様　式　C－１９、F－１９－１、Z－１９　（共通）

科研費 KAKENHI

# 科学研究費助成事業　　研究成果報告書

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研究課題名（和文）Integrated multimodal tactile sensor as large-scale distributed robotic skin for safe human-robot collaboration

研究課題名（英文）Integrated multimodal tactile sensor as large-scale distributed robotic skin for safe human-robot collaboration

研究代表者
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研究者番号：４０７９１２３１

交付決定額（研究期間全体）：（直接経費）　　3,300,000円

研究成果の概要（和文）：Since the summary is the same as in the English portion, please refer to that portion. This is because the Japanese section limits to only 200 characters which is not enough.

研究成果の学術的意義や社会的意義
The sensor we have developed has a feature that make it very versatile. This feature is the adjustable sensitivity. The sensor can be use in many situation where the range of force varies a lot.

研究成果の概要（英文）：We have developed and improved the sensors several iterations. In each, the sensor's performance was improved. Currently, the temperature of the sensor is reduced to 45 degrees. Moreover, it has been proven that the sensitivity of the sensor can be adjusted. This can be very beneficial when only 1 type of sensor are to subject to various range of force. The sensor has been improved to utilize the measurement range of the chip we used in the sensor effectively. We found that we can still improve the sensor to cover more of the measurement range. We plan to improve the sensor further and integrate the sensor into a big patch which to be installed on a robot.

研究分野：Tactile sensor

キーワード：ロボティクス　センシングデバイス

## １．研究開始当初の背景

Tactile force sensing is important for safe human-robot interaction. Moreover, to further reduce the risk of a human getting injured by the robot, one of the safest ways is to prevent any impact before it happens. Therefore, proximity sensing can be beneficial. Furthermore, having a force sensing ability as a redundant system could lead to a more reliable and safer interaction. The new ISO/TS 15066:2016 states that force and proximity sensing are needed for industrial collaborative robots.

## ２．研究の目的

Collaborative robots will share the workspace with humans, and the safety of humans is remarkably important. Combined proximity and force sensing embedded in soft skin would increase the level of human safety when human-robot collaboration happens. In this research, a modular, adjustable force vector sensing, proximity measuring, failure tolerant wiring, and 100% soft surface tactile sensor will be developed. Each sensor will be space efficient which allow it to be installed in limited space. The sensor will provide efficient interconnection between each module in order to reduce amount of necessary wires and achieve dynamic reconnection when a module is not functional. The multitude of the sensors will be installed on a robot and tested as a proof of concept. Due to the compliance and the combined proximity and force sensing, the sensors will lead to improved safety in human-robot collaboration.

## ３．研究の方法

This research will be separated into two cycles of sensor development, and two cycles of integrating and testing the developed sensor on a robotic arm. Firstly, the first version of the novel multimodal tactile sensor will be realized according to the concept showed in Figure 1. The characteristics and the functionalities of the sensor will be tested, and the result will be used on improving the sensor in the second cycle of development. Thereafter, several units of the sensor will be installed on the robotic arm and tested. Practical problems of installing the sensors on the robot are expected to be discovered the first cycle of integration. The experimental result and the solution will be used in the second cycle of integration. The test then will be performed in order to verify the ability of the sensor in providing safer and more robust human-robot interaction. Collaborative tasks will be done to evaluate the sensor.

## ４．研究成果

In [1], we have developed the first prototype of a thin, adjustable 3-axis force sensor with integrated electronics for digital signal output. The sensor was designed, assembled and tested. The sensor uses an electromagnetic coil to generate a controllable magnetic field. This magnetic field is used to adjust the sensitivity of the sensor. The result shows that the sensitivity of the sensor to displacements, as well as force, can be adjusted. However, we found that the strength of the magnetic field generated by the coil did not utilize much of the available bandwidth of the magnetic sensor.

Therefore, in [2], we further improve the sensor by using a hybrid arrangement that consists in a small permanent magnet and an electromagnet working together above a 3-axis magnetic sensor. Both layers are separated by a flexible material that provides compliance to the sensor module. The permanent magnet increases the intensity of the overall magnetic field to optimize the utilization of the bandwidth of the sensor. Three different magnet arrangements were tested and a single magnet measuring 0:97x0:51mm and with the rating of N35 was selected as optimal.

Furthermore, three different shapes of neoprene material were tested to act as Middle Layer of the sensor module. Results have shown that the most desirable shape correspond to the ’Partial’ shape, which is the one that covers the smallest area between the boards of the module.

Finally, with the new middle material design, the current version was tested with a maximum normal force of 47N while the previous version could only reach 4:5N for the same experiment.

In [3], further development has been done to improve the performance of the sensor. In [2], there were 2 issues. One issue is the high temperature when the electromagnetic coils generate the magnetic field. Another issue is the generated magnetic field is still weak; A stronger field would utilize a wider range of the sensor. Therefore, in [3], the thickness of the coil was increased 2 times. As a result, the temperature of the coil has been reduced to 45 degrees (from 50 degrees). At the same time, the strength of the generatable magnetic field increases to 0.6 mT (from 0.2 mT).

＜引用文献＞

[1] A. C. Holgado, J. A. A. Lopez, A. Schmitz, T. P. Tomo, S. Somlor, L. Jamone, and S. Sugano, "An Adjustable Force Sensitive Sensor with an Electromagnet for a Soft, Distributed, Digital 3-axis Skin Sensor," *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2018.

[2] A. C. Holgado, J. A. A. Lopez, T. P. Tomo, S. Somlor, and S. Sugano, "A Soft, Distributed, Digital 3-axis Skin Sensor Employing a Hybrid Permanent-Adjustable Magnetic Field," *2019 IEEE International Conference on Robotics and Biomimetics (ROBIO)*, 2019.

[3] A. C. Holgado, J. A. A. Lopez, T. P. Tomo, S. Somlor, and S. Sugano, "Improvements on a Sensitivity Adjustable 3-Axis Soft Skin Sensor with an Electromagnet," *2020 IEEE/SICE International Symposium on System Integration (SII)*, 2020.

５．主な発表論文等

〔雑誌論文〕　計2件（うち査読付論文　0件／うち国際共著　0件／うちオープンアクセス　0件）

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| １．著者名<br>Kristanto Harris、Sathe Prathamesh、Schmitz Alexander、Tomo Tito Pradhono、Somlor Sophon、Sugano Shigeki | ４．巻<br>3 |
| ２．論文標題<br>A Wearable Three-Axis Tactile Sensor for Human Fingertips | ５．発行年<br>2018年 |
| ３．雑誌名<br>IEEE Robotics and Automation Letters | ６．最初と最後の頁<br>4313～4320 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.1109/LRA.2018.2864669 | 査読の有無<br>無 |
| オープンアクセス<br>オープンアクセスではない、又はオープンアクセスが困難 | 国際共著<br>－ |

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| １．著者名<br>Tomo Tito Pradhono、Regoli Massimo、Schmitz Alexander、Natale Lorenzo、Kristanto Harris、Somlor Sophon、Jamone Lorenzo、Metta Giorgio、Sugano Shigeki | ４．巻<br>3 |
| ２．論文標題<br>A New Silicone Structure for uSkin - A Soft, Distributed, Digital 3-Axis Skin Sensor and Its Integration on the Humanoid Robot iCub | ５．発行年<br>2018年 |
| ３．雑誌名<br>IEEE Robotics and Automation Letters | ６．最初と最後の頁<br>2584～2591 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.1109/LRA.2018.2812915 | 査読の有無<br>無 |
| オープンアクセス<br>オープンアクセスではない、又はオープンアクセスが困難 | 国際共著<br>－ |

〔学会発表〕　計5件（うち招待講演　0件／うち国際学会　5件）

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| １．発表者名<br>A. C. Holgado, J. A. A. Lopez, T. P. Tomo, S. Somlor, and S. Sugano |
| ２．発表標題<br>A Soft, Distributed, Digital 3-axis Skin Sensor Employing a Hybrid Permanent-Adjustable Magnetic Field |
| ３．学会等名<br>2019 IEEE International Conference on Robotics and Biomimetics (ROBIO)（国際学会） |
| ４．発表年<br>2019年 |

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| １．発表者名<br>A. C. Holgado, J. A. A. Lopez, T. P. Tomo, S. Somlor, and S. Sugano |
| ２．発表標題<br>Improvements on a Sensitivity Adjustable 3-Axis Soft Skin Sensor with an Electromagnet |
| ３．学会等名<br>2020 IEEE/SICE International Symposium on System Integration (SII)（国際学会） |
| ４．発表年<br>2020年 |

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| **1．発表者名**<br>Holgado Alexis C.、Alvarez Lopez Javier A.、Schmitz Alexander、Tomo Tito Pradhono、Somlor Sophon、Jamone Lorenzo、Sugano Shigeki |
| **2．発表標題**<br>An Adjustable Force Sensitive Sensor with an Electromagnet for a Soft, Distributed, Digital 3-axis Skin Sensor |
| **3．学会等名**<br>IEEE/RSJ International Conference on Intelligent Robots and Systems（国際学会） |
| **4．発表年**<br>2018年 |

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| **1．発表者名**<br>Funabashi Satoshi、Morikuni Shu、Geier Andreas、Schmitz Alexander、Ogasa Shun、Torno Tito Pradhono、Somlor Sophon、Sugano Shigeki |
| **2．発表標題**<br>Object Recognition Through Active Sensing Using a Multi-Fingered Robot Hand with 3D Tactile Sensors |
| **3．学会等名**<br>IEEE/RSJ International Conference on Intelligent Robots and Systems（国際学会） |
| **4．発表年**<br>2018年 |

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| **1．発表者名**<br>Funabashi Satoshi、Schmitz Alexander、Sato Takashi、Somlor Sophon、Sugano Shigeki |
| **2．発表標題**<br>Versatile In-Hand Manipulation of Objects with Different Sizes and Shapes Using Neural Networks |
| **3．学会等名**<br>IEEE-RAS International Conference on Humanoid Robots（国際学会） |
| **4．発表年**<br>2018年 |

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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**６．研究組織**

| | 氏名<br>（ローマ字氏名）<br>（研究者番号） | 所属研究機関・部局・職<br>（機関番号） | 備考 |
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