Proceedings of the 11th International Conference of Control Systems, and Robotics (CDSR 2024)
Chestnut Conference Centre - University of Toronto, Toronto, Canada – 10 -12 June, 2024
Paper No. 137
DOI: 10.11159/cdsr24.137

Embedded Sensors in Intelligent Robots Achieving Performance Enhancement

Frank J. Chen[1], Zhiyue Lei[2], Norman J. Chen[3]
[1]Holy Heart of Mary High School
55 Bonaventure Avenue, St. John's, NL A1C 3Z3, Canada
fchen45_s@nlschools.ca
[2]Department of Mechanical Engineering, McMaster University
1280 Main Street West, Hamilton, ON L8S 4L7, Canada
leiz6@mcmaster.ca
[3]Software Engineering Program, University of Waterloo
200 University Avenue West, Waterloo, ON N2L 3G1, Canada
njchen@uwaterloo.ca

Abstract **-** We propose both rigid and flexible devices as embedded sensors to be integrated into intelligent robots, which achieve performance enhancement through the realization of multimodal sensing. Using flexible force sensors as an example, we show the approach to use 3D printing technology to realize sensor integration and to achieve real-time monitoring of sensing through computer interfacing and controlling. The technique proposed here exhibits enhanced multimode sensing, high degree of integration, and improved control, which are essential for intelligent robots and soft robots.

Keywords**:** embedded sensors; embedded control; flexible sensors; 3D printing; robots; intelligent robots; instrumentation

1. Introduction

Robots have been well recognized for their increasing roles in carrying out physical tasks on various occasions [1-4]. To effectively manipulate objects in complex and changing environments with high precision, a robot must possess the capability to perceive conditions to decide when, where and how it interacts with surrounding objects [5-7]. In fact, perception is one of the crucial properties of any intelligent autonomous systems, including robotics. Robotic perception includes estimation of the self, mapping of the surroundings, and proximity evaluation between the self and surroundings. Through models and technologies developed so far, the traditional rigid robotics can achieve perception through well-developed sensors and electronic devices [8]. Nevertheless, continuing efforts are undergoing to develop intelligent robots with further enhanced functionalities and high degree of integration. An intelligent robot is anticipated to analyse information and response in ways that are consistent with human social norms. To achieve such an advanced technological level, robot-specific sensors are the core components among all key technologies for intelligent robots [7]

In recent years, soft robotics, inspired from the malleable and adaptable nature of biological systems, have emerged with unique merits in comparison with rigid robots [9-11]. Soft robots can actively and passively change their shapes for safe, robust, and effective interactions through simple control methods. Some remarkable types of soft robots include jamming gripper, worm robot, octopus robot, and growing robot. The intrinsic nature of soft robots to mimic natural organisms leads them to seamlessly integrate and interact with their surroundings, enabling them to fulfil tasks that demand high levels of adaptability and sensitivity [12].

To obtain autonomy and control of soft robots, it is an essential task to achieve integration of multimode sensors onto soft robots, which are essentially soft-bodied systems, to provide sensory feedback [13,14]. The high dimensionality of soft robots complicates the selection of the type, number, and placement of sensors. One of the current barriers in the development of soft robots lies in the lack of comprehensive integration of sensor technologies. The development of technologies for sensing in intelligent and/or soft robots is a growing and challenging research front, which requires interdisciplinary efforts from the fields of materials, electronics, mechanical engineering, computer interface and control [15-17].

To truly emulate biological systems, the integration of rigid sensors, and flexible sensors in particular, is paramount, which offers real-time feedback and enhances adaptability [18]. Meanwhile, current development in flexible electronics provides technological feasibility [19,20]. Flexible sensors are low cost, wearable, and light-weighted electronic devices, which realize measurement of environmental parameters through a relatively simple structure with sufficient sensitivity. Currently, flexible devices have been developed for applications on limited occasions.

In this study, we propose a new approach and demonstrate rigid and flexible devices as embedded sensors to be integrated into intelligent robots, which achieves performance enhancement through the realization of multimodal sensing. Due to the unique advantages of flexibility, integration of flexible sensors in soft robots exhibits significant promise for a wide range of applications.

2. Methodology

Sensors are predominantly electronic devices, which are widely used for detecting external signals and the consequent responses. The measurands to be monitored by sensors cover all kinds of environmental parameters, such as temperature, force, pressure, torque, displacement, proximity, bending, rotation, curvature, to name a few among numerous possibilities [21,22]. The most important factors to evaluate the performance of a sensor include sensitivity, flexibility, repeatability, reliability, size, weight, cost, and lifetime of usage. In many cases, the users need to make judgement on all factors, even trade-offs sometimes, to identify one configuration as the most suitable approach for specific use.

2.1. Rigid Electronic Sensors

There are about 26,000 kinds of conventional sensor types that have been commercialized worldwide. These sensors can be categorized into some main groups, such as temperature and humidity sensor, gas sensor, and pressure sensor. For most common conventional electronic sensors, temperature is one of the fundamental parameters to be measured, which is directly related to the measurement of human body temperature or environmental temperature. Some types of temperature sensor can be integrated or embedded into a robot. Figure 1(a) shows some conventional electronic sensors, including weight sensor, stress sensor, accelerator position sensor, and temperature sensor. Figure 1(b) exhibits a typical temperature sensor with adapter module, which can be connected to Arduino for signal acquisition and processing. These rigid electronic sensors, with the possibility to shrink their sizes further, can be integrated or embedded in a robot.

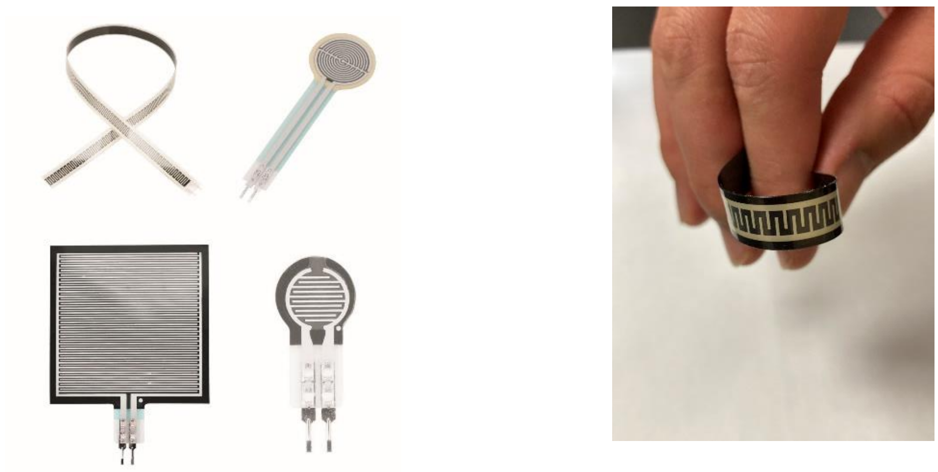
(a)

(b)

Fig. 1: Examples of some conventional electronic sensors: (a) Weight sensor, stress sensor, accelerator position sensor, and temperature sensor. (b) A temperature sensor with adapter module for Arduino.

2.2. Flexible Sensors

Flexible sensors, utilizing stretchable and flexible electronics, possess an extensive range of mechanical features. These flexible sensors have been integrated to deformable conducting material to be imprinted onto an elastic substrate via several techniques, such as transfer printing, screen printing, photolithography, microchannel moulding, and lamination. The rapid development of flexible sensors opens new opportunities for applications. Compared to the conventional rigid electronic sensors, the flexible sensors show tremendous advantages of high biocompatibility, real-time monitoring, and compatibility with soft robots. The flexible sensors have been used to monitor force, pressure, bending, tension, shear, stress and strain by converting changes into electrical signals. Continuing efforts have been focused on the enhancement of sensitivity and the improvement of mechanical flexibility. Figure 2(a) illustrates some flexible force/pressure sensors. Figure 2(b) shows the flexibility of one force/pressure sensor adopted in this study. Figure 3 illustrates the geometries and sizes of two flexible force/pressure sensors used in this study.



(a) (b)

Fig. 2: Examples of some flexible electronic sensors: (a) Force/pressure sensors of different shapes. (b) A force/pressure flexible sensor adopted in this study.

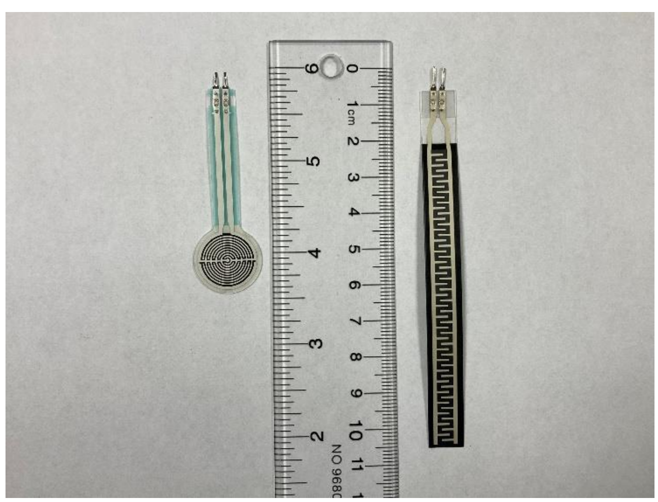


Fig. 3: Geometries and sizes of two flexible force/pressure sensors used in this study.

3. Results and Discussion

3.1. Performance of Embedded Flexible Force/Pressure Sensors

To apply a sensor in any application, calibration should be performed at the initial stage and the performance of the sensing response should be carefully evaluated. The force sensor located at left in Figure 3 was checked for its dependence of resistance on the force applied on the sensing surface and the results are shown in Figure 4 in both the linear scale and logarithm scale [23]. Figure 4(a) shows a monotonous dependence of the resistance on the applied force in a range up to a maximum of 6 kg. If the coordinates are converted to logarithmic scales, as shown in Figure 4(b), the dependence will behave almost linearly. When it is connected in a circuit, it also shows a nearly linear dependence of output voltage versus applied force. Therefore, the results indicate that this flexible device can serve as a good force sensor. A detailed discussion on the importance of force sensing in soft robotics and the theoretical aspects underlying force sensing in soft robotics can be found in Ref. [24].

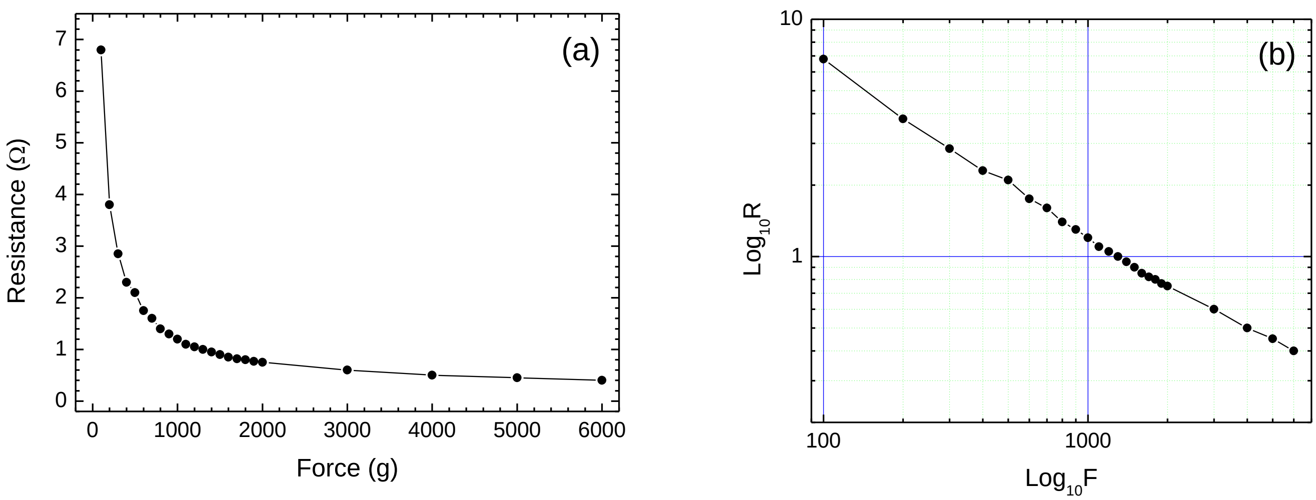


Fig. 4: Dependence of resistance on the applied force of the flexible force sensor investigated in this study: (a) Data set plotted on a linear scale; (b) Data set plotted on a Log_{10} scale.

Fig. 5: 3D printing systems used in this study.

3.2. 3D Printing Realizing Sensor Integration

Once the performance of the flexible sensor has been revealed and validated, the next step is to integrate the flexible sensor into a robot. As a newly emerged additive manufacturing technology, 3D printing has been playing an important role in the fabrication of parts and components of different materials with various shapes. Many fabrication techniques are associated with some disadvantages, such as high cost, multi-step production procedures, limited durability, as well as prototyping and grading challenges. In contrast, 3D printing is a valuable alternative approach. Though it is possible to develop flexible sensors with 3D printing technology in some cases [25,26], our focus in this study is on the integration of commercially available rigid and flexible sensors into robots. The 3D printing systems used in this study are shown in Figure 5. Figure 6 shows some fixtures fabricated in this study with the 3D printing systems shown in Figure 5. It is possible to design three-dimensional fixtures of arbitrary shapes and sizes to be compatible with various geometries of the flexible sensors to be integrated or embedded into the robot. In addition, it is also possible to select specific polymer materials of unique physical, chemical, and mechanical properties from many kinds of polymers with different properties to match with the flexible sensors.

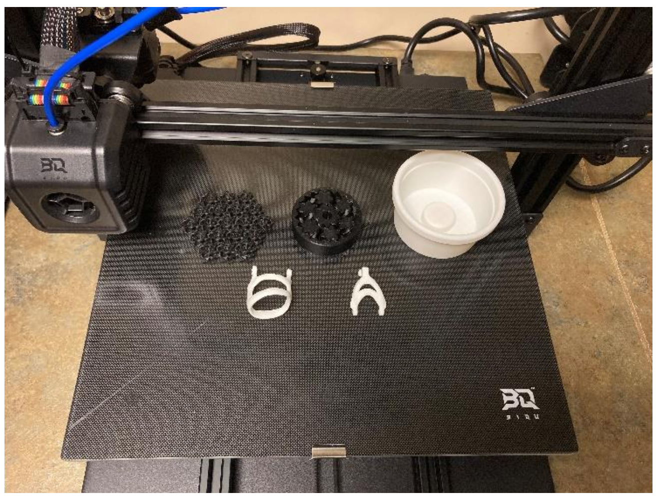


Fig. 6: Fixtures of different polymer materials with different geometries and sizes fabricated with the 3D printing systems in this study.

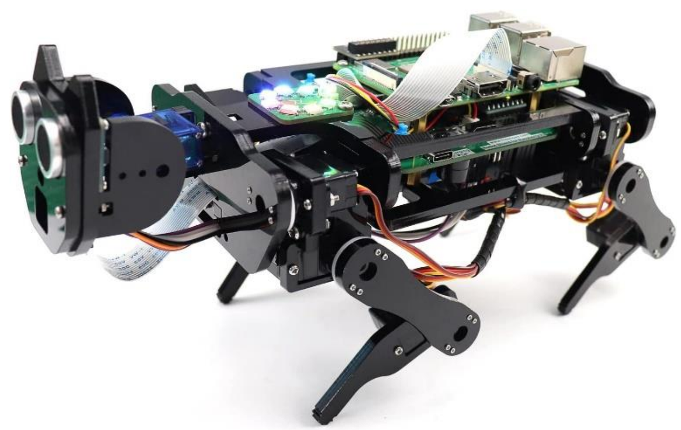
Fig. 7: Arduino and Raspberry Pi computer are used in this study to achieve computer interface and control.

3.3. Computer Interface and Control

As shown in Figure 1, the electrical signals from a flexible sensor are transmitted through an adapter module, which is then forwarded to an Arduino or Raspberry Pi, a micro-computer with a size of a credit card. Figure 7 shows the Arduino and Raspberry Pi computers we are using to achieve computer interface and control on flexible sensors as well as the robots. As many robots are controlled by Raspberry Pi computers, our approach offers great compatibility and convenience.

4. Flexible Sensors in a Robot

With the successful selection and evaluation of the suitable flexible sensors to be integrated or embedded into robots, we have been working on the embedded flexible sensors in a robot dog, as shown in Figure 8. The left figure in Figure 8 is a robot dog as a platform to install different sensors while the right figure in Figure 8 is the robot dog embedded with sensors and controlled through Raspberry Pi 4 computer together with Raspberry P13 7" touchscreen display. With the help of 3D printing technology, we succeeded in embedding rigid and flexible sensors into this robot. It is interesting to witness the enhanced capability and performance of the robot with the embedded rigid and flexible sensors, for its temperature and force/pressure monitoring capabilities. It is an ongoing project to try other types of sensors to be embedded into such a robot or other robots, thus, to achieve multimodal sensing. Despite challenges, further exploration to realize intelligent robots with enhanced sensing performance is highly feasible and promising.



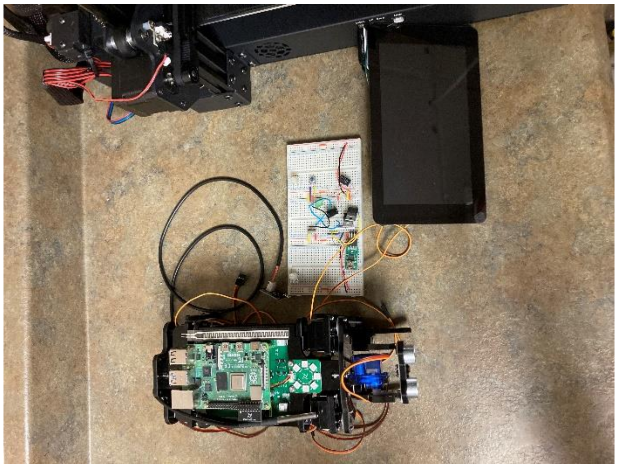


Fig. 8: A Robot dog used in this study to accommodate embedded sensors.

4. Conclusion

We propose and demonstrate rigid and flexible electronic sensors to be embedded into intelligent robots which realize multimodal sensing with enhanced capability and performance. In this study, some rigid and flexible sensors have been studied for their performance as force/pressure sensors as well as other features of these sensors on the feasibility of integration. The research in this study has demonstrated that 3D printing technology is a powerful manufacturing technology to achieve the integration of flexible sensors to robots, realizing performance enhancement. Further investigation will enable us to overcome challenges to achieve further improvement in the sensing performance, degree of integration, and enhancement of functionalities.

References

[1] J. Craig, "Introduction to Robotics: Mechanics and Control," 4th ed., Pearson, 2017.

[2] K. M. Lynch and F. C. Park, "Modern Robotics: Mechanics, Planning, and Control," Cambridge: Cambridge University Press, 2017.

[3] B. Siciliano, L. Sciavicco, L. Villani, and G. Oriolo, "Robotics: Modeling, Planning and Control," London: Springer-Verlag, 2010.

[4] P. Corke, W. Jachimczyk, and R. Pillat, “Robotics, Vision and Control,” 3rd ed., Springer Nature Switzerland AG, 2023.
[5] Z. Lin, Z. Wang, W. Zhao, Y. Xu, X. Wang, T. Zhang, Z. Sun, L. Lin, and Z. Peng, “Recent advances in perceptive intelligence for soft robotics,” Adv. Intell. Syst., vol. 5, no. 5, p. 2200329, May 2023.
[6] H. Wang, M. Totaro, and L. Beccai, “Toward perceptive soft robots,” Adv. Sci., vol. 5, no. 9, p. 1800541, Sept. 2018.
[7] K. Singh, A. Khosla, and S. Gupta, “Perspective – five sensor-centric grand challenges in soft robotics,” ECS Sensors Plus, vol. 2, p. 046601, Nov. 2023.
[8] T. G. Thuruthel, B. Shih, C. Laschi, and M. T. Tolley, “Soft robot perception using embedded soft sensors and recurrent neural networks,” Sci. Robot., vol. 4, pp. 1488, January 2019.
[9] G. J. Monkman, “Soft Robotics,” Singapore, Bentham Science Publisher, Apr. 2022.
[10] D. A. Paley and N. M. Wereley, “Bioinspired sensing, actuation, and control in underwater soft robotic systems,” Springer Nature, Nov. 2021.
[11] A. Jafari and N. Ebrahimi, ed. “Soft Robotics in Rehabilitation,” London: Academic Press, Mar. 2021.
[12] F. Tauber, M. Desmulliez, O. Piccin, and A. A. Stokes, “Perspective for soft robotics: the field’s past and future,” Bioinspir. Biomim. vol. 18, no. 3, p. 035001, Mar. 2023.
[13] C. Hegde, J. Su, J. M. R. Tan, K. He, X. Chen, and S. Magdassi, “Sensing in soft robotics,” ACS Nano, vol. 17, no. 16, 15277-15307, Aug. 2023.
[14] S. Wang, Z. Sun, Y. Zhao and L. Zuo, “A highly stretchable hydrogel sensor for soft robot multi-modal perception,” Sensors Actuators A, vol. 331, p. 113006, Nov. 2021.
[15] A. Pagoli, F. Chapelle, J.-A. Corrales-Ramon, Y. Mezouar, and Y. Lapusta, “Large-area and low-cost force/tactile capacitive sensor for soft robotic applications,” vol. 22, no. 11, p. 4083, May 2022.
[16] S. Joshi and J. Paik, “Sensorless force and displacement estimation in soft actuators,” Soft Matter, vol. 19, pp. 2554-2563, Mar. 2023.
[17] T. G. Thuruthel, P. Gardner, and F. Iida, “Closing the control loop with time-variant embedded soft sensors and recurrent neural networks,” Soft Robotics, vol. 9, no. 6, pp. 1167-1175, Dec. 2022.
[18] R. K. Gupta, “Flexible and Wearable Sensors: Materials, Technologies, and Challenges,” Boca Raton: CRC Press, 2023.
[19] K. Sakuma, “Flexible, Wearable, and Stretchable Electronics,” Boca Raton: CRC Press, May 2022.
[20] G. Shen and Y. Li, eds. “Flexible Sensors: Materials, Devices and Applications,” Singapore, World Scientific Publishing, Dec. 2024.
[21] R. A. S. I. Subad, M. M. H. Saikot, and K. Park, “Soft multi-directional force sensor for underwater robotic application,” Sensors, vol. 22, no. 10, p. 3850, May 2022.
[22] T. Torkaman, M. Roshanfar, J. Dargahi, and A. Hooshiar, “Embedded six-DoF force-torque sensor for soft robots with learning-based calibration,” IEEE Sensors J., vol. 23, no. 4, pp. 4204-4215, Feb. 2023.
[23] The data in Figure 4 come from the information from the manufacturer and the test in this study.
[24] L. Lindenroth, D. Stoyanov, K. Rhode, and H. Liu, “Toward intrinsic force sensing and control in parallel soft robots,” IEEE/ASME Trans. Mechatronics, vol. 28, no. 1, Feb. 2023.
[25] S. Sugiura, D. Hatdman, T. G. Thuruthel, Y. Hasegawa, and F. Iida, “Closed-loop optimization of soft sensor morphology using 3D printing of electrically conductive hydrogel,” Adv. Intell. Syst., vol. 5, no. 10, Oct. 2023.
[26] D. Hardman, T. G. Thuruthel, A. Georgopoulou, F. Clemens, and F. Iida, “3D printable soft sensory fiber networks for robust and complex tactile sensing,” Micromachines, vol. 13, no. 9, pp. 1540, Sept. 2022.