An industrial and applied review of new MEMS devices features

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Abstract

Silicon-based MEMS (Micro Electro-Mechanical Systems) devices have a high potential of making a new field of applications for mobile equipment. However at the same time, there are many competing conventional technologies for spreading over in many existing applications. Currently, MEMS cavities in Ink Jet Printer or MEMS sensors in automobiles are most well known applications. In this paper, one example of sensor network system was shown. And how the basic properties of the electro mechanical device such as Si-MEMS, Quartz-MEMS, piezo-electric devices affect to the total system was shown from the technical point of views and also consumer point of views. A demonstration of a blur correction system in digital camera or video caused by hand jitter was shown. Furthermore, sensor assisted navigation system was tested. Every material of sensors had excellent performances for camera and video in short-term operation. But in a long term operation such as navigation system or tracking system of a moving object, Si-MEMS sensor had a large signal drifts during the operation term. Also power consumption of various sensors were compared in sensor input and communication unit. It will be proposed that system designer has to take account of feature of each technology and has to apply MEMS technologies to their appropriate usage.

Keywords:
Si-MEMS, accelerometer, Gyro-sensor, resonator, noise, zero drift, parasitic effect
;

1. Introduction

A strong requirement of miniaturization in electrical devices is demanded topics for wireless communication and sensor application as well. For those requirements, silicon-based micro electro-mechanical systems (MEMS) are promising for these strong demands. At the same time, a high preciseness and stability are required in new application even for mobile equipment. Prof. Nguyen's group has developed Si-MEMS resonators and establishes new mainstream of those devices [1, 2].

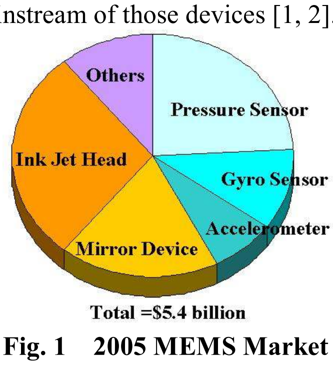

Fig. 1 2005 MEMS Market

Fig 1 shows the major MEMS market in 2005. [3] From this figure, there are two major applications for MEMS device, one is an active device such as Ink Jet printer head or micro mirror device for projector, the other is passive device such as sensor. As for sensors, more than 90% of sensors are commercialized in automobile applications. General MEMS application sensor started expanding recently, but still makes a small market.

2. Miniaturization Trend

In recent topics, miniaturized accelerometer attracted many people's interest. [4, 5] Miniaturization is an important factor for usage in handy equipment. But is it a main factor for a practical application? The size reduction is a common trend in many electrical devices.

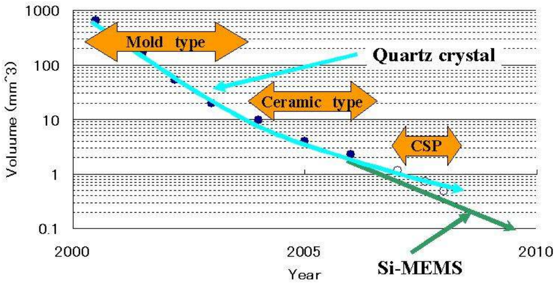

Fig. 2 Miniaturization Trend of Oscillators

Fig. 2 shows a size trend of quartz crystal oscillators. Si-MEMS oscillator makes this trend more rapidly as in shown by dotted line in a figure. Sensors and other devices seem following to this trend one or two years behind. Concerning to the noise density depending on a device size, there is a simple proportional relationship. Here is an example of the relationship between package size and noise density of Si-MEMS accelerometer. When sensor package size becomes smaller, noise density level becomes proportionally higher. In accelerometer, total noise density equivalent acceleration (TNEA) is expressed in eq. (1).

$$TNEA = \sqrt{BNEA^2 + CNEA^2}\left[\frac{m/s^2}{\sqrt{Hz}}\right]. \quad . \quad .(1)$$

As in eq. (1), TNEA is composed by two components, one is BNEA (Brownian noise equivalent acceleration) from sensing device and the other is CNEA (Circuit noise equivalent acceleration) from IC circuit. BNEA and CNEA are expressed as in eq. (2) and (3) individually.

$$BNEA = \frac{\sqrt{4k_B TD}}{M}. \quad . \quad .(2)$$

$$CNEA = \frac{\delta C(\min)}{S}. \quad . \quad .(3)$$

Here, T; temperature, D; air damping coefficient, k_B;Boltzmann's coefficient, M; effective mass, δC; capacitive resolution of IC, S; sensitivity. The sensitivity in eq.(2) is expressed in eq.(4)

$$S = \frac{2C_0}{d}\frac{M}{K_{eff}}. \quad . \quad .(4)$$

$$K_{eff} = K_{mechnical} - K_{electrical}$$

$$K_{mechnical} = 4E_x h\left(\frac{w}{l}\right)^3$$

$$K_{electrical} = \frac{C_S V^2{}_{dd}}{2d^2}. \quad . \quad .(5)$$

Here, K_{eff} ; effective stiffness of tether, $K_{mechanical}$; mechanical stiffness of tether, $K_{electrical}$; electrical stiffness of tether. From eq.(2), BNEA from sensing device is inversely proportional to effective sensor mass M. Also CNEA is inversely proportional to the effective sensor mass, since sensitivity is proportional to effective mass from eq. (4). [6] Therefore, theoretically the size reduction sacrifices its sensitivity.

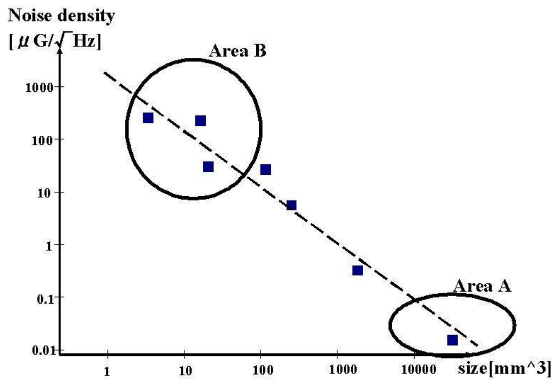

Fig. 3 Size dependency of Noise density in Conventional Si-MEMS accelerometer

In fig.3, there are two large markets existing. Area A is an accuracy dependent market such as a posture control of airplane or automobiles. Area B is a size and cost dependent market such as shock sensors for air bags in cars or for hard disks in PCs. Currently latter application does not require an accurate linearity of output signal intensity to applied acceleration force.

3. Signal flows in a sensing system and their applications

In this paragraph, the signal flows in a sensing system will be explained. These flows are shown in Fig.4.

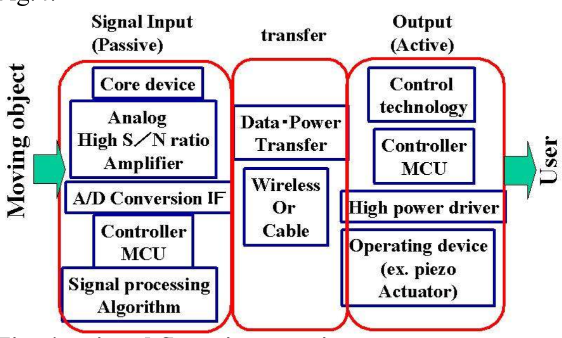

Fig. 4 signal flows in a sensing system

An external force is applied to a detection system and converted to electrical signal, amplified, digitalized, processed and converted into physical data. Then those data are transferred through the cable or wireless, to output part, which has active device within, and then converted again to driving signal, activate an active device such as MEMS actuator.

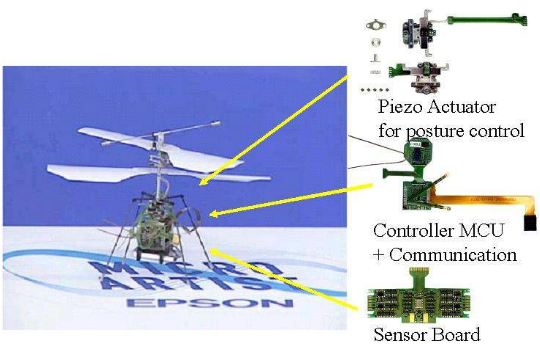

Fig. 5 Epson's micro flying robot μFR-II

In fig.5, Epson's micro flying robot μFR-II is shown as an example. μFR-II flies under auto posture control and auto driving system. Gyro sensor (core device) are installed in an input part and converted into a gradient angle of the flying body when it is unbalanced. The gradient angle which has to be corrected to a flat posture, transferred to an output part and which is converted into a shift distance of mass center (MCU + algorithm), then piezo actuator (active device + driver IC) moves its mass center just calculated distance.

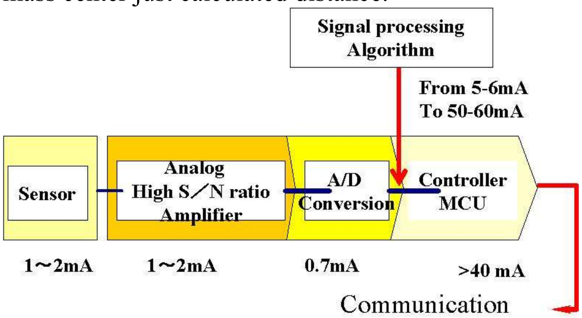

Fig. 6 Main components and their power losses in input unit

Let's think of input unit in detail. Input unit is mainly composed of five parts as in fig.6. Gyro-sensor (core device) detects μFR-II's unbalanced posture.→sensor's signal is amplified. (Amplifier)→Amplified analog signals are converted into Digital signals. (A/D converter)→Digital signals were processed by appropriate function to get a right gradient angle (algorithm) in microcomputer chip (MCU). Those signals were transferred output unit somehow (communication). In fig.6, typical power losses in each part are given. Large power is spent for signal processing and communication part.

Fig.7 is a blur correction system in digital steal camera. There are several ways to correct blur. (1). The human hand jitter is detested and a correction system shifts the lens position to compensate the shift of lens. (2). Gyro signal detect the hand jitter, and an appropriate program corrects the blurred picture based on the sensor signal. (3). Both detection of the hand jitter and correction of the picture are done by program. For this application, small gyro sensors are employed in method 1 and 2. This is a new application of MEMS gyro sensors. In here, only a narrow range of linearity in a short term is required.

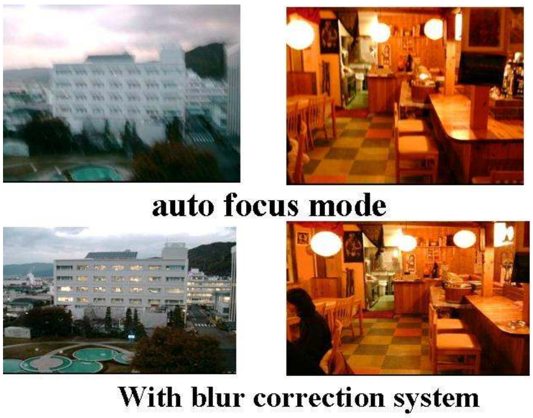

Fig. 7 Examples of blur correction system

On the other hand, inertia navigation system (INS) requires much more stable sensitivities to sensors. Fig.8 is a test module kit for INS. This unit usually employs a combination of GPS and a various sensors for a car navigation system.

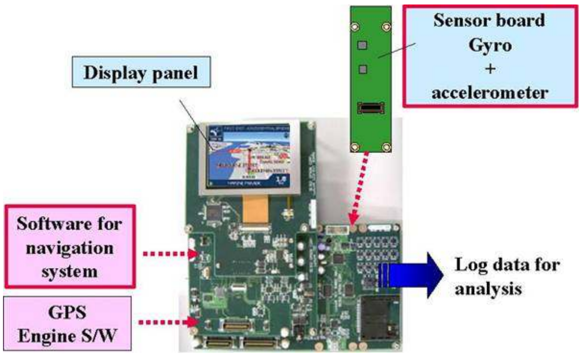

Fig. 8 Test module for INS (Inertia Navigation System)

To clarify the problems in small sensors, we used only sensor signals to determine the position. In this case, for determining the direction, integration of gyro signals was used, and for the distance, double integration of accelerometer signals was used. Here quartz crystal Gyro and Si-MEMS accelerometer were employed. Fig.9 shows the result. Solid line shows the trace line of the car, and dots are measured data of positions from INS with sensor only. From this result, output signal from sensors have a large error along the time. In this experiment, direction was determined correctly, but the driving distance calculated from accelerometer showed a large distance error from the real distance.

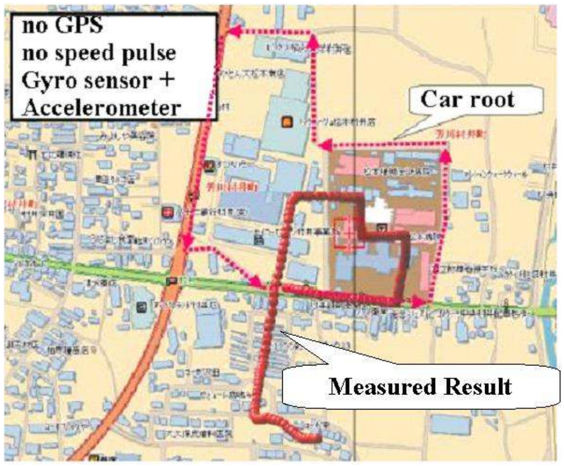

Fig. 9 Measured results from INS with sensor only

4. Effect of sensor noise to detection error

So we investigated what affects to the determination of the right position in Gyro case in various materials.

Fig.10 shows the temperature dependence of sensitivity in various material sensors. In this figure, Si-MEMS and Quartz crystal gyro had a stable sensitivity; on the other hand, Ceramic gyro had a large hysteresis in a wide range of temperature. Here it is noted that the temperature compensation circuit was already used in Si-MEMS gyro sensor.

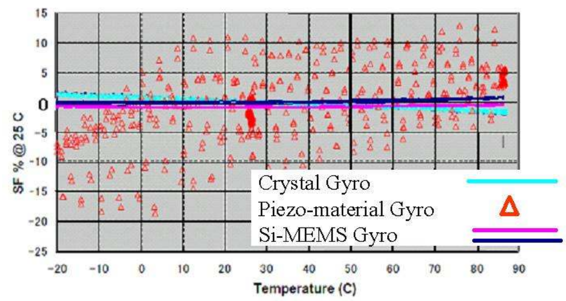

Fig. 10 Sensitivity vs. Temperature in various sensors

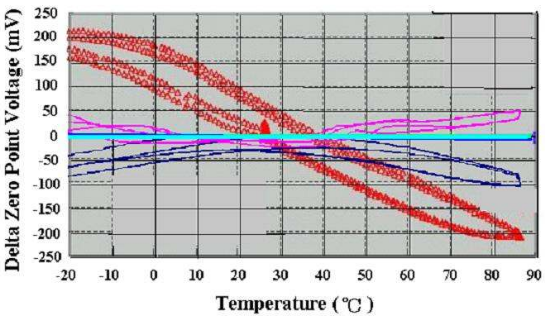

Fig. 11 Zero point Output vs. Temperature in various sensors

Fig.11 shows the output voltage under zero power applied. In this experiment, no external force was applied and left in a temperature change. Si-MEMS gyro and Ceramic gyro induced some amount of output voltage even under no forces. This is called zero drift. In accelerometer, same phenomena were observed. These sensitivity changes or voltage drifts cause measurement errors of determination of positions. There are several causes of the noise, as mentioned in 2nd Paragraph. But if core device has high Q-factor and low impedance, some factor can be eliminated. At the same time, temperature stability of sensitivity and output signal in a core device will help to reduce errors. As mentioned in this paragraph, for a long-term operation, or signal tracking application, we have to be very careful for choosing right sensor with optimal specification and right material. Because various size of sensor and various material of sensor have different sensitivities, noise densities, stabilities, and so on.

5. Power budget in an input unit

Also sensors with various kinds of materials were compared in power loss term. As shown in fig. 12, operating power in various gyro sensors were plotted. For Si-MEMS gyro, enough data were not obtained. Power losses at each component in input unit were roughly estimated and shown in fig.6. Core device and power amplifier spend around a few mA. Most power loss was spent in MCU part.

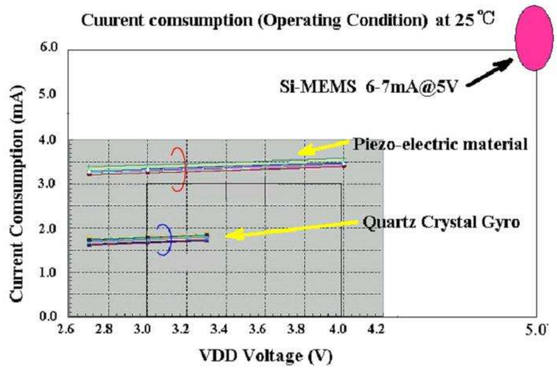

Fig. 12 Power loss in various sensors

Furthermore when data were transferred by wireless communication systems, more several tens mA will be spent optionally at the RF front end part. In MCU, the data correction in mathematical process using appropriate functions is done in this component. Therefore if data correction process was employed, operating power would become from 5-6 mA to 50-60 mA, depending on the size of algorithm. In fig, 12, Si-MEMS gyro sensor includes temperature compensation process as noted before, so that operation power was higher than other two Gyro sensors. For accurate sensing system, a large algorithm works perfectly to compensate many kinds of signal errors. At the same time you have to accept the high operating power for the large correction system.

6. Integration of MEMS on IC chip

There is one way to reduce noise level and power loss, which is an integration of MEMS on IC chip as many people started manufacturing. Fig. 13 shows resonator case. The resonator built on Si-substrate includes large parasitic capacitance. For integration, the IC chip designer also has to consider lowering the parasitic capacitance. In fig.13, two type of substrate were used for MEMS resonator. One using Si-substrate has much higher base level comparing with one using metal substrate. All transistor has certain amount of capacitance, the reduction of circuit capacitance or isolation structure of MEMS device has to be considered for the integration structure of

MEMS with IC circuit. [7]

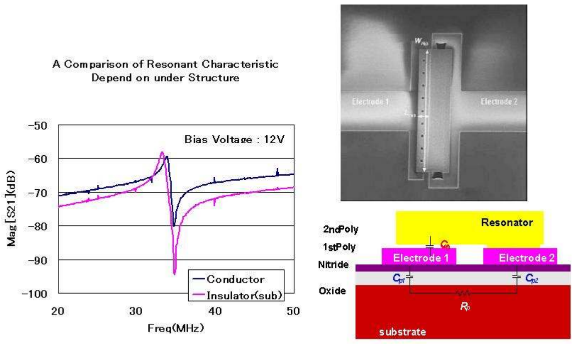

Fig. 13 Effect of parallel capacitance of MEMS device on IC

Conclusions

Miniaturization of MEMS device sacrifices their S/N ratio physically, which make loose their sensitivity or stability. Degraded property is still acceptable depending on what is required from consumers. Good algorithm in signal processing is now available and can make splendid performances. Large program for data correction requires us a high power operation. So it is not suitable for a power limited application such as a handy navigation system with a long-term operation. Again consumers have their own requirements. We have to make clear what property is really needed.

Acknowledgement

Author would like to thank to Dr. Miyazawa for his splendid work of building up a flying robot system, to Mr. Oshio, Mr. Imai Mr. Kobayashi, Mr. Watanabe for their analytical works of many kinds of sensor chips, MEMS devices, of fabrication of application modules.

References

[1] C. T.-C. Nguyen, *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 1486-1503, Aug. 1999.
[2] C. T.-C. Nguyen, in: *Proc. 42nd Design Automation Conference*, Jun. 2005, pp. 416-420.
[3] Tam Harbert, *Electronic Business,"* MEMS Market in the world", 1/Apr./2005
[4] *2006 Press Releases from analog devices*, 31/Oct./2005
[5] *News Release 2006 from Hitachi metals*, 23/Aug/2006
[6] Babak V. Amini, Siavash Pourkamali, and Farrokh Ayazi, *Proc. of IEEE MEMS 2004*, pp572-575, 2004
[7] Kazuaki Tanaka, Ryuji Kihara, Ana Sánchez-Amores, Josep Montserrat, Jaume Esteve, Proceedings of the 32nd International Conference on Micro- and Nano-Engineering, Volume 84, pp 1363-1368, 2007