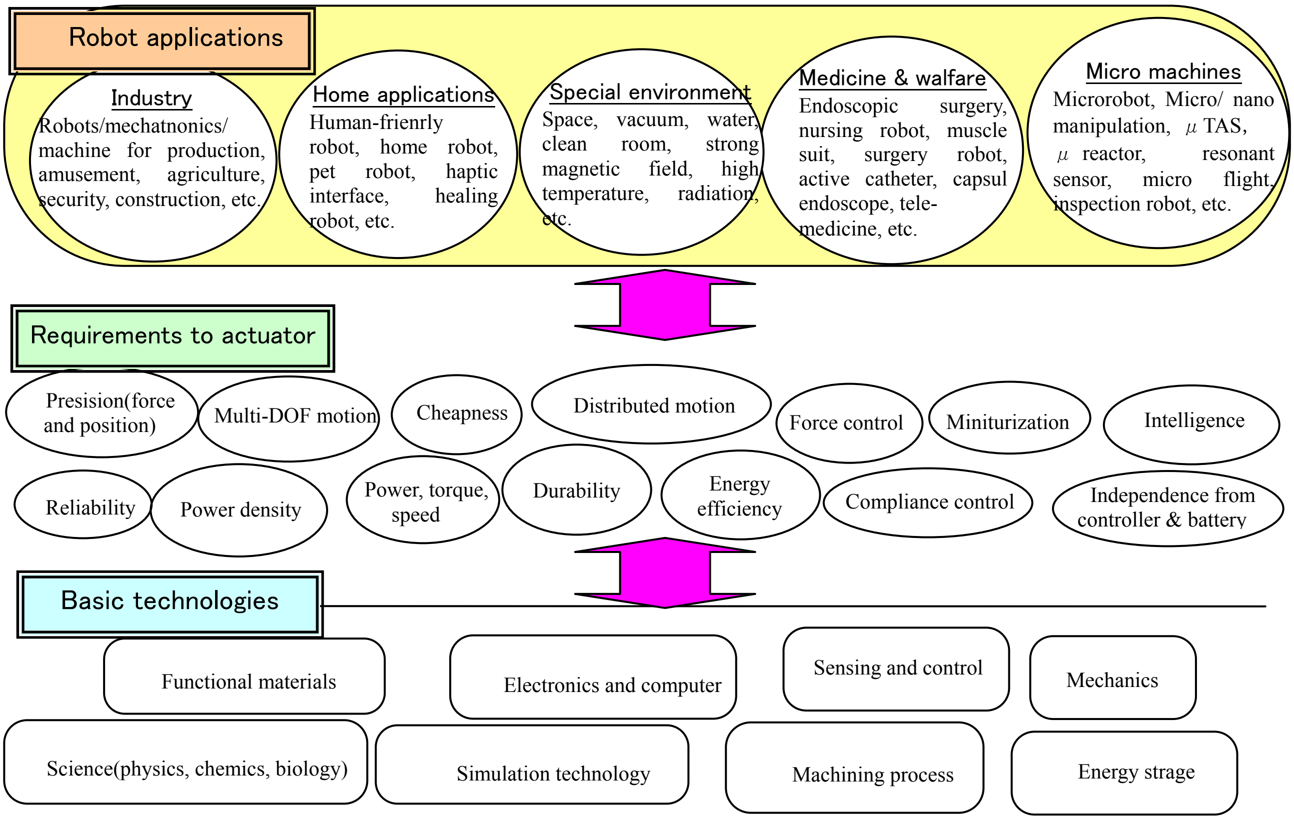


Figure 1 Summary of recent trends in actuator R&D

robots and pet robots require actuators with intelligence, force/compliance control, and safety. The required motions of actuators have also become more varied: not only rotation and linear motion, but also motions with multiple degrees of freedom, bending motions, and continuous deformation corresponding to contacting objects, for example, are required for actuators for several applications. Methods of handling micro powders and liquid in micro chemical reactors are urgently desired by chemists, and a new actuator for such applications is expected.

The present paper describes new actuators developed in our laboratory, along with their applications. These actuators are presented in four sections: (1) microactuators, (2) power actuators, (3) intelligent actuators, and (4) actuators based on new driving principles.

2. MICROACTUATORS

In order to realize microactuators smaller than several millimeters, machining processes and design technologies specialized for microminiaturization are essential. In this section, four examples of microactuators, 1) a micro ultrasonic motor, 2) a micro flask, 3) a micro solenoid, and 4) a focusing actuator for a micro camera, are shown along with machining and design technologies.

2.1 Micro ultrasonic motor [3]

Figure 2 shows an ultrasonic motor, 2 mm in casing diameter, and the piezoelectric device contained in the motor. The piezoelectric device, a bearing, and a micro spring generating the preload are integrated inside the casing. The cylindrical piezoelectric device, shown in Fig. 2, is 0.8 mm in outer diameter and 0.4 mm in inner diameter. A thin nickel electrode layer, which is electrically divided circumferentially into four electrodes, as shown in Fig. 2, is fabricated on the outer surface of the piezoelectric cylinder. Applying four AC driving voltages with 1/4 phase difference to each of the electrodes causes resonant bending motion of the piezoelectric cylinder, resulting in rotation of the shaft.

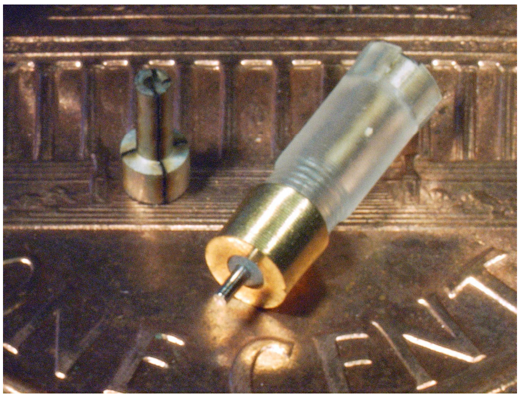


Figure 2 Micro ultrasonic motor
(left: piezoelectric device, right: assembled motor)

Finite element method dynamics analysis of the microstructures is key in determining the dimensions and materials of the piezoelectric cylinder and the casing, because resonant frequency is both very high for micro structures and very sensitive to structural dimensions, density and stiffness. Several micro machining processes are also essential, and micro shaving and grinding machining are used to realize the piezoelectric cylinder and other micro parts. Dividing the nickel electrode on the piezoelectric cylinder is realized by excimer laser ablation.

2.2 Micro flask [4]

As a new functional device for micro chemical reactors, a micro flask which realizes various operations such as stirring, mixing, heating, and rinsing, is being developed. Figure 3 shows an example of a prototype cylindrical flask made of piezoelectric ceramics. The flask is 4 mm in outer diameter and is fabricated through a micro machining process that is very similar to the process used to realize the micro ultrasonic motor. The flask successfully rotates liquid and grains in the flask.

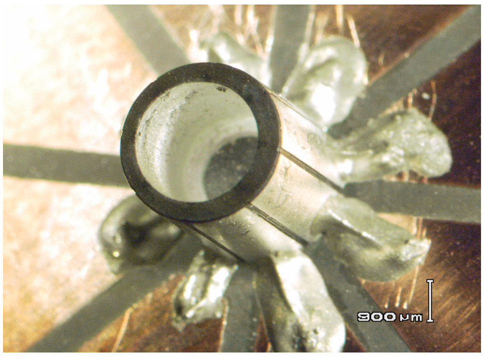


Figure 3 Micro flask

2.3 Micro solenoid [5]

One of the biggest problems in the miniaturization of electromagnetic actuators is heat generated by the coils. In addition, the static current required in order to maintain the rotor/slider position constant is critical.

Figure 4 shows a prototype micro solenoid that requires no electrical current to maintain the slider position. By fabricating the slider from a permanent magnet and designing the magnetic pass properly, two magnetically stable self-maintaining positions, at both stroke ends, can be realized. Electricity need only be provided in order to switch the slider position and is not necessary in order to maintain the slider position at position. This design greatly reduces the heat generated by micro solenoids.

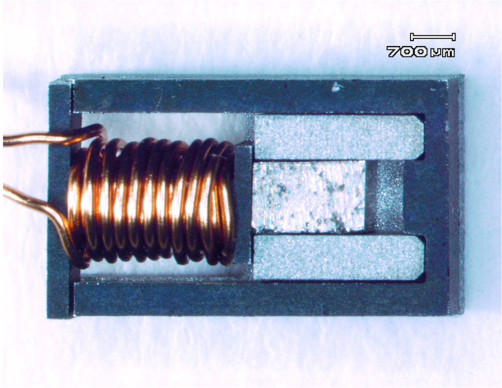


Figure 4 Micro solenoid

As shown in this example, special electromagnetic design techniques are necessary for fabricating micro electromagnetic actuators.

2.4 Focusing actuator for a micro camera [6]

The pneumatic actuator is a promising microactuator in the 1 to 10 mm size range. The pneumatic actuator realizes unique characteristics in this domain to generate a Maxwell's stress of approximately 0.7 MPa and a big moving stroke of using simple mechanisms.

Figure 5 shows a prototype pneumatic rubber actuator for driving a micro camera lens. The actuator has a rubber ring, which has an oblique inner surface and forms an air chamber with the casing, as shown in Fig. 5. The pressure in the air chamber is controlled through pneumatic tubes that drive the lens in its axial direction. The prototype actuator has a very simple structure and easily generates a large force.

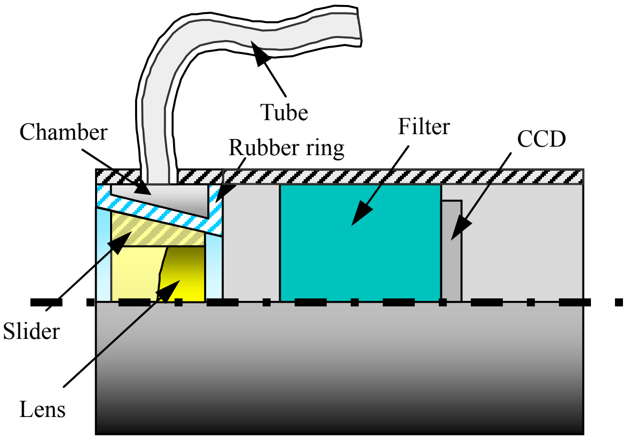


Figure 5 Microactuator for driving micro camera lens

3. POWERFULL ACTUATORS

3.1 Rescue robot actuators [7],[8]

In general, Maxwell's stress is on the order of 10^5 Pa for both electromagnetic and pneumatic actuators and is on the order of 10^7 Pa for both piezoelectric and hydraulic actuators. However, both electromagnetic and piezoelectric actuators have a moving stroke that is much smaller than that of either hydraulic or pneumatic actuators. Compared with both electromagnetic and piezoelectric actuators, the hydraulic actuator has excellent properties in that it provides both a large force and a long stroke. This section describes hydraulic actuators that were developed for rescue robots.

Figure 6 shows a power actuator with two degrees of freedom that was developed for a small, powerful rescue robot capable of negotiating and inspecting debris. The actuator is 60 mm in diameter and achieves bending motion in any direction. The actuator contains three hydraulic cylinders of 8.5 mm in diameter and is driven by a 21-MPa hydraulic system. The maximum torque of this actuator is 21 Nm in any direction.

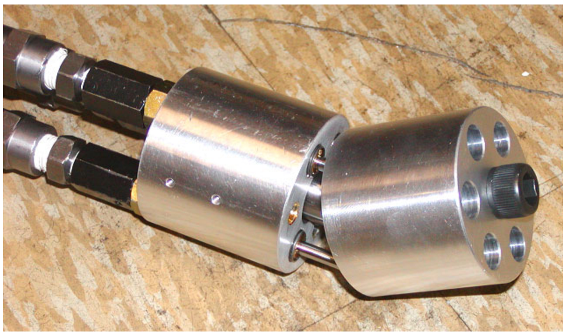


Figure 6 Power hydraulic joint with 2 DOF

Figure 7 shows a power jack rescue robot that was developed using another hydraulic actuator. The robot is designed to travel among debris and collapsed objects, to search for victims, and lift debris and collapsed objects in

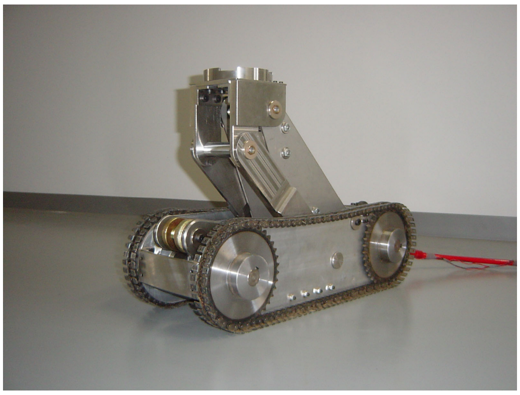


Figure 7 Power jack robot for rescue operations

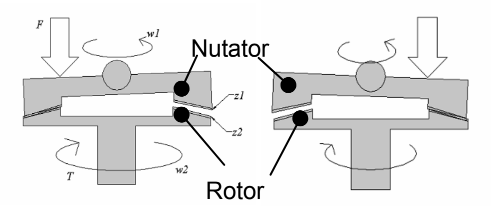
order to secure spaces for rescue operations. The dimensions of the robot are 560 × 150 × 227 (length × height × width) mm in normal mode, and the jack stroke is 245 mm. The load capacity of the jack is 3.4 tons. The actuator generates a force of 10 tons in the axial direction and is driven by a 70-MPa hydraulic system.

3.2 High-torque motors with reduction gears [9]-[11]

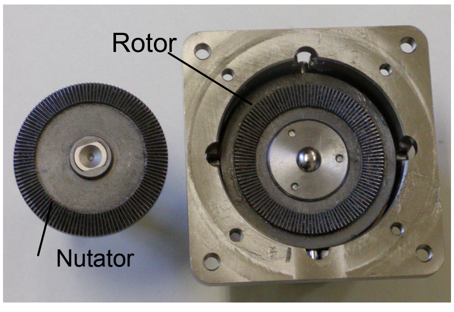
In order to design compact and powerful robot mechanisms, new actuators integrated with mechanical parts, such as reduction gears and link mechanisms, are necessary. Integrating reduction gears and actuators is especially important for small actuators because smaller actuators generally have higher speeds and lower torque.

The nutation motor shown in Fig. 8 is a typical example of such integration. The motor consists of two bevel gears, called the nutator and the rotor, which are supported by a universal joint and a rotational bearing, respectively. Because the tooth number of the nutator is one larger than that of the rotor, a nutation motion of the nutator causes a rotational one-tooth stepping motion of the rotor. The nutation is caused by pneumatic cylinders or electromagnetic solenoids behind the nutator.

Figure 8 (b) shows the interior of a nutation motor. The prototype is 50 mm in diameter and 49 mm in length, and has a maximum torque of 2 Nm. The maximum speed of the prototype nutation motor is 10 rpm, and the stepping angle is 0.5 degrees. The motor has a simple structure and is suitable for miniaturization. A small nutation motor of 10 mm in diameter was successfully developed.



(a) Driving principle of nutation motor



(b) Internal mechanism

Figure 8 Nutation motor

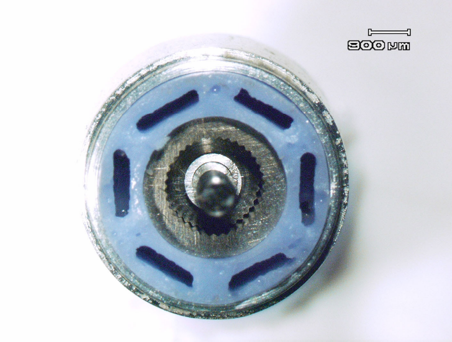


Figure 9 Micro pneumatic wobble motor

Another type of gear-integrated motor is the pneumatic wobble motor, as shown in Fig. 9. This motor consists of an internal gear, an outer gear, and a donut shaped rubber structure having six internal chambers. The two gears have different numbers of teeth. Applying pneumatic pressure in each chamber sequentially causes revolution of the internal gear, which in turn causes the outer gear to rotate. The prototype motor is 6.6 mm in diameter, 5.3 mm in length, and generates a maximum torque of 0.47 Nm.

4. INTELLIGENT ACTUATORS

Research to integrate actuators, micro processors, and various micro sensors is underway in an attempt to realize intelligent actuators that have communication ability and local control functions. A reduction in the number of cables, as well as more delicate and high performance actuator motions, can be expected to be realized using this technology.

4.1 Active polyhedron [12]

Figure 10 shows a link mechanism called the active polyhedron, which consists of 30 intelligent pneumatic cylinders. The 30 cylinders form an active icosahedron. The active polyhedron is expected to work as a haptic interface

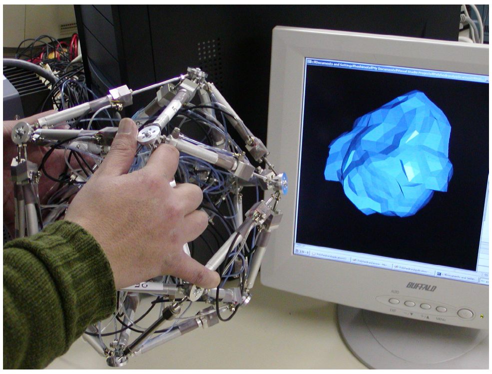


Figure 10 Intelligent cylinders and an active polyhedron

with which to present distributed physical information, such as movement, deformation, or the force to a virtual continuous object in a PC. The operator can deform virtual objects directly and feel the resulting reaction force, as if the operator were touching the actual object.

Figure 11 shows a disassembled pneumatic cylinder [13] developed for this active polyhedron. On the cylindrical rod surface, stripes having a pitch of 0.3 mm are fabricated using a YAG laser. An optical detector chip is built into the cylinder housing to detect the rod position. A pressure sensor is also equipped near the pneumatic valves. Position and force control is achieved using these sensors and pressure control valves. This cylinder is cheap, light, durable, and compact, compared to conventional linear actuators having position/force controllability.

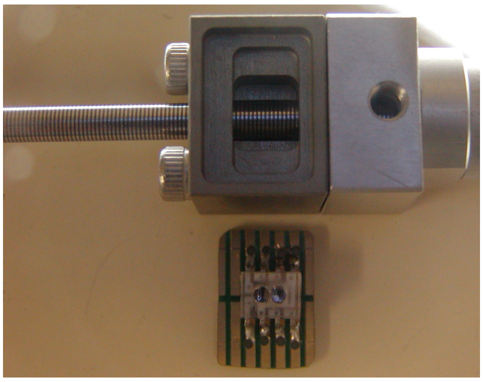


Figure 11 Intelligent pneumatic cylinder

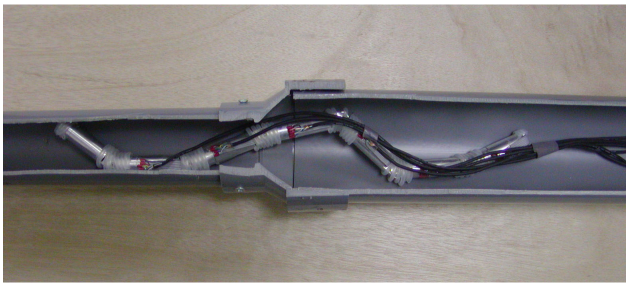


Figure 12 Snake-like robot for pipe inspection

4.2 Robots with high degrees of freedom [14]

Reducing the number of cables between the controller/energy source and an actuator is especially important for robots having high degrees of freedom.

Figure 12 shows a snake-like pipe-inspection robot that is capable of movement inside pipes of 2 to 10 inches in diameter. The prototype being developed has 13 active joints. Each motor is equipped with a micro motor driver chip and a micro PIC in order to realize the functions of local control and communication with a host computer.

5. ACTUATORAS BASED ON NEW DRIVING PRINCIPLES

Developing new driving mechanisms is one of the most important activities in actuator R&D. Four new actuators based on new driving principles are presented in this section.

5.1 Actuators to assist colonoscope insertion [15]

Inserting an endoscope into the colon is difficult. Although active colonoscopes have been researched, these instruments are still in the development stage. Actuators for this application are required to be soft enough not to injure the colon wall while being deformable enough to adapt to the curves of the colon. In addition, the actuators must generate a distributed force adequate for traveling. These requirements are difficult to be satisfied using conventional actuators.

We are developing a new driving mechanism using a thin rubber tube applied to a colonoscope. Introducing pulse pneumatic flow to a thin rubber tube enables the generation of traveling deformation waves on the tube surface, which drives the object placed on the tube. Typical experimental data for the conveyance speed is 40 mm/s when using a silicone rubber tube of 2.8 mm in outer diameter, 0.15 mm in thickness, and 1000 mm in length and a pneumatic frequency of 30 Hz. The conveyed object was a light plastic plate.

We fabricated a multi-chamber rubber tube to fit around a conventional colonoscope, and conducted insertion experiments under various conditions, as shown in Fig. 13.

5.2 Active catalysts [16]

An electrostatic handling technique for catalytic particles in micro spaces was developed. This technique enables shaking of the particles in a micro chamber in order to realize uniform mixing and acceleration of chemical reaction. In addition, this technique enables conveyance of

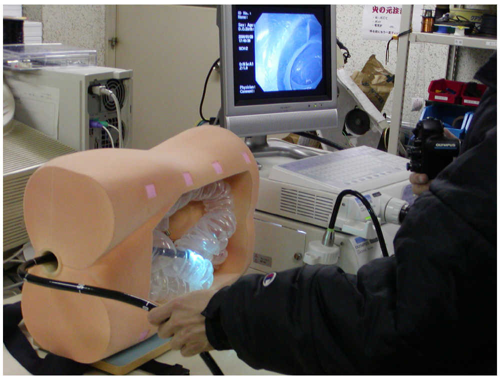


Figure 13 Inserting experiment of scope with assistance of rubber tube actuator

the particles along a micro channel in a micro reactor or in a micro TAS. Realization of such handling in micro spaces was difficult using conventional micro stirrers and micro actuators.

Figure 14 shows an example of the motions of catalytic nickel-carbon composite particles of 250 μm in diameter. The chamber shown in Fig. 14 is 3 mm in width and the exposure time of the photographs is 100 msec. The applied voltage is 1.5 kV. Catalytic particles such as zeolite and nickel-carbon composite particles ranging in size from 50 μm to 1 mm in diameter can also be driven using this technique.

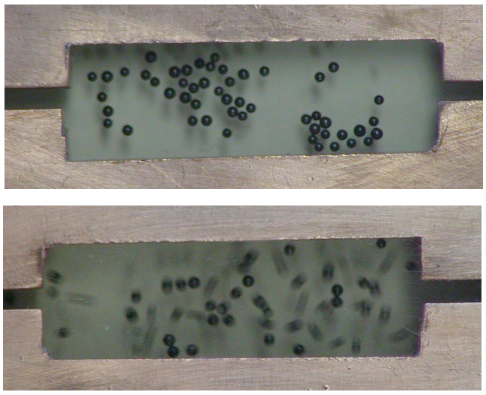


Figure 14 Motions of catalytic particles top: no voltage applied, bottom: 1.5kv applied

5.3 Compact scanning mechanism [17]

Compact scanning mechanisms with high speed and accuracy are required for precise measurement instruments and semi-conductor inspection equipment.

Figure 15 shows a prototype mechanism with 3D motion developed for a compact probe scanning mechanism for scanning probe microscopes. The mechanism is fabricated from a thin titanium plate. A piezoelectric thin layer is fabricated on the titanium plate through a hydrothermal synthesis process, forming a bimorph structure of the PZT and the titanium layers.

The prototype shown in Fig. 15 achieves a moving stroke of 98.7 μm in the x-direction, 81.4 μm in the y-direction, and 3.58 μm in the z-direction.

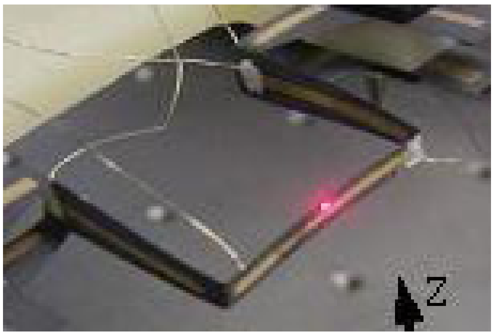


Figure 15 Compact scanning mechanism with piezoelectric film

5.4 Pneumatic bicycle [18]

Although pneumatics is not suitable for the transmission of large amounts of power, this technology is suitable for the transmission of smaller amounts of power. By applying pneumatic transmission to bicycles, rather the conventional chain transmission, two new functions may be realized: 54 gears and energy recovery.

The bicycle shown in Fig. 16 has two cylinders connected to the pedals and two cylinders connected to the rear wheel. The cylinders near the pedals generate high pressure air, which is sent to the cylinders near the rear wheel through pneumatic valves to drive the wheel. Switching the valves enables an amazing 54 gears to be realized. During braking, the cylinders connected to the rear wheel work as pumps to generate pressurized air, which is stored in an air tank, enabling energy recovery.

Figure 16 Prototype bicycle with pneumatic transmission

6. CONCLUSIONS

New actuators developed in our laboratory were described in four categories: microactuators, power, intelligence, and novel principle. The actuators are described only briefly herein and greater detail is available in the referenced literature.

The actuators presented herein range in size and power from nanometer positioning actuators, to microactuators, and to power actuators of the Mgf order force. The driving principles of these actuators are also varied; electromagnetic, pneumatic, hydraulic, piezoelectric, and electrostatic actuators were presented herein. The actuator design methods and knowledge described in this paper are common for the most part.

Actuators are among the most essential devices in industry, high technology and science, and life support technology. Novel actuators have great potential to provide breakthroughs in various fields.

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