Research and Application of Micro Electro Mechanical System

Long Wang [a], Guangwei Yang [b]

Capital Aerospace Machinery Company, Beijing 100076, China

[a] xiaobei123@163.com, [b] lijiao6688@163.com

Abstract

In recent years, with the ever-changing Internet of Things technology, as an important part of its technology the rapid development of the MEMS has been widely used in all aspects of life. This article mainly introduces the research status and application fields of MEMS technology.

Keywords

Internet of Things, MEMS(Microelectromechanical systems), Applications.

1. Introduction

The origin of MEMS was traced back to 1959 , physicist Richard Chancellor Feynman made his famous speech at the annual meeting of the American Physical Society referring to the idea of making mechanical ants when he was not aware of the miniature Many uses of machinery. In 1983, Professor Feynman proposed the concept of "ultra-small machinery" in the Jet Propulsion Laboratory. Nowadays, great progress has been made in the manufacturing technology of ultra-precision mechanical manufacturing process. A large number of new processing technologies represented by silicon processing have been applied and popularized in the world [1]. MEMS refers to the feature size between, the use of integrated circuit processing technology to mechanical and electronic components integrated devices. Due to the different research scope and emphasis of each country, there is not a uniform standard for the definition of MEMS in the world. When Japan used the term micromachine, he developed it from big machine to small machine. Japanese scholars regard 1mm-10mm as a small machine; a micro-machine; a nano-machine and a molecular machine; a US-style microelectromechanical system; a European micro-system as an intelligent micro system that has sensing , Signal processing and other functions [2].

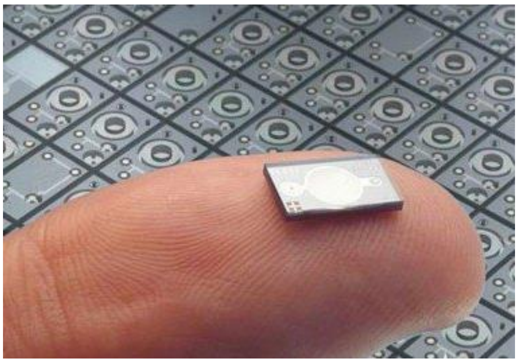

Fig. 1 MEMS chip

2. MEMS Research Status

2.1 Research State in China

Our country started the research of MEMS in the late 1980s, and has made a lot of valuable achievements such as micro-pressure sensor, micro-accelerometer, micro-gyroscope, micro-magnetometer, micro infrared sensor, micro-flow sensor, micro-sensor, micro-motor . In the micro-sensors, micro-actuators and a number of micro-system prototype has made some of the basic and technical reserves, the initial formation of several MEMS research focused areas. Including the Beijing-Tianjin region, such as Tsinghua University, Peking University, Chinese Academy of

Sciences Institute of Electronics, Nankai University; East China, such as Shanghai Metallurgical Institute, Shanghai Jiaotong University, Fudan University, Zhejiang University, China University of Science and Technology; Northeast, such as the Ministry of Information Industry Electronic BF, Harbin Institute of Technology, Changchun Institute of Optics and Mechanics, Dalian University of Technology; Northwest, such as Xi'an Jiaotong University, 618 aviation, space 771 and so on. Existing technical conditions have initially formed MEMS design, processing, packaging, testing system, in order to ensure the further development of China's MEMS technology provides a platform.

2.2 Research State in Foreign Countries.

Developed countries attach great importance to the development of MEMS technology, these industrialized countries in the original sensor as a priority for the development of technology based on the development of the continued development of MEMS as a key technology policy. The United States has identified its military applications as its main focus, focusing on the research of MEMS sensors represented by inertial devices. Japan has focused on the development of microcompartmental medical systems and micro-factories in narrow industrial space. In Europe, the focus has been on the development of micro-analysis systems, focusing on the construction of basic technologies At the same time, it attaches great importance to the development of technologies such as design, materials, processing, packaging and testing. In addition to establishing independent processing laboratories in the research institutes in the United States, it also set up a special processing and researching center for processing research and Germany has also established a BOSCH laboratory. The development of foreign MEMS technology has been more than 30 years of history, has now formed three types of production scale, large-scale enterprises in large quantities producing more than 1 million products, some companies continue to increase mass production capacity, annual production capacity of more than 10 million Only above; medium-sized enterprises with production capacity of 1-100 million / year; some institutes produce small batch products according to special requirements, the annual output of less than 10,000. In the fourth and fifth frameworks, Europe deepens the development of MEMS. Six machining centers and one competition center have been set up according to the geographical features and market demands. The product function is further expanded and perfected. MEMS devices are evolving to microelectronic components and systems. They not only have information and conversion functions, but also have intelligent functions such as self-test, self-calibration, range conversion, remote setting and wireless communication. Adapt to a variety of measurement control needs.

3. MEMS Development and Trends

MEMS history of development, integrated circuit technology is the starting point. Intel Corporation launched in 1971 Intel4004 processor chip integrates only 2250 transistors, introduced in 1982 Intel286 integrated 120,000 transistors, and in 1999 the Pentium III processor integrated transistor number reached 24000000. The alarming rate of development of integrated circuit technology is unmatched in other fields. Every 12 to 18 months, the integrated density of transistors on the chip will double. The miniaturization and multi-functional integration of electronic devices are the driving force behind micro-fabrication technology. In the mid-1960s and 1980s, MEMS developed from integrated circuit technology and undergone its embryonic stage. During this period, bulk silicon processing technology and surface processing technology matured, resonant gate transistors, thin-film silicon micro-processing pressure sensors, inkjet printers and other MEMS research is the main achievement; 90 years of the 20th century, MEMS research has entered a leap forward , Rapid development stage. National governments and private funds have set up funds to strongly support MEMS research. Analog Devices 'integrated inertial sensors for automotive airbag systems and Texas Instruments' digital light-processing chips for projection reality have all played a significant role in the field of application. In the late 1990s, the development of optical MEMS was very rapid. Researchers from all over the world competed to develop micromechanics and devices, hoping to combine binary optical lenses, diffraction gratings, tunable micromirrors, interference filters, phase modulators, etc. Components are used in areas such as optical displays, adaptive optics, tunable filters, gas spectrum analyzers and routers. In addition, bio-MEMS has gained important applications in medical fields such as retinal implantations, cochlear implants, embedded physiological sensors, and sensor-equipped smart surgical tools. Since 2000, there have been increasing numbers of companies developing MEMS-related technologies. In the next 10 to 20 years, MEMS research is expected to continue to make rapid progress. It is highly probable that several major advances have been made in this area: MEMS and interdisciplinary research; design methods and processing techniques; improved mechanical properties such as sensitivity and robustness; enhanced circuit processing capabilities, low cost circuit integration and large Area Integration Technology; Compatible integration of different types of materials in multifunction systems.

4. MEMS Research Content

4.1 MEMS Design and Processing

4.1.1 MEMS Material

MEMS material is divided into two kinds of structural materials and functional materials. Structural materials are mainly piezoelectric materials, photosensitive materials and other materials with a certain function; functional materials that have a certain degree of mechanical strength, for the construction of micro-mechanical device structure matrix material.

(1) Structural Materials

Silicon is the earliest used as a micro-sensor material. In MEMS applications, silicon has played a few of the most crucial role. Monocrystalline silicon is the most versatile body-working material because of its good heterosexual corrosion properties and compatibility with the mask material. In surface micromachining, regardless of the device structure itself is not a silicon material, single crystal silicon substrate is the most ideal MEMS structure platform. In silicon-based integrated MEMS devices, monocrystalline silicon is the primary carrier material for IC devices. Ding, Maseeh and Senturia investigated whether the stress of the doped layer is tensile or compressive. Wolfe and Tauber use dry etching to remove the etched surface material [3] [5] .

Polysilicon is used as a MEMS device surface micromachining, SiO2 mainly as a sacrificial layer, and Si3N4 mainly used for electrical isolation of the device structure. This material system has become the mainstream of surface processing technology. Polysilicon has superior mechanical properties than single crystal silicon, polycrystalline silicon and SiO2 have a higher etching selectivity. Polysilicon-related processes, such as thin-film deposition, lithography and material properties, have been thoroughly studied in ICs, resulting in the rapid development of polycrystalline silicon surface processing technology, which dominates surface micromachining. Kamins conducted in-depth research on the preparation of polysilicon, structural characteristics and other directions.

In addition to the silicon material, other semiconductor materials such as quartz, glass, ceramic and the like can also be used as a substrate material, and films such as SiO2, SiN and metal can also constitute a micromechanical structure.

(2) Functional Materials

Functional materials have energy conversion capabilities that allow for sensory and braking functions and are used in actuators that have been used in several types of MEMS actuators such as microfluidic pumps and valves, zinc oxide and PZT Electrical materials have a great attraction to MEMS, because it has electrical and mechanical conversion properties, that is, the power to the piezoelectric material will make it deformed, on the contrary will make it generate voltage stress. Magnetostrictive materials, photosensitive, gas-sensitive, bio-sensitive and current variants are also important functional materials used by MEMS.

4.1.2 Manufacture of MEMS

(1) Body Micro-machining Technology

Bulk micromachining process is an important process for manufacturing MEMS, processing is performed by etching the substrate to obtain the desired internal configuration of the inside of the silicon substrate. Its advantage is to obtain a larger geometric structure, good mechanical properties, the disadvantage is not compatible with the integrated circuit technology.

(2) Surface Micromachining Process

Surface micromachining process is still one of the important processes for manufacturing MEMS. Surface micromachining process is the use of thin film deposition, lithography and etching micromechanical structure formed on the substrate surface, the key is etched sacrificial oxide layer, forming a three-dimensional micro-mechanical structure. The sacrificial layer of this process, which is typically SiO2, is located beneath the moving parts, using hydrofluoric acid to etch SiO2, making the part a moving part. This MEMS process is compatible with integrated circuits for ease of integration with integrated circuits and mass production. MEMS micro-accelerometers and MEMS angular velocity sensors are examples of surface micromachining.

(3) The Third Generation of Micro-machining Technology

Third Generation micromachining techniques include laser-induced etching and material deposition techniques, electroless plating and etching technology, ultrasonic milling, and electron discharge technology molding method and the like. MEMS design can use the above methods to process MEMS. Further bonded wafers health and vacuum packaging of MEMS MEMS technology is an important process currently used, and LIGA micromachining processes due to the need of expensive synchrotron X-ray source, and the mask production process complicated, and therefore it is difficult to promote.

4.1.3 MEMS Packaging, Testing and Reliability

Packaging technology is one of the most critical technologies in MEMS products. Like integrated circuits, MEMS requires environmental protection, electrical leads, mechanical support and thermal access. However, the MEMS package is more complicated, and many of them are different from integrated circuits, and sometimes need to be isolated from the surrounding environment. Sometimes, they need to be in contact with the environment to influence or measure the specified physical and chemical parameters. For example, accelerometer packages require special environments , While others need to be carried out under vacuum to avoid air damping or heat conduction of the vibrating structure. It can be seen that MEMS packaging is much more complicated than integrated circuits, and the MEMS packaging needs to be based on product requirements. The cost of packaging and testing accounts for about 70% of the cost of MEMS products[3].

MEMS testing technology is MEMS development and production of an important part. Through the MEMS test can get the micro-mechanical structure and the entire MEMS system parameters, including geometric quantity, mechanical quantity, optical quantity, electromagnetism quantity, acoustic quantity and so on. MEMS testing is more difficult than integrated circuits, and includes many mechanical properties and other physical parameters in addition to testing the electrical signals.

From laboratory prototypes to a truly market-based product, reliability-related tests, such as packaging-induced stress and contact degradation, must be overcome and must be subjected to stringent reliability tests in harsh environments. However, the current test standard is only applied to the traditional semiconductor micro-system, there is no test standard for high temperature devices. Savrun et al. Developed a set of acceleration stress testing protocols to evaluate the reliability of packaged SiC pressure transducers when subjected to cyclic pressures and temperatures in excess of 140 hours at 300 degrees air[6].

4.2 MEMS Theoretical Research

MEMS basic theoretical research involves micro tribology, micro-mechanics, micro-kinematics, micro-dynamics, micro-heat transfer theory, electrostatic theory, electrostatic mechanics, simulation, CAD, optimization, reliability and other fields [7]. Basic theoretical research is made and progresses around these core issues of micro-dimensions and disciplinary infiltration. When the size of a component or system is reduced to a certain extent, many physical phenomena differ greatly from the macro-world and even undergo qualitative changes , Significant features of the nature of the force changes, physical and chemical reactions, friction and so on. In the field of small size, the inertial force with high order of the basic size of the object rapidly decreases with the reduction of the basic scale, and the adhesive force, the elastic force and the surface force in the lower order of the basic size become Performance plays a leading role in influencing the factors.

4.2.1 Kinematics of Micro-institutions

Domestic research on micro-kinematics mainly focuses on the study of configuration performance maps, pseudo-stiffness modeling, micro-kinematics modeling and analysis methods, workspace analysis, static stiffness model and other research fields. To study the design method of micro-parallel mechanism, taking the typical parallel mechanism as the research object, the relationship between the size and the performance index is analyzed to get the performance map [8] or the isotropic and the stiffness performance map [9] which reflect the relationship between the mechanism performance and the dimension parameter. The micro-kinematic analysis method uses vector operation [10] [11] and hinge displacement method [12] to analyze the operating characteristics of the mechanism. The static stiffness of the micro-parallel mechanism is based on the derived static stiffness matrix [13] . In addition, the kinematic positive solutions, the inverse solutions and their decoupling properties of the new multi-degree-of-freedom micro-parallel mechanism are analyzed, and provide the theoretical basis for the dynamic analysis, control and simplification of calibration [14] [15] [16] [17]. The study of working space in micro-parallel mechanism is the basis for the optimization of the design parameters of the mechanism. Especially for the study of minimally-invasive surgery to the surgical robot, it is very important to study the flexible working space [18].

4.2.2 Micro-dynamics Research

Because of the scale effect on the mechanical properties of the micro-scale material, the dynamic behavior of the material is obviously different from that of the traditional large-size flexible beam. The research of micro-motive force mainly involves the establishment of dynamic model and the analysis of dynamic parameters. Wu Shengbao [19] used the theory of even-stress (also known as Cosserat theory) to study the criterion of the dynamic characteristics of the micro-beam in the study of the dynamic characteristics of a rigid-flexible coupling system consisting of a rigid body and a microbeam composed of a rigid microbeam and a rigid microbeam. Effect, the Hamiltonian principle is derived to derive the rigid-flexible coupling kinetic equation in which the system considers the scale effect. On this basis, the dependence of the natural frequency of micro-beam on the micro-scale is analyzed, and the difference of the vibration frequencies of the zero-order approximation model and the first-order approximation model is compared under different rotational speeds so as to determine the difference between the zero-order approximation model The scope of application, the final analysis of the scale effect and coupling deformation on the micro-beam stiffness. For the ball-based micromanipulator, Guo Wei [20] established the system dynamics model of micromanipulator with stick-slip property under the condition of simplifying the spherical connection. Based on the dynamic friction model, the numerical method is used to analyze the influence of multiple parameters on the performance of the micromanipulator. The simulation is used to verify the model. The micro-manipulator motion test was carried out to verify the correctness and validity of the established dynamic model. Gao Rong [21] carried out a nonlinear dynamics study of the MEMS microresonator with air damping and established a nonlinear dynamics model of the microresonator, taking into account the slip boundary conditions and the lean gas effect. By using FLUENT and MATLAB, Stokes equation and kinetic equation. After comparison with foreign experiments, it can be concluded that the amplitude of the plate considering the nonlinear damping force is very close to the experimental value, the peak-to-peak error of the amplitude is only 6%, and is superior to the linear dynamic analysis. It provides a theoretical basis for the analysis of nonlinear dynamics of MEMS devices. Chen Haichu [22] developed a piezoelectric ceramic-driven ball-based microactuator prototype with a size of 30 mm × 30 mm × 50 mm, and studied the dynamics of the micro-actuator and the experimental study of the miniature shaft hole assembly. The spatial coordinates of the micro-actuator metal ball are established. The dynamic characteristics of the ball-based microactuator are analyzed and their dynamic models are established. Using the Runge-Kutta method, the dynamic parameters of the microactuator are calculated, and the simulation model of the microactuator is built by SIMULINK module of MATLAB, and its dynamics simulation is carried out.

5. MEMS Applications

MEMS technology is widely used. MEMS technology is a typical frontier research field of interdisciplinary research, covering almost all fields of natural sciences and engineering. Some microstructured devices such as micro-sensors and micro-actuators that have really become commercialized have been widely used in the fields of optical signal processing, biomedicine, robotics, automobile, aerospace, military and household electrical appliances.

5.1 Micro-sensors and Actuators

MEMS technology has revolutionized sensors and actuators. Sensors are generally used to detect and monitor the physical and chemical phenomena of the device, and actuators are used to produce mechanical movement, force and torque of the device. Sensors and actuators can be collectively referred to as transducers, transducers that enable the conversion of signals and energy from one energy source to another. Micro-sensors can be divided into two categories: physical sensors and chemical / biological sensors. Physical sensors measure physical quantities such as force, acceleration, pressure, temperature, flow rate, acoustic vibration, and magnetic field strength. Biochemical sensors measure chemistry and biomass, such as chemical concentration, pH. The binding strength of biomolecules and the interaction between proteins. Physical sensors in the electrostatic, piezoresistive effect, piezoelectric effect, thermal resistance and thermal double layer sheet bending principle has been widely used. Actuators are usually the form that converts energy from non-mechanical to mechanical energy. Common use of electrostatic, magnetic, piezoelectric, or thermal expansion to produce mechanical movement. In addition there are many actuator-driven methods: such as gas mechanics, deformation memory alloys, thermal expansion, phase change, electrochemical reactions, and frictional resistance of moving fluids.

5.2 Micro-robot

Micro-robot is an important branch of MEMS application research. Robots designed by using MEMS technology can be divided into two categories: one is to make the structure of the device miniaturization, precision to improve the positioning accuracy or fine operation of the robot; the second is to make the robot itself miniature robot. Currently in some nuclear and petrochemical industries often encounter the detection and repair of micro-pipes, the general use of micro-robot to complete. In the medical field, there is a growing demand for minimally invasive surgery using micro-robots because traditional surgery often results in physical and psychological damage to the patient. In addition, infection prolongs the recovery time of the patient. Endoscopic robot is to play the endoscope system to the body cavity in all parts. Israel developed a gastrointestinal minimally invasive endoscopic capsule with the gastrointestinal motility to do passive operation, itself not driven [24]. Domestic Li Guoli proposed a capsule endoscopic drive for the external magnetic field coils [25]; Zhou Yinsheng put forward spiral-type non-invasive medical micro robots [26].

Micro-robot's driving technology is the key technology of micro-robot development. Micro-drive into a cable-driven and cableless two categories. The advantage of cabled driving is that the energy supply is convenient and sufficient, but the micro-robot used in the special environment such as small pipelines and narrow spaces has poor mobility and limitation of movement distance and walking route. At present, micro-servo motor drive, piezoelectric ceramic drive, polymer materials drive, pneumatic drive, etc. belong to a cable drive. Cableless driving can avoid the shortage of cabled driving and is the future research direction. The existing solar-driven, external magnetic field drive are cableless drive. Micro robots are also faced with problems such as the miniaturization of actuators, the accuracy of robot position and speed recognition in small environments, the speed with which micro-vision systems handle images, wireless power and communication, autonomous motion control, and reliability issues All need to be solved [27].

5.3 Micro-aircraft

The concept of micro-aircraft (MAV) originated from the pre-research bureau of the United States Department of Defense. The definition of the maximum size of the aircraft does not exceed 15cm, mass 10 ~ 100g, the maximum range of 1 ~ 10km, cruising speed of about 30 ~ 60km / h, Time 20 ~ 60min. Micro-aircraft should have the basic characteristics of autonomous flight, carrying mission load to perform specific tasks, communication and transmission of information. Micro-aircraft research is mainly used for military purposes. Due to their small size, portability, take-off without being restricted by the site and their inability to find in the sky, the miniature aircraft can perform tasks such as military investigation, communications and electronic interference [21] and [22].

Micro-aircraft according to their layout can be divided into fixed-wing MAV, MAV rotor and flapping wing MAV three categories.

Solid wing MAV due to be closer to the conventional aircraft, the development is relatively small, is the main area of research. Black Widow [23], MicroStar, etc. are typical representatives of fixed-wing type. Rotor MAV design is more complicated than fixed wing, but the biggest advantage of rotary MAV compared with fixed-wing MAV is that vertical Takeoff and landing and hovering, mobility is good, suitable for use in relatively small space or complex terrain environment. Therefore, in the MAV research boom, micro-rotor system has also formed a research hot spot. Micro-aircraft such as "Kolibri" [22] and "Epson" [21] are all rotor designs; flapping-wing MAVs are a new type of aircraft that mimics bird or insect flying in principle unlike traditional aircraft design and aerodynamic Research area California Institute of Technology, Aero Vironment and the University of California jointly developed the mini bat "Micro Bat"; Georgia Institute of Technology developed "Entomopters." Domestic Tsinghua University, Xigong University, Beijing University of Aeronautics and Astronautics, China Southern Airlines and other colleges and universities also conducted research on micro-aircraft, and achieved some results.

5.4 MEMS Application in Dexterous Hand or Bionic Hand

To ensure the performance of dexterous and biomimetic hands with multi-finger joints, sensory information must be provided by the fingertip sensor for the dexterous hand force control and compliance control. Therefore, the development of micro multi-dimensional tip with good performance force / torque sensor is very necessary. Dexterous hands Five-dimensional fingertip force / torque sensor's main performance requirements are: compact design; high accuracy; dynamic response and so on. Harbin Institute of Technology Robot Jiang et al [23] applied a new type of electronic components designed micro five-dimensional force / torque sensor. In order to achieve these performance targets, they used the finite element optimization algorithm to design a miniature sensor elastomer structure; using BLH miniature high-resistance metal strain gauge, composed of five strain measurement half-bridge, the sensor low power consumption and low drift. The application of surface mount technology designed sensor signal conditioning circuit placed in the tiny sensor body, the sensor system to achieve the integration and miniaturization of the volume.

6. Conclusion

MEMS development goal is to explore new principles, new features through the miniaturization and integration of components and systems, open up a new area of technology and industry. MEMS can accomplish tasks that large electromechanical systems cannot afford and can be embedded in large-size systems to take automation, intelligence and reliability to a new level. In the 21st century, MEMS will gradually move from laboratories to practical applications and will have a significant impact on industry and agriculture, information, environment, bioengineering, medical treatment, space technology, national defense and scientific development.

References

[1] Mohaned Gad-el-Hak, Zhang Haixia, Zhao Xiaolin etc .. MEMS design and processing [M] Beijing: Mechanical Industry Press, 2010: 1.

[2] ZHOU Zhao-ying, WANG Xiao-hao, YE Xiong-ying, WANG Bo-xiong, LI Sha, LIU Wei-dan.Micro-electromechanical systems [J] .Chinese Mechanical Engineering, 2000, Z1: 163-168.

[3] LIN Zhonghua, HU Guoqing, LIU Wenyan, ZHANG Huijie. Development and Application of MEMS [J]. Nanotechnology and Precision Engineering, 2004,2 (2): 117-123.

[4] Chang Liu, Huang Qing'an. MEMS based system [M]. Beijing: Mechanical Industry Press, 2007: 1-8.

[5] Wang Liding. China MEMS research and development process (abridged version), [C]. MICONEX2002 Instrumentation and Automation Technology Development Conference, 2002: 17-21.

[6] Li Jianfeng, Wu Guangzhong, Fei Renyuan, Liu Dezhong, Guan Changle, Yang Xiaoyong.A dimensional model of 3-RUU micro-parallel mechanism and its performance spectrum [J] .Journal of Mechanical Engineering, 2005,41 (5): 142- 153.

[7] Liu Xinjun, Wang Jinsong, Gao Feng.Design of parallel mechanism of six degrees of freedom micromanipulator [J] .Journal of Tsinghua University, 2001,41 (8): 16-20.

[8] Bi Shusheng, Zong Guanghua. Vector analysis of hand kinematics in Delta parallel micromanipulation [J] .Beijing University of Aeronautics and Astronautics, 2003,29 (4): 339-341.

[9] Bi Shu-sheng, Wang Shou-jie, ZONG Guang-hua.Kinematics analysis of series-parallel micro-mechanism [J] .Botman, 1997,19 (4): 259-264.

[10] Liu Jigang, Micro-kinematic analysis of planar 3-RRR full-flexible robot [J] .Yanshan University, 2004,28 (4): 296-301.

[11] Yu Jingjun, Bi Shusheng, Zong Guanghua. Static Stiffness Analysis of 3-DOF Flexible Micro-robot [J] .Journal of Mechanical Engineering, 2002,38 (4): 7-10.

[12] Zhang Jianjun, Gao Feng, Jin Zhenlin, Fan Shuncheng.Research and development of structure decoupling 6-PSS parallel microoperation platform [J] . China Mechanical Engineering, 2004,15 (1): 1-4.

[13] Tian Yanling, Zhang Dawei, Run Ling. Kinematics characteristics of nano-grinding micro-positioning platform with three degrees of freedom [J] Journal of Tianjin University, 2006,39 (7): 777-782.

[14] Yang Chunhui .Kinematics model and workspace analysis of three-freedom planar parallel micro-robot [J] .Mechanical Gear, 2010,34 (1): 16-18.

[15] PAN Bo, FU Yi-li, WANG Shu-guo, YANG Zong-peng.Kinematics of endoscopic robot manipulated by minimally invasive conditions [J] .Journal of Mechanical Engineering, 2009,45 (3): 162-168.

[16] Liu Da, Wang Tianmiao. Analysis of Flexible Work Space for Minimally Invasive Surgical Robots [J]. JOURNAL OF BEIJING UNIVERSITY OF AERONAUTICS AND A, 2007,33 (2): 188-191.

[17] Wu Shengbao, Zhang Dingguo, Kang Xin.Dynamics of rigid body-micro-beam system [J] .Journal of Mechanical Engineering, 2010,46 (3): 76-82.

[18] Meron G D. The development of the swallowable video-capsule (M2A) [J]. Gastrointestinal Endoscopy (S0016-5107), 2000, 52(6): 817-819.

[19] Grasmeyer J M, Keennon M T . Development of the black widow micro air vehicle[R]. A I AA Paper, 2001.

[20] Wilson T J . Micro SAR meets MAV [J]. Aerospace America, 1999 (38) : 32 - 35.

[21] George R H. Multidisciplinary design and prototype development of a micro air vehicle[J]. J of Aircraft, 1999, 36 (1) : 227 - 234.

[22] Fearing R S . Toward micromechanical flyers [J]. The Bridge, 2001, 31 (4) : 4 - 8.

[23] Chang Liu, Huang Qing'an. MEMS based system [M] .Beijing: Mechanical Industry Press, 2007: 10-14.