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Parallel Robot Controlled by PLC and its Digital Twin

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ABSTRACT: Modern ways of device development use the concept of a digital twin. A digital twin is an accurate digital copy of something that exists or is planned to be realized in the physical world. The digital twin is not only a virtual model of the physical system, but also a dynamic data and status information carrier obtained through a series of IoT-connected sensors that collect data from the physical world and send it to machines. The digital twin provides an overview of what is happening to the device in real time. This is very important in industry as this information is helpful to reduce maintenance issues and ensure production performance. This work focuses on the design and creation of a cybernetic physical system and its digital twin, based on CAD system modeling in conjunction with simulation and programming tools connected to real and simulated control systems. This process accelerates the development of the application implementation with the possibility to create a PLC control program and tune the system already in the design phase. Thus, the physical realization can be done in parallel with the programming and creation of the HMI interface. Modular programming will further accelerate software development [1]. The created system and its digital twin serve as a unified teaching tool without the need for real devices to be used by many students and users. This approach allows testing of program algorithms without the risk of damaging physical devices and is also suitable for distance learning.

1 INTRODUCTION

Parallel robots were developed as superstructure machines with motors included in the basic structure to drive the attached arms. The advantage of this design is that it reduces the weight in the arms and therefore provides very high acceleration and speed. On the other hand, they have a low load capacity. A simplified drawing of a parallel (delta) robot is shown in Figure 1.

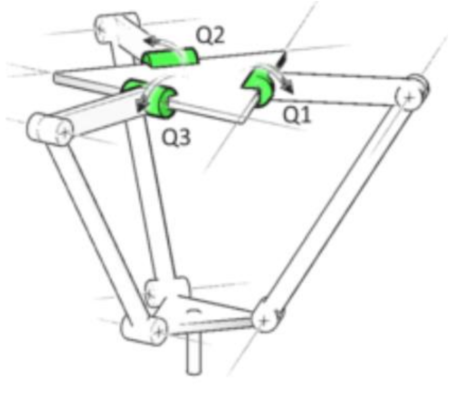

Figure 1. Three-axis parallel delta-type robot [2]

Pierrot et al. [3] provide an efficient description of the Delta kinematic structure and describe implementation focused on high speed control of a parallel robot. Mathematical models of delta robots developed with different methods and considering various views are available in a number of publications, e.g. in [4] there are simulations used first to obtain the inverse solution and spline curves and spline function, followed by obtaining the direct solution; in [5, 6] dynamics modelling and verification of a new structure of spatial parallel manipulators are presented; Liu et al. [7] obtain the forward kinematic solution by geometric method and analyze the workspace of the Delta robot. A special attention is paid to control of parallel delta robots: Aguilar-Mejia et al. [8] use an adaptive neural network controller to solve the problem of tracking trajectories; Rachedi [9] attempts to incorporate the nonlinear inverse dynamic model of the system in the H∞ control scheme; Bengoa et al. [10] present a new model based control approach, the stable Extended CTC (Computed Torque Control); Stapornchaisit et al. [11] discuss bilateral control in delta robot by using Jacobian matrix.

Delta robots can be implemented with linear or rotary actuators. Linear actuators can be hydraulic pistons or electric linear motors, which are similar in principle to standard electric motors, except that the stator is elongated. More commonly used linear actuators are mechanical actuators that use standard electric motors that include a transmission part that converts rotary motion into translational motion. This is, for example, a connection between a helix and a nut that is fixed so that it does not rotate with the helix, which moves in a corresponding direction along the helix depending on the direction of rotation. The group of delta robots with rotary drives makes up the vast majority of industrial robots. Stepper motors or servo motors are used as rotary drives, which makes it possible to determine the exact position of the rotation angle of a particular axis.

A digital twin can be used to speed up design and creation. A digital twin is an exact digital copy of something that exists or is planned to be built in the physical world. By creating a digital twin, we can improve processes, increase efficiency, and discover any problems that may arise. We can then apply these adjustments and improvements to the existing system with a much lower risk and higher return on investment.

2 PROBLEM DEFINITION

The goal of the work is the design and realization of a parallel robot based on a simulation model, the so-called digital copy (digital twin). By using a digital copy, the commissioning time of the system shall be reduced. This solution procedure is intended to create a methodology for optimizing the development of applications for industry. Based on the investigation of the application possibilities, a list of tasks for application determination is created. The control PLC, in addition to controlling the parallel robot, will form a network node to which embedded devices can be connected. Currently, there is a trend in the field of industrial buses to unify these standards and thus eliminate their mutual incompatibility.

3 CREATING A MODEL AND A DIGITAL TWIN OF THE ROBOT

Design and creation of cyber-physical systems and their digital copies, based on CAD system modeling with tools in conjunction with simulation and programming tools, connectable with real control systems and simulated (PLC sim), accelerate the development of application implementation and increase efficiency, with the possibility of creating a control program for PLC and system tuning already in the design phase, which achieves a more economically advantageous and overall more economical solution.

The use of digital twin technology improves software sustainability and rapid software development. The created digital twin will serve as a teaching tool for programming without the need for a real device.

The digital twin of the delta robot is implemented in SceneViewer 4.1. It is a free downloadable software from B&R. The principle of our project solution is shown in Figure 2. In order to create a fully functional digital copy of this workstation, it was necessary to modify the 3D model that was created. The modification of the model consisted of its division into four independent parts and the creation of a movable connection using joints (Revolve joints). The connection to the control system is realized by transferring variables using OPC UA via Ethernet TCP / IP network connection.

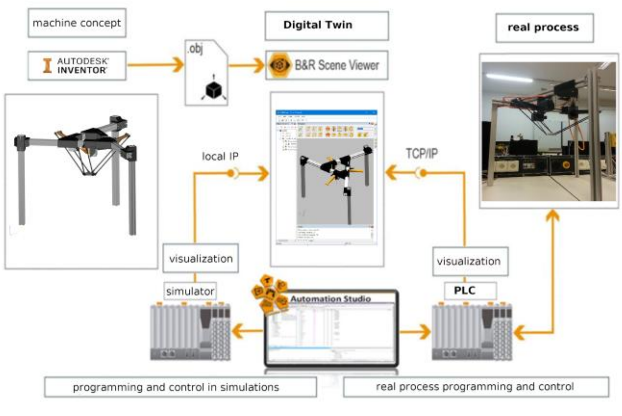

Figure 2. The principle of our solution using a digital twin

4 CONSTRUCTION OF A REAL DEVICE

The hardware realization of the delta robot is based on a simple structure with three stepper motors 80MPD1.300S014-01 (Figure 4 on the left side) in the base part driving the connected arms. The basic construction is made of 30 mm aluminum profiles. The main part - the base for the effector - is fixed with arms connected to the motors. The motors are attached to the aluminum profiles using brackets (Figure 4 on the right side), which we designed in the Fusion 360 program and cut out with a laser from iron plate. The complete structure of our delta robot is shown in Figure 5. The Delta robot is controlled by a PLC (type PPC3100) to which a Raspberry PI 4 MODEL B with a Raspberry V2 image recognition camera is connected (Figure 3).

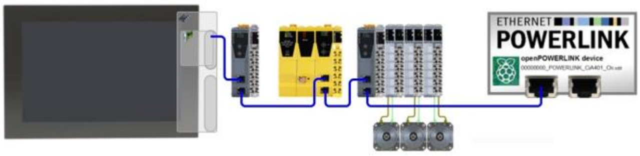

Figure 3. Hardware configuration in the Automation Studio

Figure 4. Left: Stepper motor 80MPD1.300S014-01 [12], right: console model designed in Fusion 360

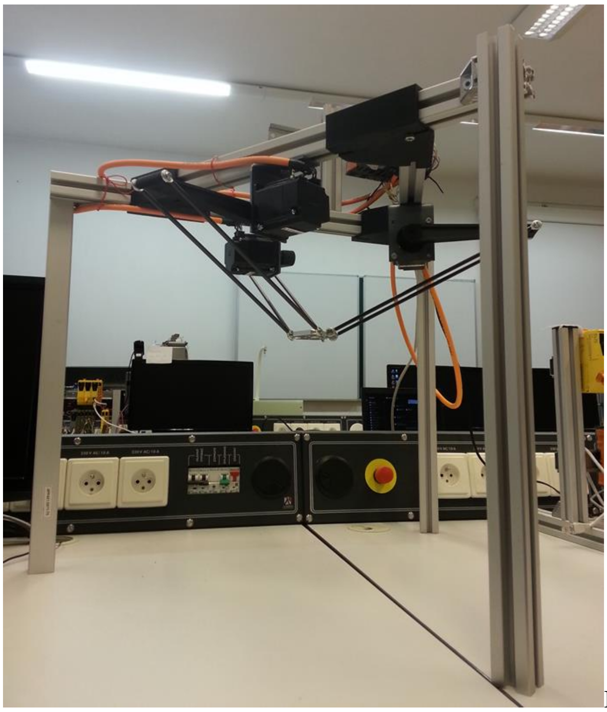

Figure 5. Our constructed delta robot

5 COMMUNICATION INTERFACE REQUIREMENT

An important requirement is the use of a deterministic, reliable and fast communication bus. Ethernet POWERLINK (EPL) is an open real-time Ethernet protocol that uses the CANopen object dictionary concept and its communication mechanisms to provide features such as interoperability, flexibility and configurability. Our solution therefore uses an industrial EPL network to connect I/O system with inverters for stepper motors, as well as conection to an embedded system (Raspberry Pi 4, which processes the image) to a PLC. This open network protocol has been implemented in an embedded system. The communication cycle time is 2000 μs. Image processing is done by Raspberry Pi using operating system Raspbian Jessie kernel 5.10 with implemented RT -PREEMPT. RT -PREEMPT is a patch for the Linux kernel that turns Linux into a real-time operating system. The cyclic test program provides a simple way to evaluate the maximum latency of the system. The cyclic test measures how long it takes to respond to an interrupt generated by the CPU timer. The measured maximum latencies dropped from 960 μs to 71 μs. The PLC programming is done via the Ethernet TCP / IP protocol.

6 PROGRAM CREATION FOR RASPBERRY PI

Image processing is a method that performs certain operations to obtain an enhanced image or to obtain useful information from an image. We use an 8MP v2.1 camera to capture images. It is also possible to use another external USB camera. The OpenCV library has more than 2,500 optimized algorithms that include a comprehensive set of computer vision and machine learning algorithms. These algorithms can be used to detect and recognize faces, identify objects, track moving objects, extract 3D models of objects, and so on. In our application, we use an algorithm to detect shapes: square, rectangle / trapezoid, triangle, and circle. After evaluating the shape, information about the type of shape and its coordinates is sent to the PLC (Figure 6 and Figure 7).

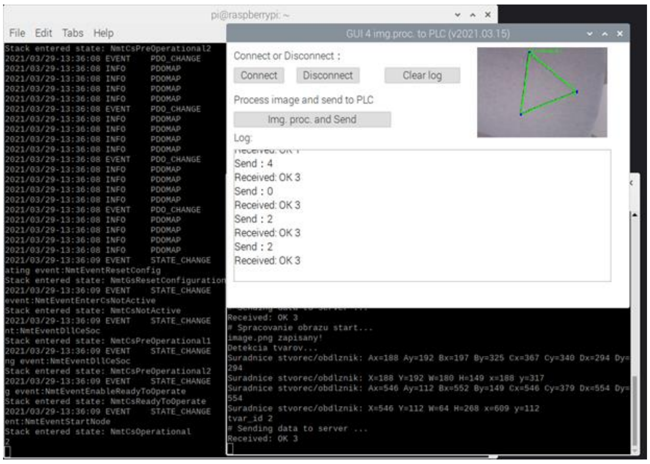

Figure 6. Programs for deterministic communication and image processing

Figure 7. A view on a robot effector

7 CREATING A CONTROL PROGRAM FOR PLC

We have created a hardware configuration according to Figure 3. By adding an XDD file (XML device description) from the source code for openPOWERLINK to the Automation Studio programming tool, we have an embedded system available. Communication parameters and I / O variables were set in the Automation Studio. The programming language for PLC programming is structured text (ST - higher programming language according to the IEC 61131 standard). The ACP10_MC and TRF_DATA13 libraries, which are part of the Automation Studio [2] and [13], were used to control the delta robot. The implementation of motor control algorithms uses the "PLCopen motion control" standard, which defines the basic function blocks that can be used repeatedly for several hardware platforms [14]. This reduces development, diagnostics and maintenance costs. We have implemented our own forward and inverse kinematics; the forward kinematics is described in chapter 8. A visualization is also created for the control program, which allows the user to select several modes of operation: manual motor control, learning mode - training of movement from sensed positions and movement based on the recognized shape.

8 CONTROL SYSTEM

The forward kinematics determine the position and orientation of the tool center point given the values for the actuated joint angles of the robot. Drawing of the delta robot spheres is shown in Figure 8.

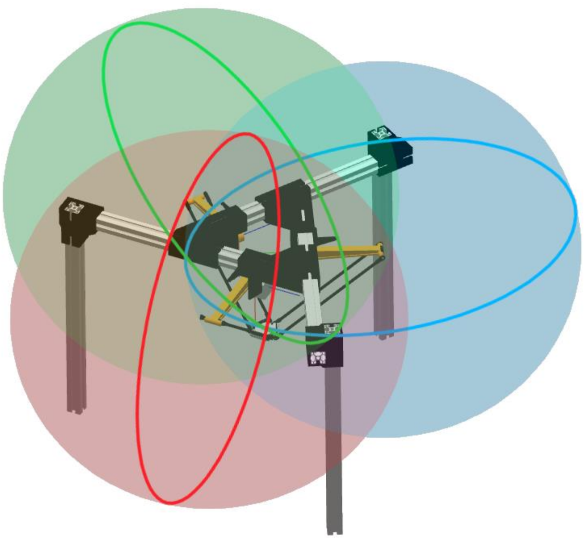

Figure 8. Drawing of the delta robot spheres

To find the coordinates (x, y, z), we need to solve set of three equations of spheres which can be created with radius re. From the equation for a sphere:

$$(x-x_i)^2+(y-y_i)^2+(z-z_i)^2=r_e^2 \quad (1)$$

here are equations of three spheres:

$$x^2+(y-y_1)^2+(z-z_1)^2=r_e^2 \quad (2)$$

$$(x-x_2)^2+(y-y_2)^2+(z-z_2)^2=r_e^2 \quad (3)$$

$$(x-x_3)^2+(y-y_3)^2+(z-z_3)^2=r_e^2 \quad (4)$$

modified as:

$$x^2+y^2+z^2-2y_1y-2z_1z=r_e^2-y_1^2-z_1^2 \quad (5)$$

$$x^2+y^2+z^2-2x_2x-2y_2y-2z_2z=r_e^2-x_2^2-y_2^2-z_2^2 \quad (6)$$

$$x^2+y^2+z^2-2x_3x-2y_3y-2z_3z=r_e^2-x_3^2-y_3^2-z_3^2 \quad (7)$$

When:

$$w_i=x_i^2+y_i^2+z_i^2 \quad (8)$$

then:

$$x_2x+(y_1-y_2)y+(z_1-z_2)z=\frac{(w_1-w_2)}{2} \quad (9)$$

$$x_3x+(y_1-y_3)y+(z_1-z_3)z=\frac{(w_1-w_3)}{2} \quad (10)$$

$$(x_2-x_3)x+(y_2-y_3)y+(z_2-z_3)z=\frac{(w_2-w_3)}{2} \quad (11)$$

When we subtract (4)-(5):

$$x=a_1z+b_1 \quad (12)$$

$$y=a_2z+b_2 \quad (13)$$

then:

$$a_1=\frac{1}{d}\left[(z_2-z_1)(y_3-y_1)-(z_3-z_1)(y_2-y_1)\right] \quad (14)$$

$$a_2=-\frac{1}{d}\left[(z_2-z_1)x_3-(z_3-z_1)x_2\right] \quad (15)$$

$$b_1=-\frac{1}{2d}\left[(w_2-w_1)(y_3-y_1)-(w_3-w_1)(y_2-y_1)\right] \quad (16)$$

$$b_2=\frac{1}{2d}\left[(w_2-w_1)x_3-(w_3-w_1)x_2\right] \quad (17)$$

$$d=(y_2-y_1)x_3-(y_3-y_1)x_2 \quad (18)$$

Now we can substitute (12) and (13) in (5):

$$\left(a_1^2+a_2^2+1\right)z^2+2\left(a_1+a_2\left(b_2-y_1\right)-z_1\right)z+ \\ +\left(b_1^2+\left(b_2-y_1\right)^2+z_1^2-r_e^2\right)=0 \tag{19}$$

Finally, we need to solve this quadratic equation and find *z*, and then calculate *x* and *y* from (12) and (13).

To meet the requirement of safe process control, the system would need to be analyzed to implement safety functions with a PLC. The articles [15], [16] and [17] address this issue.

9 CONCLUSION

We have successfully designed a delta robot model, which we used in SceneViewer to create a digital twin that is connected to a PLC control system programmed in Automation Studio. The variables are transmitted using OPC UA. A digital twin of the robot helped us to facilitate and optimize the construction of a real delta robot. We constructed the delta robot from aluminum parts and plastic parts printed on a 3D printer. The robot controller allows you to control it manually in three axes, learn endpoint positions, and run a shape recognition subroutine using the openCV library and render them to the robot endpoint. The result of the project is a fully functional parallel robot that can be used in teaching and in promotional activities. Also, a digital twin of the robot can be used for simulation, experimentation, and training, either with a connection to the robot or without the need for physical hardware. Employment of robotics in specific, high-value naval applications is an opportunity that exists but has not been fully used yet [18].

ACKNOWLEDGEMENTS

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