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Successful development of a material-based reservoir computing device and its application to robotics

— Recognizing products that AI robots grasped —

KYUTECH, Japan – A research group led by Prof. Hirofumi Tanaka and Prof. Hakaru Tamukoh at the Research Center for Neuromorphic AI Hardware, Kyushu Institute of Technology (Director: Hirofumi Tanaka), in collaboration with former Prof. Takuji Ogawa at Osaka University and Prof. Gimzewski at the University of California, Los Angeles (UCLA) has applied a random network of single-walled carbon nanotube[*1] (SWNT)/porphyrin[*2] (Por)-polyoxometalate[*3] (POM) composite as a reservoir computation[*4] (RC) device, a kind of artificial intelligence device. They have succeeded in classifying the grasping object by using the tactile signals from the hand part of the robot arm (Fig. 1). This is one of the world's first examples of robot control using an "in-materio"[*5] reservoir device, which allows nanomaterials to carry out a computation, and is expected to be used in the future for energy-saving AI systems and situational awareness functions for autonomous robots working in the home. The results of this research were published online in the German scientific journal "Advanced Intelligent Systems" on 4/Jan/2022 (Germany standard time) DOI: 10.1002/aisy.202100145.

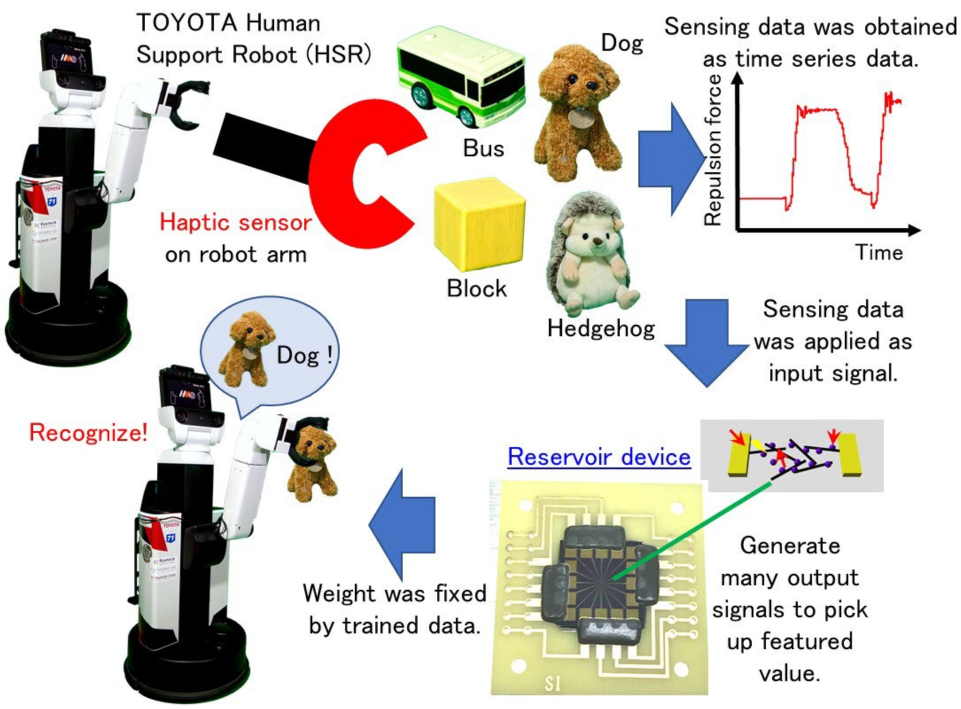

Figure 1: In-materio Reservoir Device with SWNT/Por-POM Random Network Recognition of Object Grasped by Robot Arm

Research Points

- Success in developing a material-based physical (in-materio) reservoir arithmetic element.

- The first application of in-materio reservoir computation to the recognition of grasping objects.

- The developed reservoir computing device is expected to be applied to complex AI problems such as time series prediction and voice recognition in the near future.

Research Background

To artificially mimic the human brain, it is necessary to mimic the dynamic reservoir of randomly connected neurons and synapses, which has been achieved with the advent of artificial neural networks (ANNs). Furthermore, RC, a type of ANN, enables learning of time series data by faithfully reproducing the random feedback of signals in the reservoir, and as a result, RC is an efficient, fast, simple, and biologically more suitable for mimicking machine learning architecture, making it a candidate for future AI systems.

Almost all RC research has been performed on software. However, the realization of RC systems using only software is difficult in the future in terms of power consumption due to the downsizing of transistors being limited to increasing of performance according to "Moore's law," and a paradigm shift to hardware is essential. Therefore, research on physical reservoirs, which use physical behavior as a computational tool in parallel with software, is currently attracting attention, and research on physical reservoirs using the behavior of octopus legs, optical systems, and magnetic spins has been progressing gradually.

Among them, it is a very new attempt that material itself carries out the computation in physical reservoir like our present research. In the field of materials science, nanomaterials, in particular, have become a promising choice for building reservoir structures due to their strong nonlinear conduction[*6] and have been applied to many studies to solve time series prediction such as speech classification tasks.

Research Contents

It is the first to show the potential of materials engineering-based RC applications for classifying the robot-arm grasping object. By using the sensing data of the object grasped by Toyota's Human Support Robot (HSR) hand as an input signal, we successfully performed an in-materio RC task that correctly classified different grasping objects.

We reported experimental results of neuron-like spike generation using SWNT and POM composites in Nature Communications in 2018. Our investigation of RC in this system was limited to theoretical predictions at the same time (H. Tanaka et al., Nat. Commun. 9, 2693 (2018). DOI: 10.1038/s41467-018-04886-2).

In this study, we first attempted to prove the theoretical prediction experimentally. SWNTs with a one-dimensional structure can be dispersed in solution, and a thin film of a random recursive network can be easily formed on filter paper during filtration, which can be transferred to any substrate in a large area by simply dissolving the filter paper in solvent vapor. This ease of fabrication can be structurally reproduced in the reservoir. In this structure, when a stimulus is received at any point of the reservoir, it is possible to create a parallel signal (information) flow throughout the network, just like the brain.

In order to enhance the nonlinearity of the reservoir, we chose Por-POM molecules, which are particles of about 1 nanometer in diameter consisting of transition metal ions linked by oxygen atoms, and can store multiple charges. The charge capacity of POM changes significantly upon bias application in the presence of donor molecules such as porphyrins, which causes a non-ohmic response having negative differential resistance[*7] (NDR). Due to the similar benzene ring structure of SWNTs and porphyrins, Por-POM molecules can be physically adsorbed onto SWNT surfaces by simple sonication, and SWNT/ Por-POM composites can be easily fabricated. Por-POM composites can be easily prepared.

In order to fundamentally understand the RC properties, RC devices were constructed using SWNT/Por-POM random structures placed between equally spaced multi-electrodes (Fig. 2). The output current response from each electrode was investigated by electrochemical impedance spectroscopy[*8] (EIS), which revealed the presence of resistive - capacitive SNWT/Por-POM junctions of different sizes, resulting in a non-uniform network distribution similar to that of the brain. The number of neurons and the density of connections in the brain are very heterogeneous, which is useful for data processing. Since the information in the brain is generally encoded as electrical signals resulting from electrochemical ion transfer between neurons, when an external stimulus propagates through such a branched network, random ion transfer takes place at the junctions of different neurons. This allows the input information to be output as time-series signals recorded at different spatial points, maximizing information processing and efficient learning.

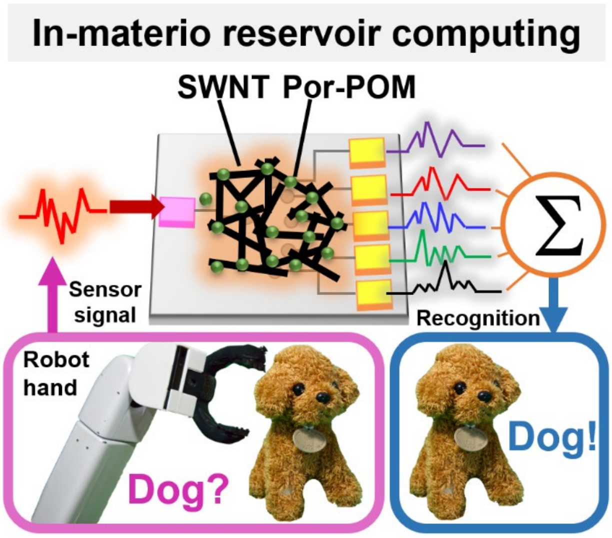

Fig.2 Procedure of grasping product recognition by robot hand using RC device [Fig.2 is from Adv. Intell. Sys.]

We first used SWNT/Por-POM as the RC device and performed a simple RC task of waveform generation with a maximum accuracy of 90%. In addition to this, a more complex task of grasping object recognition was also performed. In both the cases, the system was configured in two stages: the first stage consisted of an In-materio SWNT/Por-POM reservoir with multiple dynamic outputs being processed, and the second stage was used for software training. The input signal for object classification was a time series of tactile signals obtained by the Toyota HSR grasping different toys, and each input signal was transformed into a different time series signal with a high feature value at each electrode for learning. As a result of the trial, the device was able to classify all objects, regardless of surface hardness, with almost the same accuracy as the software RC.

Integrating AI into robots is very important in the future, especially in terms of caring for the elderly and disabled. Object recognition by camera images is commonly used, but misclassification occurs in low-light environments. Therefore, a tactile sensor is strongly recommended for object grasping tasks. For this purpose, our results show that material-based RC is a wise choice, as it can achieve efficient computation with a biological interface. With the success of the In-materio RC device, we were able to show the potential for further development of AI systems.

Future prospect

A research team led by the Kyushu Institute of Technology has fabricated an SWNT/Por-POM network device for RC applications. A random network of SWNTs and Por-POM was formed on an aluminum electrode pattern, and electrical measurements were performed that showed characteristic nonlinear dynamics originating from the inherent electronic charging and discharging properties of Por-POM. The SWNT/Por-POM is expected to have the same information processing capability as the brain in the near future and can be applied to other complex AI problems such as time series prediction and speech recognition.

[*1] Single-walled carbon nanotubes (SWNTs): Carbon nanotubes are nanometer-sized cylindrical (tube-like) materials composed entirely of carbon, which have a cylindrical structure made up of sheets of benzene rings (=graphene), which are hexagonally arranged carbon atoms laid out on a flat surface. A single layer of this cylinder is an SWNT.

[*2] Porphyrin: A general term for a macrocyclic planar compound consisting of four five-membered rings (pyrroles) containing one nitrogen atom bonded alternately to four carbon atoms, which exists as the basic skeleton of extremely important natural pigments such as heme and chlorophyll in substances that take on colors such as vegetables, fruits, and meat (blood).

[*3] Polyoxometalates (POMs): Anionic species formed by condensation of oxoacids, common in early transition metal elements other than Group 3. Polyacids composed of metal elements can be regarded as molecular ionic species of metal oxides. The chemical formula is $[M_xO_y]^{n-}$, which is also called metal oxoacid.

[*4] Recurrent neural network, Reservoir computation: A type of artificial neural network (ANN) that has become the mainstream of current AI systems, a system that allows signal feedback at each level is called a recurrent NN (RNN). Figure 3a shows the typical structure of RNNs, and Figure 3b shows the typical structure of RC. The advantage of RC over RNNs is that the computation of the joint weights in each unit of the intermediate layer (Fig. 3(a)) is not required on the computer, thus reducing the power consumption. Recently, Tanaka et al. have fabricated electrical circuits with random nets using Ag/Ag2S core-shell nanoparticle random networks [1] and conductive polymer networks [2] and successfully generated arbitrary waveforms by reservoir operations by applying multiple electrodes, which can be used as RNNs. We have applied for a patent, including the SWNT/POM peripheral technology [3].

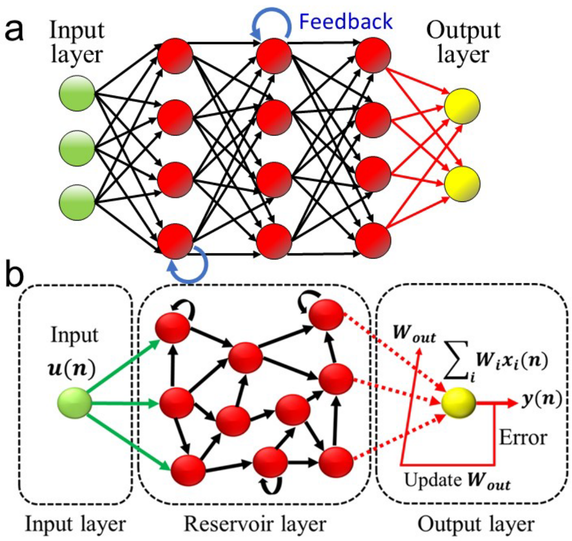

Fig. 3a. Schematic of ANN. An RNN allows the feedback of information (blue circle arrow) at the nodes (red circles). The sum of products for all incoming signals are calculated at all nodes, which is similar to output layer in b. b. Schematic of reservoir network. Calculations in the middle layer are not required when treated as a black box. Learning is conducted only at the output layer.

[1] H. Tanaka et al., Jpn. J. Appl. Phys. (2021). [2]Y. Usami, H. Tanaka et al., Adv. Mater. Published online. (2021).

DOI:10.1002/adma.202102688. [3]Tanaka et al., Special Application 2020-174660, Three-Dimensional Electrical Devices.

[*5] In-materio: It means "in the matter." It is used here in the sense that the material itself takes over the computation instead of the computer software or electric-circuit hardware consisting of the electric circuit.

[*6] Nonlinear conduction: A conduction phenomenon in which the electrical conductivity varies with the applied electric field intensity. One of the causes is the formation of a hot electronic state in which the temperature of the carrier rises compared to the lattice temperature. In this case, nonlinear conduction is caused by the change in relaxation time due to the increase in the average velocity of the carriers and the change in the concentration ratio of the carriers distributed in each valley in Si and GaAs, which have a multi-valley electronic structure. When extreme negative resistance occurs, the oscillation phenomenon also occurs.

[*7] Negative differential resistance: A characteristic of certain types of electric circuits and elements in which the current flowing through them decreases as the voltage applied between the terminals increases. This behavior is in contrast to that of an ordinary resistor, where the current increases proportionally with the applied voltage according to Ohm's law, and the resistance value becomes positive. Positive resistors consume power when current flows through them, while negative resistors can increase the power of an electrical signal under certain conditions and perform the function of amplification.

[*8] Electrochemical impedance spectroscopy (EIS): A potential (current) signal is input to an electrode, and the response current (potential) is analyzed. By comparing the sinusoidal input signal and its response, the frequency dependence of the impedance (or admittance) in the material is determined. The measurement of the frequency dependence of impedance is used to identify the equivalent circuit in a material.

Detail information about the paper

Title: Emergence of In-Materio Intelligence from an Incidental Structure of a Single-Walled Carbon Nanotube–Porphyrin Polyoxometalate Random Network

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About Kyushu Institute of Technology

Kyushu Institute of Technology (Kyutech) is a Japanese national university that was originally founded in 1907 and opened in 1909 as a private institution called the Meiji College of Technology. Throughout more than 110 years of its history, Kyutech has been contributing to industrial development in Japan through research and education in engineering fields. Currently, Kyutech aims to foster inter-disciplinary and innovative research with its 11 research centers and two research units in various research fields such as space, environment, energy, AI, IoT, data science, LSI, robotics, biology. Kyutech also promotes international research collaborations with overseas universities for establishing an international industry-academic alliance which brings Kyutech a diverse research environment in its laboratories. In such a diverse and inter-disciplinary environment, Kyutech has been recognized as the academic institution that launched the largest number of small satellites in the world since 2012 and still holds the top position until 2021. Also, such an environment enables Kyutech to contribute to engineering education nationally and globally. In 2017, the BIRDS satellite project, in which students from developing countries build and operate their countries' first satellites, was awarded GEDC Airbus Diversity Award as the best example of bringing diversity to engineering education. Furthermore, one of the student project teams supported by Kyutech for its hands-on education won 1st place in World Robot Summit (WRS) 2 years in series for the service robotics category. For the future, Kyutech will continue contributing to local and global society through its technology, knowledge, and education.
Website: https://www.kyutech.ac.jp/english/

Prof. Tanaka, Director of Research Center for Neuromorphic AI Hardware (Neumorph Center), Kyushu Institute of Technology (Kyutech), JAPAN.

Prof. Tanaka's comment: Neumorph Center at Kyutech is a research center where researchers from a wide range of fields, including four research divisions, materials, electrical and electronic circuits, numerical modeling, and AI robotics, working together to develop next-generation AI systems. In order to reduce the power consumption of present AI systems, it is necessary for a paradigm-shift of software to hardware, and also to shift from digital drive to analog drive since there is a limit to the power consumption reduction of hardware. In this process, AI device fabrication based on materials engineering plays an important role. We are focusing on the fact that the chemical reactions and dynamic properties of materials themselves can be used for AI processing, and are developing AI devices that work with completely new materials and principles. Neuromorphic AI hardware research is a budding field, and the Neumorph Center is the first research organization in Japan in this field. With the success of the application of the In-materio reservoir device to AI robotics, we will continue to work vigorously to spread this field, which has a small population of researchers all over the world.

website: https://www.brain.kyutech.ac.jp/~neuro/?lang=en