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Robotic Measurement for Electrical Property of Polymers by Force-Sensing Robot toward Materials Lab-Automation

Yuki Asano[1], Kei Okada[2] and Junichiro Shiomi[1]

***Abstract*— With the background of research on materials laboratory automation, this study aims to construct an automation system for measuring dielectric property, which is an electrical property of materials. The automation system is composed of the combination of a manipulation by a force-sensing robot and a control system for the measurement instrument. As challenges for the automation system, we worked on stabilizing a polymer film placement during insertion into the measurement instrument, implementing a communication control system between different platforms, and constructing a polymer film transfer environment. In the measurement experiment using the automation system, it was confirmed that the dielectric properties could be measured as well as that of a human.**

I. INTRODUCTION

Lab-automation and data-driven development through the collaboration of robots and machine learning is accelerating autonomous execution of scientific experiments in the fields of materials, biology, and chemistry [1][2][3][4][5][6][7][8].

We have been working on the automation of polymer material development. We also have developed the automation of polymer pressing process [9] and the implementation of a lab-automation system for enabling closed loop of an experiment [10]. In order to complete the whole processes of the development, it is important to automate not only the pressing process but also the characterization process measuring physical properties of the material as a benchmark.

To achieve this, automation of the characterization process is necessary through automation of measurement instruments. Several automated instruments that are equipped with the function of automated measurement after manual specimen placement by mechatronics mechanism inside its body have been developed [11][12][13]. Another type of automation has conducted using LabVIEW that is an integrated software to manage multiple instruments, experimental process flow and data [14]. On the other hand, there are few examples automating the whole process of measurement including the specimen handling to the property measurement that requires integration of robotic manipulation and instrument control.

In this paper, we describe the development of a robotic measurement system for dielectric properties, which integrates specimen handing and measurement (Fig. 1). Dielectric property we focused on this paper is one of the important electrical properties for the development of next-generation devices for information processing in the information society.

This paper is organized as follows: In Section I, the motivation and the target of this study were stated. Dielectrometer instrument used in this study and the detail of its automation system are described in Section II and Section III respectively. Evaluation experiments of robotic measurement for electrical property is described in Section IV. Finally, in Section V, the conclusion and future works are stated.

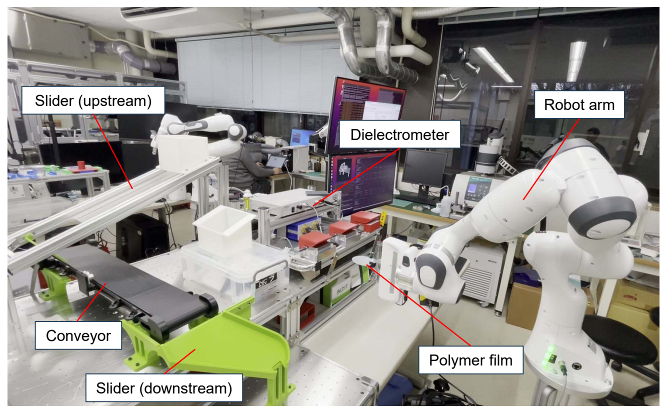


Fig. 1. Robotic measurement system of dielectrometer instrument

II. ELECTRICAL PROPERTY MEASUREMENT IN MATERIALS LAB-AUTOMATION

A. Dielectric property in materials development

In this study, we focus on dielectric property as one of the electrical properties. Dielectric constant is a physical quantity related to how a molecule responds when an external electric field is applied to a material. It is considered important in mobiles or data processing devices used with high-frequency bands such as 5G, which have been developed in recent years. The development of materials, the dielectric dissipation, which is related to the heat loss when an electric field is applied, and the relative dielectric constant, which is the ratio between those of a material and the air, are used as benchmarks. (Hereafter, the relative dielectric constant is described as the dielectric constant.)

B. Dielectrometer

1) Measurement instrument: The dielectric measurement system used in this study (TE mode Cavity Resonator, AET Inc.) is shown in Fig. 2. It has three measurement instruments with different frequencies (10, 28, and 40 GHz). Each instrument has a gap of about 0.3 mm, and the dielectric

[1] Yuki Asano and Junichiro Shiomi are with Graduate School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-8656, Japan. yasano@g.ecc.u-tokyo.ac.jp, shiomi@photon.t.u-tokyo.ac.jp
[2] Kei Okada is with Graduate School of Information Science and Technology, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-8656, Japan. k-okada@jsk.t.u-tokyo.ac.jp

constant and dissipation factor can be measured by inserting a film-shaped specimen of polymers into the gap.

2) Measurement software: Normally, the measurement is performed by a person who sets the polymer film on the instrument and then operates the dedicated software GUI on the Windows PC (Bottom of Fig. 2). In addition, this measurement system has API control commands that can execute measurement by the commands from an external computer.

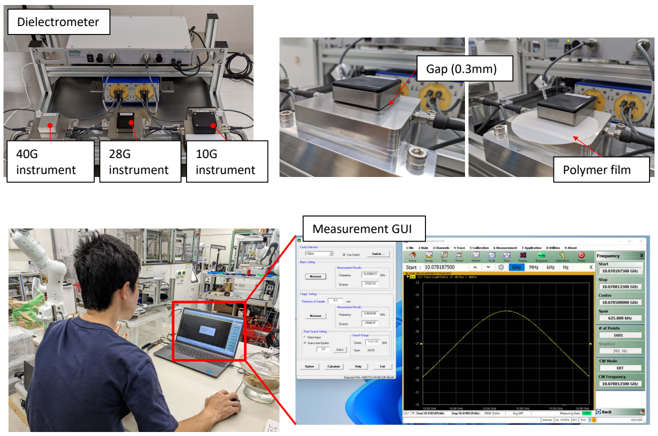


Fig. 2. Dielectrometer used in this study

3) Measurement specimen: A polymer molded in film form is used as the specimen for the measurement (hereafter, term sample means film specimen). The thickness of the film should be less than 0.3 mm under the measurement restrictions of the instrument. The polymer film is made by heating and pressing the granular polymer material in a press machine, and then forming it into a film (Fig. 3). The films formed in this way are used in measurement processes for various physical properties, such as the dielectric constant measurement in this study.

Fig. 3. Producing process of film specimen of polymers by heat pressing

C. Challenges and approaches for robotic measurement system

The challenges in implementing an automation system for dielectric constant measurement and the approach taken in this study are summarized as follows.

1) Stabilization of the polymer insertion placement
In this measurement, the polymer film must be placed in the narrow instrument gap. In addition, the polymer film must cover the measurement area of the instrument correctly. As shown in Fig. 4, it is important to stabilize the measurement point of the polymer because the measured property varies depending on the measurement point. Thus, it is important to stabilize the insertion for each direction of the instrument to obtain precise measurement values (Fig. 5). Humans usually ensure delicate sample placement using their eyes and tactile sensing. In this study, contact detection using the robot's force sensing and the fabrication of an insertion aid cover to be set on the main body of the instrument were conducted.
2) System integration of measurement and robot control software
It was necessary to construct an integrated system of the measurement system regularly used in the materials development field and the control system regularly used in the robotics field. In this study, we implemented an integrated system that does not depend on different OS platforms by implementing a communication system using Web sockets on ROS middleware that supports multiple platforms.
3) Integration with polymer film transport
Since film-type specimen is used in this measurement, it was necessary to construct a film transport system. In this study, a conveyor-based transfer system was constructed. In addition, an automation system for a series of dielectric constant measurements was built by integrating the transport system with the communication and instrument control system described above. In constructing the system, we were conscious of the connection with the previous press process. We also considered the scalability to a large-scale system that automates and connects multiple processes of material development.

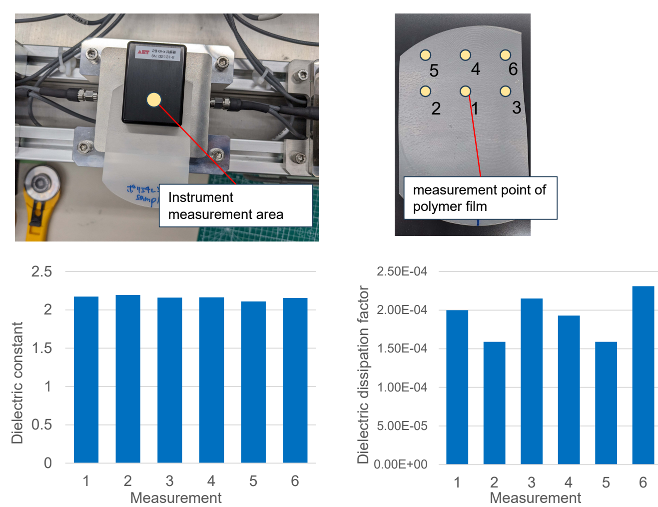
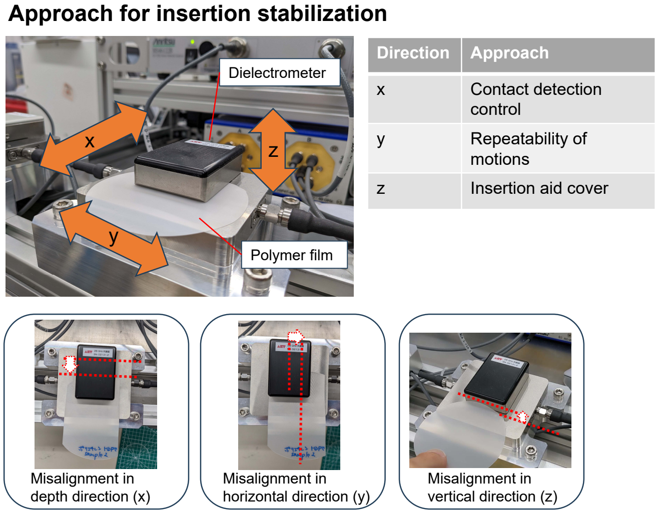


Fig. 4. Difference of dielectric properties by different measurement points. Dielectric constant differs less but dissipation factor differs larger.



Direction	Approach
x	Contact detection control
y	Repeatability of motions
z	Insertion aid cover

Fig. 5. Approach for insertion stabilization of polymer film. Contact detection for x-direction is effective to adapt different film sizes depending on the polymer pressing in the previous process. Insertion cover for z-direction is effective to guide uncertain position of the film edge due to the flexibility of the film

III. Automation System of Dielectric Property Measurement

A. Robot arm

A force-sensing robot arm is used as a manipulator to grasp the polymer film and set it on the instrument. Franka Research 3 (FR3, Franka Emika Inc.), an articulated cooperative robot arm with 7 degrees of freedom, was used as the robot arm (Fig. 6). FR3 is a robot arm with built-in torque sensors in all axes of the joints. Under static conditions, the reaction force acting on its end-effector can be obtained from each joint torque by using the basic Jacobian equation. This external force is used for contact detection to stabilize polymer insertion and placement.

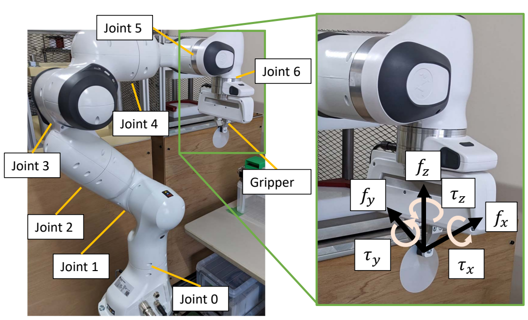


Fig. 6. Collaborative robot arm FR3.

B. Insertion stabilization in vertical direction by insertion aid cover

To assist the robot in inserting the film, an insertion aid cover which has the angled opening was fabricated and attached to the instrument (Fig. 7). Although the vertical gap of the instrument is only about 0.3mm, this cover allows for vertical misalignment and smooth insertion of the film.

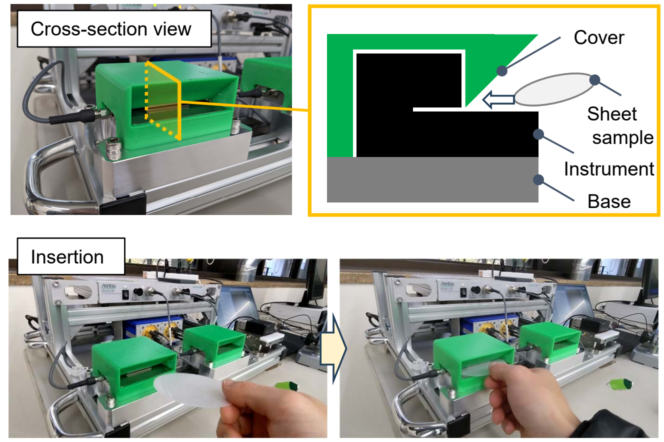


Fig. 7. Insertion stabilization by the insertion aid cover

C. Insertion stabilization in depth direction by contact detection

1) Concept and control flow: The control flow of contact detection is shown in Fig. 8. After the start of the insertion motion, we implemented a motion control that monitors the force in any direction and stops the motion judged as contact if the force exceeds the threshold value. Force-sensing values are published via ROS msgs and the robot control node subscribes them with a certain period.

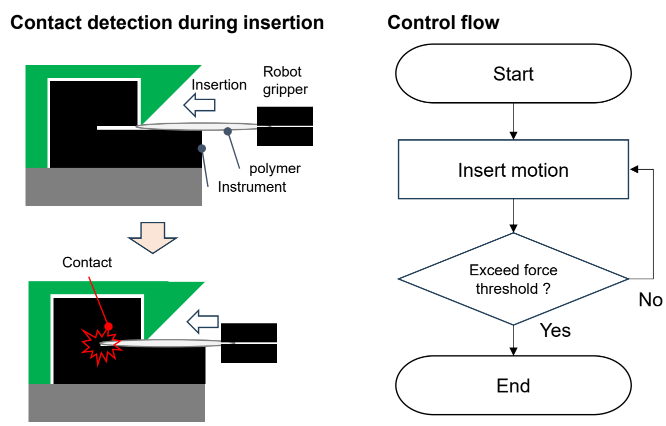


Fig. 8. Concept and control flow of contact detection

2) Force threshold of contact detection: During polymer insertion by the robot, the tip force data of the robot arm shows the trend shown in Fig. 9. Force value changes except in the period of contacting were observed due to the force-sensing mechanism of FR3, which calculates the tip force from the torque sensors of all axes. Based on this point, the robot motion after grasping the polymer could be classified into the approaching motion, the insertion motion, and the leave motion from the instrument. During the insertion motion, a sudden increase in force due to contact was observed around 27[s], which indicated contact between the polymer film and the instrument. Here, we experimentally set the force threshold to be 5[N], which was the value that was not exceeded during the approach and leave motions but was reached during the insertion motion. The polymer was HDPE in this study. Values are likely to be differed when other polymers or film shapes are used.

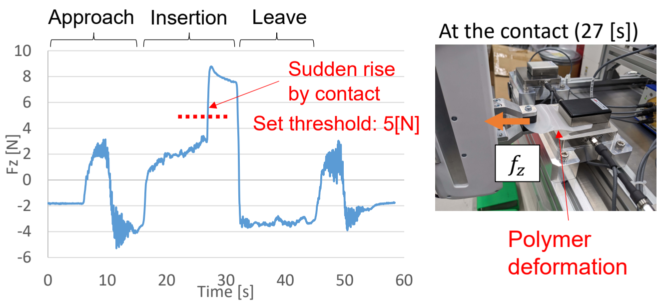


Fig. 9. Fingertip force during polymer film insertion.

3) Verification of contact detection: Fig. 10 shows the verification experiment of contact detection. In the case of no contact detection, the magnified image shows that there is a gap between the edge of the polymer and the instrument, and the force data shows no sudden rise, which confirms that no contact is detected. On the other hand, in the case with contact detection, the enlarged image shows the close proximity of the polymer edge and the instrument, and the force data shows a rapid increase, which confirms that the polymer and the instrument are in contact with each other inside the hidden area. In both cases, the arm positions in the z-axis were determined with the fixed value and the film edges were guided by a human to guide successful insertions.

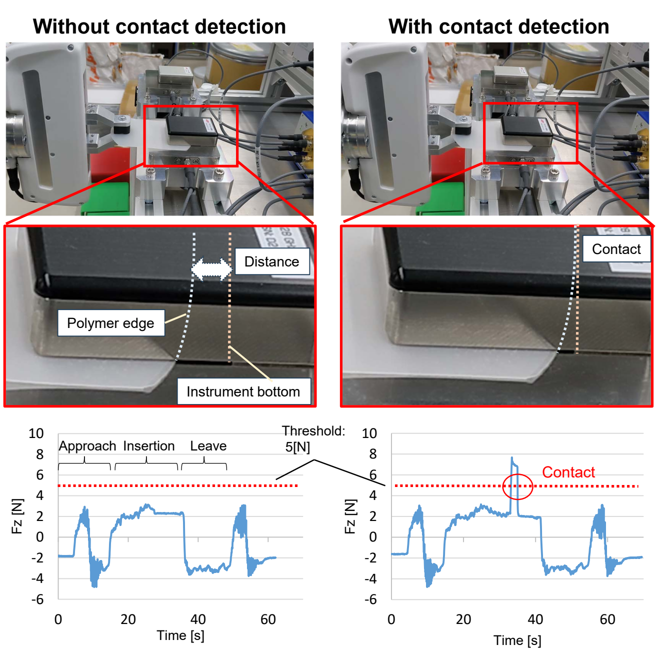


Fig. 10. Comparison of polymer film insertion with and without contact detection

D. Polymer transport by conveyor

Assuming that the polymer film produced in the previous pressing process is transferred to the robot arm, we constructed an automatic polymer transfer environment using sliders and a conveyor. Fig. 11 shows the concept and appearance. The polymer film fed into the inlet is transferred in that order, the upstream slider, conveyor, and downstream slider. After the downstream slider, a robot arm grasps the polymer located at the specified position, and then measures dielectric property with the instruments.

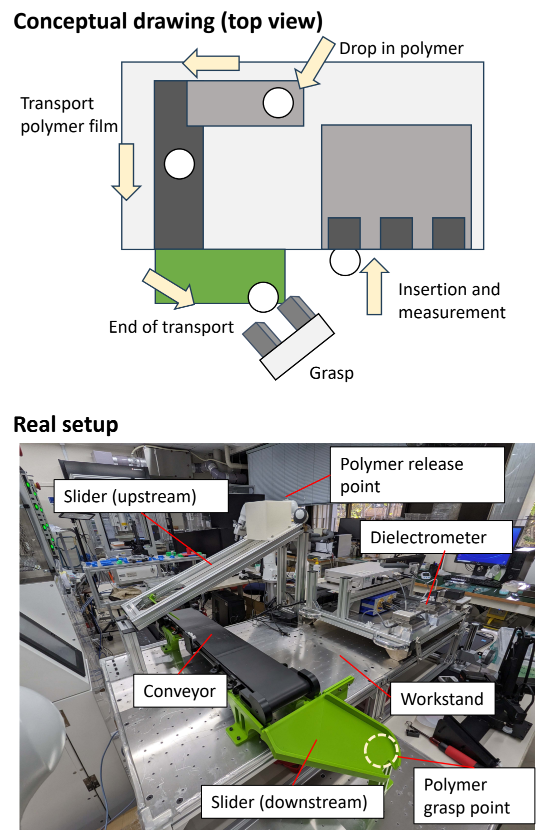


Fig. 11. Automated transport environment for polymer film

E. System configuration

A communication system between the robot control PC (Ubuntu) and the instrument control PC (Windows) was implemented using web sockets on ROS which was a multi-platform middleware to realize sequential control even between different OSes (Fig. 12).

The conveyor system was also implemented on ROS, so that it could be started and stopped by control signals using ROS topic. Implementation of the experiment manager program enables to control each process and to manage the progress status.

IV. Robotic Measurement and Evaluation of Dielectric Property

A. Robotic measurement

Robotic measurement of dielectric property is shown in Fig. 13. In the motion flow, the robot arm first grasps a polymer film specimen. Next, the specimen is manipulated and inserted into the instrument, and the movement is stopped by contact detection. Finally, the measurement command is sent to perform the dielectric constant measurement.

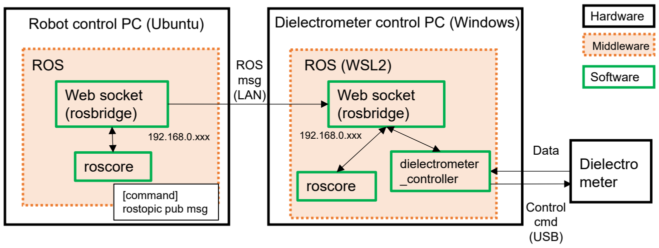


Fig. 12. System configuration of robotic dielectric property measurement

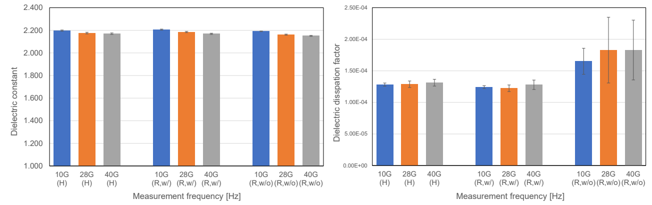


Fig. 14. Measurement result of dielectric constant (left) and dissipation factor (right) by the robot and a human. Human, robot with contact detection, and robot without contact detection were conducted.

Three press-formed polyethylene films were used as measurement specimens (Fig. 13). The measurement was performed three times for one instrument (27 times in total for 10, 28, and 40G instruments). The mean and standard deviation were calculated.

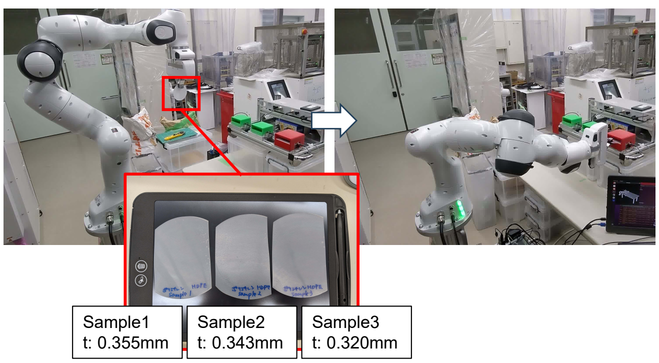


Fig. 13. Robotic measurement of dielectric property and polyethylene samples

B. Evaluation of robotic measurement

1) Comparison of measurement value: As an evaluation of robot measurements, we compared the results of measurements by the robot and a human. The left of Fig. 14 shows the results of the dielectric constant measurement. The right of Fig. 14 shows the results of the comparison of the dielectric dissipation factor. As a result of the comparison, it could be confirmed that the dielectric constant was about 2.2 for both the human and the robot, and that the standard deviation was low. The dissipation factor was about 1.2-1.3 with low standard deviation in human and robot measurement with contact detection. On the other hand, values were in different trend and deviation was large in the robot measurement without contact detection. The reason of this was considered that the sample position in the measurement was not stable in the experiment and the fact that dissipation factor was a delicate measurement value which was easily influenced by the measurement position of the sample (see Fig. 4). From the above, it was confirmed that contact detection was effective and the mean and standard deviation of the measured values by the robot are comparable to those by humans.

2) Comparison of measurement time: Fig. 15 shows the comparison of measurement time. The robot measurement time was 2100 [s] compared to 2031 [s] for the human measurement. The robot measurement took more time due to the aspect that the robot moved at low speed during contact detection control. However, there is potential for speeding up the robot measurement by tuning the manipulation speed and optimizing motion path.

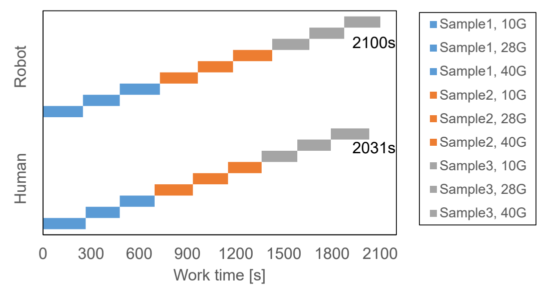


Fig. 15. Measurement time by the robot and a human.

C. Integrated measurement experiment

We conducted an integrated dielectric measurement experiment by linking a series of developed elements. Fig. 16 shows the experiment and Fig. 17 shows the measurement results. In the experiment, the polymer film was dropped to the upstream slider by a human at the beginning of the experiment, and the command to start the robot operation was sent by a human. As a result, it could be confirmed that the robot could perform the measurement in this integrated automation.

In the future, it is appropriate to evaluate the results of multiple numbers of measurements, as in the comparison experiment described in the previous section. In addition, for more advanced automation, it is important to automatically feed the polymer film by connecting and integrating with the previous press process. It is also necessary to control robot operation by detecting the end of conveyor transfer and to implement an experimental condition management system for these processes.

V. CONCLUSIONS

This paper describes the implementation of an automatic measurement system using a robotic arm for dielectric constant measurement in the laboratory automation of polymer material development. In order to automate the dielectric property measurement by the robot, it is important to stabilize the insertion of the polymer into the instrument. Contact detection by force sensing and fabrication of a cover to

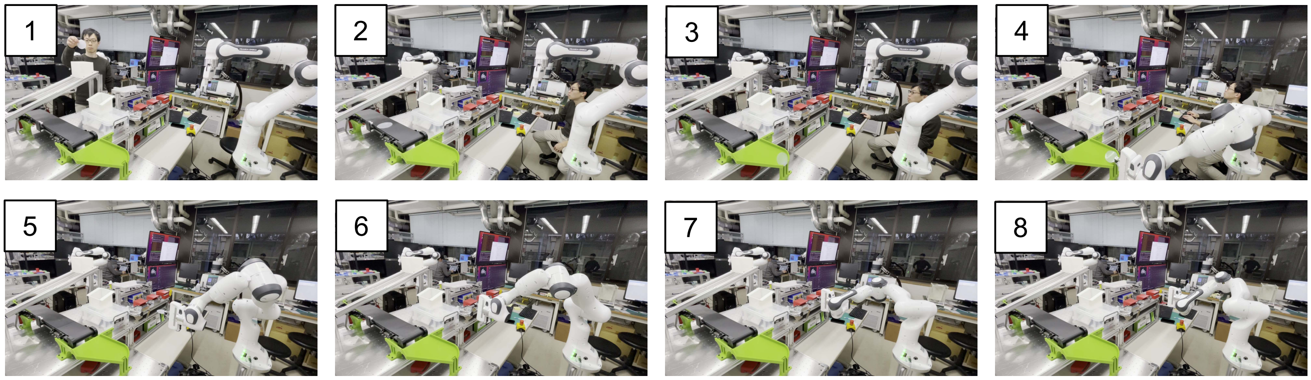


Fig. 16. Integrated measurement experiment

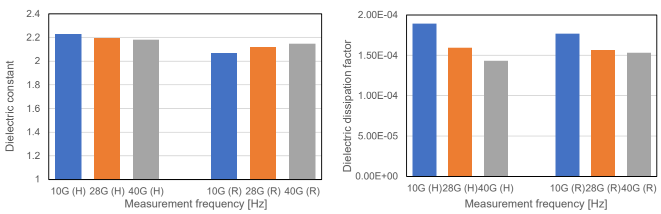


Fig. 17. Measurement results of the integrated measurement experiment. Left: dielectric constant, right: dielectric dissipation factor

assist insertion were carried out. In addition, to integrate the measurement software and robot control software, a multi-platform communication control system was implemented. Seamless execution of the two software realized a series of dielectric measurement processes. Moreover, a conveyor system was constructed for transporting the polymer film to the robot. This enabled smooth connection between the measurement and the press processes. In the comparison experiment, it was confirmed that the measurement results by the robot were comparable to those obtained by human. Furthermore, we confirmed that a series of measurement processes work through an integration experiment in which the development elements were integrated.

In the future, we will work on solving problems for the replacement of the dielectric constant measurement process by robots in actual laboratory experiments. In terms of efficiency and speed, it is important to improve the automatic measurement system by faster manipulation. In addition, we aim to realize laboratory automation for material development consisting of multiple processes and to develop innovative materials by connecting with the press molding process, which is the process before the measurement, and by constructing a closed loop to optimize the material parameters by feedback of the measured physical properties.

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