

# Development, Kinematic Modeling and Analysis of 3 (DoF) Pneumatic Gantry Robot

Awad Eisa G. Mohamed, and Abuobeida Mohammed Elhassan

**Abstract**—Low friction pneumatic cylinders are now being considered in applications for which only electric motors or hydraulics were previously considered suitable. One potential application of low friction pneumatics is robotic for metallurgical operations where the high power to weight ratio and low cost could be exploited. As part of an ongoing project to develop a pneumatic robot, this paper presents the kinematic analysis of pneumatic cylinder characteristics that simplifies controller design. Using mathematical modeling and simulation, non-linearity of modern pneumatic systems has been investigated. The derived models give an excellent representation of the system, despite the inclusion of a simplified friction model.

**Index Terms**—Pneumatics, Robot, Simulation, Modeling.

## I. INTRODUCTION

Robot kinematics is mainly falling in to two types: forward and inverse kinematics. Forward kinematics is also known as direct kinematics. In forward kinematics, the length of each link and the angle of each joint are given, and we have to calculate the position of any point in the work volume of the robot [1]. In inverse kinematics, the length of each link and position of the point in work volume is given and we have to calculate the angle of each joint. To accomplish a task in an application, we need to control the position and orientation in various coordinate systems such as world, work piece to tool. In order for a robot to go to certain place at certain orientation conveniently, it is necessary to know the relationship between the joint coordinate system and some other systems, such as base or tool systems [2]. Robots are used in many industries like automobile, semiconductor, electronics, aerospace food and beverage, pharmaceutical, consumer goods, plastics, construction, and medical devices. However, the use of robots for metallurgical operations such as hot-metal ladle handling, heat treatment etc. is rather limited due to many environmental and safety reasons [3][4].

In the present work, the development of foreword kinematic modeling and simulation for the pneumatic robot (scaled-down model) is described in detail.

## II. PNEUMATIC ROBOT ARM FOR PICK AND PLACE

The main features of the Unit are: a) 3 Three axis

Cartesian type manipulator, b) each degree of operation by rod-less and double acting pneumatic actuators, c) Air Operated vacuum gripper, d) Capacitive proximity sensor for detecting the presence of the bucket containing components for heat treatment and e) Two types of operational convenience, push – button for continuous operation and on/of, switch for one cycle operation.

The function of the above Pick & Place robot is: a) to detect the presence of the bucket in front of the capacitive proximity sensor and b) to pick the basket of components to be heat treated/ ladle for pouring, and place it in the furnace / to position over moulds in a gentle manner.

Fig. 1 shows the constructional details of the 1:8 model of the proposed robotic system for metallurgical operations. This scheme is proposed to be extended for three-dimensional robot later.

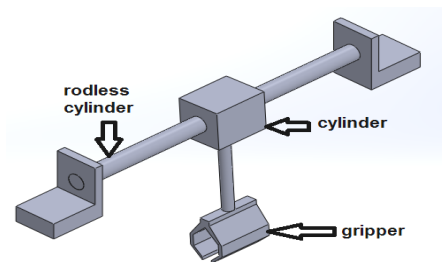


Fig. 1: Schematic diagram of the Robot

## III. FABRICATION, TESTING AND USE IN A MANUFACTURING APPLICATION

Fig. 2 shows the scaled down model of the fabricated pneumatic robot under testing. After a large number of trials with this robot, a full three-dimensional Cartesian robot for use in a metallurgical/heat treatment shop is developed based on similar scheme.

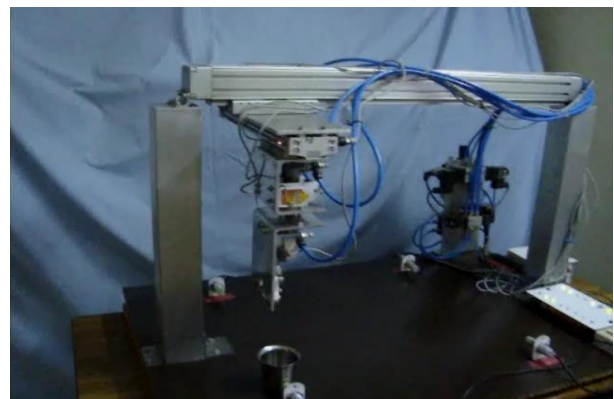


Fig. 2. Pneumatic Robot under testing

Fig.3 shows the three-dimensional Cartesian robot, in which station 1 can be the input station for the raw buckets

Published on June 2, 2020.

A. E. G. Mohamed, Department of Mechanical Engineering, Omdurman Islamic University, Sudan.

(e-mail: sirairabi@gmail.com)

A. M. Elhassan Department of Communication Engineering, Al-Neelain University, Sudan.

(e-mail: dr.obida@hotmail.com)

containing components to be heat treated, station 2 corresponding to a heating oven for quenching or tempering, station 3 for the vat of quenching medium or a sand bed for slow cooling and station 4 for unloading of the buckets on an output conveyor.

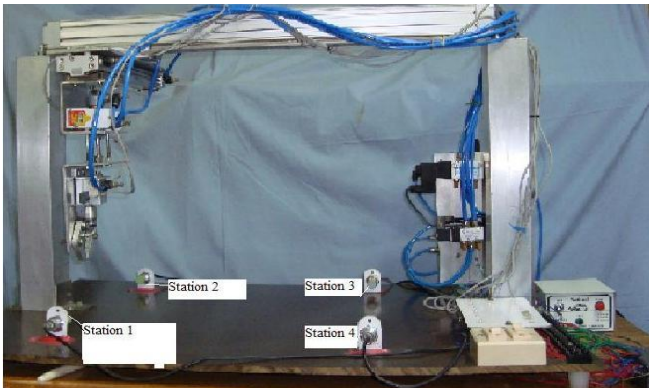


Fig.3. Cartesian pneumatic robot Configured as in a metallurgical factory

#### IV. KINEMATIC MODELING OF PNEUMATIC ROBOT

The manipulator transformation matrix and D-H representation [5].

Fig.4 and table 1, show the kinematic modeling of the mechanism of the robot scheme.

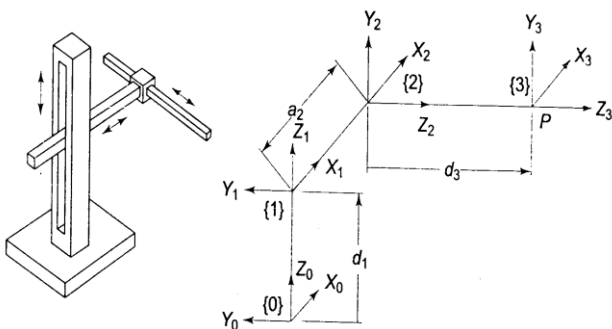


Fig. 4: Frame assignment for a 3-DOF Cartesian configuration arm

TABLE I: JOINT LINK PARAMETERS FOR CARTESIAN ROBOT

Link	$a_i$	$\alpha_i$	$d_i$	$\theta_i$
1	0	0	$d_1$	0
2	$a_2$	$90$	0	0
3	0	0	$d_3$	0

The transformation matrix at every joint is given by Danavit – Hardenberg representation

$$D-H = \begin{bmatrix} C\theta_{i0} & -S\theta_i C\alpha_i & S\theta_i S\alpha_i & a_i C\theta_i \\ S\theta_i & C\theta_i C\alpha_i & -C\theta_i S\alpha_i & a_i S\theta_i \\ 0 & S\alpha_i & C\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_1 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

$$A_2 = \begin{bmatrix} 1 & 0 & 0 & a_2 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$$A_3 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

After using the above transformations,

$$A_1 A_2 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & a_2 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Therefore, the final transformed matrix is given by

$$D-H = \begin{bmatrix} 1 & 0 & 0 & a_2 \\ 0 & 0 & -1 & d_3 \\ 0 & 1 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

Hence,

- $X_E = a_2, Y_E = d_3, Z_E = d_1$

The end-effector coordinators are  $(a_2, d_3, d_1)$  and in the present case are:  $a_2 = 200$  mm,  $d_3 = 500$  mm,  $d_1 = 30$  mm at the end of the operation of the pneumatic cylinder.

#### A. Forward Kinematic Analysis

The position of end-effector  $(3_q)$  with respect to the base coordinate system  $(0_q)$  can be found as bellow [6] : Assume that:

$$0q = [q_x, q_y, q_z, 1]^T \quad (5)$$

$$3q = [q_u, q_v, q_w, 1]^T \quad (6)$$

Then

$$0q = 0_{A_3} 3q \quad (7)$$

$$\begin{bmatrix} q_x \\ q_y \\ q_z \\ 1 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & a_1 + d_3 \\ 0 & -1 & 0 & -d_3 \\ 1 & 0 & 0 & a_3 + a_2 + a_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} q_u \\ q_v \\ q_w \\ 1 \end{bmatrix} \quad (8)$$

$$\begin{bmatrix} q_x \\ q_y \\ q_z \\ 1 \end{bmatrix} = \begin{bmatrix} q_w + a_1 + d_3 \\ -q_v - d_2 \\ q_z + a_3 + a_2 + d_1 \\ 1 \end{bmatrix} \quad (9)$$

By comparing the tow side of equation (9) we can get:

$$q_x = q_w + a_1 + d_3 \tag{10}$$

$$q_y = -q_v - d_2 \tag{11}$$

$$q_z = q_u + a_3 + a_2 + d_2 \tag{12}$$

by arrangement  $E_q$ . (10, 11,12) we get:

$$q_u = q_z - a_3 - a_2 - d_1 \tag{13}$$

$$q_v = -q_y - d_2 \tag{14}$$

$$q_w = q_x - a_1 - d_3 \tag{15}$$

**B. Linear Velocity of End-Effector (V)**

By using Jacobean relationship we can found End-effector velocity as follow:

$$V = \begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix} = \begin{bmatrix} d_x \\ d_y \\ d_z \end{bmatrix} = J \cdot \begin{bmatrix} \dot{d}_1 \\ \dot{d}_2 \\ \dot{d}_3 \end{bmatrix} \tag{16}$$

$$V = \begin{bmatrix} dq_u \\ dq_v \\ dq_w \end{bmatrix} = J \cdot \begin{bmatrix} \dot{d}_1 \\ \dot{d}_2 \\ \dot{d}_3 \end{bmatrix} \tag{17}$$

$$J = \begin{bmatrix} \frac{\partial q_u}{\partial d_1} & \frac{\partial q_u}{\partial d_2} & \frac{\partial q_u}{\partial d_3} \\ \frac{\partial q_v}{\partial d_1} & \frac{\partial q_v}{\partial d_2} & \frac{\partial q_v}{\partial d_3} \\ \frac{\partial q_w}{\partial d_1} & \frac{\partial q_w}{\partial d_2} & \frac{\partial q_w}{\partial d_3} \end{bmatrix} \tag{18}$$

By deriving equations (13, 14, 15) we can get:

$$\frac{\partial q_u}{\partial d_1} = -1 \tag{19}$$

$$\frac{\partial q_v}{\partial d_1} = 0 \tag{20}$$

$$\frac{\partial q_w}{\partial d_1} = 0 \tag{21}$$

$$\frac{\partial q_u}{\partial d_2} = 0 \tag{22}$$

$$\frac{\partial q_v}{\partial d_2} = -1 \tag{23}$$

$$\frac{\partial q_w}{\partial d_2} = 0 \tag{24}$$

$$\frac{\partial q_u}{\partial d_3} = 0 \tag{25}$$

$$\frac{\partial q_u}{\partial d_3} = 0 \tag{26}$$

$$\frac{\partial q_w}{\partial d_3} = -1 \tag{27}$$

Substitute Equations (19, 20... 27) into equation (18) we get:

$$J = \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \tag{28}$$

We note that this is Jacobean matrix it has no singular points and the robot can move into any point of its workspace. Then:

$$V = \begin{bmatrix} \dot{d}_u \\ \dot{d}_v \\ \dot{d}_w \end{bmatrix} = \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} \dot{d}_1 \\ \dot{d}_2 \\ \dot{d}_3 \end{bmatrix} = \begin{bmatrix} \dot{d}_1 \\ \dot{d}_2 \\ \dot{d}_3 \end{bmatrix} = [\dot{d}_1 \ \dot{d}_2 \ \dot{d}_3]^T \tag{29}$$

**C. Forward Kinematic Gantry Robot System-Study & Result**

The robot performance is related to the specification of its tasks. A task can be interpreted as a temporal relation between kinematics and inertial parameters. After the definition of the manipulator movement, the kinematics parameters are obtained for the specified path. Then these data are solved by MATLAB, which results are used to determine the end-effectors extremity position and velocity. For the given set of parameters, a program in MATLAB is made. Developed model is used to determine position of end-effectors. For the values of  $a_2 = 200$  mm,  $d_3 = 500$  mm,  $d_1 = 30$  mm, results obtained is as curve shown in Fig 5.

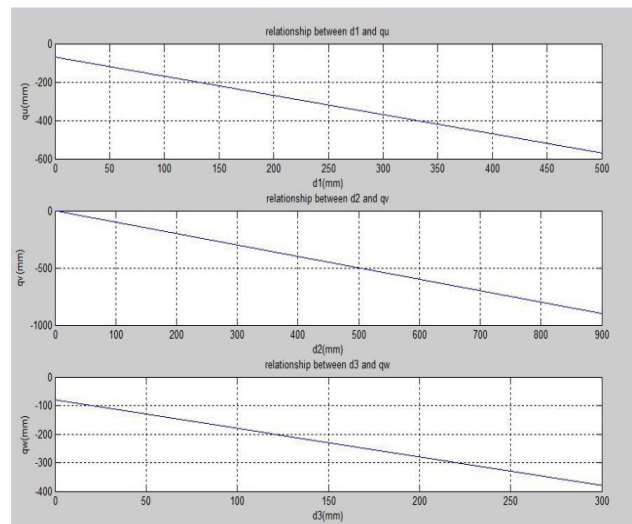


Fig 5. Position of the end-effectors VS Joint variables

**V. CONTROL SYSTEMS**

The control system is designed based on PLC instead of human power. The development of this system can be eliminated the usage of human power to pick up things, increase productivity, efficiency, pinch the production time, Rapid, flexible and safe by experiments [7][8].

The control system is configured by using a programmable logic controller as a controller as well as magnetic proximity sensors for sensing purpose and solenoid direction control valves for actuation.

The control scheme is given in Fig.6 [9][10].

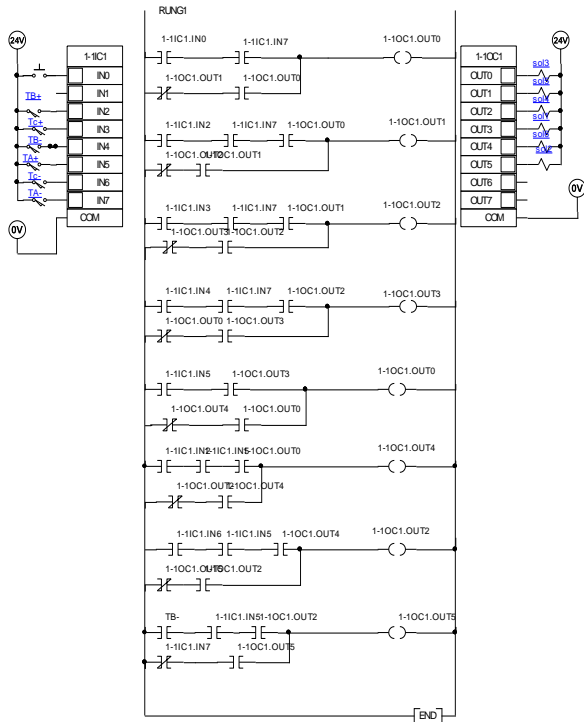
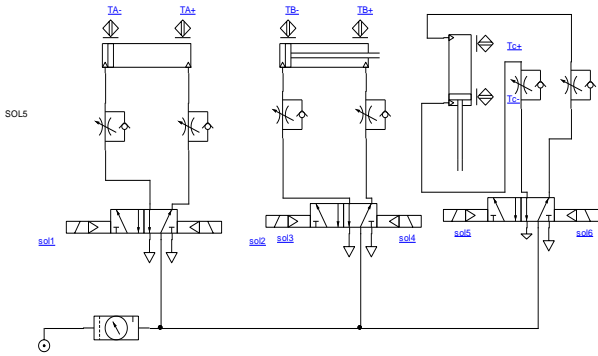


Fig.6. Control scheme for the robot

VI. SIMULATION OF THE ROBOT SCHEME

The simulation of the robot scheme has been carried out using automation studio software. [3] In these simulations, the rod less cylinder is operated with a pressure of 5 bar. Figs.7-10 show variation of a) linear speed of rodless, b) vertical cylinder for picking up the bucket, c) gripper cylinder and d) acceleration of the rodless cylinder.

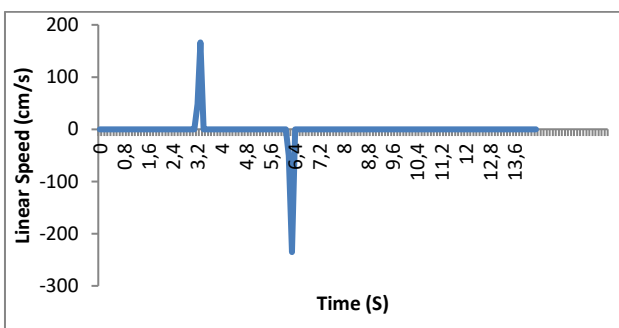


Fig. 7. The variation of linear speed of rodless cylinder 200 mm with time in pressure 5 bar

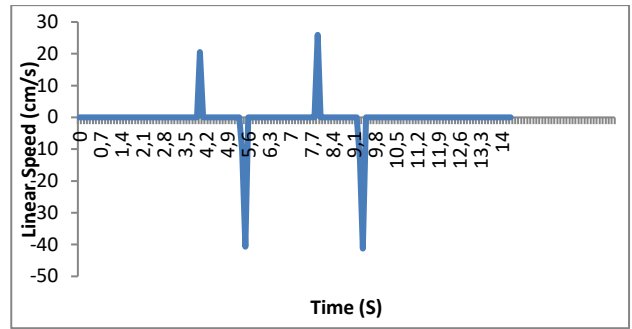


Fig. 8. The variation of linear speed of vertical cylinder with time in pressure 5 bar

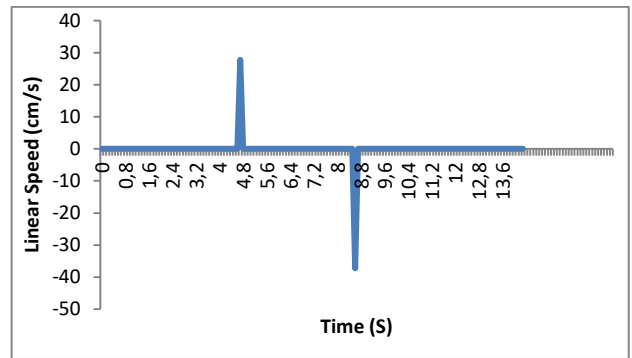


Fig. 9. The variation of linear speed of gripper cylinder with time in pressure 5 bar

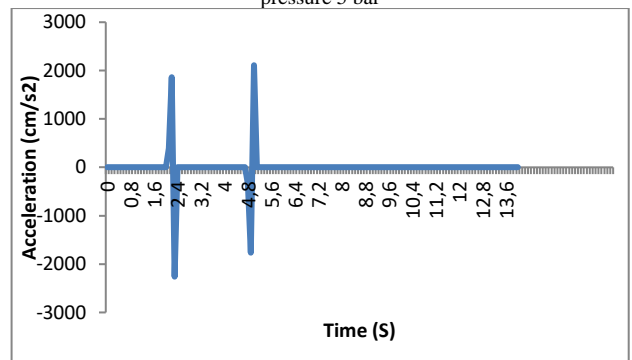


Fig.10. The variation of Acceleration of rodless cylinder 200 mm with time in pressure 5 bar

VII. CONCLUSIONS

A three-dimensional pneumatic robot is produced at first which is amplified later into an undeniable robot for utilization in a metallurgical application. The general conduct of the reenactment nearly looks like that of the real framework. The modest PLC controller has ended up being sufficient for utilization in such application.

Simulation is done by means of Automation Studio, version 5.6 software. Automation Studio is a system design, simulation, and documentation software solution for the design and support of automation, hydraulics, pneumatics and electrical systems. Parameters of position, velocity, acceleration, pressure variation and flow are obtained from the simulations and compared with those obtained from a video analysis and physical measurements.

The measured values of position and velocity obtained from computer simulation are compared with those obtained through measurements and found to correlate fairly well. The discrepancies in results between simulation and performance are due to friction, which is not truly accounted in the simulation process.

## REFERENCES

- [1] Thomas R. Kurfess Ph.D., P.E., Robotics and Automation Handbook, CRC Press.2005.
- [2] Michael G. Pinches and Brian G.Callear, Power Pneumatics, Prentice Hall, Europe, 1996.
- [3] Richardson R, Plummer AR, Brown MD, Self-tuning control of a low friction pneumatic actuator under the influence of gravity. Accepted for publication by Control systems technology, April 1999.
- [4] Richardson R, Austin ME, Plummer AR. Development of a physiotherapy robot, Proceedings of the international biomechanics workshop, 1999; Enshede 19-21 April 116-120.
- [5] Frank L.Lewis, Robot Manipulator Control Theory and Practice-Copyright © 2004 by Marcel Dekker, Inc.
- [6] Reza N. Jazar, Theory of Applied Robotics, Second Edition, Springer Science and Business Media, LLC 2006, 2010.
- [7] W. Bolton, Programmable logic controllers – An Introduction, Second Edition, Newness, 2000.
- [8] H. Kazerooni, Design and Analysis of Pneumatic force Generators for mobile Robotic System. IEEE/ASME transactions on Mechatronics, Vol. 10. No. 4, August 2005.
- [9] R.Richardson A.R.Plummer, M.Brown Modeling and simulation of pneumatic cylinders for a physiotherapy robot, *School of Mechanical Engineering, University of Leeds,UK, 2006.*
- [10] Awad E. G. Mohamed, Investigation on Pneumatic Robot for Metallurgical Processes, PhD, thesis, Osmania University, India, 2010.



Internet of Things.



Things.

**Awad Eisa G. Mohamed**, Associate Professor, Department of Mechanical Engineering, Omdurman Islamic University (Sudan), graduated in mechanical engineering in Aleppo University, Syria in 1990.

He obtained his M.Sc. in manufacturing engineering in 1998, from Khartoum University, Sudan, and PhD. In Automation and Robotics from Osmania University, Hyderabad, India in 2010.

His research interest falls in the area of Robots and automation, Artificial Intelligence, and Industrial

**Dr. Abuobeida Mohammed Elhassan**, Associate Professor, Department of Communication Engineering, Al-Neelain University (Sudan), He obtained his M.Sc. in Communication engineering in 2000, from Al-Neelain University, Sudan, and PhD. In Remote Sensing from Damascus University, Damascus, Syria, in 2007.

His research interest falls in the area of Remote Sensing, Artificial Intelligence, Image Processing, Robots and automation, and Industrial Internet of