ATLANTIS PRESS

Journal of Robotics, Networking and Artificial Life
Vol. 7(4); March (2021), *pp.* 222–226
DOI: https://doi.org/10.2991/jrnal.k.201215.002; ISSN 2405-9021; eISSN 2352-6386
https://www.atlantis-press.com/journals/jrnal

Research Article

Study on Hybrid Position/Force Teaching and Control Method for 6 DoF Manipulator Utilizing f-PAWTED

Quang-Trung Chu[1], Hiroki Tanaka[1], Hideki Inuzuka[1], Yoshifumi Morita[1,*], Masao Sakai[2]

[1]*Department of Electrical and Mechanical Engineering, Graduate School of Engineering, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya, Aichi 466-8555, Japan*
[2]*Industrial Research Center, Aichi Center for Industry and Science Technology, Onda-cho 1-157-1, Kariya-shi Aichi 448-0013, Japan*

ARTICLE INFO

Article History

Received 26 November 2019
Accepted 09 June 2020

Keywords

Direct teaching method
hybrid position/force control
teaching pendant
robot manipulator

ABSTRACT

In this study, a parallel wire-type teaching device with a force sensor and a hybrid position/force teaching and control method are developed to facilely teach robot manipulators using human hands instead of teaching pendants. A direct teaching method based on a hybrid position/force control is proposed to teach robots the desired position and force trajectories. The effectiveness of the developed device and method in teaching the robot manipulator is confirmed experimentally.

1. INTRODUCTION

Robot teaching technology is essential for adequately exploiting robots. A teaching pendant has been widely utilized in the manufacturing industry for this purpose. Several teaching methods have been proposed by extant studies [1,2]. A direct teaching method using impedance control was proposed to teach robots the desired trajectories while directly moving an end effector [3]. However, this method consumes a significant amount of time, and the response of the robot during operation is poor. Hence, a Parallel Wire-type Teaching Device (PAWTED) and a direct teaching position control method were proposed [4]. An operator can handle a PAWTED to teach a Six-Degree-of-Freedom (6-DoF) robot any arbitrary three-dimensional trajectories within the working space in a short period. Subsequently, the robot can reproduce the teaching position trajectories precisely [5]. Nonetheless, the developed PAWTED cannot teach and playback both the desired position and force trajectories simultaneously.

In this study, a PAWTED with a Force Sensor (f-PAWTED) and a hybrid position/force teaching and control method were developed to overcome these problems. The effectiveness of the f-PAWTED and the proposed control method is verified experimentally.

2. PARALLEL WIRE-TYPE TEACHING DEVICE WITH A FORCE SENSOR

2.1. f-PAWTED Mechanism

The PAWTED comprises a moving platform, six wires, and a base. Meanwhile, the f-PAWTED comprises the PAWTED and a force sensor, as shown in Figure 1. The force sensor is fixed on the top face of the moving platform. The base comprises three holders, six rotary encoders, and six flat spiral springs fastened to the end of the robot arm. The moving platform is connected to the base by a system of six wires. Therefore, an operator can move the moving platform freely in a three-dimensional space. Figure 2 shows the teaching and playback operation using the f-PAWTED. In the teaching mode, the f-PAWTED measures the drawn length of the wires, whereas the operator moves the moving platform. It computes the position and orientation of the teaching tool based on the drawn lengths. In addition, the force for teaching data exerted by the end of the robot arm is measured by the force sensor. All teaching data are transformed to the robot's reference frame Σ_0 and saved in a computer. During the teaching mode, the robot is controlled to track and maintain the moving platform at a constant distance. In the playback mode, the moving platform is fastened to the holders and the robot reproduces the teaching trajectories.

2.2. Theoretical Transformation

2.2.1. *Teaching mode*

As shown in Figure 2, Σ_H and Σ_R are the coordinate frames attached to the moving platform and the end of the robot arm, respectively. The teaching position/orientation vector of the teaching tool with respect to frame Σ_0 is denoted by ${}^{0}\boldsymbol{r}_t\ R^6$.

$$ {}^{0}\boldsymbol{r}_t = [({}^{0}\boldsymbol{p}_t)^T, ({}^{0}\boldsymbol{\eta}_t)^T]^T, \tag{1}$$

where ${}^{0}\boldsymbol{p}_t$ and ${}^{0}\boldsymbol{\eta}_t$ are the present position and orientation vectors with respect to frame Σ_0, respectively. They are obtained from

*Corresponding author. Email: morita@nitech.ac.jp

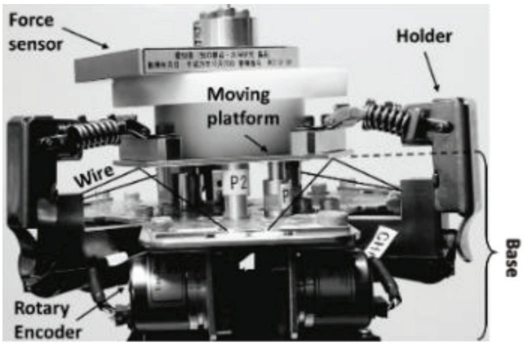

Figure 1 | f-PAWTED.

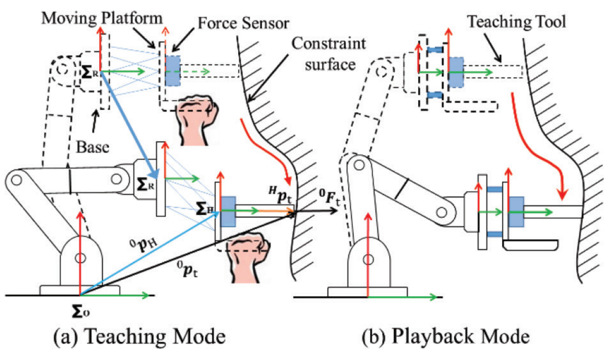

Figure 2 | Operation using f-PAWTED. (a) Teaching mode. (b) Playback mode.

$$[({}^{0}\boldsymbol{p}_t)^T, 1]^T = {}^{0}\boldsymbol{T}_H[({}^{H}\boldsymbol{p}_t)^T, 1]^T, \quad {}^{0}\boldsymbol{\eta}_t = {}^{0}\boldsymbol{R}_H\,{}^{H}\boldsymbol{\eta}_t,$$
$${}^{H}\boldsymbol{p}_t = [0, 0, l_h]^T, \qquad {}^{H}\boldsymbol{\eta}_t = [\boldsymbol{\phi}, \boldsymbol{\theta}, \boldsymbol{\psi}]^T,$$

where ${}^{i}\boldsymbol{T}_k$ and ${}^{i}\boldsymbol{R}_k$ denote the homogeneous transform matrix and the rotation matrix from frame Σ_k to Σ_i, respectively, l_h is a known parameter, and $[\phi, \theta, \psi]$ are roll, pitch, and yaw angles, respectively.

Similar to vector ${}^{0}\boldsymbol{r}_t$, the teaching force/torque vector ${}^{0}\boldsymbol{F}_t$ with respect to frame Σ_0 is expressed as

$${}^{0}\boldsymbol{F}_t = [({}^{0}\boldsymbol{f}_t)^T, ({}^{0}\boldsymbol{\tau}_t)^T]^T, \tag{2}$$

where ${}^{0}\boldsymbol{f}_t$ and ${}^{0}\boldsymbol{\tau}_t$. are the present force and torque vectors of the teaching tool with respect to frame Σ_0, respectively. They are expressed as follows:

$${}^{0}\boldsymbol{f}_t = {}^{0}\boldsymbol{R}_H\,{}^{H}\boldsymbol{f}_t, {}^{0}\boldsymbol{\tau}_t = {}^{0}\boldsymbol{p}_H \times {}^{0}\boldsymbol{f}_t + {}^{0}\boldsymbol{R}_H\,{}^{H}\boldsymbol{\tau}_t,$$

in which ${}^{0}\boldsymbol{p}_H$ denotes the position vector of the origin of frame Σ_H with respect to frame Σ_0. ${}^{H}\boldsymbol{f}_t$ and ${}^{H}\boldsymbol{\tau}_t$ are the present force and torque vectors of the teaching tool expressed in frame Σ_H, respectively. They are calculated from the values measured by the force sensor.

2.2.2. Playback mode

In the playback mode, the moving platform is fastened to the base; therefore, $\Sigma_R = \Sigma_H$ and ${}^{R}\boldsymbol{T}_H = \mathbf{I}, {}^{0}\boldsymbol{T}_H = {}^{0}\boldsymbol{T}_R$. The position and force data are saved as follows:

$${}^{0}\boldsymbol{r}_p = [({}^{0}\boldsymbol{p}_p)^T, ({}^{0}\boldsymbol{\eta}_p)^T]^T, {}^{0}\boldsymbol{F}_p = [({}^{0}\boldsymbol{f}_p)^T, ({}^{0}\boldsymbol{\tau}_p)^T]^T \tag{3}$$

3. HYBRID POSITION/FORCE TEACHING CONTROL METHOD

A hybrid control method is proposed based on the principle that there are some directions in which position is controlled and other directions in which force is controlled. Upon a specific task, these directions change, but a single direction is never used to control both the position and force [6]. Our task is to teach the teaching tool position and force trajectories on a spherical surface using the robot attached to the f-PAWTED. The operator pushes the teaching tool with a force against the working surface while moving the teaching tool. Subsequently, the robot reproduces the teaching trajectories comprising the position and force. We assigned a moving constraint frame Σ_C on the working surface, as shown in Figure 3. The origin O_C coincides with the present point A_k. The Z_C axis shows that the force-control direction is normal to the working surface. The Y_C axis is along the teaching trajectory on the working surface. The X_C axis is assigned to be normal to Z_C and Y_C, making Σ_C a right-hand coordinate system. The X_C and Y_C axes show position-control directions. The position of the teaching point A_k expressed in the working frame Σ_W ($O_W - r\alpha\beta$) comprises three parameters, (r, α_k, β_k), as shown in Figure 3 where r is the sphere radius, α_k denotes the angle between Y_W and vector $\overrightarrow{O_wA_{kx}}$, and β_k denotes the angle between Z_W and vector $\overrightarrow{O_wA_k}$. The teaching and playback data are transformed to frame Σ_C as follows:

$$[({}^{C}\boldsymbol{p}_t)^T, 1]^T = {}^{C}\boldsymbol{T}_0[({}^{0}\boldsymbol{p}_t)^T, 1]^T, {}^{C}\boldsymbol{n}_t = {}^{C}\boldsymbol{R}_0\,{}^{C}\boldsymbol{\eta}_t, \tag{4}$$
$${}^{C}\boldsymbol{f}_t = \mathbf{I}_1\,{}^{C}\boldsymbol{R}_0\,{}^{0}\boldsymbol{f}_t,\ {}^{C}\boldsymbol{f}_p = \mathbf{I}_1\,{}^{C}\boldsymbol{R}_0\,{}^{0}\boldsymbol{f}_p \tag{5}$$

where $\mathbf{I}_1 = \text{diag}[0, 0, 1]$.

Subsequently, the compensating control law of the force response in Z_C-axis direction is expressed as

$$\begin{aligned}{}^{C}\boldsymbol{p}_p(n) = {}^{C}\boldsymbol{p}_t(n) + \boldsymbol{K}_P[{}^{C}\boldsymbol{f}_t(n-1) - {}^{C}\boldsymbol{f}_p(n-1)] \\ + \boldsymbol{K}_D\left[\frac{{}^{C}\boldsymbol{f}_t(n-1) - {}^{C}\boldsymbol{f}_p(n-1)}{dT}\right],\end{aligned} \tag{6}$$

where $\boldsymbol{K}_P$ and $\boldsymbol{K}_D$ are the feedback gain matrices, and dT is the sampling time.

4. EXPERIMENTS

In this study, experiments were conducted to investigate the effectiveness of the proposed method on a 6-DoF robot manipulator (DENSO WAVE, VS-060) equipped with the f-PAWTED. Specifically, the task of writing an arbitrary curve on a spherical surface was performed. For this purpose, we created a drawing tool comprising a force sensor, pen holder, and pen as the teaching tool. The pen holder and force sensor were fastened to the moving platform. The pen was attached to the head of the force sensor and placed inside the pen holder without contact. The force sensor can measure the three orthogonal components of the force and the

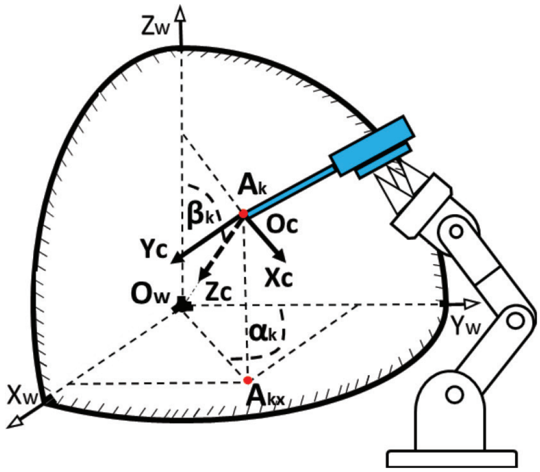

Figure 3 | Moving constraint frame on spherical surface.

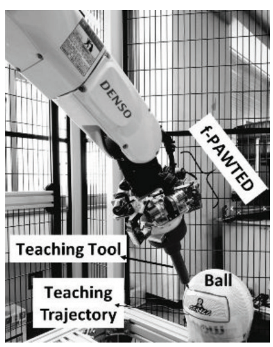

Figure 4 | Playback motion of a robot equipped with f-PAWTED.

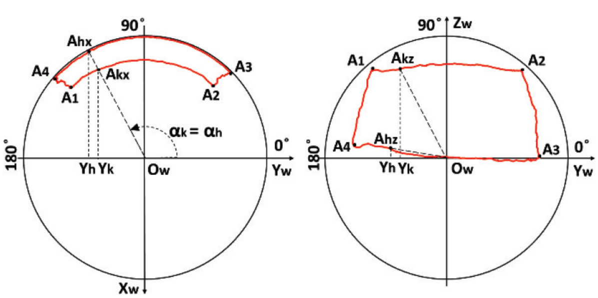

Figure 5 | Teaching trajectory on spherical surface.

three components of the moment exerted on the pen. In the teaching mode, an operator grasps the pen holder and draws a curve on the dodge ball with a radius of 85.5 mm while pushing the pen against the surface of the ball. Subsequently, in the playback mode, the robot reproduces the teaching curve, as shown in Figure 4.

In the teaching mode, the operator manipulated the pen holder to teach the robot a closed curve starting from point A_1 toward points A_2, A_3, and A_4, and then returned to A_1, as shown by the red curve in Figure 5. The controller saves the teaching data during movement, including both the position and force data of the teaching tool. In the playback mode, the data of the playback force exerted by the end of the robot arm on the dodge ball are transformed to frame Σ_C. Based on the teaching and playback data of the force, an adjustment was performed according to Equation (6).

The experimental results of the force are shown in Figure 6. The horizontal axis denotes the step number of the control sequence of the robot-dedicated controller. The sampling time was 0.05–0.10 s, which depends on the movement distance of each step. The green and red lines denote the force response in the Z_C-axis direction in the teaching and playback modes, respectively. The first A_1 in Figure 6 represents the starting point. The next points A_2, A_3, A_4, and A_1 show the steps when the teaching tool reaches A_2, A_3, A_4, and A_1, respectively. The red line follows the green line relatively well with a mean error of 0.249 N.

The position teaching trajectories with respect to frame Σ_W are illustrated in Figure 7. In Figure 7, graphs (a) and (b) denote angles α and β, respectively. When the pen moved from A_2 toward A_3 and from A_4 toward A_1, angle α remained steady at approximately 45° and 135°, respectively. In addition, angle β remained stable at approximately 60° and 90° when the pen moved from A_1 toward A_2 and from A_3 toward A_4, respectively. As shown in Figure 7, the robot tracked the desired position trajectory closely. The mean

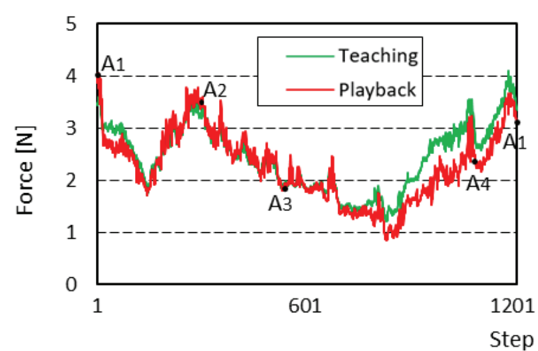

Figure 6 | Force response in Z_C-axis direction during teaching and playback modes.

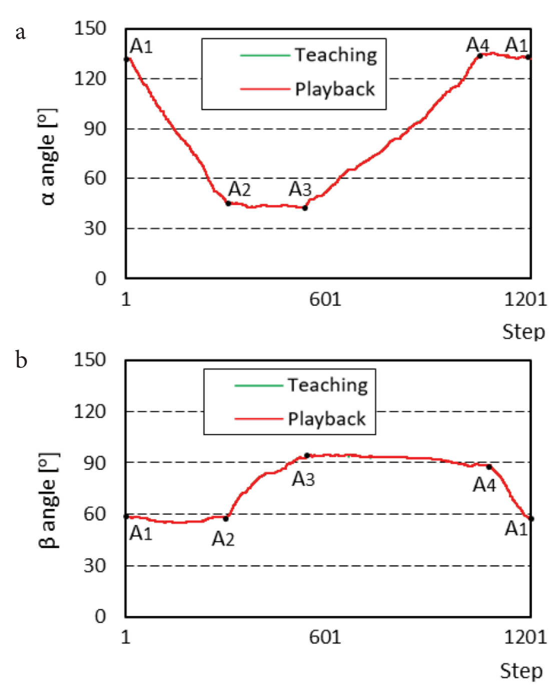

Figure 7 | Position trajectories of teaching tool during teaching and playback modes. (a) Angle α; (b) angle β.

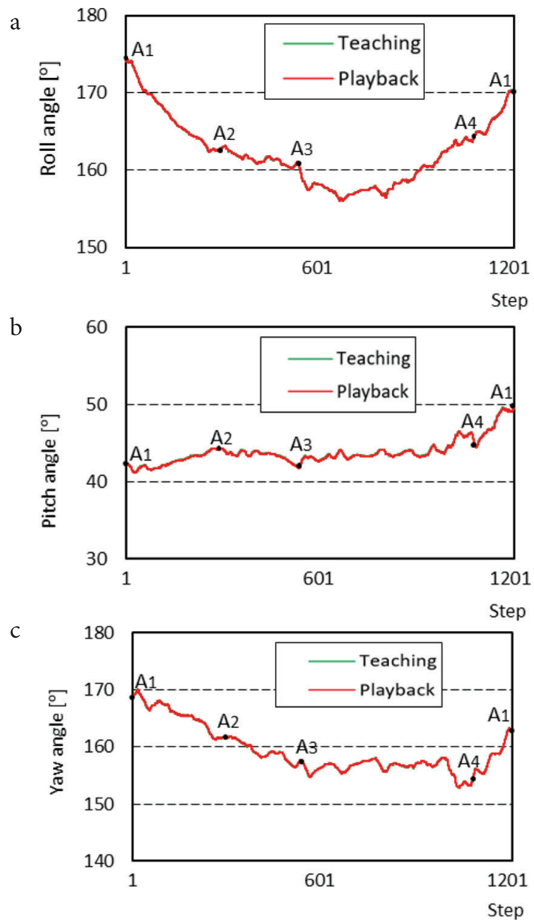

Figure 8 | Orientation trajectories of teaching tool during teaching and playback modes. (a) Roll angle; (b) pitch angle; (c) yaw angle.

errors between the teaching and playback modes of the angles α and β were 0.138° and 0.122°, respectively.

Figure 8 shows the trajectories of roll, pitch, and yaw angles of orientation of the teaching tool expressed in robot's reference frame Σ_0 in both the teaching and playback modes. The playback orientation trajectories closely pursued the teaching ones. The mean errors between the two modes of the roll, pitch and yaw angles were 0.031°, 0.044° and 0.038°, respectively.

5. CONCLUSION

An approach for teaching and directly controlling both the position and force of robot manipulators using a f-PAWTED and a hybrid position/force control method were presented. The proposed method was validated by writing a closed curve on a spherical surface. Hence, this demonstrates the prospect and applicability of the hybrid position/force teaching and control method in industrial processing.

CONFLICTS OF INTEREST

The authors declare they have no conflicts of interest.

REFERENCES

[1] S. Masaru, Direct teaching for robot, J. Robot. Soc. Jpn. 13 (1995), 627–628 (in Japanese).
[2] M. Kanji, Offline teaching, J. Robot. Soc. Jpn. 13 (1995), 611–614 (in Japanese).
[3] Y. Mochizuki, T. Matsui, Direct teaching method for hybrid control applying impedance control, J. Robot. Soc. Jpn. 12 (1994), 328–334 (in Japanese).
[4] S. Sakai, S. Noritaka, M. Yoshifumi, Development of parallel wire mechanism for robot teaching, J. Jpn. Soc. Mech. Eng. Ser. C 79 (2013), 4321–4329 (in Japanese).
[5] S. Sakai, S. Noritaka, M. Yoshifumi, Performance evaluation of robot teaching method with parallel wire mechanism, T. Soc. Sig. Process. Appl. Technol. Jpn. 16 (2013), 72–78 (in Japanese).
[6] T. Yoshikawa, Foundations of Robotics-Analysis and Control, The MIT Press, 1990.

AUTHORS INTRODUCTION

Mr. Quang-Trung Chu

He received the B.S. degree in Mechatronic Engineering in 2018 from Hanoi University of Science and Technology, Vietnam. He is currently a Master's student at the Department of Electrical and Mechanical Engineering, Nagoya Institute of Technology, Japan. His research interest is the application of robot teaching technology in the mechatronic systems.

Mr. Hiroki Tanaka

He received the B.S. degree in Electrical and Electric Engineering in 2019 from Nagoya Institute of Technology, Japan. He is currently a Master's student at the Department of Electrical and Mechanical Engineering, Nagoya Institute of Technology, Japan. His research interest is the application of robot teaching technology in mechatronic systems.

Mr. Hideki Inuzuka

He received the B.S. degree in Electrical and Computer Engineering and the M.S. degree in Computer Science and Engineering from Nagoya Institute of Technology, Japan in 2014 and 2016, respectively. He is currently a PhD student at the Department of Electrical and Mechanical Engineering, Nagoya Institute of Technology, Japan. His current research interest includes industrial robots and teaching devices. He is a member of the JSME and IEEJ.

Dr. Yoshifumi Morita

He received the M.S. and PhD degrees in Electrical and Computer Engineering from Nagoya Institute of Technology, Japan in 1989 and 1998, respectively. He is currently a Professor at the Department of Electrical and Mechanical Engineering, Nagoya Institute of Technology. His current research interests include rehabilitation support robots, medical support systems, and robot teaching technology. He is a member of the SICE, IEEJ, RSJ, and IEEE, among other.

Dr. Masao Sakai

He received the PhD degree in Computer Science and Engineering from Nagoya Institute of Technology, Japan in 2016. He is currently a Researcher at the Aichi Center for Industry and Science Technology. His current research themes are robot teaching technology and risk assessment of robots. He is a member of the JSME, IEEJ, and RSJ.