A 1.7MM^3 MEMS-ON-CMOS TACTILE SENSOR USING HUMAN-INSPIRED AUTONOMOUS COMMON BUS COMMUNICATION

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ABSTRACT

A bus-connected tactile sensor system composed of MEMS-CMOS integrated force sensors was developed. A capacitance-to-digital convertor for force sensing, a data reduction processor and a serial bus communication controller are implemented by a laboratory-designed ASIC (Application Specific Integrated Circuit). These functions enable the tactile sensor to be connected with a serial bus cable, and to autonomously transmit sensing data using CSMA (Carrier Sense Multiple Access) protocol. By applying a novel MEMS-CMOS integration technology, the integrated tactile sensor can be directly mounted on a flexible printed circuit board. The chip size is 2.54mm × 2.54mm × 0.27mm, i.e. 1.7mm^3, and there are 20 through-silicon interconnection using saw-diced lateral tapered grooves. The digital data from the completed tactile sensor contains 32 bit force sensing data, which corresponds to an external force linearly. Data reduction processing based on threshold operation and adaptation inspired by tactile receptors was carried out to overcome packet collision problem. Finally, the serial bus network was demonstrated using three sensors to evaluate the network performance.

KEYWORDS

Tactile sensor , sensor network, MEMS-CMOS integration, wafer level packaging

INTRODUCTION

There has been increasing demand on whole-body tactile sensors for safe and natural interaction between human and robots. Although there have been many publications on whole-body tactile sensing [1], there are two major problems not yet solved to date. One is considerable increase in the number of wires from a CPU (Central Processor Unit) to many sensors. The other problem is large amounts of sensing data. If every sensing data of each sensor distributed on a robot body are transmitted toward the CPU, the computation and communication will be overloaded. Many tactile sensor system have been proposed to overcome these problems. The proposed solutions include bus connection based on an established protocol for reducing the number of wires, and data compressing for reducing data traffic, which are realized using a processor near the tactile sensor chip or sheet. However, these components are assembled on a print circuit board, limiting the flexibility and density of sensor installation on the whole robot body [2, 3 ,4].

To address the above problems, we developed an integrated tactile sensor as small as 1.7mm^3 consisting of a data processing/transmission CMOS LSI and a MEMS capacitive sensor. The integrated CMOS enables force sensing, data reduction and serial communication. Similarly in the tactile receptor of human which generates nerve impulses only when touched, the tactile sensor is designed to transmit the small packet which contains force sensing data and ID only when the applied force exceeds a predetermined threshold value. Each tactile sensor transmits packets according after checking the bus to avoid packet collision.

In this paper, basic functions such as force sensing and data reduction processor were confirmed on the integrated tactile sensors, and finally network property was experimentally evaluated by intentionally generating packet collision.

BUS TACTILE SENSOR SYSTEM

System overview

Figure 1 shows an overview of the tactile sensor system, where MEMS-on-CMOS integrated tactile sensors are directly mounted on a flexible cable. Using the flexible cable, the tactile sensors can be attached on both flat and curved surface of robots at any suitable pitches. Each tactile sensor share the common bus line composed of 2 power lines (V18, V33), 1 signal line (DATA) and 1 ground line (GND). The receiver named "relay node" is

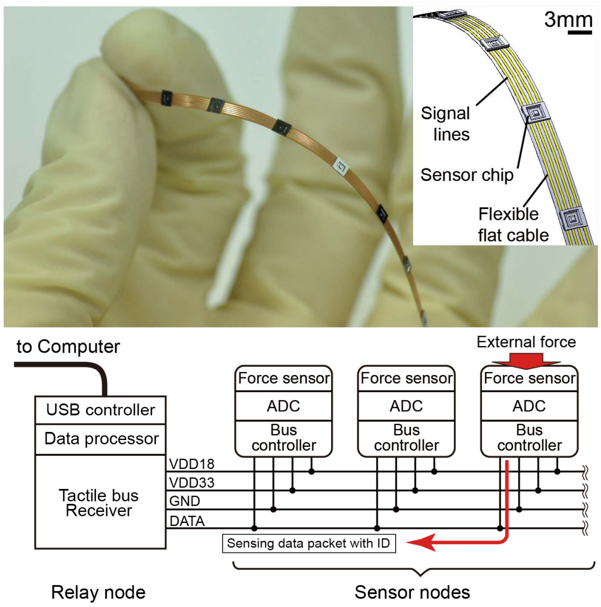

Figure 1: Tactile sensor using autonomous common bus communication.

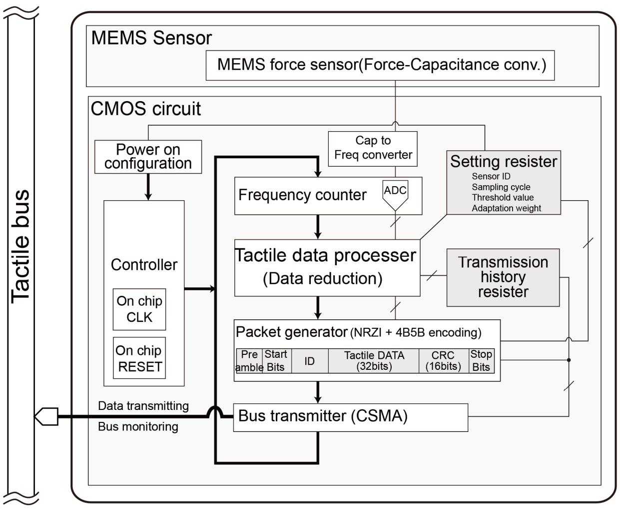

Figure 2: Block diagram of the integrated tactile sensor.

connected on the end of the flexible cable. The relay node collects packets from the tactile sensors, verify the data and transmit the received data toward the CPU through a USB cable.

The detailed block diagram of the integrated tactile sensor is shown in Figure 2. The CMOS-based ASIC (Application Specific Integrated Circuit) offers 3 functions of sensing, data processing and communication. An external force is detected as the capacitance change of a Si diaphragm, and converted into a digital value through a capacitance-frequency converter based on a Schmitt-trigger oscillator. The sampled data is processed according to data reduction algorithm, and packed into a 32 bit packet including 8 bits sensor ID, 16 bits CRC (Cyclic Redundancy Check) code and some bits for asynchronous serial communication. The assembled packet including preamble, start bits and stop bit is encoded with 4B/5B and NRZI (Non return to zero Inverted) code for CDR (Clock and Data Recovery) and collision avoidance, and transmitted autonomously without any external controls. The CSMA (Carrier Sense Multiple Access) protocol is adopted for collision-free autonomous communication. The parameters related to the three functions can be changed by a power-on configuration scheme. The packet generation rate, data reduction parameters, and bus communication parameters can be changed. During starting time, which is a certain period just after supplying power to the sensor nodes, the relay node transmits 411 bit data for the configuration. The sensor nodes receive the configuration data using oversampling CDR, because asynchronous serial communication is used. These data are stored in the setting resister of the sensor nodes until the next power-off.

Prototyped an integrated tactile sensor

The structure and photograph of the prototyped tactile sensor are shown in Figure 3. The integrated device was wafer- level-packaged in a low profile of 0.27mm and a small footprint of 2.54mm × 2.54mm, i.e. 1.7 mm^3. The bulk-micromachined Si diaphragm was stacked on the ASIC, which forms a 10μm gap parallel-plate capacitor with an initial capacitance of 7pF. The electrical feed-through is achieved by lateral V-shaped groove near the scribe line. The MEMS and the ASIC wafer are bonded with BCB (Benzocyclobutene) polymer, with which the V-shaped grooves are filled. The ASIC was implemented using a 0.18μm CMOS technology. The several on-chip clock frequency are prepared from 1.2MHz to 50MHz and the average power consumption is 3.6mW @ 1.2MHz operation.

Figure 4 shows the measured output signals from the completed integrated device to which external force is applied. The data field includes converted force data as show in Figure 4 (a). The relationship between external forces and decoded digital values is shown in Figure 4 (b). Since a force-to-capacitance converter of the MEMS and a capacitance-to-frequency converter of the circuit canceled their parabolic characteristic of transduction each other, the linear response of the digital output to the external force was observed. This result well agrees with mechanical and electrical simulation. Based on the simulation, the deformation of the diaphragm is 300nm and capacitance change is 10fF, when 1N normal force is

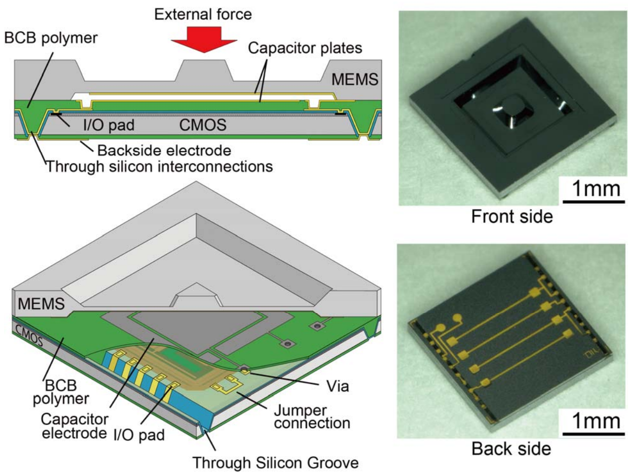

Figure 3: Device structure and completed tactile sensor chip.

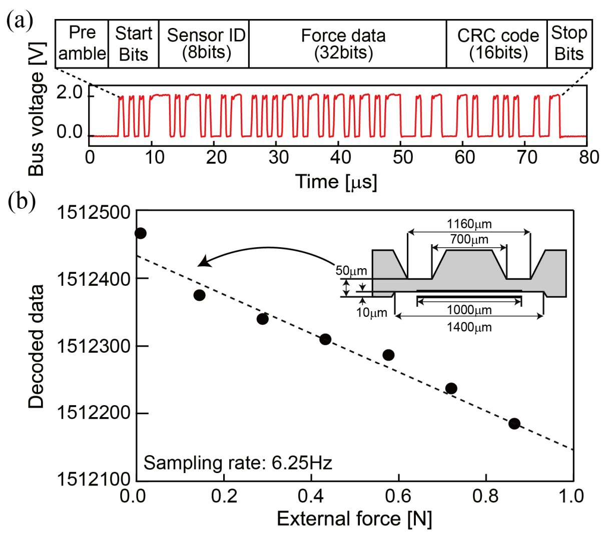

Figure 4: Output signal and sensing characteristic of the integrated tactile sensor. (a) Digital output and (b) Response to external force.

applied. The resolution in the unit of bit/N is inversely proportional to the sampling rate of the Schmitt trigger circuit, and 8bit/N at 6.25Hz sampling.

Autonomous network using CSMA protocol

Since the tactile sensors on the robot body are not always or entirely pressed in practical use, most of sensors just generate zero force data except for sensors in a touched region. Meanwhile, the fast response time is required to detect unexpected collision or the sign of slippage. Therefore, only important data is transmitted by threshold operation and adaptation like a tactile receptor of human skin [5]. By the threshold-based operation, weak force data below the pre-defined threshold value is filtered and not transmitted on the bus. By the adaptation, transmission interval time is lineally-increasing during applying constant strong forces over the threshold value. After a judgment on whether the sensing data should be transmitted or not, the autonomous data transmission is followed by bus traffic monitoring, i.e. the bus is shared based on CSMA. Each sensor has an independent on-chip clock, and transmits packets asynchronously. In contrast to a centrally managed network, packet collision is inevitable for CSMA, when more than two tactile sensors transmit within the time as short as propagation delay. If the collision occurs, the throughput of the common bus deteriorates, and thus the collision must be suppressed by the data reduction mentioned above. A distinctive features of our network is emphasizing high speed response and scalability at the cost of the reliability and perfection of data.

EXPERIMENTS

Data reduction experiments

The data reduction function was tested by applying electrical stimulation to the ASIC instead of force to the tactile sensor. Figure 5 shows packets on the bus and decoded sensing data for 140ms, during which the electrical stimulation was applied for 100ms. Without the data reduction, data was transmitted continuously at a frequency of 5.5kHz (Figure 5 (a)). By the threshold operation, the number of the tactile data was reduced by 59% (Figure 5 (b)). In the threshold-based operation, weak force data below the pre-defined threshold was filtered and not transmitted on the bus. A further data reduction of 37.4% (i.e. 96.7% in total) was achieved in conjunction with adaptation (Figure 5 (c)). By the adaptation, transmission interval time was lineally increasing during applying constant strong forces over the threshold value.

Collision rate measurement

Although autonomous bus communication using CSMA protocol improves response time compared to the centrally-managed communication, packet collision will become a critical problem as the quantity of packet increases. Since packet generation rate can be adjusted by the power-on configuration, collision rate as a function of network traffic can be experimentally confirmed under various bus traffic conditions. This experiment was done using a small system composed of three integrated tactile sensors.

Each sensor was connected to a common signal line and initialized by the power-on configuration as it continuously transmits packets without data reduction at the same packet generation rate. The bus voltages for various packet generation rates are shown in Figure 6. Collided packets have bus signal higher voltage than that of successful packets, because a pull-down resistor is inserted between signal and ground line for this purpose.

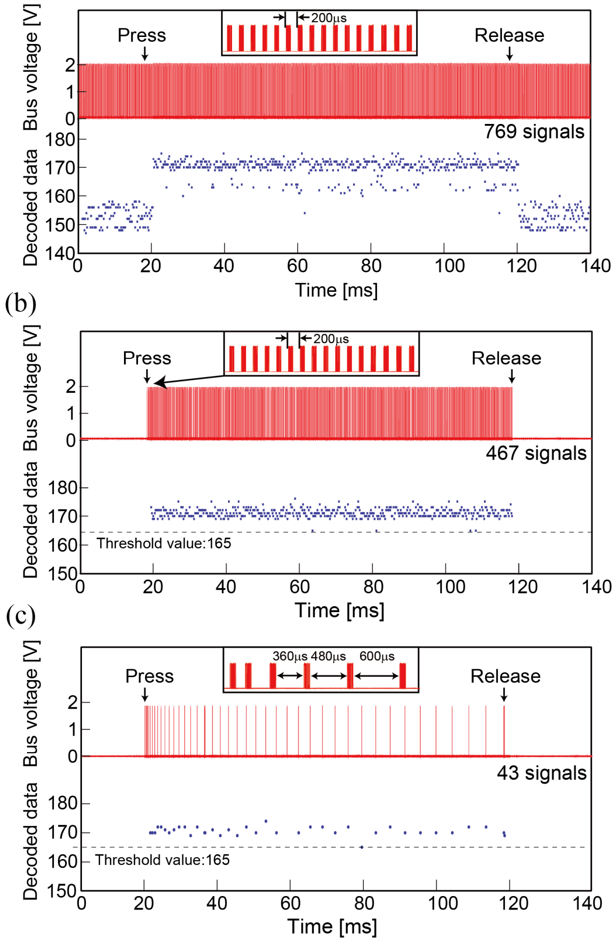

Figure 5: Data transmission with/without data reduction (a)without data reduction, (b) with threshold operation, (c) with threshold and adaption operation.

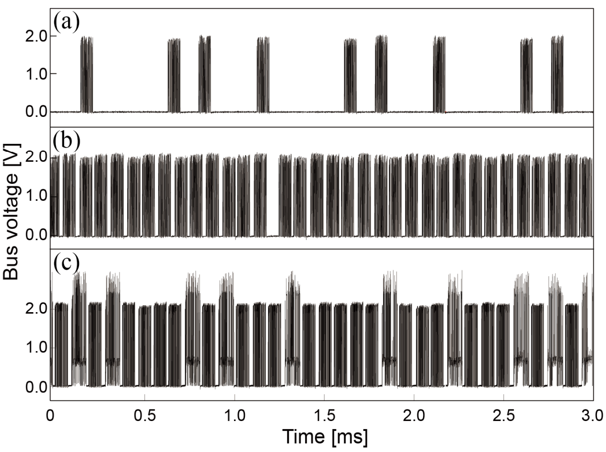

Figure 6: Bus traffic for various packet generation rate of (a) 3.3kHz, (b) 13.8kHz and (c) 17.4kHz.

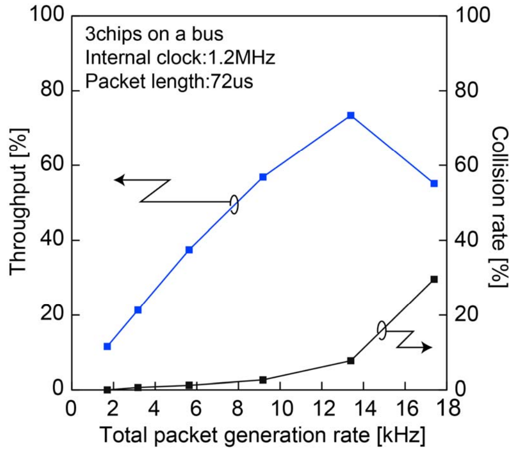

Figure 7: Data collision rate as a function of sampling rate of a single chip.

As shown in Figure 6 (a), the collision signal was not observed, when bus occupancy was small. If the bus occupancy reached maximum as shown in Figure 6 (b), further packets generation resulted in collisions as shown in Figure 6 (c).

Figure 7 shows the data collision rate and the throughput of the bus line as a function of the packet generation rate in total. The throughput is defined by the sum of packet length of successful packets divided by the measurement interval. To intentionally generate packet collision even in the small system, a clock frequency was set at 1.2 MHz, which was minimum frequency of on-chip clock. The highest data throughput (73%, 1Mbps) was obtained, when all of the sensors transmit each data at 4.6kHz (13.8kHz in total). This packet generation rate means that the response time of tactile sensor become ~200µs, if the bus monitoring time and packet collision are neglected. We obtained the fact that the collision rate is negligible when the throughput is less than about 50%. Since 90% reduction of tactile data can be achieved by the adaption like Figure 5, both low-collision and fast response data transmission can be realized in this system. For a large system composed of many sensors, each sensor works at a higher clock rate. At a clock frequency of 50MHz, scalability of the system and response time can be improve because network traffic decreases proportionally to network speed.

CONCLUTION

The tactile sensor which can be connected on a flexible cable was proposed. A specially-designed ASIC was integrated with a MEMS force sensor, and offered functions such as sensor readout, data processing and autonomous serial communication on a tiny chip. The digital packet contains force sensing data, showing a linear response against external force. A unique bus network protocol based on CSMA protocol was implemented, and data reduction by threshold operation and adaptation was demonstrated to overcome packet collision problem, which is inevitable for CSMA. Based on packet collision experiments using a small system working at a intentionally decreased clock frequency, the effectiveness of the data reduction for high speed response was experimentally confirmed.

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