Skillful Manipulation of Electronic Musical-Note-Type Instrument Using Industrial Humanoid Robot

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***Abstract*—Industrial robots contribute significantly to productivity improvements, quality improvements, and cost reductions at production sites. Among the industrial robots, those that can cooperate with humans without safety measures or output limitations on the motors of their axes are known as cooperative robots. In the manufacturing field, there is a growing demand for production lines where humans and robots can coexist and cooperate instead of those where robots perform all processes on their own. In this study, we focus on a cooperative robot fabricated using a 3D resin printer and aim to improve its operation using the same tools as humans. As an example of such an application, we attempt to develop a sound-feedback-based motion for manipulating an electronic musical instrument called an "otamatone". First, the hardware for grasping the object is created using a 3D printer, and notes on the modeling process are described. We then construct an advanced sound feedback system using the Robot Operating System (ROS) to identify the sounding position and pitch of the instrument. In this study, we propose a partial model-matching method for determining the Proportional–Integral–Derivative (PID) gains of the servomotors of each joint of a robot. Consequently, the accuracy of the robot's motion improves and the accuracy of the intended musical performance is enhanced.**

***Keywords*—robotics, control engineering, 3D printer, sound feedback**

I. Introduction

In recent years, active efforts have been made to solve productivity and working population declines in the service sector because of robotics, which has been exemplified by new robot strategies. In particular, production lines in which humans and robots coexist and cooperate are being seriously considered. Robots that work together with humans with high precision are called cooperative robots, and can be installed without safety fences [1]. In this study, we focus on cooperative robots fabricated by a 3D resin printer and use them to pioneer a technique for playing a new note-type electronic musical instrument called an "otamatone", aiming for advanced robotic motion for using the same tools as humans [2]. In this study, we used a Robot Operating System (ROS), which is expected to be open-source software for next-generation robotic development. ROS are characterized by their ability to communicate with and control multiple PCs and robots [3]. The advantages are that the robot can be moved remotely and distributed processing can be performed to ease the computational burden on each PC. In a previous study, a camera was used to track the position of an object, and the position information was communicated to the robot arm using the ROS for feedback. In this study [4], we developed a control work frame in which audio data obtained from a musical instrument are analyzed in frequency and fed back to the robot control using ROS. In general, Proportion Integration Differentiation (PID) gain determination methods for controllers can be classified into experimental and model-based approaches. Experimental approaches include the Ziegler-Nichols marginal sensitivity method and step response method [5, 6]. However, these experimental approaches are considered undesirable because they require the induction of limited oscillations that may damage the robot. Gain scheduling has also been proposed as a model-based method for the PID gain determination [7]. However, the purpose of this study was to evaluate the PID gains obtained from the robot's performance on a piece of music, which requires both responsiveness and positional accuracy, making the evaluation of PID gains difficult. Furthermore, PID gain scheduling using reinforcement learning has been proposed [8, 9]. However, because the robot used had seven axes and the time to be evaluated was approximately 25 s, the time required for reinforcement learning was significant and may not be practical. Therefore, in this study, we use a partial model-matching method to determine the PID gains. The advantage of this method is that the desired response can be obtained simply by determining the transfer function of the target system. Model-Based Development (MBD), widely used in robot development and other fields, was employed in this study

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to improve the efficiency of robotics research [10, 11]. This method is characterized by the fact that the interaction of various systems can be understood prior to experimentation, and the actual behavior can be verified in simulation. This makes the verification of the actual system more efficient and reduces the burden on the system. Section II describes the specifications of the experimental apparatus, industrial humanoid robot (Sciurus 17), and electronic musical-note-type musical instrument (otamatone). Section III describes the design of the end effector, and Section IV describes the workflow for music production and system identification. Section V describes the control parameter determination using the identified system to improve the accuracy of the robotic motion.

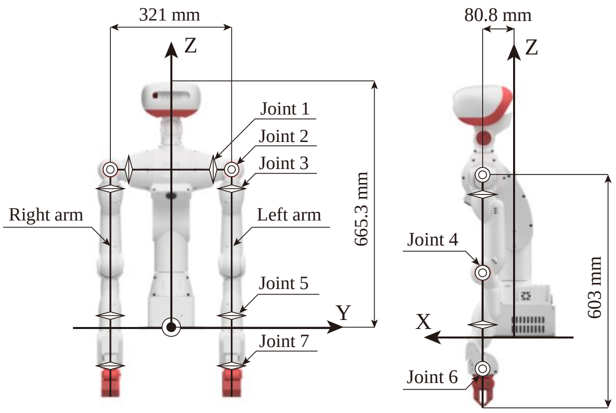
II. Experimental Device

A. *Humanoid Robot (Sciurus 17)*

Fig. 1 shows the joints and dimensions of the Sciurus 17 (manufactured by R.T. Corporation), which is the industrial humanoid robot used in this study. Table I lists the specifications of the robot's movements. The entire body of Sciurus 17 was fabricated using a 3D printer, and its CAD data are available as open-source data. Servo motors manufactured by Dynamixel were used in the joints of Sciurus 17: XM540-W270 for joints 1 and 2; XM540-W350 for joints 3, 5, 6, and 7; and XM540-W150 for joint 4.

TABLE I. Sciurus 17's Specifications

Control method	Electric flow, Location, Angle
Number of axes	20
Working range diameter	1331 mm
Maximum speed	0.05 rpm
Liftable weight	500 g



(a) Front view (b) Side view

Fig. 1. Humanoid robot (Sciurus 17).

B. *Note-type Electronic Musical Instrument (Otamatone)*

Fig. 2 shows the otamatone (manufactured by Meiwa Denki), which is the musical instrument used in this study. The otamatone was played by applying concentrated pressure to the handle, and the frequency changes, as shown in Fig. 3, were achieved by changing the position of the pressure application. While playing an otamatone, the continuous change in frequency makes it difficult for the desired pitch. Therefore, when the pressure position moved vertically downward, the frequency increased nonlinearly. When handled by humans, it is common practice to start playing after identifying the correspondence between the pressure position and frequency (pitch) of the sound through preliminary trials.

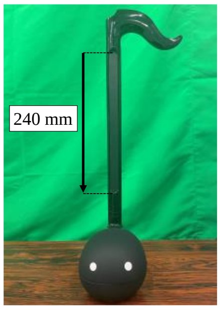


Fig. 2. Otamatone.

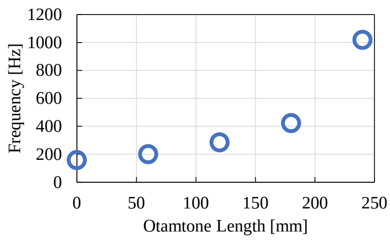
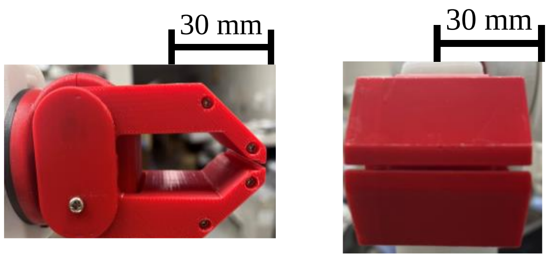


Fig. 3. Frequency shift.

III. Experimental Conditions

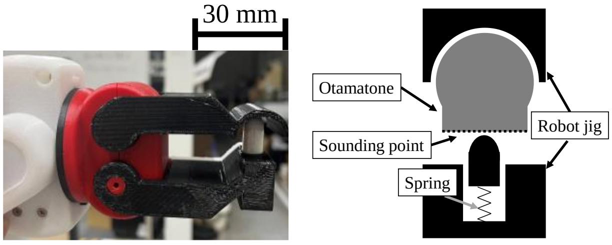
A. *End-Effector Design*

The shape of the end-effector of the default robot is shown in Fig. 4. In this state, the pressure position of the sounding part of the otamatone is not fixed at a specific point and sound cannot be produced. Therefore, a 3D printer was used to fabricate the end effector of the robot, as shown in Fig. 5. A 3D printer was used for modeling with a MakerBot Replicator 2X manufactured by Altec Corporation, and ABS resin was used as the material. It has been reported that a molded object shrinks by approximately 1% owing to cooling during the molding process of the 3D printer [12]. Therefore, in this study, we set a scale of 101% to account for this shrinkage when modeling with a 3D printer.



(a) Side (b) Front

Fig. 4. Default end-effector shape.



(a) Side (b) Rough sketch

Fig. 5. Designed end-effector shape.

B. End-Effector Design

Fig. 6 shows the workflow from the scale search to music production. One feature of the ROS used in this study is that it allows for communication between different systems. In ROS, each node registers its own IP address and port number with the ROS master, and the ROS master uses this information to recognize the sender (publisher) and receiver (subscriber) of the data for communication between the nodes. These features allow remote control of the robot, ease the computational burden on the systems, and enable the distributed processing. In a previous study, multiple mobile robots were controlled via wireless communication, and swarm control using graph theory with ROS communication was used to reduce the computational burden of the image and position information [13]. In this study, the processing burden for solving the frequency analysis, inverse kinematics in robot control, etc., is expected to be enormous. Therefore, we performed distributed processing of the scale search for otamatone tones using the two systems. The pitches searched were C4 (261.63 Hz), D4 (293.67 Hz), E4 (329.63 Hz), and G4 (391.99 Hz). The sound of the otamatone was analyzed using a Fast Fourier Transform (FFT) with a connected tuner at a sampling frequency of 44,100 Hz and a frequency resolution of 10.76 Hz. The frequency of the speech data comprises the fundamental frequency and its overtones. The purpose of a tone search is to determine the fundamental frequency. This phenomenon is known as autocorrelation (AC), and an AC function was used in this study [14], which is the sum of the products of the values at all positions while shifting two identical audio data points by one sample. The AC function could stably detect the fundamental frequency because the peak value decreased at higher frequencies. In the pitch search, Proportional–Integral–Derivative (PID) control is applied to the deviation between the fundamental frequency of the command value and that obtained from the otamatone. The PID control parameters are the proportional gain $K_p = 5.0\times10^{-4}$, integral gain $K_i = 1.0\times10^{-3}$, and derivative gain $K_d = 1.0\times10^{-3}$. This procedure was used to search for pitches and measure the joint angles of the robot for the four target pitches.

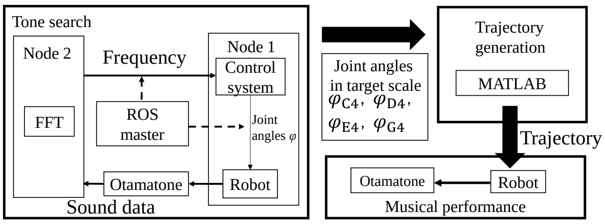


Fig. 6. Workflow from scale search to music production.

C. Music Production

The trajectory for playing music was generated using inverse kinematics in MATLAB, based on the joint angles measured beforehand. In this study, a trajectory robot was instructed to perform movements while playing the otamatone. The music played was "Mary Had a Little Lamb". The initial posture of the robot is shown in Fig. 7. In the experiment, the robot was designed to grasp the otamatone and move only its left arm, similar to a scale search. The joint angles of the robot were obtained during the experiment using a controlled communication system, and the actual trajectory of the robot was measured using forward kinematics. The command values of the y_l [mm] coordinates of the left-arm end effector are shown in Fig. 8.

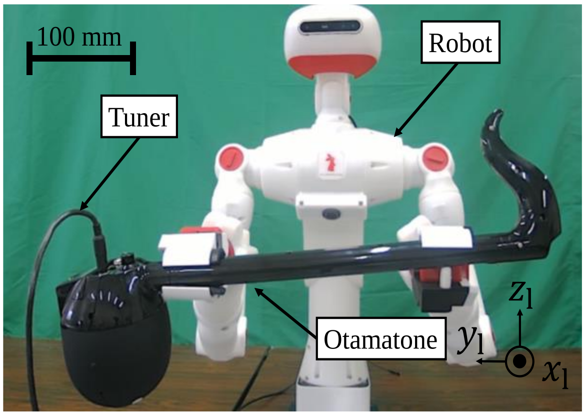


Fig. 7. Initial experimental setup.

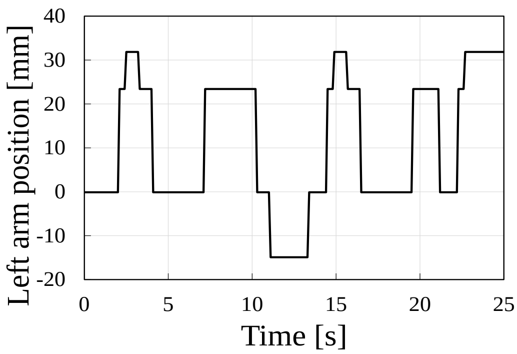


Fig. 8. Command trajectory.

IV. System Modeling

A. Modeling with MATLAB/Simulink, Simscape Multibody

In this study, we present a model-based optimization of the control parameters for performance. The model of each joint of the robot considered in this study is a combination of a white-box model, in which all mathematical expressions and parameters are known, and a black-box model, in which some parameters are unknown. MATLAB/Simulink and Simscape Multibody are effective methods for creating such models [15, 16]. The joints of the Sciurus 17 use servomotors manufactured by Dynamixel, and each parameter was set according to the manufacturer's manual. The known system model was created using MATLAB/Simulink with $Ci(s)$ as the controller using PID control and $P_i(s)$ as the control target, and the unknown model was created using MATLAB/Simscape Multibody with the physical model $M_i(s)$. A block diagram of the model is shown in Fig. 9; the various parameters are listed in Table II, where the proportional gain K_{pp}, integral gain K_{ip}, and differential gain K_{dp} are used, and i is the joint number mentioned in Fig. 1. The transfer function of the entire system in Fig. 9 is shown by Eq. (1). The system input is the command value of the joint angle φ_{in}, and the output is the actual joint angle φ_{out}. Fig. 10 shows the simulation results and measured values of the playing motion obtained using the model shown in Fig. 9. The default values for the PID control gains were K_{pp} = 6.25, K_{ip} = 0, and K_{dp} = 0, indicating that the modeling is effective.

TABLE II. System Model Parameters

Parameter	Value
Voltage constant K_α	0.678 V/rad
Torque constant K_{ti} (i = 1, 2)	2.409 Nm/A
Torque constant K_{ti} (i = 3, 5, 6, 7)	1.783 Nm/A
Torque constant K_{ti} (i = 4)	1.659 Nm/A
Inductance L	0.05 H
Electric resistance R_i (i = 1, 2)	2.5 Ω
Electric resistance R_i (i = 3, 5, 6, 7)	5.2 Ω
Electric resistance R_i (i = 4)	2.7 Ω

$$Cyr_i(s) = \frac{C_i(s)P_i(s)}{1+C_i(s)P_i(s)} \quad (1)$$

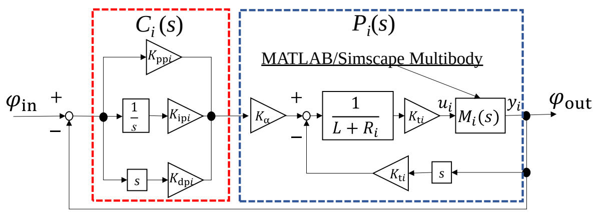


Fig. 9. Block diagram of the simulation model.

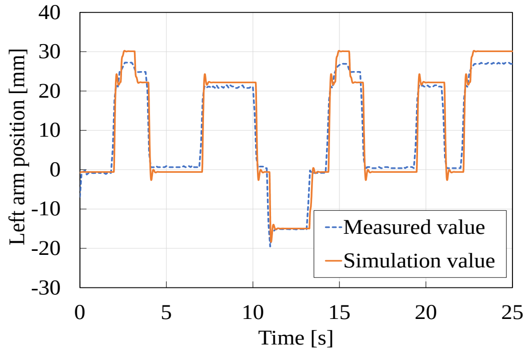


Fig. 10. Comparison of simulation and measurements.

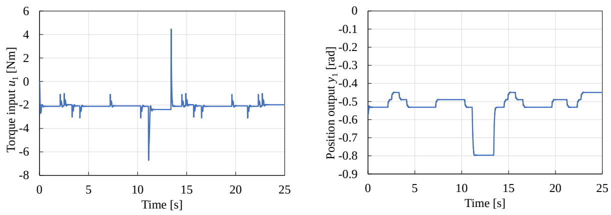
B. System Identification of Black-Box Models

In this study, it was necessary to clarify the transfer function of $M_i(s)$ to determine the control parameters described in the next section. The input u_1 [Nm] and output y_1 [rad] of $M_i(s)$ in Fig. 9 are shown in Fig. 11. From these inputs and outputs, system identification was performed using the MATLAB/ System identification toolbox. [17] The transfer function to be identified is the quadratic-delay system expressed in Eq. (2). A nonlinear least-squares method with a linear search was used for identification [18]. The identification results for $M_i(s)$ are listed in Table III.

$$M_i(s) = \frac{A_i}{s^2+B_i s+C_i} \quad (2)$$

TABLE III. Identification Result

Parameter	Value
A_i, B_i, C_i (i = 1, 2)	0.112, 1.985, 1.308
A_i, B_i, C_i (i = 3, 5, 6, 7)	0.264. 1.532, 0.897
A_i, B_i, C_i (i = 4)	0.137, 1.352, 0.805



(a) Input u_1 (b) Output y_1

Fig. 11. Inputs and outputs used for identification (i = 1).

V. Results and Discussion

A. Experiment Result

Fig. 12 shows the coordinates y_l of the command value and actual measured value at the left-arm end effector. The PID control gains were set to the default values, as mentioned in the previous section. Fig. 12 shows that the motion did not follow the command value, resulting in a steady deviation. This may be owing to the use of inappropriate PID gain parameters.

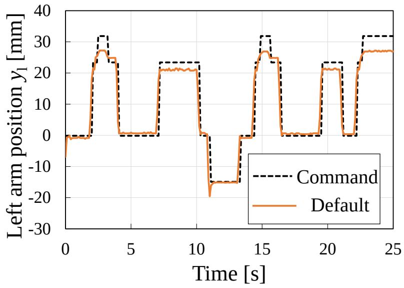


Fig. 12. Comparison of command position and measured position.

B. Experiment Result

In Section IV.B, we describe the transfer function $Mi(s)$ of the system. Using this function, we apply a partial model-matching method for model-based PID gain determination [19]. The partial model-matching method approximates the outputs of the control target $G_{yri}(s)$, as shown in Eq. (2) with the outputs of the normative model G_{m3}; the inverse of $G_{yri}(s)$ can be expressed using Eq. (3) using the McLaurin expansion, and the PID gains were determined by matching the lower-order coefficients with the inverse of G_{m3} in Eq. (4). δ_1, δ_2, and δ_3, are the first to third-order coefficients in the McLaurin expansion of the inverse of the control target. ω_m is the immediacy parameter and α_1 and α_2 are the stability parameters. The binomial coefficient, Butterworth coefficient, and ITAE standard forms were available as normative models [20–22]. The normative model has several standards. In this paper, $\omega_m = 1$, $\alpha_1 = 2.171$, and $\alpha_2 = 1.782$ are used as the ITAE minimum standard form such that the step response overshoot of the normative model is 2.0% [23]. The gains for each joint are listed in Table IV. Fig. 13 shows the actual measured values of the end effector and the change in frequency during the performance of a piece of music by the otamatone using the gains in Table IV. Fig. 13 (b) shows that the PID gains obtained by the partial model-matching method improved the accuracy of the otamatone performance. To compare the positional accuracy between the default values in Figs. 12 and 13(b), using the partial model-matching method, the error norm between the command value and the measured value was obtained using Eq. (6) [24]. Therefore, the error norm ΔN = 24.1 mm for the default value and ΔN = 10.4 mm for the case using the partial model-matching method. This implies that the positional accuracy of the y_l coordinate, which is important for performance accuracy, was significantly improved. In addition, considering the default performance in Fig. 13(b), we observe that the pronunciation becomes continuous. This may be due to poor positional accuracy in the direction of the z_l coordinate, where gravity is applied, causing the robot's end-effector to apply pressure to the otamatone at a time when it should not sound during a performance using otamatone, resulting in continuous sounding during the performance. In this respect, in the performance using the PID gain obtained by the partial model-matching method, each pronunciation is played separately, and not only the accuracy in the y_l direction but also the positional accuracy in the z_l coordinate direction, where gravity is applied, is improved, indicating that the entire performance is more complete.

$$G_{m3} = \frac{{\omega_m}^3}{s^3 + \alpha_2 \omega_m s^2 + \alpha_1 {\omega_m}^2 s + {\omega_m}^3} \tag{3}$$

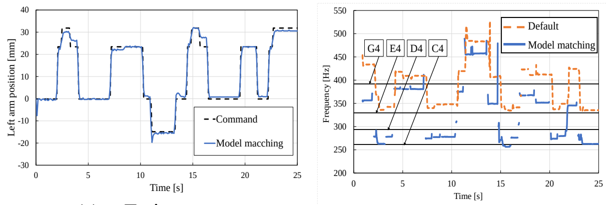
$$1 + \frac{1}{C_i(s) P_i(s)} = 1 + \delta_1 s + \delta_2 s^2 + \delta_3 s^3 \tag{4}$$

$$\frac{1}{G_{m3}} = 1 + \frac{\alpha_1}{\omega_m} s + \frac{\alpha_2}{{\omega_m}^2} s^2 + \frac{1}{{\omega_m}^3} s^3 \tag{5}$$

$$|f(t) - g(t)| = \sqrt{\int_{t=25}^{t=0} (f(t) - g(t))^2 dt} \tag{6}$$

TABLE IV. RESULTS OF THE PARTIAL MODEL-MATCHING METHOD

Parameter	Value
K_{ppi}, K_{ipi}, K_{dPi} (i = 1, 2)	4.06, 4.12, 1.83
K_{ppi}, K_{ipi}, K_{dPi} (i = 3, 5, 6, 7)	4.53, 4.10, 2.87
K_{ppi}, K_{ipi}, K_{dPi} (i = 4)	4.63, 4.44, 3.88



(a) Trajectory (b) Frequency

Fig. 13. Results of the partial model-matching method.

VI. CONCLUSION

This study aimed to improve the behavior of cooperative robots that use the same tools as humans. As one of the applications, we proposed a method to improve the robot's performance using an electronic musical note-type instrument called an "otamatone." We conducted experiments using an industrial humanoid robot, Sciurus 17, and an otamatone, and proposed a method to improve the accuracy of the robot's movements using a 3D printer to design end effectors, a pitch search method, and a partial model-matching method to determine the PID gains. The experimental results showed that a musical-scale search can improve the accuracy of a robot's motion. The experimental results showed that the scale search enabled the robot to play a piece of music, and that modeling and PID gain adjustment using the partial model-matching method were effective in the performance motion of the otamatone. This research achieved the application of advanced control technology to cooperative robots for precise movements, such as playing a piece of music.

CONFLICT OF INTEREST

The authors declare no conflicts of interest associated with this manuscript.

Author Contributions

Mikio Ozawa conducted the research mainly with the help of Daiki Kato and Hiroaki Hanai; Mikio Ozawa wrote the paper; Hiroki Kato programmed the robot's movements; Hiroaki Hanai was in charge of its creation using a 3D printer; Hirogaki and Aoyama determined the policy; all authors had approved the final version.

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