様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

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 sensitivity-adjustable 3-axis tactile and proximity sensor as distributed, robust, and soft robotic skin system for safe human-robot collaboration

研究課題名（英文）Integrated sensitivity-adjustable 3-axis tactile and proximity sensor as distributed, robust, and soft robotic skin system for safe human-robot collaboration

研究代表者

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研究成果の概要（和文）：低価格のコンプライアンス型静電容量式力・近接センサー "Safe Skin "が開発されました。このセンサーは最大400㎜の距離と最大40Nの力を感知することができ、このセンサーのテストを行い、その結果はIROS 2021に掲載されました。センサーの性能を評価するために、3つのサイズのセンサーをテストしました。120×120のサイズが最も良い性能を発揮する。
提案されたセンサーのいくつかのユニットが、ロボットアームであるNICEBOTに取り付けられました。その際、センサーのいくつかの特性がテストされた。特に、センサーの計測に影響を与える外乱と自己感知による影響について調べた。

研究成果の学術的意義や社会的意義
With the force/proximity sensors installed on a robot, it can provide proximity and contact force information that can be used by the robot to adjust its action in order to ensure the safety of nearby humans while being able to work. The current version provide promising results for future research.

研究成果の概要（英文）：A low-cost compliant capacitive Force/proximity sensor called "Safe Skin" has been developed. The sensor can sense the distance up to 400 mm and the force up to 40 N. The sensor was tested, and its result was published in IROS 2021. Three sizes of sensors were tested to evaluate their performance. The size of 120 x 120 gives the best performance.
Several units of the proposed sensor were installed in NICEBOT, a robot arm. Several characteristics of the sensors then were tested. In particular, the external disturbance and the effect of self-sensing that affects the measurement of the sensor was studied.

研究分野：Tactile Sensor

キーワード：Tactile sensor　Proximity sensor　Capacitive sensor

様　式　C－１９、F－１９－１、Z－１９（共通）

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

In this research, a soft capacitive-based combined force and proximity sensor was developed. With this sensor installed, a robot will be able to sense the proximity of approaching humans and the contact force. The information of the 2 sensing modalities allows the robot to adjust or adapt its action to ensure the safety of the humans while being able to continue working if possible.

３．研究の方法

In the beginning (FY2019), a modular, adjustable force vector sensing, proximity measuring, and 100% soft surface tactile sensor was developed and tested (***Originally proposed sensor***). The proximity sensing is based on capacitive while the force vector sensing is based on Hall effect. The sensing characteristics of the sensor were tested. Based on the result, the 2nd version of the sensor was created to improve the sensitivity of the sensor.

However, since FY2020, we explored the possibility of a new sensor (***New sensor***) where both proximity and force sensing are based on capacitive. The sensor will be able to cover curved surface.

As for the new sensor, firstly, several prototypes of a single capacitive-based force and proximity sensor was developed and tested to find the best configuration that provides the best sensing characteristic. This configuration involves the size of capacitive electrodes, the distances between layers of the electrodes, and the dielectric materials used for creating those distances.

The sensing characteristics considered here are proximity sensing range and resolution, force sensing range and resolution, and signal-to-noise ratio (SNR) of both proximity and force sensing.

After the best configuration was determined, several units of the sensors were installed on a robotic arm to further test the sensor with respect to disturbances from robot's motor and cables. Furthermore, the performance of the sensor installed on a curved surface of the robot was tested as well.

４．研究成果

Originally proposed sensor

We further improve the performance of the sensor. We implemented a hybrid arrangement that consists in a small permanent magnet and an electromagnet. This increases the intensity of the magnetic field increase the utilization of the bandwidth of the chip. Moreover, we have fixed the issue of high temperature of the electromagnetic coil and further increase the strength of the generated magnetic field. As a result, the temperature of the coil has been reduced to 45 degrees. At the same time, the strength of the magnetic field increases to 0.6 mT.

New sensor

Individual units of sensors were tested to determine the best configurations. The sensors with the combination of 7 electrode sizes and 3 distance choices were tested. The best configuration of the sensor can sense human hand at a distance up to 400 mm and the contact force up to 40 N.

The sensor can also cover the curved surface of the robot. The sensing characteristic of the curved version is slightly inferior to the flat one. Both concave and convex curved surface can be covered with the sensor. Both proximity and force sensing capability of the sensor remains functional.

The sensors installed on the robot were affected by the disturbances. Specifically, the SNR of the sensors were increased resulting in the decreased proximity sensing distance. It was suspected that the disturbances were due to the motors of the robotic arm and the cables of the arm. However, the sensors still able to perform well; the sensors can sense the proximity and force.

The disturbance would be taking care of in the future work. A method to reduce the effect of the disturbance will be studied.

５．主な発表論文等

〔雑誌論文〕　計3件（うち査読付論文　0件／うち国際共著　3件／うちオープンアクセス　0件）

１．著者名 Wang Zhen、Gao Heyang、Schmitz Alexander、Somlor Sophon、Tomo Tito Pradhono、Sugano Shigeki	４．巻 -
２．論文標題 "Safe Skin" - A Low-Cost Capacitive Proximity-Force-Fusion Sensor for Safety in Robots	５．発行年 2021年
３．雑誌名 2021 IEEE International Conference on Robotics and Automation (ICRA)	６．最初と最後の頁 807-813
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/IROS51168.2021.9636308	査読の有無 無
オープンアクセス 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 該当する

１．著者名 Yan Gang、Schmitz Alexander、Funabashi Satoshi、Somlor Sophon、Tomo Tito Pradhono、Sugano Shigeki	４．巻 -
２．論文標題 SCT-CNN: A Spatio-Channel-Temporal Attention CNN for Grasp Stability Prediction	５．発行年 2021年
３．雑誌名 2021 IEEE International Conference on Robotics and Automation (ICRA)	６．最初と最後の頁 2627-2634
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/ICRA48506.2021.9561397	査読の有無 無
オープンアクセス 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 該当する

１．著者名 Sathe, P., Schmitz, A., Kristanto, H., Hsu, C., Tomo, T.P., Somlor, S., Sugano, S.	４．巻 -
２．論文標題 Development of Exo-Glove for Measuring 3-axis Forces Acting on the Human Finger without Obstructing Natural Human-Object Interaction	５．発行年 2020年
３．雑誌名 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2020)	６．最初と最後の頁 4106-4113
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/IROS45743.2020.9341609	査読の有無 無
オープンアクセス 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 該当する

〔学会発表〕　計2件（うち招待講演　0件／うち国際学会　2件）

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

１．発表者名 A. C. Holgado, J. A. A. Lopez, T. P. Tomo, S. Somlor, and S. Sugano
２．発表標題 Improvements on a Sensitivity Adjustable 3-Axis Soft Skin Sensor with an Electromagnet
３．学会等名 2020 IEEE/SICE International Symposium on System Integration (SII)（国際学会）
４．発表年 2020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 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関