# Design and Implementation of a Digital Twin to Control the Industrial Robot Mitsubishi RV-12SD

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**Abstract.** This paper presents a case study of using a digital twin model to control and monitor a real industrial robot. The digital twin and user interfaces are designed and implemented in the Unity 3D environment. The inverse kinematics of the robot is analytically calculated. Both the digital twin and the physical model (the robot Mitsubishi RV-12SD) is successfully integrated, and the data flow can be exchanged one another to control both the models to work together. The real system integration and the collaborating scenarios demonstrate the potential and advantage of the proposed method to develop a smarter programming, controlling and monitoring system for industrial robots.

**Keywords:** Digital twin · Welding robot · Inverse kinematics

## 1 Introduction

In recent years, the welding robot plays an important role in several manufacturing industries such as automotive industry, shipbuilding industry, etc. The use of the welding robot for welding complex mechanical parts is to increase the productivity of the production and reduce the use of manpower for manufacturing enterprises. Generally, in order to generate a program (G-code file) for a welding robot, the programmers usually use two main methods: (i) the teaching method and (ii) the CAD-based offline programming method. The teaching method is mostly used in practice to prepare programs for a welding robot rather than the CAD-based offline programming method. However, for welding complex parts with continuous seam welds, the use of the teaching method is not flexible and even impossible. For example, when teaching a robot to weld a seam curve of very high curvature, it is impossible to orient exactly the welding torch of the robot. In this situation, the CAD-based offline programming method is applicable to produce more precise command blocks for a welding robot.

With the advances in new-generation information technologies, digital twin, AI and bigdata analytics are considered as the key technologies to achieve more smart welding robotic systems. To make full use of these technologies, in making more smart decisions, such as self-optimization of real time welding process and online monitoring of real time


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status for welding systems, which is to help enterprises to improve the flexibility and efficiency of the productions, and to increase the productivity and the quality of products, is challenging. The benefits of using digital twin for smart welding robot is enormous, however its adoption in real manufacturing is still in nascent stage. In the literature, most of the published papers focus on the framework design, implementation and pilot applications of a digital twin for a manufacturing process, e.g. [1–9]. An overview for incorporating digital twin technology into manufacturing models was presented in [1]. The potential use of a digital twin for diagnostics and prognostics of a corresponding physical twin was studied in [2]. The idea for using a sensor data fusion to construct a digital twin with a virtual machine tool was shown in [3]. The use of the machine learning approach and other data-driven optimization methods to improve the accuracy of a digital twin was investigated in [4–6]. The dynamic modelling of a digital twin based on the approach of discrete dynamic systems was studied in [7]. Some case studies about digital twin were presented in [8, 9].

In this paper, we present a novel technique to design a digital twin incorporated with an inverse kinematic modelling to control a real industrial robot. First, a digital twin connecting with the physical twin – the robot arm Mitsubishi RV-12SD - is designed with the support of CAD tools and Unity 3D software. Second, the inverse kinematics model of the robot is formulated and incorporated with the digital twin. Last, the connection between the digital twin and physical twin is implemented in a manner that the physical twin and the digital twin can be operated in unified scenarios, and the robot can be programed, controlled and monitored from the digital twin and its interfaces.

## 2 Design of a Digital Twin in Unity 3D

Unity Game Engine (Unity 3D) is a professional software for making games directly in real time. This software can be used to create user interfaces (UI) that helps users to easily manipulate and build applications (Fig. 1).

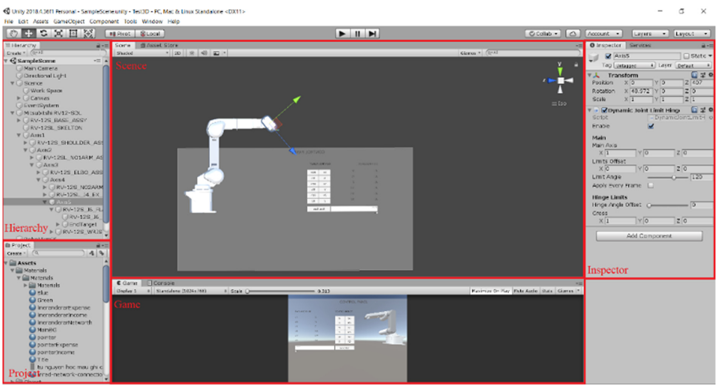


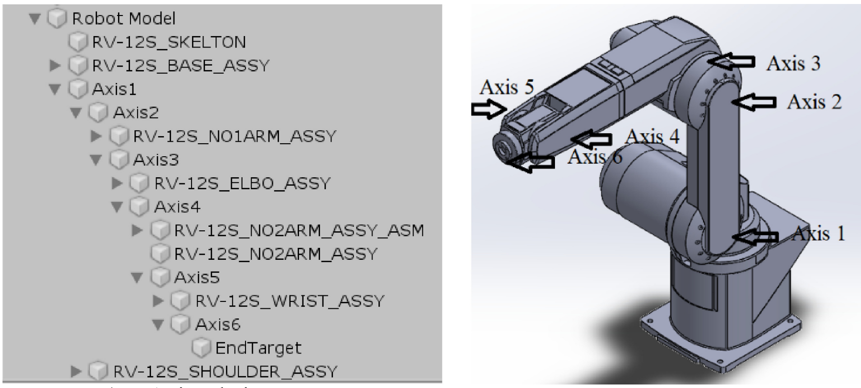

**Fig. 1.** Unity 3D interfaces (1. Scene 2. Game 3. Inspector 4. Hierarchy 5. Project)

A Unity's interface usually consists of scene, game, inspector, hierarchy and project. Scene window displays objects, in which the objects can be selected, dragged and dropped, zoomed in/out, and rotated. Game window which is viewed from a camera in a game, is a demo game screen. Inspector window is to view all components and their properties. Tab Hierarchy shows game objects and tab project displays assets in a game. One important thing is that the output data of a digital model and the simulation scenarios of the model can be used to communicate with a corresponding physical model. Generally, Unity 3D provides many convenient and effective utilities for 3D model building and simulation, the simulation scenarios of a digital model connected with a physical model can be implemented all together in real time. With these advantages, Unity 3D provides an ideal environment build a digital twin. Therefore, in this study, we use Unity 3D to design a digital twin for the industrial Robot Mitsubishi RV-12SD.

Building a digital twin in Unity 3D includes 2 steps:

*Step 1. Building 3D model using CAD Software*

In this study, we use SolidWork software to design all components of the 3D model of the robot Mitsubishi RV-12SD. However, the files in STL/STP format is not available in Unity 3D (.fbx,.obj formats). Therefore, to import 3D model from SolidWorks 2020 into Unity 3D requires a middle-ware (CAD Exchanger software) convert STL/STP file to.fbx (filmbox) file. Figure 2 shows the 3D model designed for the robot Mitsubishi RV-12SD.

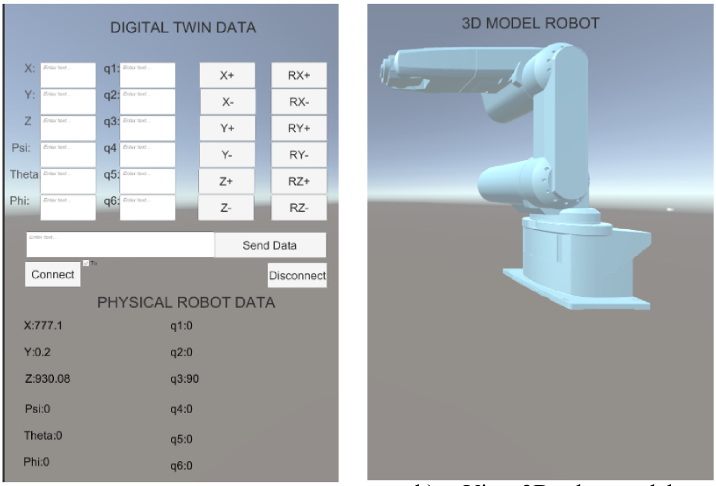



a) Axis relation b) Axis of 3D model

**Fig. 2.** 3D model in Unity3D

Step 2. Building a Digital Model

After converting and rendering the 3D model into a virtual environment, the model can be used to program in the virtual environment and interact with the physical robot. Unity 3D creates virtual environment to control and monitor the real industrial robot, it provides tools for designing user interfaces. In this manner, a real robot operation can be controlled and monitored from designed UIs. In this case study, a control panel has been designed (Fig. 3) to show parameters (joint angles) feedbacked from the real robot. The values of the joint angles (q1 to q6) are transferred to the virtual model to simulate the robot's motion in parallel with the real robot operation. To program the digital model, the C# programming language is used.




a) Control panel b) View 3D robot model

**Fig. 3.** Design of user interfaces

To control the robot, the inverse kinematic model of the robot is formulated, which uses the position (X, Y, Z) and the rotation (RX, RY, RX) of end-effector to calculate joint angles of the physical robot.

An important aspect when building a digital model is the connection between virtual and real environment. In this paper, the connection method based on the RS232 communication is selected which exchanges data between the physical robot and the virtual space. The information is exchanged in both-ways that include joint angles and actual robot status signals.

## 3 Inverse Kinematic Modelling of the Robot

The inverse kinematic modeling of a robot plays an important role in calculating the values of the joint variables ($q_1$, $q_2$, $q_3$, $q_4$, $q_5$, $q_6$) for control the physical robot in connection with a Digital Twin [10–14]. In this section, we present a analytical solution to the inverse kinematic problem of the robot Mitsubishi RV-12SD. Figure 4 show the feasible workspace of the robot, and Fig. 5 shows the kinematic diagram of the robot mechanism.

Note that the Denavit-Hatenberg method is used to define all the link frames as usual. With the kinematic parameters listed in Table 1, the transformation matrices and calculated as follows.

$$\mathbf{R}_1^0 = \begin{pmatrix} \cos(q_1) & 0 & -\sin(q_1) \\ \sin(q_1) & 0 & \cos(q_\cdot) \\ 0 & -1 & 0 \end{pmatrix}; \ \mathbf{R}_2^1 = \begin{pmatrix} \cos(q_2) & -\sin(q_2) & 0 \\ \sin(q_2) & \cos(q_2) & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad (1)$$

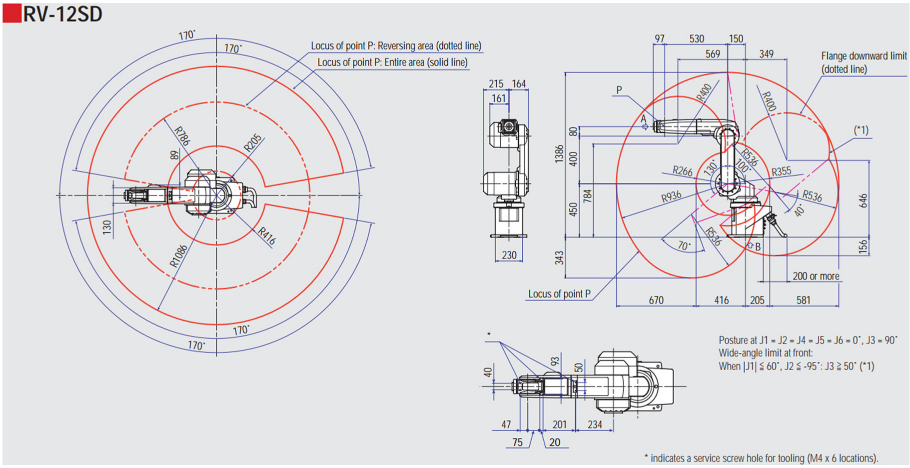



**Fig. 4.** The workspace of robot RV-12SD

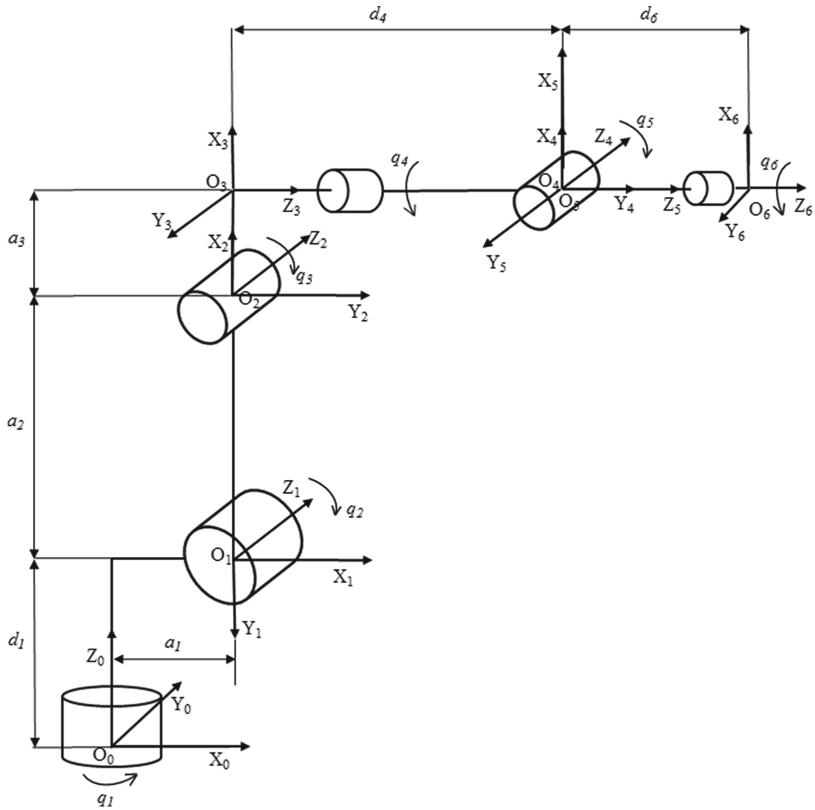


**Fig. 5.** Kinematic diagram of robot RV-12SD

**Table 1.** DH parameters

| Link | $\theta_i$ | $d_i$ | $a_i$ | $\alpha_i$ |
|---|---|---|---|---|
| 1 | $q_1$ | $d_1$ | $a_1$ | $-\frac{\Pi}{2}$ |
| 2 | $q_2$ | 0 | $a_2$ | 0 |
| 3 | $q_3$ | 0 | $a_3$ | $-\frac{\Pi}{2}$ |
| 4 | $q_4$ | $d_4$ | 0 | $\frac{\Pi}{2}$ |
| 5 | $q_5$ | 0 | 0 | $-\frac{\Pi}{2}$ |
| 6 | $q_6$ | $d_6$ | 0 | 0 |

$$\mathbf{R}_3^2 = \begin{pmatrix} \cos(q_3) & 0 & -\sin(q_3) \\ \sin(q_3) & 0 & \cos(q_3) \\ 0 & -1 & 0 \end{pmatrix};\ \mathbf{R}_4^3 = \begin{pmatrix} \cos(q_4) & 0 & \sin(q_4) \\ \sin(q_4) & 0 & -\cos(q_4) \\ 0 & 1 & 0 \end{pmatrix} \tag{2}$$

$$\mathbf{R}_5^4 = \begin{pmatrix} \cos(q_5) & 0 & -\sin(q_5) \\ \sin(q_5) & 0 & \cos(q_5) \\ 0 & -1 & 0 \end{pmatrix};\ \mathbf{R}_6^5 = \begin{pmatrix} \cos(q_6) & -\sin(q_6) & 0 \\ \sin(q_6) & \cos(q_6) & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{3}$$

$$\mathbf{R}_E = \mathbf{R}_6^0 = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \tag{4}$$

In Eq. (4),

$$\begin{aligned} a_{11} &= \cos(\psi).\cos(\theta).\cos(\varphi) - \sin(\psi).\sin(\varphi) \\ a_{12} &= -\cos(\varphi).\sin(\psi) - \cos(\psi).\cos(\theta).\sin(\varphi) \\ a_{13} &= \cos(\psi).\sin(\theta) \\ a_{21} &= \cos(\theta).\cos(\varphi).\sin(\psi) + \cos(\psi).\sin(\varphi) \\ a_{22} &= \cos(\psi).\cos(\varphi) - \cos(\theta).sin(\psi).\sin(\varphi) \\ a_{23} &= \sin(\psi).\sin(\theta);\ a_{31} = -\cos(\varphi).\sin(\theta) \\ a_{32} &= \sin(\theta).\sin(\varphi);\ a_{33} = \cos(\theta) \end{aligned} \tag{5}$$

With a desired posture of Robot arm, the end effector position could be defined via $x_E, y_E, z_E$ and orientation is ψ, θ, φ. From that, rotation matrix $\mathbf{R}_E = \mathbf{R}_6^0$ can be written to find $q_1$, $q_2$ and $q_3$.

It is clearly seen that the values of the three joint $q_4$, $q_5$, $q_6$ do not affect the center wrist ($O_5$) position. On one hand, $O_5$ position in coordinate $O_6$ $X_6$ $Y_6$ $Z_6$ is 0, 0, $-d_6$, so the position of the wrist center can be calculated from the position of end effector $(x_E, y_E, z_E)$ as

$$\begin{bmatrix} x_w \\ y_w \\ z_w \end{bmatrix} = \begin{bmatrix} x_{0_5} \\ y_{0_5} \\ z_{0_5} \end{bmatrix} = \begin{bmatrix} x_E - d_6.R_{E13} \\ y_E - d_6.R_{E23} \\ z_E - d_6.R_{E33} \end{bmatrix} \tag{6}$$

The position of $O_5$ on $X_0Y_0$ plane is described as shown in Fig. 6.

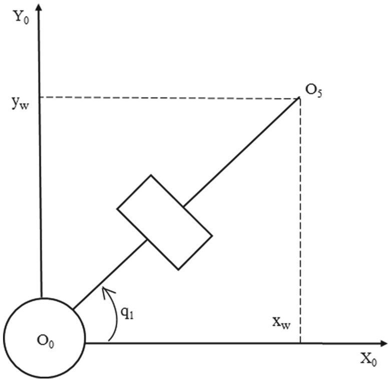



**Fig. 6.** Projection of $O_5$ on plane $X_0Y_0$

In this manner, $q_1$ can be calculated as

$$q_1 = \text{atan2}(x_w, y_w) \tag{7}$$

On the plane of Link1 and Link2, the joint $q_1$ and $q_2$ are involved as shown in Fig. 7.

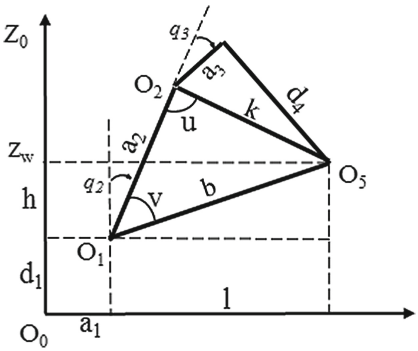



**Fig. 7.** Projection on the plane of Link2 and Link3

As seen in Fig. 7, q2 and q3 can be easily calculated. Note that $l = \sqrt{x_w^2 + y_w^2} - a_1$; $h = z_w - d_1$; $k = \sqrt{a_3^2 + d_4^2}$; $b = \sqrt{l^2 + h^2}$.

$$\cos(u) = \frac{a_2^2 + k^2 - b^2}{2.a_2.k} \tag{8}$$

$$u = a\tan 2(2.a_2.k, a_2^2 + k^2 - b^2) \tag{9}$$

$$q_3 = \Pi - a\tan 2(a_3, d_4) - u \tag{10}$$

$$q_2 = a\tan 2(h, l) - v \tag{11}$$

$$\cos(v) = \frac{a_2^2 + b^2 - k^2}{2.a_2.b} \tag{12}$$

$$q_2 = a\tan 2(h, l) - a\tan 2(2.b.a_2, a_2^2 + b^2 - k^2) \tag{13}$$

In order to calculate $q_4$, $q_5$ and $q_6$, the rotation matrix $\mathbf{R}_3^0$ and $\mathbf{R}_6^3$ must be calculated.

$$\mathbf{R}_3^0 = \mathbf{R}_1^0.\mathbf{R}_2^1.\mathbf{R}_3^2 = \mathbf{R}_P \tag{14}$$

$$\mathbf{R}_3^0 = \begin{pmatrix} \cos(q_1).\cos(q_2+q_3) & \sin(q_1) & -\cos(q_1).\sin(q_2+q_3) \\ \cos(q_2+q_3).\sin(q_1) & -\cos(q_1) & -\sin(q_1).\sin(q_2+q_3) \\ -\sin(q_2+q_3) & 0 & \cos(q_2+q_3) \end{pmatrix} \tag{15}$$

$$\mathbf{R}_6^3 = (\mathbf{R}_3^0)^{-1}.\mathbf{R}_6^0 = \mathbf{R}_P^{-1}.\mathbf{R}_E = \mathbf{R}_A = \begin{pmatrix} R_{A11} & R_{A12} & R_{A13} \\ R_{A21} & R_{A22} & R_{A23} \\ R_{A31} & R_{A32} & R_{A33} \end{pmatrix} \tag{16}$$

On the other hand,

$$\mathbf{R}_6^3 = \mathbf{R}_4^3.\mathbf{R}_5^4.\mathbf{R}_6^5 = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \tag{17}$$

Hence

$$\begin{aligned} b_{11} &= \cos(q_6).\cos(q_4).\cos(q_5) - \sin(q_4).\sin(q_6); \\ b_{12} &= -\cos(q_4).\cos(q_5).\sin(q_6) - \sin(q_4).\cos(q_6); \\ b_{13} &= -\cos(q_4).\sin(q_5); \\ b_{21} &= \cos(q_6).\sin(q_4).\cos(q_5) + \cos(q_4).\sin(q6); \\ b_{22} &= -\sin(q_4).\cos(q_5).\sin(q_6) + \cos(q_4).\cos(q_6); \\ b_{23} &= -\sin(q_4).\sin(q_5); \; b_{31} = \cos(q_6).\sin(q_5); \\ b_{32} &= -\sin(q_5).\sin(q_6); \; b_{33} = \cos(q_5) \end{aligned} \tag{18}$$

Note that $R_6^3 = R_A$, hence we have

$$\tan(q_4) = \frac{R_{A23}}{R_{A13}}; \; q_4 = a\tan 2(R_{A13}, R_{A23}) \tag{19}$$

$$\cos(q_5) = R_{A33}; \; q_5 = a\tan 2(R_{A33} \pm \sqrt{1 - R_{A33}^2}) \tag{20}$$

$$\tan(q_6) = \frac{-R_{A32}}{R_{A31}}; \; q_6 = a\tan 2(R_{A31}, -R_{A32}) \tag{21}$$

Finally, the values of all the joint variables $q_1$, $q_2$, $q_3$, $q_4$, $q_5$ and $q_6$ are analytically calculated with Eqs. (7, 10, 13, 19, 20, 21).

## 4 Connection of Both the Twins and Control the Robot

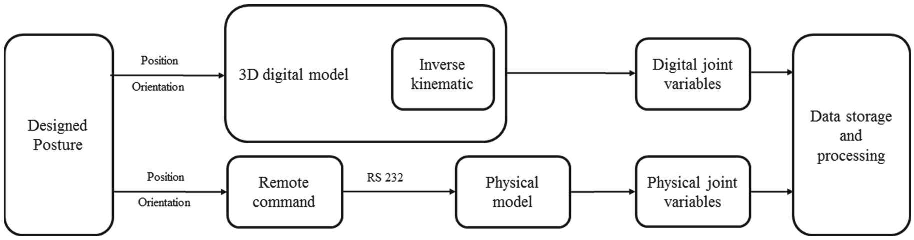



**Fig. 8.** Data flow for the communication between the robot and the digital twin model.

To transfer the kinematic data from a control computer to RV-12SD robot controller, command blocks containing a frame of characters are sent to the robot controller through a RS232 port. This protocol makes it easy for constructing a data flow throughout the software and hardware to enable the twin models (3D digital on computer and physical robot). In this digital-physical system, the kinematic data will be stored and used for other control and monitoring purposes when both the twins operate together in real time (Fig. 8).

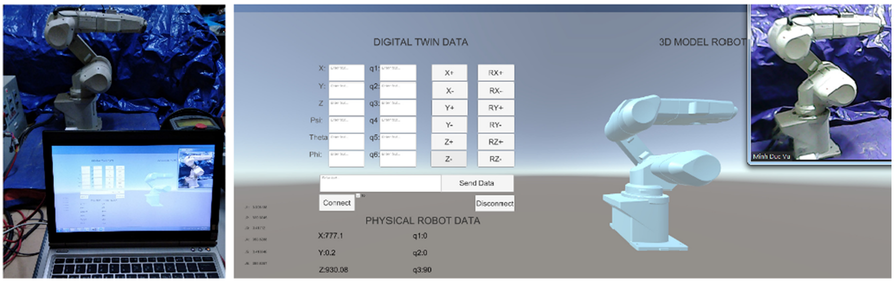



**Fig. 9.** Testing digital twin model

Figure 9 shows the integration of both the designed digital twin and the physical twin (the robot). After several testing scenarios, it has shown that both the models can collaborate well. By using the control panel with the digital twin model, it is able to control real robot from a virtual environment. Note that by using buttons (X+, X–, Y+, Z+, Z–, RX+, RX–, RY+, RZ+, RZ–) with the added window containing a camera signal of the real robot behavior, the real robot movement interacted with the digital twin simulation can be monitored effectively.

## 5 Conclusion

In this paper, a case study about design and implementation of a digital twin for control and monitoring a real industrial robot was presented. The 3D digital twin is designed in

Unity 3D software, which provides advantages for the collaboration and the real time data connection between the physical-digital models. The inverse kinematics of the real robot is studied and an analytical inverse kinematic solution is yielded, which makes it more effectively and precisely for the control of the robot in cooperation with the digital twin. The implementation and testing results shows that controlling and monitoring a real robot with the support of a collaborating digital twin model is feasible and applicable. This method makes it possible to improve the smartness of a robotic system by using the advancement of the recent development of ICT technology. Using this physical-digital twins for offline programming, testing-simulation, control and monitoring when a robot is required to weld a complex path of high curvature is the future work of this study.

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