

氏名	あさの しょう 浅野 翔
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指導教員	東北大学教授 田中 秀治
論文審査委員	主査 東北大学教授 田中 秀治 東北大学教授 小野 崇人 東北大学准教授 昆陽 雅司 東北大学准教授 室山 真徳

## 論文内容要旨

Robot technology is expected to play an important role for solving the problems in the current aging society with declining labor force and increasing the burden for nursing care and home assistant. Service robots have attracted attention in recent years, and the development has been promoted. In contrast with industrial robots, service robots are designed to operate in human environments such as homes and hospitals without fences or other safety measures. Most of the robotic tasks are carried out with physical contact to objects, thus tactile information is indispensable for safe operation (e.g. detection of unintended collisions) and behavior execution in human-robot interactions. Tactile sensors are required to be implemented on the whole body of a robot like humans to operate safely and appropriately. The human skin has numerous receptors to sense mechanical stimuli (e.g. pressure, vibration, and stretching), temperature, and pain. The functions of threshold and adaptation help to emphasize important stimulus like strong and continuous contact force. The tactile signal information is transmitted from receptors in the skin to the brain by numerous nerve fibers. The contact state of objects to robots also needs to be converted to an electric value, and the sensing data should be transmitted to a processing unit. Different from the human skin, tactile sensors must be connected to the detection circuit with a small number of wires to avoid prevention of motion of robots. Previous works have reported distributed tactile sensors on a large area of a humanoid robot by serial bus connection or matrix scanning. The sensors are flexible, and they can be implemented on curved surfaces of a robot. However, the discrete components used for the sensors are relatively large in size, which causes low spatial resolution. Most of the sensors can detect normal force (pressure) only, although detection of shear force is important for dexterous manipulation by sensing force direction. Recently, 3-axis tactile sensors have been developed based on microelectromechanical systems (MEMS) technology.

MEMS-based tactile sensors with high spatial resolution like fingertips or palms of humans have been reported, but the sensor and the readout circuit are connected one-by-one, therefore the number of wires will increase for connecting many sensors. Connection by relatively long wire also increases delay, noise, and parasitic capacitance. MEMS tactile sensors with integrated circuits (ICs) have been developed in previous works, however detection of shear force is not examined by MEMS-IC integrated tactile sensors. To address the problems and requirements, I propose new heterogeneously integrated MEMS tactile sensors with a flip-bonded large scale integration (LSI) on a low temperature cofired ceramic (LTCC) via-wafer. The objective of this study is to develop fundamental technologies for design, fabrication, and evaluation of the integrated tactile sensor toward practical use, and to show the usefulness by applying to robotic tasks of recognition of material properties using active sensing.

Fundamental technologies for design, fabrication, and evaluation was developed using an 1-axis integrated tactile sensor. The capacitive sensing method was adopted because of easy integration with the LSI circuit from a foundry, availability of 3-axis force sensing, and temperature independency. The heterogeneous MEMS-LSI integration enables reduction of the parasitic capacitance as well as the miniaturization. The sensor structure, which is composed of a flip-bonded LSI substrate with a sensing diaphragm on an LTCC via-wafer, allows the sensing structure to face outward for receiving contact force with providing the data and power lines from the backside. Au-Au thermo-compression bonding with planarized Au bumps was employed to connect the LSI substrate and the LTCC via-wafer with sealing the capacitive sensor structure. After bonding, the diaphragm for sensing force was formed by anisotropic etching of the LSI substrate, and the backside interconnection for bus connection was formed by electroplating and metal etching. The fabricated sensors were surface-mounted on a flexible bus line by an anisotropic conductive film (ACF) for electrical connection with adhesion. The fabrication process is simpler compared to the conventional surface-mountable sensors by through silicon vias (TSVs), which is helpful to realize high yield because of the small number of the fabrication steps. The process temperature within 350°C is also applicable to the LSI substrate with a low thermal budget. The sensor performance to force as well as the eigenfrequency were estimated by finite element method (FEM) simulation. The FEM simulation was used to estimate the capacitance change as well as the maximum principal stress. The eigenfrequency of the designed structure was estimated to be much higher than the motion of robots and the measurable stimulus frequency of mechanoreceptors of the human skin. The electrical connection was evaluated by measuring the current-voltage characteristics of the protection diodes which is incorporated in the LSI circuit. The fabricated all 45 integrated tactile sensors showed correct characteristics, and thus the

high yield for the electrical connection was shown. Although the measurement was done by five substrates with a small size of 20 mm square (each substrate has nine integrated tactile sensors), this high yield as well as the relatively simple fabrication process are good to apply medium volume production. The measured bonding strength was  $37.8 \pm 9.3$  MPa, which is acceptable for actual use. The fabricated sensor surface-mounted on a flexible bus line showed sensitivity as high as 0.529 Count/mN up to 1 N at a sample rate of 1 kHz with a small noise corresponds to less than 8.8 mN. The sensitivity could be adjusted after surface mounting by changing the count period of the configuration data from a host software. Human-inspired operations of threshold and adaptation were demonstrated for effective data reduction of less importance (e.g. continuous weak force). These functions for adjustment of the sensitivity and the response time as well as effective data reduction based on human-inspired operations are helpful to control sensing parameters according to applications and requirements. The surface-mounted sensors on a flexible and stretchable bus line, which was able to stretch up to 50%, operated correctly even with 10% stretching of the bus line.

The technologies developed for the 1-axis integrated tactile sensor was extended to development of a 3-axis integrated tactile sensor to realize detection of force direction and slip for dexterous manipulation. For enhancement of sensitivity and fabrication throughput, the capacitive gap was narrowed, and the diaphragm with a boss was formed by deep reactive ion etching (DRIE) to obtain a boss with vertical side wall and to increase fabrication throughput. In order to increase bonding strength, the bonding temperature and the bonding pressure were increased to 300°C and about 130 MPa, respectively. Three dimensional (3D) printed pins were used for applying normal and shear force independently to the boss of the sensor. The measured sensitivity at a sample rate of 81 Hz was as high as over 34 Count/mN for normal force and about 15 Count/mN for shear force with small noise level of less than 1 mN. The hysteresis and the average cross-axis sensitivity were also as small as less than 2% full scale and 11%, respectively. The sensor performance is good for robots to sense contact force with high sensitivity as well as small cross-axis sensitivity and hysteresis. The parasitic capacitance attached to the Z-axis sensor capacitor was estimated as 0.96 pF. The power consumption was estimated to be 5.8 mW (1.2 mW for 3.3 V power which is used for input-output and analog circuits, and 4.6 mW for 1.8 V power which is used for digital circuits). The temperature dependency of the fabricated sensor was as small as less than 7.5 mN for X-axis, 69 mN for Y-axis and 15 mN for Z-axis within the temperature range from room temperature (22°C) to 60°C. The two fabricated sensors surface-mounted on a flexible bus line operated without crosstalk even when force is applied to the sensors.

Finally, the integrated tactile sensor was applied to robotic tasks to recognize material properties of contact objects by active sensing, which is difficult to perform without tactile sensors. For the demonstrations, a sensor platform LSI with capacitive readout circuits and on-chip temperature sensors with readout circuits was used for development of integrated tactile sensor to realize 3-axis force and thermal sensation. The protruding boss and stopper was formed to concentrate contact force and prevent large diaphragm deflection, respectively. The sensor structure is advantageous in heat transmission from/to the on-chip temperature sensor because of the low thermal conductivity of the LTCC via-wafer. The fabricated sensor with stopper bumps could detect normal force up to 5 N, while the sensitivity dropped after the stopper contact to the LTCC substrate. The fabricated sensor could detect the force direction even when the combined normal and shear force is applied. The on-chip temperature sensor operated with sensitivity of 0.47°C, which is within the designed range. The integrated tactile sensors were surface-mounted on a printed circuit board (PCB) to implement on a 3D-printed robotic finger. Hardness of grasped objects could be recognized by the change of the measured force while narrowing the gap of the fingers (i.e. pressing the object). When grasping a soft object like rubbers, measured force saturated after the gap of the fingers decreased enough because the contact force was applied to not only the boss of the sensor but also the frame of the sensor and the PCB. There was a correlation between the saturation force and the Young's modulus of the object. On the other hand, the contact force concentrated on the boss of the sensor if a hard object like woods is grasped, and the measured force rapidly increased. Recognition of temperature of the grasped object was demonstrated by the change of the output value of the on-chip temperature sensor when grasping a plastic bottle with cold or hot water. The material of contact objects with different thermal conductivity (Al, Ti, glass, and acrylic) was shown to be recognized by the measured temperature drop of the integrated tactile sensor, which was heated up to around 46°C. These results demonstrate that the integrated tactile sensor developed in this study is useful for robots to identify the properties of the contact object using active sensing.

In this study, MEMS-LSI integrated tactile sensors with the following features have been successfully developed: (1) surface-mountable on a flexible and stretchable bus line with millimeter resolution; (2) 3-axis force and temperature sensation with adjustable sample rate, high force sensitivity, small cross-axis sensitivity, and small hysteresis; and (3) simple fabrication process. The integrated tactile sensor implemented on a robot finger demonstrated recognition of the material properties of a grasped object. The integrated tactile sensors developed in this study is useful for the tactile sensation of robots working with humans.

# 論文審査結果の要旨

今後、人と協働するロボットが工場、病院、オフィス、家庭などで使われるようになるには、人や周囲の物体との接触を検知し、また、人との身体的接触をもって作業やコミュニケーションを行うことが求められる。そのため、ロボットの各所に多数の触覚センサを配置したいという要求がある。この要求を満たすためには、触覚センサが超小形かつ高性能で、しかもセンサとコントローラとの間の配線ができる限り少なくなる形態で、多数個、実装できるように構成されていなくてはならない。これを具現化する方法として、3軸力センサをMEMS技術で実現し、信号処理やバス通信を担うLSIと集積化する方法が有望である。

本論文は、信号処理やバス通信を担うオリジナルのLSI、「センサプラットフォームLSI」を用いて集積化触覚センサを構成するにあたり、センサプラットフォームLSIにダイヤフラムからなる力センサ構造をMEMSプロセスによって作り込み、これを再配線基板となるLTCC基板と接合してウェハレベルパッケージングする構造を提案し、その設計、試作、評価、および応用検討を一貫して行った成果をまとめたものであり、全編5章からなる。

第1章は序論であり、研究の背景、従来技術、触覚センサの技術課題などが述べられた後、本研究の目的が示されている。

第2章では、ここで提案する触覚センサを実現するにあたって必要となる技術要素、特に設計法、作製法、および実装法に関して述べている。これらの技術要素を開発するにあたり、1軸の触覚センサを試作対象とし、有限要素法による構造設計、配線設計、MEMSプロセスによる試作、フレキシブルバス配線へのセンサ実装などが行われている。試作した触覚センサは、機械的堅牢性、外力に対する応答、バス通信機能などについて評価され、設計通り動作することが確認されている。これは、センシングから信号処理、バス通信に至るまで全ての機能が超小形チップに実装されたはじめての集積化触覚センサであり、重要な成果である。

第3章では、第2章に述べた成果に基づき、3軸の集積化触覚センサを開発した成果について述べている。ロボットで触覚センサを利用することを想定した場合、せん断力の検出が求められている。そこで、設計や製造に関わる技術要素の開発に用いた1軸触覚センサを拡張し、3軸触覚センサを開発している。試作した触覚センサの3軸力への応答、消費電力、実用化する際に重要になる温度安定性などが評価されている。また、フレキシブルバス配線上での動作も確認されている。これらは、この集積化触覚センサの実用化に繋がる有用な成果である。

第4章では、第3章までに述べた集積化触覚センサのロボット応用に向けてなされた開発について述べている。ロボット応用を想定して、ロボットハンドに触覚センサを取り付けて、物体を把持するとともに物体の硬さと温度を認識する実験が行われている。また、ロボットハンドに把持された物体に滑り方向の力が加わった状態を想定し、触覚センサでせん断力を検出する実験が行われている。これらの実験に用いる集積化触覚センサは、第3章で述べられたものを改良したものであり、本章ではその設計と試作についても述べている。これらは、この集積化触覚センサのロボット応用での有用性を実証したものであり、重要な成果である。

第5章は結論である。

以上要するに本論文は、信号処理やバス通信を担うLSIと集積化されたMEMS触覚センサについて、設計、作製、実装などに関わる技術要素の開発から、1軸センサと3軸センサの開発と評価、さらにロボットハンドに実装しての応用評価まで行った一連の研究の成果をまとめたものであり、バイオロボティクスおよびマイクロシステム工学に寄与するところが少なくない。

よって、本論文は博士(工学)の学位論文として合格と認める。