Development of a sensor system for animal watching to keep human health and food safety

— A health monitoring system for chickens by using wireless sensors —

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We have been developing wireless sensor nodes for monitoring animal health and networks that care animal groups. “Animal Watch Sensors” - miniaturized, light, flexible and maintenance-free sensor nodes, will be utilized for the early detection of avian influenza outbreaks in poultry farms to defend human beings from an influenza pandemic. Key technologies to realize the sensor network system are ultra low power “event-driven” sensor nodes and a direct-conversion type receiver system for ultra short message communication. These technologies are developed by the integration of MEMS technology, life science and information technology.

Keywords : Wireless sensor nodes, sensor network, digital MEMS, event-driven, avian influenza

1 Introduction

The outbreak and pandemic of influenza (influenza A virus subtype H1N1) in 2009 is still fresh in our memory. There is now a rising concern for a new flu that may possess strong toxicity, through the reassortment and mutation of the avian influenza subtype H5N1 virus and the human influenza virus. According to the estimate by the Ministry of Health, Labour and Welfare, the death toll in Japan may reach maximum 640,000 people in case of a pandemic equivalent to the Spanish flu in 1918. Around the world, mainly in Asia, the outbreaks of bird flu and infection of humans have been confirmed. In Japan, the outbreaks of avian influenza subtype H5N1 were observed in Kyoto and Yamaguchi in January 2004 and in Miyazaki and Okayama in January to February 2007, and the virus remains a major threat to the safety of the humankind.

There are basically four measures that can be taken by the poultry farms against bird flu:

1) Strengthen measures to prevent virus invasion by enhancing hygienic control and wild bird control,
2) Strengthen surveillance monitoring at the farms,
3) Speed up diagnosis, and
4) Engage in early eradication of the virus through quarantine measures at affected farms.

The National Institute of Animal Health (NIAH) has been actively conducting the research for 3), or the development of genetic testing to detect the gene of the diversified bird flu virus. The research teams led by AIST are working on the development of 2), or the surveillance system for the farms. For the measures against bird flu infection at the poultry farm, if the period from infection to death is 1~2 days due to extremely strong virus toxicity, the outbreak can be detected in a relatively short time because the abnormal increase in bird deaths will be obvious and the farmers are obligated to report such abnormality. However, as shown in Fig. 7, strong toxicity means strong transmissiveness, and it is highly likely that the infection has spread widely by the time the situation becomes visible. This not only increases the loss of business but also is dangerous to the farmers themselves. On the other hand, if the toxicity is not strong, it may be difficult to tell it apart from other factors, and quick report may not be done if the number of bird deaths is within the range that does not obligate reporting. Moreover, the poultry farms have been scaling up rapidly in recent years, and along with the problems of aging farmers and lack of farmhands, signs of failing health among chickens that can normally be detected may be missed. It is desirable to introduce a technology that allows high-level monitoring of the health of chicken population, for the early discovery of bird flu outbreak from the perspective of maintaining public health and food safety, as well as increasing productivity.

With this background, this study is an attempt to develop a network system that monitors the health of the chickens at the poultry farms as shown in Fig. 1. Basically, this is a system where the wireless sensor nodes are attached to some percentage of chickens, or in the future to all chickens, to monitor their activity levels and body temperature, and to manage their health conditions. For example, if a node detects abnormal body temperature, the temperature change pattern can be referenced to the accumulated experimental data to automatically determine the possibility of bird flu infection,

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or estimates can be made about whether the pattern of change is for the group or the individual, or whether it is an infection or some environmental control problem. Then, a warning is issued to the farmer or a report can be sent automatically to the veterinarian or the authorities, as needed.

We became aware of the necessity of downsizing, power reduction, and cost reduction of the node to realize the wireless sensor network system. The key is the utilization of the micro electro mechanical systems (MEMS) and its fusion with the related fields. MEMS are expected to be the main player of the "more than Moore" (advancement of the electronic device through diversification of its function) and has matured as the manufacturing technology for various sensing devices or man-machine interface devices. In this paper, we shall describe the experimental infection data obtained in this project, and explain the development concept of the ultra-low power (ULP) small wireless sensor node utilizing the MEMS technology.

2 Animal watch sensor nodes

As mentioned before, this study is a development of a monitoring system for chicken health that can be applied to the early detection of bird flu outbreaks. The developing wireless sensor node is called the "animal watch sensor node" because it is being considered for application to wild animals and pets, as well as livestocks other than chicken (Fig. 2). Table 1 shows the comparison of the human node and the animal watch sensor node that is expected to be used with relatively small livestock such as poultry. It is important to note that the node to be developed is totally different in requirements from the ones developed for humans, and the technological hurdle for low power consumption is fairly high.

Looking specifically at power consumption, the node lifespan must be about two years since the egg-laying hens are processed (as spent hen) in about 550 days[1]. Assuming the use of SR721, a silver oxide button battery weighing about 0.5 g that is also used in watches, since the official battery capacity of SR721 is 25 mAh, the average current consumption must be kept at 1.4 μA or less to ensure a two year operation. The wireless sensor node is usually composed of the sensor element, sensor interface circuit, microcontroller unit (MCU), wireless communication IC, and power source. As shown in table 2, the current consumption of the microcontroller and the wireless communication IC in standby mode only is about 1 μA even when low-energy consumption microcontroller is used. Therefore, achieving the current consumption of 1.4 μA or less is not simple, considering the current consumption of sensor and amplifier in standby and operating modes, as well as for the microcontroller and wireless transmission during operation. Therefore, in this research, the node with average power consumption of 1 μW level (current consumption 0.65 μA), or 1/1000 of conventional product, is achieved by reducing the power consumption of transmission and sensing, rather than by achieving further low-power consumption for the semiconductor elements such as the microcontroller. This means that the strategy of research is to achieve low energy consumption by methods such as raising the efficiency of sensing and transmission by dramatically reducing the standby power, minimizing the frequency and quantity of sensing and transmission, or increasing the efficiency of the antenna.

The most important concept in "minimizing the frequency and quantity of sensing and transmission" is the concept of "event driven". To simply reduce the frequency and quantity of sensing and transmission, intermittent operation is

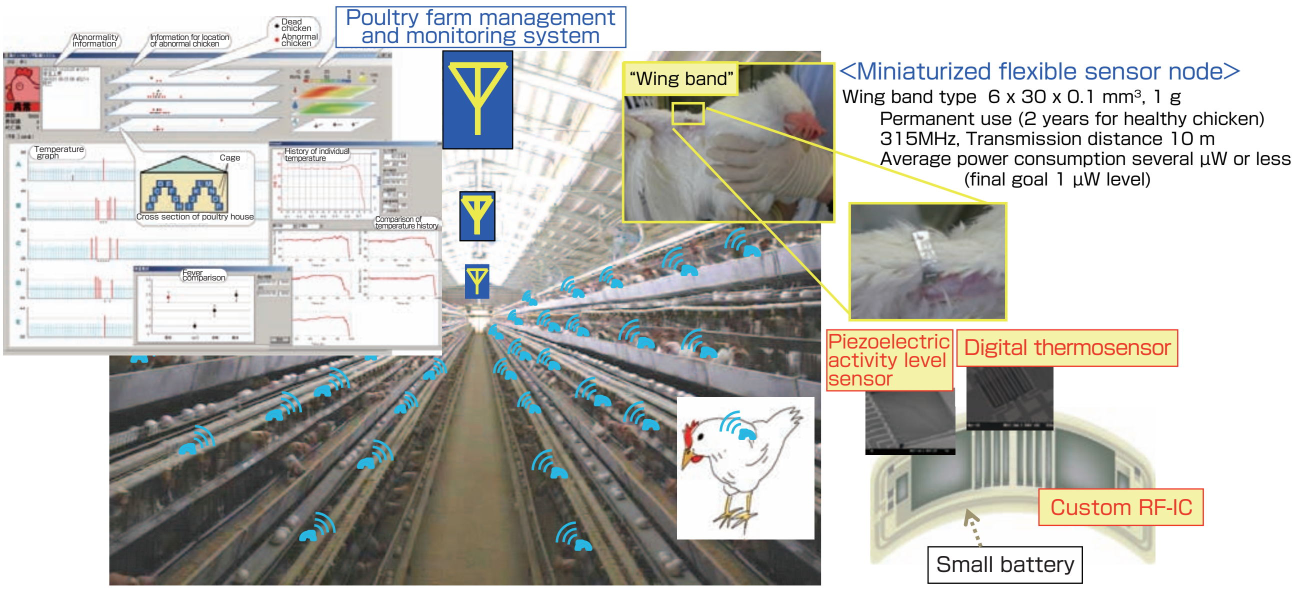

Fig. 1 Image of the chicken health monitoring system

sufficient. For example, if the chicken health management is to be done by temperature measurement, it is not necessary to take measurements every minute, but once in 30 minutes is sufficient. In this case, it is not difficult to keep the average current consumption to about 0.1 μA for sensing and transmission, and it is possible to keep the consumption at 1.4 μA or less even if combined with standby current consumption. However, like in the case of humans, there are diseases that accompany high fever and those that do not. We decide whether we should visit a hospital based on whether there is a decrease in activity, such as “I feel tired” or “I don’t have energy”, rather than basing the decision on temperature alone. Therefore, we thought that some kind of activity level sensor was needed for this animal watch sensor node. In fact, as shown in Fig. 7, in some H5N1 viruses with particularly high toxicity such as the Yamaguchi strain, death may occur without marked increase in temperature. In such cases, early detection is not possible by temperature monitoring alone, but it is known that infection estimate can be based on decreased activity level[3]. In the case where the activity level is monitored, only the activity status at the moment can be known if the measurement is taken once in 30 minutes, and it is difficult to determine whether the animal is active based on the figures of that moment only. Therefore, in this research, rather than the time-driven type where the activity is monitored and transmitted at certain intervals, we opted for the event-driven type where the monitoring and transmitting are done when an activity above some threshold takes place. The difficulty of an event-driven type is the selection of the appropriate event and setting of the threshold. One of the originalities of this research was we obtained the threshold by analyzing the data for the experimental infection of chickens and developed a suitable sensor accordingly.

Also, since the power needed for transmission is proportional to the amount of messages, the shortening of the transmitted message is important as well as the reduction in transmission frequency. Other than the data itself, the message includes the overhead, such as the preamble for clock synchronization

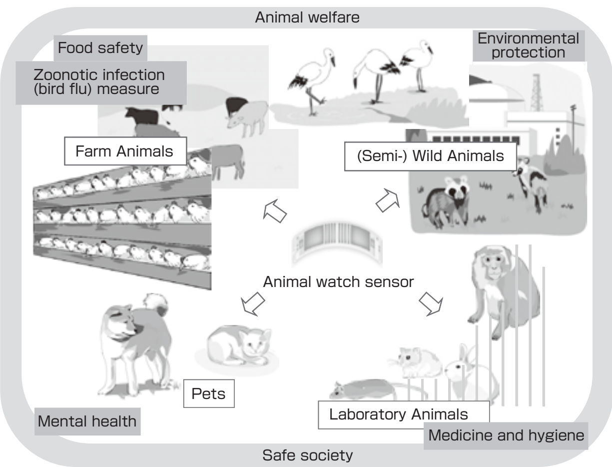

Fig. 2 Application of the animal watch sensor

Table 1 Comparison of the animal watch sensor node and the human health monitoring node

Main specs \ Sensor Node	Animal watch sensor node (mainly for chicken)	Human health monitoring node
Node size and weight	In case of chicken, few cm square, few g or less	Typically watch size, several ten g is acceptable as weight
Power source	Recharge impossible and basically, maintenance free	Charging frequency for cell phone is acceptable
Receiver and communication distance	At least 10 m communication performance necessary	Receiver is cell phone, communication distance is 1 m or less
Sensor type	As for now, thermosensor and activity level (acceleration) sensor	Thermosensor, activity level (acceleration) sensor, heart rate sensor, ECG sensor, etc.
Node cost	About 100 yen (1 US dollar or 1 euro)	Several thousand yen or more

Table 2 Example of the typical current consumption value of devices that comprise the wireless sensor node

	Microcontroller (MCU: MSP430)	Wireless communication (RF) IC
Sleep mode	0.8 μA[2]	About 0.2 μA
Operation (wireless transmission) mode	250 μA/MIPS[2]	About 650 μA (1 mW)

and the unique word for frame synchronization, and the ID (identification code for the node). In this study the overhead is eliminated by employing the new simultaneous multi-channel reception method, and the message is shortened by using the transmission frequency and baud rate as the ID[4]. Moreover, in theory, it is possible to create a minimal message with one-third the conventional content, composed only of the temperature data and parity bit (the simplest 1 bit error detecting code) by calculating the activity level from the transmission intervals[5].

As mentioned above, to achieve the chicken health monitoring system for poultry farms, the most important technical point is achieving the low-energy consumption of the wireless sensors. To achieve this, it is necessary to set the appropriate event and threshold by experimentally determining the activities and disease conditions of the chickens, and to develop the corresponding device and node system. Table 3 is a summary of the main elemental technologies to realize the system. In this research, the experimental animal infection and analysis using the wireless sensor node, the development of the low-energy consumption MEMS sensor suitable for the event-driven method based on the data obtained from the animal experiments, and the development of other elemental devices were done according to the development process shown in Fig. 3. Then, the prototype node was fabricated, the monitoring system for the experimental poultry house was created, and the issues in applying the system to the poultry house were extracted. In the future, the working node incorporating the developed elemental devices will be developed and a monitoring system using the nodes will be created. These will be used for the demonstration in the experimental poultry house.

3 Strategy for achieving ultra low power consumption of the nodes

To achieve a small (can be attached to the wing), lightweight (about 1 g), flexible and maintenance-free (2-year lifespan) wireless sensor node, we devised a new digital sensor using the MEMS switch[6][7]. This digital MEMS sensor is composed of an array of switch sensors, is capable of directly outputting digital signals without an AD conversion circuit, and can be used as a start-up trigger of the wireless sensor node in sleep (clock stop) modes. The individual switches that compose the sensor are micromechanical switches that use the MEMS technology, and do not require power for ON/OFF of the switch itself. Specific explanation will be provided using the digital bimetal thermosensor and digital piezoelectric accelerometer developed in this research.

Figure 4 shows the schematic diagram of the digital bimetal thermosensor[7]. It is very simple in principle, and is composed of an array of bimetal cantilevers that come in contact with the opposite electrode above a certain temperature. Since the normal body temperature for chickens is about 41 °C, it can be considered that a fever is occurring due to some health abnormality if the temperature rises above 42.5 °C as in the case of infection by the Yokohama strain, as shown in Fig. 7. Therefore, a bimetal cantilever that turns ON at 42.5 °C or above is installed. When the contact is ON due to temperature increase, the node wakes up from sleep, and transmits a message that includes only the fact that the contact is ON as the sensing information. This is the basic thinking of the event-driven concept. In the case of the intermittent operation mode using a timer, the detection timing is determined by the set interval regardless of the occurrence of the temperature increase event, while in the event-driven node, the moment of temperature increase can be detected instead of the temperature value. The event-driven type can be used to shift the node from the sleep mode to the emergency time-driven measurement mode, instead of sending one transmission at the occurrence of the event. For the event, the individual difference can be considered, as well as multiple bimetal cantilevers can be installed for each temperature value setting to detect the rough temperature change. For example, if the multiple bimetal cantilevers of different sizes are installed and the ON temperatures are set at certain intervals such as 0.5 °C, it can be used as a digital thermosensor. The meaning of "digital" here is that it is possible to detect the digital signal of 1100, or the four switches of ON, ON, OFF, OFF, if the sensor output is the digital signal itself, and this can be included in the message without alteration. The ON detection of a mechanical switch can be done with very low power, and the standby power of the sensor is basically the power for the semiconductor switch. While the bimetal switch can be fabricated without the MEMS technology, the use of MEMS technology is vital in order to achieve the downsizing and cost reduction of the bimetal thermosensor, since the multiple three-dimensional microstructure can be realized at once on a silicon wafer without an assembly process.

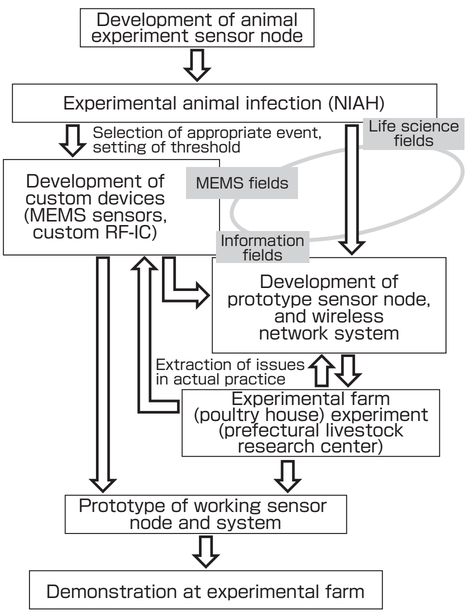

Fig. 3 Overall picture of the development process (outline of the scenario)

Table 3 Main elemental technologies for the chicken health monitoring system

ULP wireless sensor node	Digital bimetal thermosensor
	Digital piezoelectric accelerometer (activity level sensor)
	Custom RF-IC (event-driven type)
	miniaturized antenna (315 MHz)
	Flexible node packaging technology
Direct conversion receiver system	
Poultry house monitoring system	

The activity level sensor can be constructed from the mechanical switch that turns ON when the acceleration of certain level or higher is inputted, but we developed a sensor where piezoelectric thin-film is formed over the cantilever, as shown in Fig. 5. Here, the technological details will not be provided[8][9], but the power is generated by the piezoelectric effect when the cantilever is activated, and the transistor can be turned ON or OFF using this power. In theory, a digital accelerometer with zero-power consumption is possible. As in the bimetal thermosensor, it is possible to arrange the cantilevers with different sensitivity, but it is also possible to arrange a series of the same cantilevers[6] or devise the circuit to extract the digital output that corresponds to a certain acceleration threshold with one cantilever[10]. From the result of the experimental infection using the experimental node that will be described in chapter 5, it is known that health abnormality can be detected 10 hours beforehand[3] by counting the number of occurrences of accelerations surpassing the threshold within a certain time (30 minutes, for example) and by comparing the number with the number for 24 hours beforehand, even for the Yamaguchi strain where no significant temperature increase could be seen. The activity level can be counted with low power if a generating piezoelectric sensor is used. To realize such a device at a small size and low cost, piezoelectric MEMS technology that combines the MEMS and piezoelectric thin film formation technologies is necessary.

As shown in Fig. 6, it is necessary to use the digital MEMS sensor that matches the event-driven type to achieve the ULP node, and also customize the semiconductor elements such as the microcontroller and the radio frequency integrated circuit (RF-IC). As mentioned before, the event-driven node that we developed in this research is a device “where the sensor directly sends out the digital signals, then the node wakes up from the sleep mode and transmits the digital signals wirelessly”. Therefore, the node does not require any high-grade arithmetic processing, and a RF-IC with simple processing function such as a sensor interface and a message writing function is sufficient. Conversely, if one is to install an over-spec universal microcontroller, realization of the chicken node is impossible in terms of power and cost. While the new technological development for semiconductor element technology is not necessary for the introduction of such custom-made RF-IC, there is no example anywhere in the world of RF-IC specialized for event-driven nodes, and it is a key device that must be designed and developed by us on our own. Of course, the increased flexibility of the substrate and downsizing and flexibility of the antenna are also important for practical use.

4 Image of the animal watch sensor

The specifications of the wireless sensor node scheduled for realization by the end of this research project (end of FY 2011) are as follows.

Size/weight of node: substrate (flexible) size 6 × 30 × 0.1 mm^3, weight (including batteries) about 1 g
Attachment method: Wing band
Sensor: digital bimetal thermosensor, digital piezoelectric accelerometer (activity level sensor)
Wireless transmission: frequency 315 MHz band (310~320 MHz), modulation GFSK, line-of-sight communication distance of 10 m or more
Standby power consumption: 0.5 μW or less
Power source: silver oxide battery (1.55 V)

This wireless sensor node transmits data but does not receive. The primary reason is because the reception standby power is large and it cannot fulfill the necessary specs for size and cost, but it is also because the node does not have to receive. The node must be able to receive if there is a need for communication between the nodes or for receiving the re-transmission request in case of a bad reception. For this system, since the frequency of data transmission is once every 30 minutes to 1 hour with short transmitted messages of 10 bits or less, there is hardly any chance of collision of the transmission signals even if there are over 10,000 nodes. However, in the event-driven system, high communication reliability is demanded because one data transmission is extremely important. In this research, the basic concept is to employ an advanced receiver in order to simplify the node system that is subjected to harsh boundary conditions.

With this way of thinking, we employed and are developing the direct conversion method as the reception method of this research. This method is also called the software-defined radio, where the frequency spectrum in the range 310~320 MHz as discussed above is received, stored on the memory, and then analyzed to read the message. We are developing the receiver system by fabricating the prototype of the simultaneous multi-channel receiver. Using this method, it will be possible to identify the nodes by frequency and transmission data rate, and

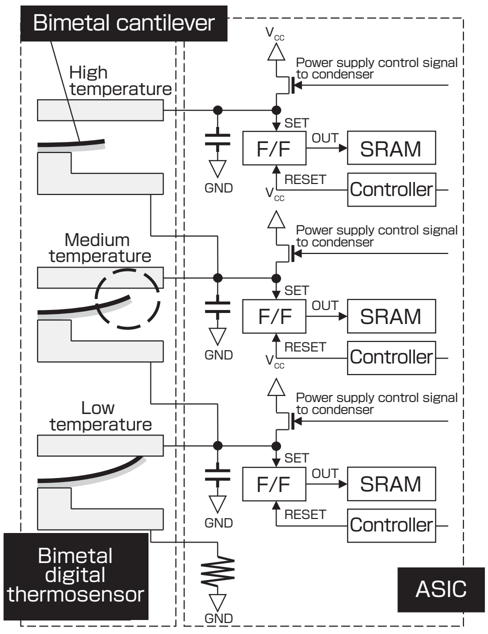

Fig. 4 Digital bimetal thermosensor

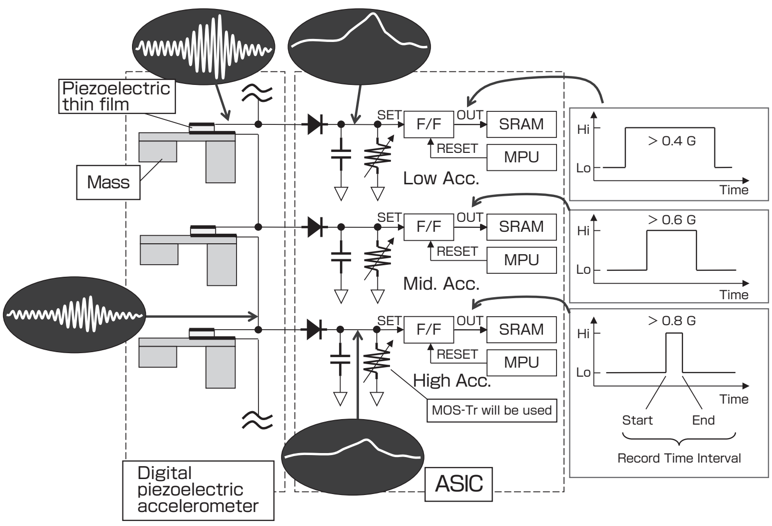

Fig. 5 Digital piezoelectric accelerometer

as mentioned earlier, data reception will be possible without the overhead such as the preamble. Also, by comparing the reception signal intensity of each node, the location of the node at 1 m or less precision can be known. This allows the detection of the outbreak and spread of the disease, as well as the location of the chicken with health abnormality without conducting ID management of the nodes. Another point of shortening the message is the estimation of activity level by reception frequency. For example, in the simplest model, a switch that turns ON when there is an acceleration that surpasses a certain threshold is installed, and one message is transmitted when the number of ONs reaches a certain level[11]. If the activity level is high, the transmission intervals shorten, and when the activity is low, the transmission intervals lengthen. Therefore, the reception interval represents the activity status. Although we cannot tell whether the activity level is abnormal from one transmitted data alone, the activity level monitoring with consideration of the individual differences will be possible by comparing with past data. Using this method, it will not be necessary to include data for the activity level in the message, and ultimately, only the output from the digital thermosensor and parity bit during signal transmission is necessary. For the development of this reception system, the fabrication of the prototype of the simultaneous multi-channel receiver and the confirmation of its operation, the check of the effectiveness of the basic message analysis software, and the development of the algorithm for identifying the node position have been completed. It has been experimentally confirmed that the node location identification can be obtained at 1 m or less precision in an ideal environment.

As explained above, downsizing and weight reduction, low power consumption (longer lifespan), and cost reduction are done by simplifying the node through the employment of the high-performance receiver system.

5 Experimental infection and prototype system

As mentioned earlier, one of the important points of this research is to study the disease state of the chickens to optimize the sensor node. At the start of this research project, although it was known that the bird flu that occurred in the Japanese poultry farms could be a threat to humanity, there was no study on how the body temperature changed when the chickens became infected by H5N1. The only data that existed were qualitative data on the daily behavior of chickens in good health and how that may change when infection occurred. The digital MEMS sensor or the event-driven node could be realized only by understanding the properties of the subject, or chicken characteristics in this study, and therefore the research team engaged in experimental infection.

In the experimental infection conducted by NIAH, it was shown for the first time from the results of the temperature behavior using the wireless sensor node[14] shown in Fig. 7, that “the fever development and time of death of chickens infected by the highly pathogenic avian influenza virus differ according to the strain”[12], and that “the transmissibility of avian influenza virus among the chickens is correlated to the amount of virus excreted”[13]. The prototype node used in the experiment had exterior size of a one-yen coin and weight of 3 g or less (including weight of the battery) to reduce the burden on the chickens in the experimental infection and poultry house experiment. It also included a thermosensor to measure body temperature and accelerometer to monitor the activity level, as well as the time-driven wireless module that obtained and transmitted the temperature and acceleration data at a certain time interval (can be freely set).

In the above experimental infection, the acceleration data as well as the temperature data were recorded. Based on these finding and data, an infection determination program was developed using both the temperature and activity level patterns. This was compared to the conventional data, and it became possible to discover (recognize) the possibility of infection early and automatically. Moreover, the number of probes and individual thresholds can be set in the digital thermosensor, and the activity level sensor can be set with appropriate acceleration threshold. Also, the virus

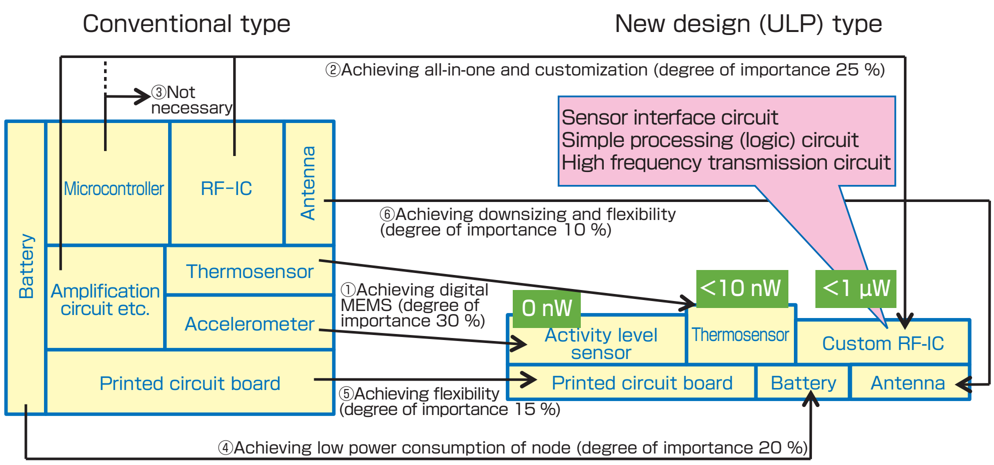

Fig. 6 Comparison of the ULP wireless sensor and the conventional sensor

transmission simulation program is created using the data for the rate of infection spread to study the relationship between the node concentration and the time required to discover the infection, and this is utilized in the development of the monitoring program[3]. In this simulation, if it is determined that an infection is suspected when three chickens behave abnormally, it is known that by attaching the sensors to 5 % of the chickens, detection can be done two days faster than the visual observation currently set by the government.

To extract the issues when such wireless sensing system is used in the poultry house, the above prototype node is made into a wing band so it can be easily attached to the chickens. Also, we are reviewing a health management system for poultry farms to monitor the heat stress during summer, by setting up the wireless network system in an experimental poultry house in the Ibaraki Prefectural Livestock Research Center[14].

6 Progress and prospect of the research

The objective of this research is to complete the practical level chicken health monitoring system by the end of FY 2011. While there are some differences in the progress of development of the elemental technologies listed in table 3, at this point, the overall achievement level compared to the initial goal is 60~70 %. For the digital piezoelectric accelerometer that is being developed as the key device among the elemental devices, we are ready to conduct demonstrations of the prototype node using the test device. For the digital bimetal thermosensor, the development of the new structure for manufacturing at the wafer level including the packaging process is in progress[15], and an investigation for a mass production process will be done in FY 2010. For custom-made RF-IC, design and a prototype are being done for scheduled completion in November 2010, and the node that is close to the final goal is to be completed within FY 2010. The technological issues include:

- Development of the software for the reception system, and
- Development of the low-cost wafer-level packaging technology for the digital MEMS sensor.

Particularly, the packaging technology greatly affects the manufacture cost of the digital MEMS sensor device, and it is necessary to optimize not only the packaging process but also the manufacturing process of the device itself.

The final goal of this research is the practical use, or the introduction to the sites of commercial poultry farming, rather than constructing a “practical level” system and demonstrating it. However, there are various issues that cannot be solved by technological development alone. In addition to the development of low-cost attachment and removal, there are issues of how to make this technology improve the farm productivity, and how to establish a government monitoring system.

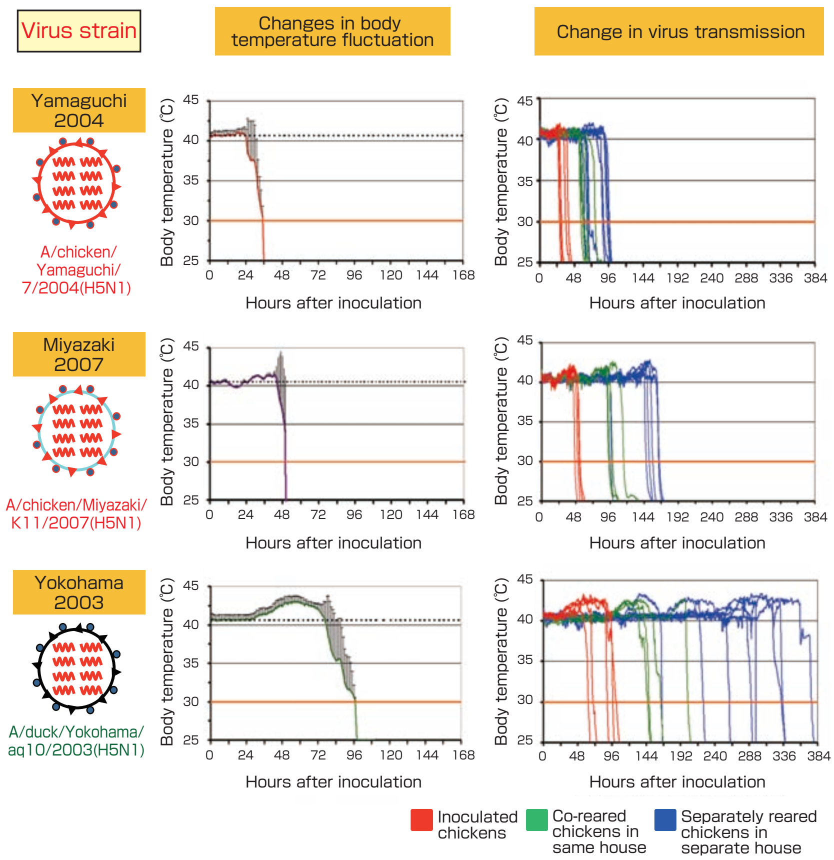

Fig. 7 Examples of data obtained by experimental infection

In this research, by focusing the research on the rather special use in the chicken health monitoring system, we are trying to reduce the cost of the active (type that does not require leader unlike the RF tag) wireless sensor node, which currently is no less than several thousand yen at least, to about 100 yen. We are also trying to downsize and reduce the weight to a band-aid level. Since this node cannot measure the vital signs, application to humans may be limited. However, monitoring the temperature and activity level (liveliness) is basic to health management, and we wish to consider the health monitoring of infants and the elderly who must be monitored continuously at hospitals and homes.

7 Conclusion

What became apparent when working on this research is the fact that the researches on MEMS and packaging technology are only part of the technologies needed to solve the entire issue. MEMS research is basically a research for the manufacturing process technology, and it is about “drilling an extremely narrow, deep, and straight hole”. However, as such technologies are becoming mature in the 21st century, we are facing the issue of what (for what purpose and for which specifications) we shall make. We thought one of the answers was a device that can be used in ultra-small wireless sensor node, and started this research. However, whether MEMS itself was really necessary for the chicken health monitoring was frequently discussed. Fortunately, we were able to position the MEMS technology as being absolutely necessary, but if the boundary conditions change (for example, if it is used for pigs and cows), whether MEMS is necessary must be discussed in each case.

In the beginning, the main issue of this research was the early detection of bird flu at farms, but as we talked with the livestock researchers, we started to consider the animal watch sensor from the perspective of animal welfare. With the upscaling of animal husbandry, the people of the metropolitan area are loosing the sense that they are consuming animal products, perhaps because the sites of production are far away from the city. Of course, livestocks are industrial animals and cannot be considered on the same level as pets and wild life. However, when one realizes that the eggs, milk, or meat are obtained from overweight animals that are fed high calorie food and may harbor risks of production diseases, we may want to reconsider whether we wish to consume such food. In Europe and the United States, the thinking of livestock welfare is spreading, and the approval system for Welfare Quality Products will be launched in 2010. In the evaluation committee for this system, the technological issues raised are “animal based measurement” or the assessment of “how the animals feel”. Therefore, we believe the animal watch sensor will become more important from the point of maintaining the welfare of the livestock, as an interface technology with animals.

While many of the concepts and technologies for the wireless sensor network described in this paper were generated by focusing on the application to the chicken health monitoring, the individual technologies can be applied to other fields such as environmental monitoring including agriculture and disaster prevention. I think another major product of this research is to recognize that conducting the research with focused application may be an efficient way for pioneering a field or for creating inventions.

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Authors

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Completed the doctoral course at the Graduate School of Engineering, The University of Tokyo in 1994. Joined the Research Center for Advanced Science and Technology, The University of Tokyo, as assistant in 1994, and become lecturer and assistant professor. Joined AIST in 2007. Deputy director of the Research Center for Ubiquitous MEMS and Micro Engineering in 2010. Engaged in research for piezoelectric MEMS, MEMS probe card, MEMS packaging, wireless sensor node, and others. Research Director of the "Development of the Animal Watch Sensor for Safety" of the Core Research for Evolutional Science and Technology (CREST), Japan Science and Technology Agency (JST) since 2006. Engages in research for weaving MEMS as the Director of Macro BEANS Center, Bio Electromechanical Autonomous Nano Systems (BEANS) Project of the New Energy and Industrial Technology Development Organization (NEDO). In this paper, was in charge of the development of the MEMS sensor and the wireless sensor node.

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Completed the doctoral course in applied electronic engineering at the Graduate School of Electronic Science and Technology, Shizuoka University in 2001. Independent researcher at the Gunma Industrial Technology Center in 2002. Worked as chief researcher of the R&D Center, Taiyo Yuden Co., Ltd. and also as the special appointment lecturer of precision mechanical engineering at the Graduate School of Engineering, The University of Tokyo in 2006 to present. Has engaged in research and development of the elements and signal processing of humidity sensor, silicon piezoresistance pressure sensor, sapphire capacitance pressure sensor, and ball inclination sensor. Currently works on the development of the event-driven communication protocol in ultra low power wireless sensor, as well as the development of the piezovibration power generation system, ULP custom LSI, and small antennae for 300 MHz band, at the "Development of the Animal Watch Sensor for Safety" of JST CREST. For this paper, was in charge of the development of the ULP technology and the wireless network system.

Kenji Tsukamoto

Completed the master's course at the Graduate School of Agricultural Science, The University of Tokyo in 1982. Joined the National Institute of Animal Health, Ministry of Agriculture, Forestry and Fisheries in 1982. Worked as researcher, chief researcher, head, and senior researcher from 2007. Engaged in epidemiological survey of wild birds for avian influenza and genetic diagnosis method from 2004. Joined the "Development of the Animal Watch Sensor for Safety" of JST CREST as main joint researcher in 2006, and works on the analysis of changes in disease states of chicken infected with bird flu virus, as well as the analysis of molecular basis of avian pathogenesis. In this paper, mainly worked on the experimental infection and the development of the prototype system.

Discussions with Reviewers

1 Configuration of the wireless sensor node

Comment (Toshimi Shimizu, Research Coordinator (current affiliation: Deputy Director General), AIST)

The conceptual points and their degree of importance (or difficulty) of the newly designed wireless node corresponding to an event-driven type are unclear. As a plan, I think you should compare the configurations of the conventional wireless node and the newly designed one, list the issues for each element, and explain the importance (or difficulty) of each. I think that will enhance the understanding of the general readers including engineers who are not familiar with MEMS.

Answer (Toshihiro Itoh)

Revisions were made in Fig. 6 as you instructed.

2 Technical terms

Comment (Toshimi Shimizu)

The National Institute of Animal Health (NIAH) is listed as the joint research institute. As far as the reviewer knows, there are several veterinarians at the NIAH, and from veterinary standpoint, what are the recent research trends for preventing infection of chickens? Please also add some comments from the point of technical policy and measures of the Ministry of Agriculture, Forestry and Fisheries.

Answer (Toshihiro Itoh)

We added some explanation in the second paragraph "measures at the poultry farm…" in "1 Introduction".

Comment (Toshimi Shimizu)

There are several difficult English terminologies for the general readers including engineers. For example, "time-driven", "preamble", "parity bit", "direct conversion", "custom-made RF-IC", and "vital signs" are terms that may be used often in your field, but are incomprehensible to general readers. I think you should explain them sufficiently.

Answer (Toshihiro Itoh)

At least, for the terms you indicated, we added explanations as much as possible at first appearances.

3 Advantage of using the MEMS technology

Question (Jun Hama, Evaluation Department, AIST)

You explain that power consumpution of animal sensor can be extremely reduced by using MEMS technology,which allows creating an all-in-one structure, in addition to simiplifying the animal sensor. Can you specifically tell us the advantages of the manufacturing process for sensors?

Answer (Toshihiro Itoh)

A three-dimensional mechanical structure is necessary to achieve the switch sensor. The MEMS technology is good at creating the three-dimensional microstructure and the protective packaging structure all at once on the silicon wafer. It can be considered the only technology to realize such devices including small and low-cost three-dimensional mechanical structure. Specifically, the MEMS technology is mandatory for creating the oscillator with piezoelectric thin film and the encapsulation structure for the accelerometer, and for creating the bimetal cantilever array, contact, and encapsulation structures for the thermosensor.

4 Setting of the threshold

Question (Jun Hama)

How did you actually set the threshold to determine the abnormal activities? Please explain the decision process within the range you may disclose.

Answer (Toshihiro Itoh)

We conducted several experiments using dozens of chickens at NIAH using the wireless sensor nodes. Basically, we set the thresholds for temperature and acceleration by comparing the temperature and acceleration data of the chickens inoculated with the virus (with several virus strains) and the non-inoculated chickens.

5 Cost reduction

Question (Jun Hama)

To reduce the cost of the health monitoring system, I am sure you've done lots of devising, such as minimizing the sample number of chickens to which the nodes are attached in the technological development of an inexpensive sensor system. Is there any statistical difference in the total sample number of animals depending on the characteristic of the animals?

Answer (Toshihiro Itoh)

I am not sure there is any difference according to the character of the animals, but I've heard from the expert at NIAH that 0.3~1 % is probably sufficient as the number of samples to watch the health of the chicken population at a poultry farm. Also, by simulating the relationship between the sensor concentration and detection time (the time required from the first infection of the chicken to the determination of abnormality and reporting) using the experimental data, we think about 5 % is the minimum number needed.

6 Realization of the MEMS technology

Question (Jun Hama)

You are attempting the product realization and diffusion of the chicken health monitoring as one of the ways to pioneer the use of the MEMS technology. Please explain specifically the prospect for an outlet that emphasizes the superiority of the MEMS technology.

Answer (Toshihiro Itoh)

In general, I think the MEMS technology is a core manufacturing technology for all kinds of sensors that demand downsizing and cost reduction. Therefore, various sensor interface devices in an ambient society[Note)] will be realized by the MEMS technology. A system with a similar concept will be applicable to the health behavior monitoring of animals other than chickens. For other use such as monitoring the environment of some facility, it must be reconsidered from step 1 (including whether MEMS is necessary). However, the concept of making the nodes as "light" as possible so it can be spread widely and profusely while making the receiver system advanced, is effective for the application to environmental monitoring including agriculture and disaster prevention.

Note) Ambient society: While the "ubiquitous society" is a world where the necessary information can be retrieved "anytime, anywhere, by anyone", the "ambient society" is a world where the necessary information is provided by the environment that surrounds the person as it senses the person's situation.