Application of image recognition technology in digital twinning technology: Taking tangram splicing as an example

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Abstract

Background: With the rapid development of digital twinning technology, the compatibility of digital twinning technology to other technologies is continuously enhanced. It is because of this that the application of image recognition technology in digital twinning technology becomes a reality. However, the key technology of digital twin, the virtual-actual mutual control technology, is not mature enough, and the image recognition technology applied in digital twin technology also has the problem of coordinate system transformation, which becomes an important link of image recognition technology in digital twin.

Methods: Based on the above two problems, we take the tangram splicing project as an example to realize a virtual-actual mutual control method, so that the digital twinning technology can be well presented. Furthermore, we implement an image recognition applied to the conversion of digital twinning technology, so that digital twinning technology and image recognition have a seamless connection, allowing the application range of digital twinning technology to be further expanded.

Results: In this paper, image recognition technology is successfully applied to digital twin technology by adopting the conversion between different coordinate systems and the real and virtual real time control, which makes the applicability of digital twin technology in high-tech fields such as smart factories and smart manufacturing to a higher level.

Conclusions: Finally, through the tangram splicing project, the motion trajectories of the robotic arm and the tangram are consistent with the virtual robotic arm and the tangram in the computer. It is proved that our method can well combine digital twinning technology and image recognition technology.
Keywords
Digital twin, image recognition, robotic arm

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Author roles: Yang Y: Conceptualization, Formal Analysis, Methodology, Validation, Writing – Original Draft Preparation, Writing – Review & Editing; Yang X: Funding Acquisition, Investigation; Li Y: Investigation, Methodology, Supervision; Zou J: Investigation, Supervision; Shi M: Investigation, Supervision; Yang B: Investigation, Supervision; Guo C: Investigation, Supervision; Hu R: Investigation, Supervision; Shi C: Investigation, Supervision; Lu X: Investigation, Supervision; Li Y: Investigation, Supervision

Competing interests: Shanghai Zhijiang Intelligent Technology Co., Ltd. provided most of the funding for this paper, including the hardware and software of all experimental equipment and the assistance of some personnel. At the same time, Shanghai Zhijiang Intelligent Technology Co., Ltd. also trained me on digital twin technology. The real objects contained in this paper are owned by Shanghai Zhijiang Intelligent Technology Co., Ltd. and not owned by me personally.

Grant information: 1. National Key R&D Program of China (Grant No. 2021YFB3501700). 2. Shanghai Science and Technology Committee (STCSM) Science and Technology Innovation Program (Grant No. 22N21900400). 3. National Natural Science Foundation of China (Grant No. 12104311).

The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

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How to cite this article: Yang Y, Yang X, Li Y et al. Application of image recognition technology in digital twinning technology: Taking tangram splicing as an example [version 1; peer review: awaiting peer review] Digital Twin 2022, 2:6
https://doi.org/10.12688/digitaltwin.17451.1

First published: 14 Apr 2022, 2:6 https://doi.org/10.12688/digitaltwin.17451.1
Introduction

In 2012, Glaessegen and Stargel defined digital twin as “an integrated multiphysics, multiscale, probabilistic simulation of a complex product, which functions to mirror the life of its corresponding twin”. Digital twin consists of three parts: the physical product, the virtual product and the linkage between physical and virtual product. At present, the application of digital twin is not common, but digital twin has great potential. At the end of 2016, Gartner, a world-renowned IT research and consulting firm, pointed out in its ‘Top 10 Trends for 2017’ that “hundreds of millions of objects will soon be represented by digital twins”.

Image recognition technology is an important field of artificial intelligence, it refers to the image object recognition, in order to identify a variety of different patterns of the target and object technology. Image recognition technology, as a mature technology, has experienced several peak stages of technological development, and gradually tends to be stable. It is listed as one of the ten typical technology applications in the White Paper on the Judicial Application of Internet Technology issued by the Beijing Internet Court in 2019.

At present, there are very few cases in which image recognition technology is applied to digital twin. However, according to the technical difficulties of image recognition technology and digital twin technology itself, we can deduce what difficulties will exist in the application of image recognition technology to digital twin technology:

- Coordinate system transformation: The transformation of the coordinate system involves the transformation from three dimensions to two dimensions. The transformation of the three-dimensional coordinate system to the two-dimensional coordinate system involves the projection relationship between the dimensions, which is the key point of the transformation.

- Virtual-actual mutual control: The difficulty of virtual-actual mutual control is the real-time linkage between the model and the real object, and the real-time linkage relies on modeling accuracy, real-time connectivity of communication and other important factors.

In this paper, image recognition technology is applied to the digital twin technology, which makes the visual realization of the digital twin more accurate. In this paper, we use the image recognition technology with the digital twin, and the mechanical arm workstation as the chosen research object. We study the key steps and key points in the application of image recognition to digital twin technology, summarize the difficulties in application, and finally verified tangram experiments. Finally, the application of image recognition technology in digital twin technology is successfully realized.

Methods

Hardware preparation

Hardware preparation respectively includes a set of conventional tangram components, KUKA KR6 mechanical arm and its accessories (KUKA Robotics Co., LTD), S7-1200 model programmable logic controller (PLC)(SIEMENS), and a Windows system computer host.

Tangram components. Two 40cm*40cm*3cm pure black bottom plates which are made of ordinary stone were used in this experiment, which were divided into left bottom plate and right bottom plate. The right bottom plate is used to place the scattered tangram components, and the left bottom plate is used to place the stitched tangram components. The bottom plate is black in order to facilitate color processing in the late image recognition. In addition, a set of conventional tangram components is used. The dimensions of tangram components are shown in Figure 1. The central position of each piece of tangram is marked with a pencil line, and the initial rotation angle is specified to facilitate image positioning in the later stage.

KUKA KR6 Mechanical arm and components. The KUKA KR6 mechanical arm (KUKA Robotics Co., LTD) has six axes of freedom, each with a rotation angle of more than 120°, and repeatable accuracy of 0.015mm to 0.2mm, as shown in Figure 2. In this experiment, a two-dimensional industrial camera (Hangzhou Hikvision Digital Technology Co., Ltd.) is
installed on the sixth axis of KUKA KR6 mechanical arm for image recognition, and a circular filling light is installed around the camera. In the process of camera shooting, the annular light filling lamp exposes and fills the light to ensure the consistency and reliability of each image collection. In addition to the image acquisition component, the sixth axis of the KUKA KR6 mechanical arm is equipped with two pneumatic modules, which are respectively connected to two five-point two-way solenoid valves to provide enough suction to suck the tangram. The air valve is connected to the sixth shaft through the air pipe, and the elastic suction cup is installed in the front of it to prevent the physical damage caused by excessive overextension of the mechanical arm.

**S7-1200 PLC.** The control system adopts PLC of SIEMENS S7-1200 and 16×24VDC input and output modules, as shown in Figure 3. PLC selected the configuration 1215DC/DC. S7-1200 model PLC provides 16 input (I) ports and 16 output (O) ports, a total of 32 I/O ports. S7-1200 model PLC also provides the PROFINET communication protocol, for the establishment of virtual I/O channel to convert the real output into analog output to control the KUKA KR6 mechanical arm. In this paper, the PROFINET protocol is used to reduce the communication time between PLC and KUKA KR6 mechanical arm. In this way, the influence of electromagnetic wave on pulse signal is reduced and the accuracy of the experiment is improved. S7-1200 PLC, as the central control system of this experiment, is mainly responsible for multidimensional processing of the KUKA KR6 mechanical arm data and real-time data transmission between KUKA KR6 mechanical arm and the simulation software, Demo3D.

**Software preparation**
In this experiment, the upper computer uses Windows system, and all software supports Windows 7/8/10 system.

*The simulation software.* This experiment uses Demo3D (2015) as the simulation software. Demo3D has a high fidelity animation, simulation and control platform for logistics system, and ADAPTS to various types of PLC. Demo3D communicates with the PLC through OLE for Process Control (OPC) standardized protocol, which is shown in Figure 4. In this experiment, Demo3D software, as the final verification software, was responsible for the motion simulation of the KUKA KR6 mechanical arm model and the tangram component model.

![Figure 3. S7-1200 programmable logic controller (PLC) and its configuration accessories.](image)

![Figure 4. OLE for Process Control (OPC) server.](image)
**Image processing and ordering software.** A draggable graphical user interface (GUI) is set in the command software (software coded by the authors which issues tangram instructions), which contains all the tangram models. You can use the mouse to drag each piece of tangram and adjust its position and angle, as shown in Figure 5. The position of the tangram model in the upper left GUI interface is the actual position of the final real tangram on the left board.

**Objectives of the experiment**
This experiment aims to realize the application of image recognition technology in digital twin through digital twinning software and mechanical arm. Finally, the experiment was validated by combining the scattered jigsaw puzzle pieces into a given shape. The experimental process is shown as follows, and as shown in Figure 6:

- **Build models:** Scale modeling of all experimental related components was performed using SolidWorks (2020). A trial version of SolidWorks is available here.

- **Establish a spatial coordinate system:** By controlling the KUKA KR6 mechanical arm, the spatial coordinate system was established according to the establishment rules.

- **Image recognition:** Through the image processing software VisionPro and image processing algorithm, we conducted image processing of the tangram photos.

- **Coordinate system transformation:** By taking points in pixel coordinate system and spatial coordinate system respectively, the transformation relationship between pixel and spatial coordinate system is established.

- **Virtual actual mutual control:** By transforming the coordinate systems used by different software, the virtual-real mutual control was realized and the time required for communication was reduced.

In this experiment, the PC and PLC respectively act as the main control device and the upper computer system, as shown in Figure 7. As the only interface with the user, the PC is responsible for macro-control between the real system and the virtual model. The PC is also responsible for monitoring the real system and displaying the simulation results in real time while reading the user input and downloading the corresponding program to PLC. As the control device of this experiment, PLC is responsible for the micro-control between the real system and the virtual model, and establishes the connection between the real system and the virtual model through the OPC protocol.

**The experiment process**

**Model establishment and import.** Through SolidWorks, build tangram workbench, tangram model, KUKA KR6 mechanical arm and other components of the model and convert to IGS format. This is then imported into Demo3D and the appropriate model size is selected in Demo3D, as shown in Figure 8.

**Establishment of spatial coordinate system.** By manipulating KUKA PAD to move KUKA KR6 mechanical arm, the spatial coordinate system is calibrated, as shown in Figure 9.
The calibration coordinate system is to establish a spatial coordinate system based on KUKA KR6 mechanical arm and its camera components. The spatial coordinate system is used to determine the actual position of the model only in the software.

In this experiment, a point vertical to the top left vertex of the tangram workbench is taken as the origin of the coordinate system, an edge of the tangram workbench is taken as the X-axis, and the edge that passes through the origin of the coordinate system and is perpendicular to the X-axis is taken as the Y-axis.

First of all, the robot arm was moved through KUKA PAD to find the best position of the visual acquisition point, and...
the position was recorded. The best visual location is to just capture the position of the whole tangram working platform. Second, install the locating pin in KUKA KR6 mechanical arm shaft 6 above, and control the KUKA PAD. Use the global mobile mechanical to make the positioning needle point to the upper left corner of the black bottom plate, then switching model for axial movement. Move up a small distance in the direction of the Z axis, record the origin for the location. Then, according to the selected origin, the adjacent two sides are determined as X axis and Y axis, and the mechanical arm is moved along an axis for a certain distance through the axis movement mode. Then, the position is recorded. Similarly, use this method to operate on another edge and record its final location. According to the above four points (origin of coordinate system, bottom vertices, point on the X-axis, point on the Y-axis), a unique three-dimensional coordinate system can be determined, which is the spatial coordinate system of this experiment.

**Image processing.** After the establishment of the coordinate system, the tangram is randomly placed on the right plate, and the image is collected by moving the mechanical arm to the position of taking photos through KUKA PAD. After the image is sent back to a host computer, the exposure, RGB (red, green, blue), colorless, gray scale adjustment and some image recognition algorithm adjustments are carried out to make the overall color difference of the picture more obvious. Since the color of the bottom plate of tangram is black, the background color of the image after processing must be black, and the tangram after the above processing must be gray in different brightness. In order to make the gray difference more obvious, before the first image processing, a layer of white cardboard was padded to increase the gray level distinction. The gray level is shown in Figure 10. Then, according to the actual situation, select gray areas of different brightness and give them a tangram label.

**Pixel-spatial coordinate system transformation.** The pixel coordinate system is the picture coordinate system. The unit of the pixel coordinate system is the pixel point, that is, each pixel point is a specific position. Since pixel coordinate system is two-dimensional coordinate system and spatial coordinate system is three-dimensional coordinate system, perspective projection method which involves extending the coordinate system by mapping, is used to realize the conversion between the pixel and spatial coordinate systems. The specific scaling relationship of perspective projection is shown in Figure 11 and Figure 12.

First of all, the vertex and the center position of the tangram are selected as the position information points of the tangram, in which the center position is the accurate position of the robot arm to absorb the tangram. All the tangram plates were randomly placed on the workbench and moved the mechanical arm to the position of the visual point for shooting. Then, the attachment of the mechanical arm was replaced and the positioning needle was installed. Then, the positioning needle was moved to all the position information points respectively by moving the mechanical arm, so as to record the specific positions of all the tangram plates in the spatial coordinate system.

Secondly, the corresponding position information points are selected from the current gray image and recorded. Finally, a total of seven groups of data (corresponding to seven tangrams) including X, Y axis parameters, rotations and parameters used in special cases, such as height or error adjustment were recorded and a rotation matrix was established based on these 7 groups of data. The specific implementation effect is shown in Figure 13.

**Real-time virtual-actual mutual control**

**Real-time virtual-actual mutual control of mechanical arm.** Real-time virtual-actual mutual control of the mechanical mainly involves three key aspects: on the one hand, PLC can read, process and forward the position information of the mechanical arm in real time; on the other hand, Demo3D can control the motion trajectory of the mechanical model in real time; however, the real-time communication between PLC and Demo3D is also involved. In Demo3D, instead of
directly controlling the robot arm model, Demo3D uses the embedded QuickLogic programming module to complete the motion control of the robot arm model. The QuickLogic programming module is the robot programming module that comes embedded with Demo3D. The QuickLogic programming module encapsulates a large number of underlying functions and presents these functions in a modular way, simplifying the overall motion control process of the robot.

For the information communication between PLC and Demo3D, address mapping is adopted. Each axis of the mechanical arm is represented by a unique address in the PLC memory and Demo3D memory, and the mapping relationship between the PLC memory address of the mechanical and Demo3D memory address is the key to the real-time virtual-actual mutual control of the mechanical arm. The specific mapping relationship of the mechanical arm’s address is shown in Figure 14.

Real-time virtual-actual mutual control of the mechanical is divided into the following four steps, and it is shown in Figure 15.

1. PLC reads the position of the mechanical arm: the PLC and the mechanical arm are connected through the network cable, and through the PROFINET protocol for information interaction, PLC by reading the six axes of the mechanical arm corresponding to the I/O port to obtain their current position.

2. Data processing by PLC: the position information of the robot arm read back by PLC is the initial information, and its information format does not conform to the call format of QuickLogic module. Therefore, the format of the initial information is converted through the built-in module of PLC to make it conform to the call format of QuickLogic module, and the processed data is stored in the intermediate register.

3. QuickLogic call data: the QuickLogic module directly calls the position information of the corresponding mechanical arm in the PLC intermediate register, and by setting the cyclic call function in the QuickLogic module, the position information is refreshed and read once every 0.01s. The program code is shown in Figure 16.

4. Model motion feedback: After the QuickLogic module reads the position information, the position information is fed back to Demo3D, which is then fed back to the robot arm model, finally making the movement of the robot arm and the movement of the model present the same state.

**Virtual-actual mutual control of tangram.** Each tangram in Demo3D contains three position parameters, which are the X axis, the Y axis and the rotation angle \( \alpha \). The position variable of tangram object belongs to the spatial coordinate system, while the position variable of tangram model belongs to the pixel coordinate system. As for the rotation angle, the center point and initial rotation angle of tangram have been set to 0° during the initial model matching. The point table information of tangram is shown in Figure 17.

After the shooting of the robot arm at the position of the visual point is completed, the tangram model is placed to the corresponding position according to the transformation of the coordinate system. It is worth mentioning that the rotation angle of each piece of tangram is determined by the way of rotation overlap. By overlapping the center point and rotating the angle to the initial rotation angle, the rotation angle of tangram is obtained.
In the actual end, after image processing, the mechanical arm moves to the position above the tangram to be moved, opens the cylinder, draws the tangram, and then moves the tangram to the preset position in the order software. At the virtual end, when the cylinder is opened, Stick function in QuickLogic is called (STCIK function is to set the parent-child function, and the set child unit will move along with the parent unit). The moving tangram is set as the child of the robot arm model and moves along with the robot arm. When the cylinder is closed, Stick function is also used to cancel the sub-level relationship between the tangram and the mechanical arm, so as to complete the movement of the virtual tangram. The Stick function call of the tangram is shown in Figure 18.

Through the experimental steps of this paper, the virtual-actual mutual control of tangram project is finally completed, as shown in Figure 19. As shown in the Figure 19, the mechanical arm and the mechanical arm model, and the tangram and the tangram model are in the same state.

**Conclusions**

In this experiment, image recognition technology is applied to digital twin through a tangram splicing project, which expands the application field of digital twin, excavates the possibility of image recognition technology in multiple fields, and provides a way to realize the fusion of image recognition technology and digital twin. The seamless integration of image...
Figure 17. Tangram point table.

| MD1000 | ReadFromPLC m_t1.quliacX |
| MD1004 | ReadFromPLC m_t1.quliacY |
| MD1008 | ReadFromPLC m_t1.quliacA |
| MD1012 | ReadFromPLC m_t2.quliacX |
| MD1016 | ReadFromPLC m_t2.quliacY |
| MD1020 | ReadFromPLC m_t2.quliacA |
| MD1024 | ReadFromPLC m_t3.quliacX |
| MD1028 | ReadFromPLC m_t3.quliacY |
| MD1032 | ReadFromPLC m_t3.quliacA |
| MD1036 | ReadFromPLC m_t4.quliacX |
| MD1040 | ReadFromPLC m_t4.quliacY |
| MD1044 | ReadFromPLC m_t4.quliacA |
| MD1048 | ReadFromPLC m_t5.quliacX |
| MD1052 | ReadFromPLC m_t5.quliacY |
| MD1056 | ReadFromPLC m_t5.quliacA |
| MD1060 | ReadFromPLC m_t6.quliacX |
| MD1064 | ReadFromPLC m_t6.quliacY |
| MD1068 | ReadFromPLC m_t6.quliacA |
| MD1072 | ReadFromPLC m_t7.quliacX |
| MD1076 | ReadFromPLC m_t7.quliacY |
| MD1080 | ReadFromPLC m_t7.quliacA |

Figure 18. Tangram stick function call.
recognition technology and digital twinning technology can be applied in many fields, such as express sorting in the logistics industry, product screening in the manufacturing industry, and even in the field of education to provide students with a practical training course on digital twinning technology. In summary, digital twin is destined to go to the stage of history, in which image recognition technology plays a very key role, and the application of image recognition technology in digital twin is destined to become the trend of the next era.

Data availability
The underlying data and software code cannot be made publicly available because of the privacy policy of Shanghai Zhijiang Intelligent Technology Co., Ltd, who sponsored and provided the technical support for all of the paid software and hardware used in this study. Due to trade secrets and company-related privacy policies, the data and code cannot be provided publicly. Interested readers/reviewers can contact Yifan Yang via email (493712389@qq.com) to request access to the underlying data and code. Interested parties should provide a proposal of what they want to do with the data, and this proposal would need to be confirmed by Shanghai Zhijiang Intelligent Technology Co., Ltd. Normally, use for academic research purposes will be permitted and any requests for commercial use will be denied.

Acknowledgements
Thanks to the corresponding author of this article, Mr. Shi Chengzhang, technical director of Shanghai Zhijiang Intelligent Technology, for his strong support of this experiment.

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