論文 Wireless Link System for Communication and Energy Transmission of Microrobot*

光本直樹 Naoki MITSUMOTO　鶴田和弘 Kazuhiro TSURUTA　柴田貴行 Takayuki SHIBATA　川原伸章 Nobuaki KAWAHARA

Miniaturizing the wireless link systems is now becoming an important technology for wireless data communication and energy supply. We have succeeded in developing a completly wireless link micromachine. It is achieved using microwaves and light. The robot consists of a CCD camera, a locomotive device, a system control circuit and wireless energy supply and communication devices. The robot moves within a 10mm diameter pipe without wire and observes the inner surface of the pipe using the installed CCD camera. We have developed a compact control circuit which controls all the devices installed in the robot through external commands and transmits the image data from the CCD camera. As for the control circuit, the power consumption and the size are greatly restricted so that they may be installed on the robot. In order to reduce the size of the circuit, we have newly developed an image data communication LSI based on new architecture. The LSI is made from 0.35μm CMOS technology, and is 3.9mm by 3.9mm. To make the control circuit compact, we used a flip chip assembly for the LSI and eight more ICs in the robot. Through a fabricated prototype of the microrobot, we have successfully confirmed the wireless image data communication of 2.27 frames per second and control of the robot through microwave technology.

Key words : Wireless, Micro-wave, Image data communication, Micromachine

1. INTRODUCTION

Figure 1 shows an image of micromacine, which is operated under complete wireless link condition. This machine travels in a 10mm metal pipe without wire, takes pictures of inside the pipe, and transmits the image data back to an outside host.[1] Image transmission, signal communication and energy supply are done via microwave and light. It also generates multiple voltages for locomotive mechanism (15V),[2] camera (-7V, 80V), LSI (3.3V) and every device after receiving and converting the microwave. The dimension of the system is 10mm in diameter and 50mm in length, in which all the devices such as a CCD camera for vision, an actuator for locomotion, a LSI for control, RF module, microwave antenna, photovoltaic device for energy supply and communication are installed. Through the development of the prototype micromachine, problems unique to micro technology were identified. The biggest problem was wiring for the power supply and signal monitoring. Even the diameter of the wire as thin as 18μm, the weight of the wire is too heavy enough for the 1g micromachine and the hardness of the wire is too thick for the machine. Therefore, the wire limits the movement of the machine. For that reason the wireless link system is necessary for the microrobot.

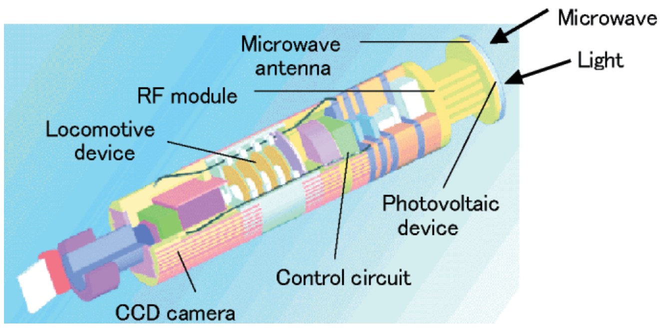

Fig.1 System image of wireless micro robot for inspection on inner surface of tubes

2. Component Devices

2.1 CCD micro camera module

The CCD micro camera module has been developing by TOSHIBA. The CCD camera module consists of several functional devices, such as a mirror, a mirror rotation mechanism, a focusing mechanism, a micro lens, a 100,000 pixels CCD and a CCD imaging data transmission circuit as shown in **Fig.2**. These devices have been integrated to achieve 9.2mm diameter CCD micro camera module. The mirror rotation mechanism and focusing mechanism have electrostatic actuators which are operated at 80V. The lens is mounted on the inner cylinder of the focusing mechanism.

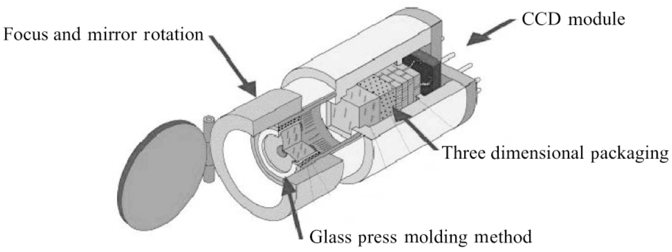

Fig.2 Image of CCD micro camera module

2.2 Locomotive mechanism

We have developed a new actuator whose displacement is larger compared with the piezoelectric stacked actuator.[4] This mechanism enlarges the displacement of the actuator but reduces the generating force. Therefore, the actuator has multi-layered structure, which controls the generating force by the layer number. The locomotive mechanism consists of eight-layered PZT bimorph actuator, a center shaft which connects the center of the each bimorph, and four cramps which connect the edges of the each bimorph as shown in **Fig.3**. When the actuator is operated at 15V, it deforms approximately 6μm between center shaft and cramps. The locomotive mechanism is driven by the saw-toothed wave voltage and moves in a pipe by the inertia drive method.

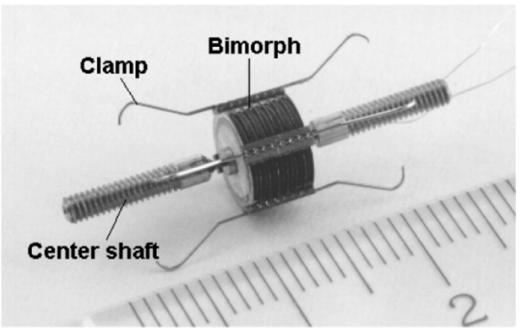

Fig.3 Locomotive mechanism of 8-layered PZT bimorph actuator

2.3 RF module

The RF module, as shown in **Fig.4**, consists of a stacked patch antenna, two rectifying circuits, a communication circuit and a photovoltaic device formed on the antenna. The antenna receives two frequencies of microwaves; 22GHz for energy supply and 24GHz for communication, and isolates them. The rectifying circuit converts the microwave for energy supply (22GHz) into direct current. The communication circuit receives the host command (24GHz) and answers the voltage condition of the robot and the image data of the CCD.

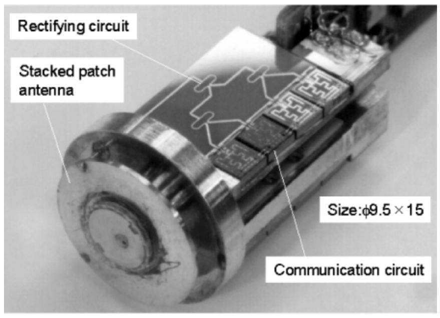

Fig.4 RF module

The communication MMIC modulates and demodulates microwaves with the signal from the control LSI. The size of the circuit is 7mm by 9.5mm. Communication bit rate is 2.5Mbits per second.

3. Control Circuit

3.1 System control LSI

In order to recognize control commands from the host, control all the component devices installed in the robot and transmit CCD image data to the host without wire, the system control circuit is essential in the wireless in-pipe micro inspection robot. The control circuit must be compact and have low power consumption, because the size and the power consumption of the robot are limited by the diameter of the pipe, 10mm and the supply power of 650mW. Therefore, we have developed a system control LSI based on a new idea for image communication.

Figure 5 shows the block diagram of system control LSI. In the LSI, the command from outside host controls the installed devices, such as the CCD camera, the electrostatic mirror actuators, piezoelectric locomotive actuator, and so on. Image data from the CCD camera is transmitted to the host.

The most difficult point for the LSI is its size of less

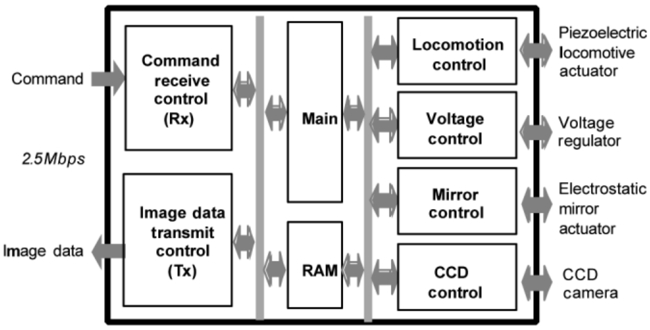

Fig.5 Block diagram of system control LSI

than 4mm by 4mm. The Chip size of the LSI strongly depends on the installed memory size.

Figure 6 shows a relation between chip size and installed memory size. Conventional image communication LSIs for MPEG2 are plotted in the gray area, the chip size of the LSIs is more than 100mm^2. Our requirement, however, is in the black area, the chip size is less than 16mm^2. The conventional LSI needs a large memory and a large chip size, because the image data unit for communication is a frame, and several ten Mega bits memory for the frame data are included in the LSI.

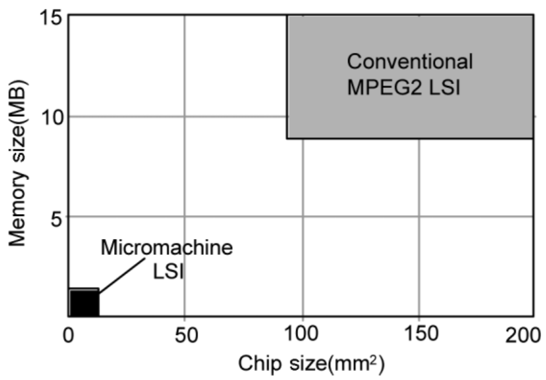

Fig.6 Relation between chip size and installed memory size

Our solution for the problem is changing the image data unit from a frame to a line. We have proposed a new architecture of a communication LSI for the micro robot. In the system, the image data is transmitted line by line without data compression. The required memory size is greatly reduced to only three line memories.

Figure 7 shows the developed system control LSI for the micro robot.

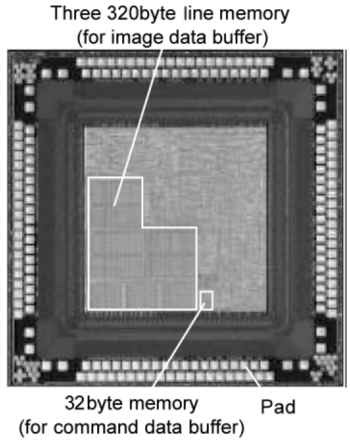

Fig.7 Developed system control LSI

The chip is designed by using 0.35μm CMOS technology gate array, and has the size of 3.9mm by 3.9mm. The number of the gates of the LSI is around 40K gates. 70% of the total gate is used for memory and 30% of it is used for communication and control logic. The clock frequency of the LSI is 20MHz, and the maximum power consumption is only 45mW.

The LSI generates a timing signal to generate the saw-toothed wave voltage for the locomotion. The timing signal controls the direction and the speed of the robot according to the host command.

The LSI also controls the CCD and generates timing signals to operate the focusing and mirror rotation mechanism.

The LSI converts the image data of the CCD to digital and transmits it to the RF module at the frame rate of 2.27 frames per second. Because the image-transmitting rate of the LSI is slow, there is a problem that pictures are blurred when the micro robot moves while taking pictures. Therefore, the LSI has a function of automatic intermittent locomotive motion for taking pictures; the robot repeats a motion of locomotion for 0.5 seconds to 1.5 seconds without taking pictures and stops to take two-frame pictures before proceeding.

3.2 Other circuits

The control circuit consists of a voltage regulator and a voltage monitor, the system control LSI and a drive circuit of the locomotive mechanism. The voltage monitor detects the output voltage of the RF module and sends the data to the LSI. The LSI converts the data to digital and sends it to the RF module.

The drive circuit generates a saw-toothed wave voltage from DC voltage supplied from the voltage regulator. In order to make the circuit compact, we developed a simple drive circuit.[5] The circuit consists of four analog switches, two resistors, and the PZT actuator used as a capacitor. In this circuit, the combination of the PZT actuator and resistors works as a CR circuit to generate the saw-toothed wave voltage. The gate array controls switches, and generates forward and backward voltage.

3.3 Packaging in control circuit

To make the control circuit compact, we used a flip chip assembly for the gate array and the other eight ICs. The system control LSI is made of 0.35μm CMOS: the pad pitch is 120μm and the pad size is 88μm, which is shown in **Fig.8**. Therefore, stud bumps whose diameters are approximately 50μm are formed on each pad of the bare chips. The bumps are bonded on a fine pitch 6-layered printing circuit board (PCB) by using an anisotropic conducting paste (ACP). The chips are precisely aligned, mounted and heated on the PCB by a chip bonding machine. The ACP is composed of heat-hardening resin and many conductive particles. Advantage of the ACP is that the contacts between bumps and PCB are done by heating with low stress. **Figure 9** shows developed PCB.

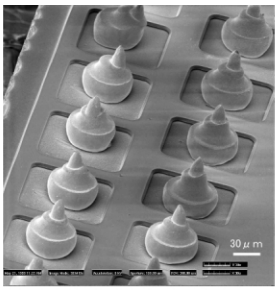

Fig.8 50μm stud bumps formed on the pads

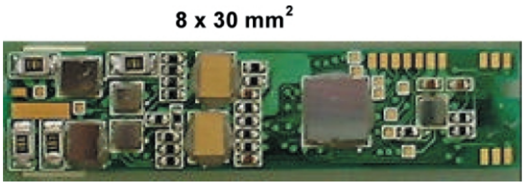

Fig.9 Developed PCB used a flip chip assembly

4. Systematization

4.1 Host

The total system of the wireless inspection micromachine consists of the micro robot and the host. **Figure 10** shows a schematic diagram of the system. The micro robot and the host communicate with microwaves. The host computer generates commands to control the micro robot such as the speed and the direction of the robot. Furthermore, the host receives the voltage and image data from the micro robot, displays this data and controls the level of the microwave for the power supply. The communication bit rate is 2.5Mbits per second. The command data is transferred to the robot, in which the microwave is modulated by an amplitude shift keying method (ASK). The voltage and the image data are transferred from the robot by a phased shift keying method (PSK), because a compact and low power consuming wireless communication device is strongly needed for the micro robot. ASK demodulation method reduces the size of the demodulation circuit in the micro robot. PSK modulation method reduces the power consumption of the modulation circuit in the micro robot.

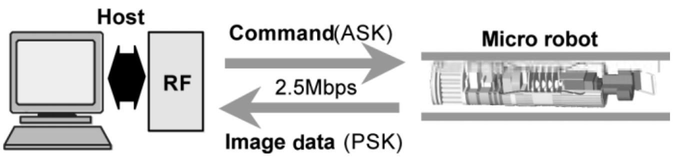

Fig.10 Schematic diagram of the system

In general, when a microwave of fixed frequency is transmitted in the pipe, a standing wave is produced between the coaxial waveguide adapter and the antenna attached to the micro robot. The received power is fluctuated more than 10dB and depended on the distance between the transmitter and the micro robot, because the micro robot moves in the pipe. In order to stabilize the received power, a 6dB attenuator using microwave absorber is placed to suppress the standing wave between the coaxial waveguide adapter and the micro robot. In addition to this, the frequency of the microwave signal is continuously swept between 21.5GHz and 22.5GHz so that the microwave does not stay at the resonance frequency. Moreover a polarizer is placed to circumferentially polarize the direction of the microwaves so that the micro robot can receive steady power, if the robot rotates in the pipe. Thus, stable energy transmission has been achieved. In addition to this, the circumferential directions of the two frequencies of microwave signals; for energy and communication are reversed to separate them.

4.2 Developed Prototype System

In our previous work, we developed a wireless energy supply method utilizing microwaves.[4] We also developed a 15mm diameter in-pipe locomotive mechanism whose power was supplied from outside by microwave signals.[5]

As prototypes of the robot, we have developed three different systems, such as A type, B-type and C-type. The A-type consists of the locomotive mechanism, the control circuit and the RF module. It could move within a pipe of 10mm in diameter, receive the commands from the host, transmit the voltage data of the RF module to the host and receive microwave energy of 480mW from the host.[6]

The B-type prototype system consists of the RF module with photovoltaic devices and the control circuit. Through the B-type, multiple voltage generation of 80V, -7V, 3.3V and 15V using the light supply and the microwave supply have been confirmed.

The C-type prototype system consists of the CCD camera module, the RF module and the control circuit as shown in **Fig.11**.

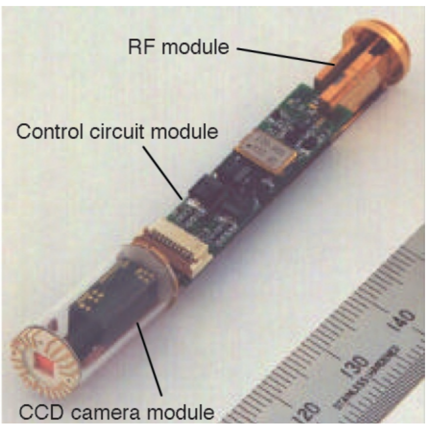

Fig.11 Developed the C type prototype system

Through the C-type, wireless image data communication and control by using microwave have been investigated, and the expected operations which are wireless CCD camera control and wireless image data transmission of 2.27 frames per second have been confirmed as shown in **Fig.12**.

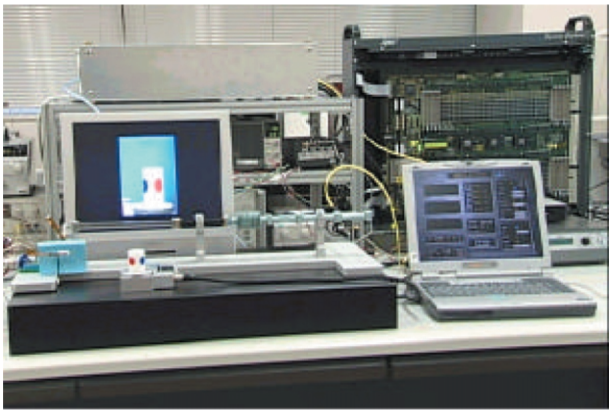

Fig.12 Experimental scene (C type)

5. CONCLUSION

We have developed a complete wireless link microrobot. It can control all the devices installed in the robot by an outside command and transmit the image data of the CCD camera. As for the control circuit, the power consumption and the size are greatly restricted in order to be installed in the robot. In order to reduce the size of the circuit, we have newly developed an image data communication LSI based on a new architecture. Through the fabricated prototype, we have successfully confirmed the wireless image data communication of 2.27 frames per second and control of the robot by using microwaves.

ACKNOWLEDGMENT

A part of this work was performed under the management of the Micromachine Center as the Industrial Science and Technology Frontier Program (ISTF), Research and Development of Micromachine Technology of METI, supported by New Energy and Industrial Technology Development Organization (NEDO).

REFERENCES

1) T. Idogaki, H. Kanayama, N. Ohya, H. Suzuki, and T. Hattori," Characteristics of Piezoelectric Locomotive Mechanism for an In-Pipe Micro Inspection Machine ", Proceedings of the 6th International Symposium on Micro Machine and Human Science, pp. 193-198, 1995, IEEE

2) T. Higuchi, M. Watanabe, and K. Kondou," Precise positioner utilizing rapid deformations of a Piezoelectric Element ", JSPE-54-11, pp. 2107-2112, 1988

3) H. Yamada, T. Togasaki, T. Terui, M. Kimura, K. Ooi and H. Sudo," Advanced three-dimensional assembly technology for high-density CCD micro-camera system module ", Proceedings of the fifth International Micromachine Symposium, pp. 179-184, 1999

4) T. Shibata, T. Sasaya, and N. Kawahara," Microwave Energy Supply System for In-Pipe Micromachine ", Proceedings of the 1998 International Symposium on Micromechatronics and Human Science, pp. 237-242, 1998, IEEE

5) T. Sasaya, T. Shibata and N. Kawahara," In-Pipe Wireless Micro Robot ", Transducers `99 Digest of Technical Papers Vol. 2, pp. 1058-1061, 1999

6) H. Nishikawa, T. Sasaya, T. Shibata, T. Kaneko, N. Mitsumoto, S. Kawakita and N. Kawahara," In-Pipe Wireless Micro Locomotive System ", Proceedings of the 1999 International Symposium on Micromechatronics and Human Science, pp. 141-147, 1999, IEEE

＜著　者＞

光本　直樹
（みつもと　なおき）
基礎研究所　工学博士
マイクロマシン技術の応用システム開発に従事

鶴田　和弘
（つるた　かずひろ）
基礎研究所
マイクロマシン技術の応用システム開発に従事

柴田　貴行
（しばた　たかゆき）
基礎研究所
マイクロマシン技術の応用システム開発に従事

川原　伸章
（かわはら　のぶあき）
基礎研究所　工学博士
マイクロマシン技術の応用システム開発に従事