Journal of Sensors

Sensors of Digital Twin Systems

Lead Guest Editor: Houssem Jerbi
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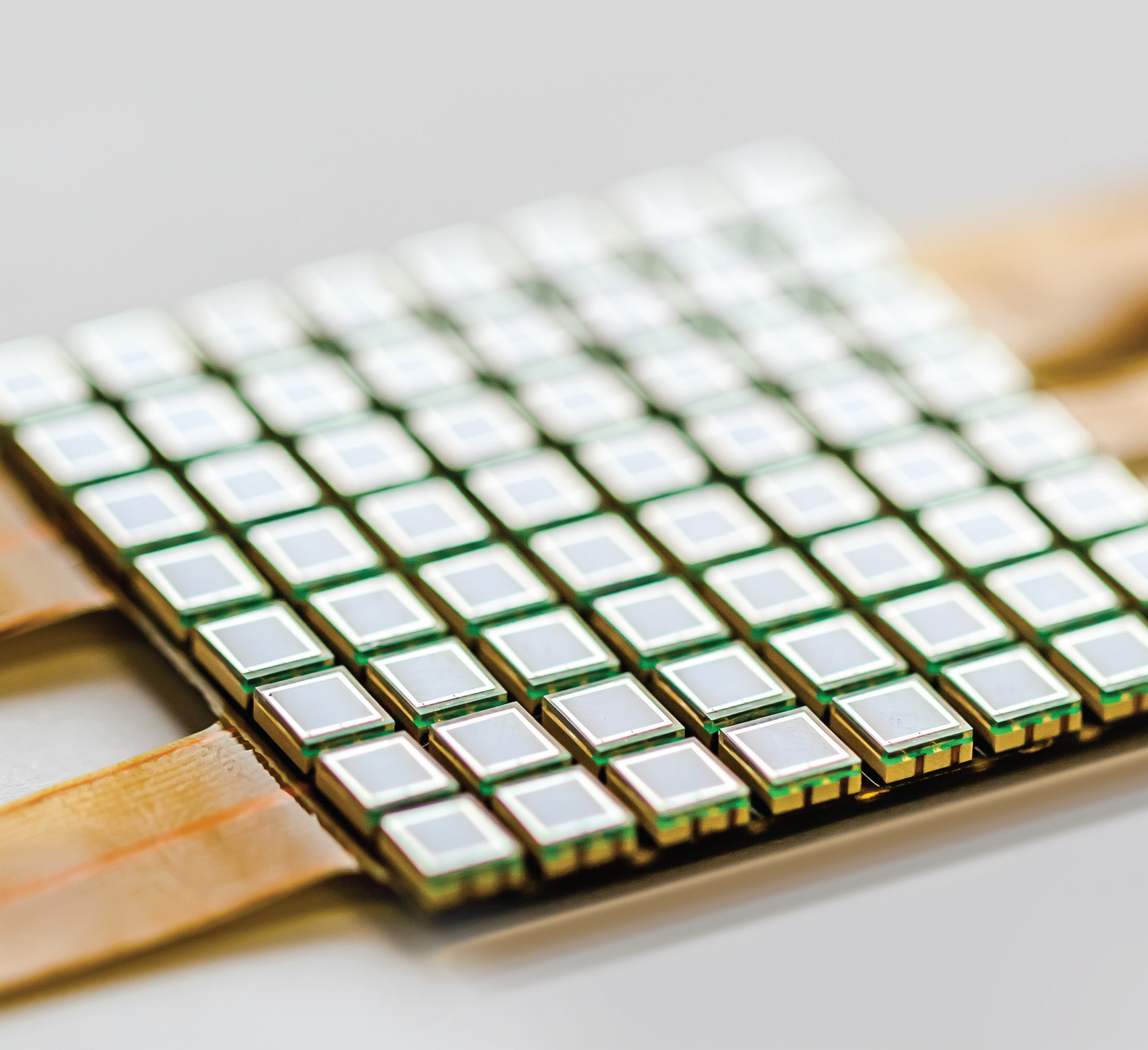

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Research Article

On-Board Digital Twin Based on Impedance and Model Predictive Control for Aerial Robot Grasping

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Aerial manipulation of objects has a number of advantages as it is not limited by the morphology of the terrain. One of the main problems of the aerial payload process is the lack of real-time prediction of the interaction between the gripper of the aerial robot and the payload. This paper introduces a digital twin (DT) approach based on impedance control of the aerial payload transmission process. The impedance control technique is implemented to develop the target impedance based on emerging the mass of the payload and the model of the gripper fingers. Tracking the position of the interactional point between the fingers of gripper and payload, inside the impedance control, is achieved using model predictive control (MPD) approach. The developed on-board DT offered a model where interaction with the unknown payload and aerial robot dynamics is informed. Beside this, the results showed the ability of the introduced DT to foretell the conditions of the forces acting on the payload which helped to predict the situation of aerial manipulation process. Additionally, the results showed that the DT model could detect real-time errors in the physical asset.

1. Introduction

Digital twin (DT) is a modern application that provides advanced interconnection between real systems and their corresponding virtual representation. Compared to digital model and digital shadow, the data linkage in DT can be transferred from the real system and its corresponding virtual representation in both directions [1]. Hence, DT can detect the abnormality of the system either as on-board or off-board manners. In the on-board diagnostics process, the operation of detecting the abnormality of the system is implemented by sensors and actuators which are equipped in the system itself. The DT compares the outputs of the sensors and actuators with the virtual model to diagnose any unexpected outcome. Regarding the off-board diagnostics process, the operation of detecting the abnormality is remotely implemented from the system by cloud [2]. The performance of DT to predict abnormality of systems in real time can be improved by applying new technologies such as three-dimensional laser scanners [3]. As presented in Table 1, DT is implemented for various purposes such as manufacturing processes, industries, smart cities, healthcare, constructions, and robotics [4–6].

DT is implemented to enhance the manufacturing process of products in terms of time and amount of wastage where a model setting for injection molding machine aids modelling cases of production steps [14]. Merging the DT with abnormality detecting in machines of industries showed its high ability to diagnose abnormality in rolling

Table 1: DT applications in various situations.

DT sector	Application
Manufacturing processes	DT is applied to collect the data of production lines in order to find the best models of the manufacturing processes [7].
Industries	DT is applied at industry level to predict the need of maintenance and monitor services on products after sale [8].
Smart cities	DT can be applied in smart cities in datasets of urban, cooperation with stakeholders, and security [9].
Healthcare	DT is applied to monitor the tibiotalar joint of patients who did ankle and foot surgery [10].
Constructions	DT is applied with cyberphysical systems to (1) enhance control and automation in the constructions [11] and (2) help in the design and maintenance in a company [12].
Robotics	DT is applied in robotics which are in interaction with humans in Industry 4.0 [13].

bearing [15]. In Industry 4.0 of modern drivers [16], DT has become the major technology which is implemented to integrate the data linkage between the real and virtual machines [17]. The application of artificial intelligence algorithms has a significant effect on the DT systems regarding autonomous driving, production workshops, and smart city traffic [18]. Recently, since 2018, DT systems have started to be integrated within the robotic platforms in many situations in order to enhance the performance of robotics in their specific applications. In [19], by Malik and Bilberg, the process of controlling the cooperation between the human and robot is improved by applying DT. The cooperation task of assembly is simulated by computer to provide a digital representation of the system where the digital representation continuously existed during the production process of the human-robot system. The production of the system has been improved by the real-time monitoring of the physical components. The situation of a manufacturing firm which has a team of human and robotics is introduced for establishing and approving the DT structure. In [20], by Joordens and Jamshidi, DT is applied to help the design process of swarm robotics which was not easy to be tested during setup and control such as robotic fish. In the beginning, the robotic fish was practically produced with the ability of primary swimming. A DT of the robotic fish is developed and transformed to virtual reality which provided the simulations to be implemented and fixed during robotic fish swimming. In [21], by Vassiliev et al., DT is applied to develop a new robotic system that can be used in mechanisms of walking robotics. The designed DT robotic platform showed its behaviour to enhance the control process and algorithms. In [22], by Sørensen et al., a special industrial assembly system is introduced where digitalized assembly orders are developed by an operator. The orders of the operators are visually developed in blocks which provide the feature of programming the robotic system visually. DT allowed us to monitor the execution of the system in real time. In [23], by Kaigom and Roßmann, a robotic DT is presented which assisted and improved the implementation of cyberphysics in robotics. The results showed that the developed robotic DT system can be applied in various situations. In [24], by Douthwaite et al., DT is developed to support the safety of cooperation between multirobotics in manufacturing plants. The introduced framework of the DT supported flexible performance of operator-identified cyberphysical circumferences and utilities for safety test and control. However, in aerial robotics, a remarkable proportion of applications are directed towards aerial payload transportations (APTs) [25]. Since the payload tasks are generally associated with handling objects of various unmeasurable physical properties, they need to be controlled by advanced techniques [26, 27]. With advanced control techniques [28], the term of the interactional control process has been integrated with the model of the robot platform from one side and the unknown payload from another side [29]. Hence, the APT processes are affected by many unknown parameters and disturbances. Unknown parameters represent the unknown weight, shape, size, and so on of the payloads. The disturbances represent the external effects during the flight of the aerial robotics that could disturb the transportation process such as wind. Consequently, it is essential to introduce an approach to compare the ideal physical parameters of the aerial robot system with the real physical parameters in real time for diagnostic purposes. In this paper, a physical digital twin (PDT) approach is developed to introduce a model for real-time diagnosis in order to foretell the conditions of the forces acting on the payload which helped to predict the situation of the ATP process. The impedance control technique is implemented to control the interaction process within the payload where the target impedance is based on emerging the mass of the payload and the model of the gripper fingers. Tracking the position of the interactional point between the fingers of gripper and payload, inside the impedance control, is achieved using model predictive control (MPD) approach.

The rest of the paper is organized as follows: Section 2 presents the interactional model of the aerial robot. Section 3 introduces the implemented impedance control technique to track the interactional force between the payload object and gripper. Section 4 explains the implemented MPD approach which is included to track the position inside the impedance control algorithm of Section 3. In section 5, the designed DT of the aerial robot is developed. In Section 6, simulation results of the developed DT model are introduced. In Section 7, the conclusions of this study are presented. In Section 8, recommendations of future work of this research are explained.

2. System Model

This section presents the interactional model of the aerial robot of this study. Generally, aerial robotics consists of UAV and robotic arms. The UAV has various mechanical configurations [30] of potential sensor systems [31]. The aerial robotic arm grasped payloads via a gripper which is attached at the end of the third link of the aerial arm. Interactional modelling of the payload grasping process is considered in this part. Assuming the gripper shown in Figure 1, it can grasp a specific payload by moving its fingers simultaneously via one actuator. The fingers are assumed to be designed based on the principle of 4-bar linkage mechanism where the rotational motion of the actuator is translated to linear movement.

The schematic gripper/payload model during situations of none-contact, instance-contact, and interactional-contact is shown in Figures 2(a)–2(c), respectively.

It is assumed that a potential payload of mass M_p is to be held by closing up the fingers of the gripper. The interactional force $F_{p,i}$, $i = 1, 2$, between the two fingers and the payload is induced once the gripper contacts the latter. Each finger is modelled as second-order system of mass, stiffness, and damping coefficient $M_{f,i}$, $K_{f,i}$, and $D_{f,i}$, respectively. The coordinates of the spring and damper of each finger, at point 1, relative to the origin of the gripper O_{gripper} and to the payload mass are denoted by $X_{O,i}$ and $X_{P,i}$, respectively. The current position of each finger is X_i. This position, i.e., X_i, is the command of the gripper/payload system while $F_{p,i}$ is the force that is intended to be controlled. Referring to the schematic diagram of the interactional model shown in Figure 2(c), each finger exerts a force of equation (1) on the payload:

$$F_{p,i} = M_p \ddot{X}, \tag{1}$$

while the force that the payload applies on the finger is presented in

$$F_{f,i} = M_{f,i}\ddot{X}_i + D_{f,i}\left(\dot{X}_i - \dot{X}_{O,i}\right) + K_{f,i}(X_i - X_{O,i}), \tag{2}$$

where $F_{f,i} = -F_{p,i}$. Regarding the aerial robot platform, it has UAV of type quadcopter while its aerial arm has serial three links of rotational joints as shown in Figure 3. The gripper, which represents the end effector, is attached to the end of the aerial arm. The position of the gripper is achieved by rotation of the propellers of the quadcopter and the joints of the aerial arm.

The schematic representation of the aerial robot is shown in Figure 4 where the subscripts q, aa, and ar correspond to UAV quadcopter, aerial arm, and aerial robot, respectively. Assume that P_q and $\varnothing_q$ are the position and orientation of the UAV quadcopter relative to the quadcopter frame $\{q\}$, respectively. The orientation $\varnothing_q = [\vartheta\, \theta\, \Psi]$, where ϑ, θ, and Ψ represent the rotation angle around x_q, y_q, and z_q axes, respectively. The position vector is $P_q = [x_q\, y_q\, z_q]$ while all the joints of the aerial arm are included in the coordinate vector $\beta = [\beta_1\, \beta_2\, \beta_3]$. Consequently, the overall state of the aerial robot is represented in

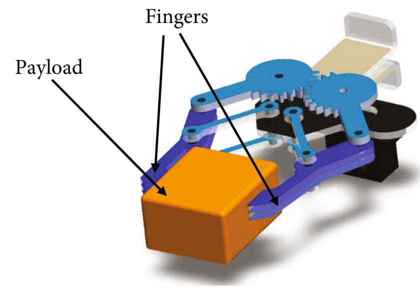

Figure 1: Gripper of the aerial robot.

$$\rho = \left[{P^i_{\text{ar}}}^T \quad {\varnothing^i_{\text{ar}}}^T \quad \beta^T \right]. \tag{3}$$

Referring to Figure 4, the coordinate frames of the inertia and the end effector are denoted by $\{i\}$ and $\{\text{ef}\}$, respectively. The end effector represents the contact point position of the gripper fingers with the payload which can be calculated with respect to $\{i\}$ according to

$$P^i_{\text{ef}} = P^i_q + R_q P^q_{\text{ef}}, \tag{4}$$

where P^i_q, R_q, and P^q_{ef} represent the position of the UAV quadcopter relative to $\{i\}$, rotation of the UAV quadcopter relative to $\{i\}$, and the position of the end effector relative to $\{q\}$. On the other hand, both the linear and angular velocities of the end effector can be obtained from

$$\dot{P}^i_{\text{ef}} = \dot{P}^i_q + \text{Skew}\left(R_q P^q_{\text{ef}}\right)\omega_q + R_q \dot{P}^q_{\text{ef}}, \tag{5}$$

$$\omega^i_{\text{ef}} = \omega_q + R_q \omega_{q,r}, \tag{6}$$

where ω_q and $\omega_{q,r}$ represent the angular and relative angular velocity of the UAV quadcopter in $\{q\}$, respectively. Dynamics of the aerial robot is obtained by applying following Euler-Lagrange approach in

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{\rho}} - \frac{\partial L}{\partial \rho} = T_{\text{total}}, \tag{7}$$

where L, explained in equation (8), represents the difference between the total kinetic and potential energies of the aerial robot $K_{\text{ar,total}}$ and $U_{\text{ar,total}}$, respectively:

$$L = K_{\text{ar,total}} - U_{\text{ar,total}}, \tag{8}$$

while T_{total} represents the total torque applied on the aerial robot. In more detail, the total torque includes three main parts: the thrust forces of the UAV quadcopter rotors u, the forces applied by the rotors on the aerial robot body

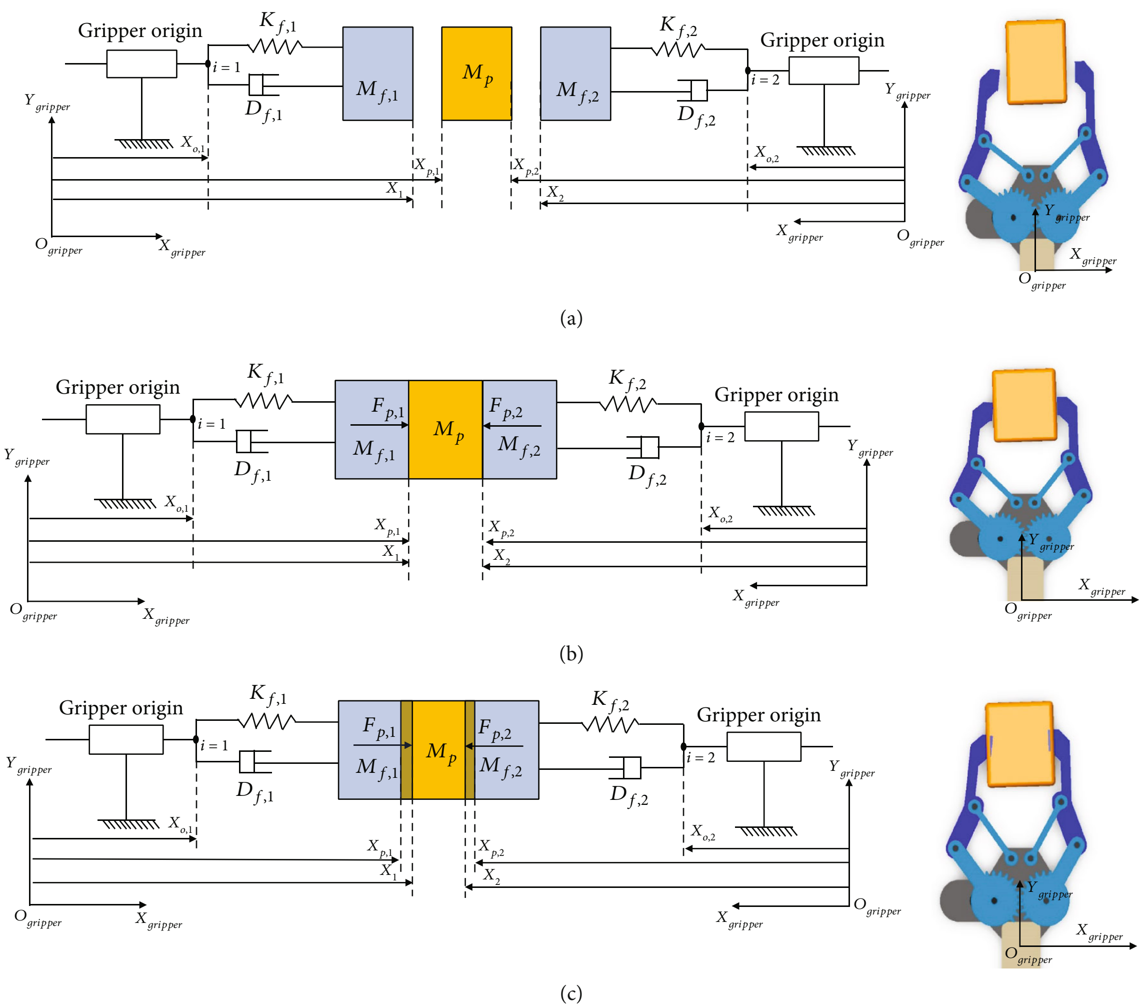

Figure 2: Schematic model of the gripper/payload situations. (a) None-contact, (b) instance-contact, and (c) interactional-contact.

$F_{\mathrm{ar,body}}$, and the forces generated by the aerial arm F_{aa}. The total kinetic energy of the aerial robot can be obtained from

$$K_{\mathrm{ar,total}} = \frac{1}{2} m_q \dot{P}_q^{i\,T} \dot{P}_q^i + \frac{1}{2} \dot{\varnothing}_q^{i\,T} R_q^{\,T} \begin{bmatrix} 1 & 0 & -\sin\theta \\ 0 & \cos\vartheta & \cos\vartheta\cos\theta \\ 0 & \sin\vartheta & \cos\vartheta\cos\theta \end{bmatrix}^T \left(R_q I_q R_q^{\,T}\right) \begin{bmatrix} 1 & 0 & -\sin\theta \\ 0 & \cos\vartheta & \cos\vartheta\cos\theta \\ 0 & \sin\vartheta & \cos\vartheta\cos\theta \end{bmatrix} \dot{\varnothing}_q^i + \sum_{i=1}^{3} \frac{1}{2} m_{\mathrm{aa},i} \dot{P}_{\mathrm{aa},i}^T \dot{P}_{\mathrm{aa},i} + \frac{1}{2} \omega_{\mathrm{aa},i}^T \left(R_q R_i^q I_i \left(R_i^q\right)^T R_q^T\right) \omega_{\mathrm{aa},i}, \tag{9}$$

where the matrices m_q and I_q represent the mass and moment of inertia of the UAV quadcopter, respectively, the same for $m_{\mathrm{aa},i}$, and I_i which represent the mass and the moment of inertia of the corresponding link of the aerial arm. Regarding the total potential energy, it is obtained from

$$U_{\mathrm{ar,total}} = m_q g v_z^T P_q^i + \sum_{i=1}^{3} m_{\mathrm{aa},i} v_z^T \left(P_q^i + R_q P_{\mathrm{ef}}^q\right), \tag{10}$$

where $v_z = [0\,0\,1]^T$. By inserting equations (9) and (10) into equation (8), the Lagrange function L of the aerial robot is

Figure 3: The aerial robot platform.

obtained which is applied in equation (7) to find the final dynamic model of the aerial robot in

$$M_{ar}(\sigma) + D_{ar}(\sigma, \dot{\sigma})\dot{\sigma} + G_{ar}(\sigma) = T_{total}, \quad (11)$$

where the matrices M_{ar}, D_{ar}, and D_{ar} denotes the aerial robot inertia, Coriolis, and gravity, respectively. In the next section, impedance principle will be designed to control the interactional contact forces $F_{f,i}$ by moving the position of the finger X_i.

3. Impedance Control

The control algorithm is implemented using impedance techniques as shown in Figure 5 to track the interactional force between the payload object and gripper. MPD approach is applied to track the position. The aim of this control algorithm is to provide the required impedance between the position of each finger X_i and the interactional force $F_{f,i}$.

The target impedance is dynamically controlled by the stiffness $K_{t,i}$, damping coefficient $D_{t,i}$, and mass $M_{t,i}$. Hence, equation (12) represents the reference impedance where $X_{r,i}$ and $F_{r,i}$ are the reference displacement and interactional force, respectively.

$$M_{t,i}(\ddot{X}_i - \ddot{X}_{r,i}) + D_{t,i}(\dot{X}_i - \dot{X}_{r,i}) + K_{t,i}(X_i - X_{r,i}) = F_{t,i} - F_{f,i}. \quad (12)$$

In a potential application of impedance approach, a tracking position task as an effect of dynamics of an aerial robot manipulator is the result between the current and the target position of the finger. Hence, in term of the target position $X_{t,i}$, the equation of trajectory tracking in equation (13) can be obtained from equation (12):

$$M_{t,i}(\ddot{X}_{t,i} - \ddot{X}_{r,i}) + D_{t,i}(\dot{X}_{t,i} - \dot{X}_{r,i}) + K_{t,i}(X_{t,i} - X_{r,i}) = F_{t,i} - F_{f,i}. \quad (13)$$

The error of position is determined from

$$E_p = X_{t,i} - X_i. \quad (14)$$

In a steady-state situation, the tracking error of the interactional force $E_{f,i} = F_{t,i} - F_{f,i}$ is calculated in

$$E_{f,i} = \frac{K_{t,i}K_{f,i}}{K_{t,i} + K_{f,i}}\left[\frac{F_{t,i}}{K_{f,i}} + X_{P,i} + E_p - X_{r,i}\right]. \quad (15)$$

In the case of reaching the required position via the MPC, the reference position in equation (16) can be calculated from equation (15):

$$X_{r,i} = \frac{F_{t,i}}{K_{f,i}} + X_{P,i}. \quad (16)$$

In this case, the reference position can be generated from existing the values of the finger stiffness and payload location according to the target international contact force value. In the next section, the MPD approach is applied to track the position.

4. Model Predictive Control

In the presented MPD, the constrained aerial robot system is solved in optimization approach at each step of time T_{step} to reduce the position tracking error in the impedance control algorithm of Section 3. The states of the aerial robot x can be controlled by torque inputs T_{input}. It is assumed that the solution of optimization is obtained at time $t_n = nT_{step}$, where n is a positive number. The value of α ranges from "1" to the steps of the estimation horizon "M." Consequently, the optimization algorithm of the MPC is written in

$$\begin{aligned} &\min_{u} f(x_n, T_{input}, t_n), \\ &\text{Subject to} \\ &x_{n+1} = g(x_n, T_{input,n}), \\ &X_{P,i,min} \le h(x_n, T_{input,n}) \le X_{P,i,max}, \\ &x_{min} \le x_n \le x_{max}, \\ &T_{input,min} \le T_{input,n} \le T_{input,max}. \end{aligned} \quad (17)$$

The input torque vector is the control inputs that cause the motion of the aerial robot which is represented as $T_{input,n} = [T_{input,n}\ T_{input,n+1} \cdots T_{input,n+M-1}]$; g denotes the model of the aerial robot. The generic constraint in equation (17) is denoted by h while the generic cost function f is represented by the general form in

$$f(x_n, T_{input}, t_n) = \sum_{j=1}^{M-1} f + \left\| T_{input,n+j} - T_{input,n+j-1} \right\|^2 W_{T_{input}} + \left\| T_{input,n+M} \right\|^2 W_t, \quad (18)$$

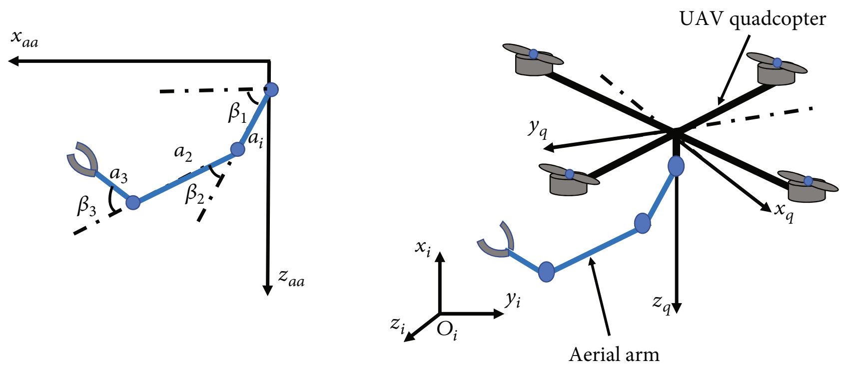

FIGURE 4: The schematic model of the aerial robot.

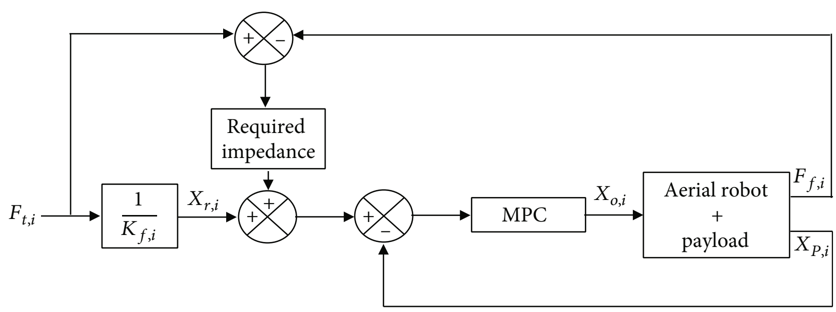

FIGURE 5: Impedance control block diagram.

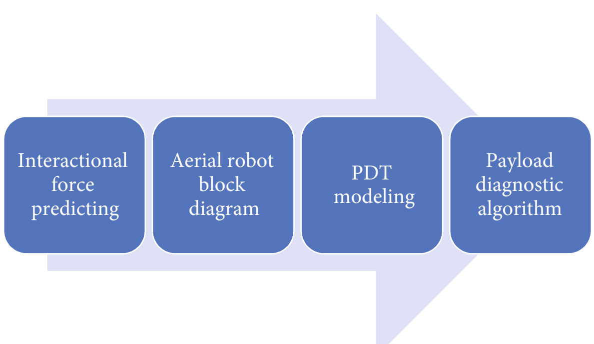

FIGURE 6: On-board PDT parts.

where $W_{T_{\text{input}}}$ and W_t denote the weights of the input control and cost of the terminal, respectively. The f, which is equal to $f(x_{n+1}, T_{\text{input},n+j}, T_{\text{step},n})$, represents the target cost function that wants to be minimized. This cost function, i.e., f_i, is designed to execute the task of position control during interaction with the payload in

$$f = \sum_{j=0}^{M-1} \left\| \text{Error}_X (x_{n+j}) \right\|^2 W_{\text{tast}} + \left\| \text{Error}_{\text{gripper}} (x_{n+M}) \right\|^2 W. \tag{19}$$

In equation (19), the error of interaction position between each finger and the payload is denoted by Error_X which is obtained from

$$\text{Error}_X = P^i_{\text{ar}}(x_{n+j}) - P^i_{d,\text{ar}}(t_{n+j}). \tag{20}$$

Tracking the position error is affected by the desired location of the point of interaction between the finger and the payload $P^i_{d,\text{ar}}$ over the estimated horizon. The task and terminal weigh matrices in equation (19) are denoted by W_{tast} and W, respectively. Since the manoeuvres are not our aim of this model, the tilt of the aerial robot is not considered in the suggested MPC. Consequently, the control input in equation (21) is directly obtained from derivation equation (3):

$$T_{\text{input}} = \dot{\rho} = \left[\dot{P}^{i\,T}_{ar} \quad \dot{\varnothing}^{i\,T}_{ar} \quad \dot{\beta}^T \right]. \tag{21}$$

Generating the control input in equation (21) aims to get zero Error_X. Thus, the function g in equation (17) is only the integration of T_{input}.

5. Physical Digital Twin

In this section, on-board PDT model is developed to detect a potential future payload. The detection of payload via PDT is mentioned as on-board predicting where the derived dynamic model and the developed control algorithm in the previous sections are implemented to mimic the process of payload grasping by the aerial manipulator. As shown in Figure 6, the PDT parts that are developed in this section includes predicting the interactional forces between the

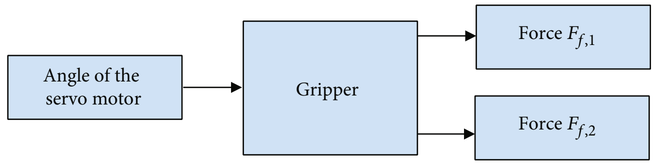

Figure 7: Block diagram of the gripper system.

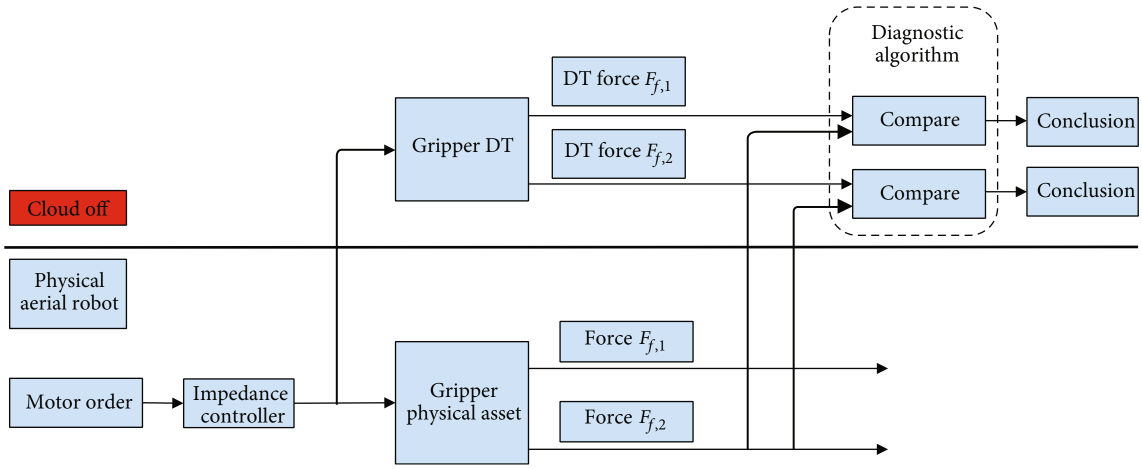

Figure 8: On-board diagnostic algorithm.

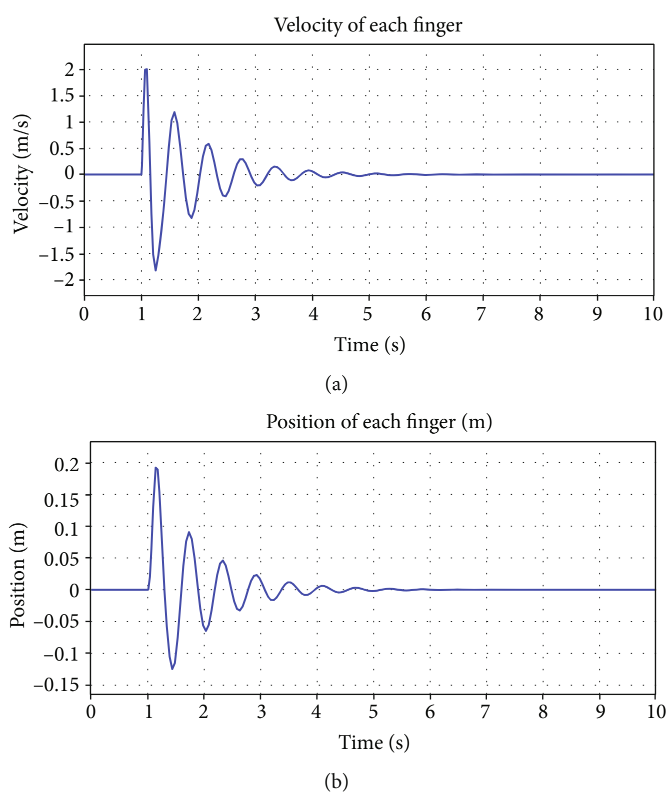

Figure 9: Response of fingers of gripper to impulse function. (a) Velocity and (b) position.

gripper and the payload, block diagram of the aerial robot, PDT modelling, and the algorithm of diagnosing the existing of payload.

The gripper of the aerial robot, as explained in Section 2, has one actuator to simultaneously control the movement of the two fingers. The interactional force is calculated

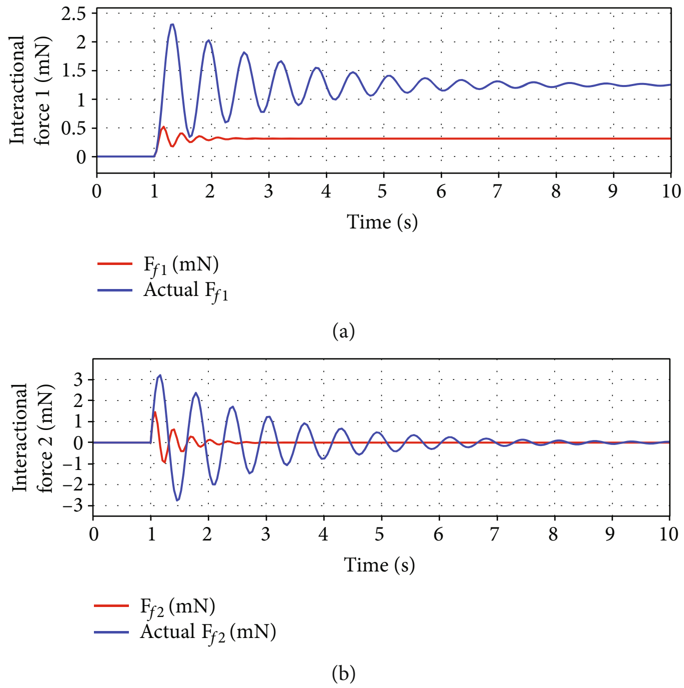

Figure 10: Diagnosing interactional force failures.

according to equation (2). Block diagram of the gripper system is shown in Figure 7. The system has one input which represents the angle of servomotor of the gripper. The outputs of the system are the interactional forces explained in Section 3 which are represented in equation (12).

Detecting payload depends on the orientation of the aerial robot, furthermore the angle of the servomotor. The main idea depends on measuring the interactional forces. If the measured international forces deviate from the interactional forces of the PDT model, an error message will appear to indicate that there was a fault. The implemented diagnostic algorithm is shown in Figure 8.

The developed diagnostic algorithm takes a specific decision according to the results of comparing the measured interactional forces and the DT interactional forces. This will help in diagnosing faults that can be accorded during payload transportation.

6. Simulation Results

Simulation tests, using MATLAB, are implemented in this section to examine the performance of the developed DT model. The DT model is created using SimMechanics™ where the input and the outputs were the angle of the motor gripper and the interactional forces, respectively. The dynamics of the aerial robot system in equation (11), MPD in equation (17), are implemented in MATLAB script file programs. On the other hand, the gripper shown in Figure 1 is modeled using SimMechanics™. The impedance controller is integrated within the DT model to calculate the interactional forces between the fingers of the gripper and the payload. The DT model of the aerial robot shown in Figure 8 is assumed to grasp the payload by the appropriate forces by rotating the motor of the gripper. Due to the fact that the payload is not directly connected by joints with the aerial robot, in addition to the SimSpace™ blocks, the DT model included programming equations (1) and (2) which relate the motion of the gripper and the payload in MATLAB script files. The DT model calculates the interactional forces to monitor the process of grasping a potential payload. The comparison is implemented to diagnose the failure of supporting the required interactional forces. In the first test, the aerial robot physical asset response is examined against impulse function. The position and velocity of each finger of the gripper is shown in Figure 9. The first test showed the functionality of the developed model to represent aerial robot physical asset part in Figure 8. The velocity and the position of each finger of the gripper is obtained as a reaction for input impulse at time 1 sec.

Next, detecting errors in the aerial robot system using the developed DT model of this study is verified in the second test. The response of the system shown in Figure 10 when the fingers of the gripper touch the payload.

The results showed the ability of the developed DT model to diagnose problem. Hence, the process of aerial payload transforming can be monitored online, and any problem in the aerial robot platform can be immediately detected. The simulation failure results showed the ability of the developed DT model to diagnose error of international forces online. When the real model does not support the appropriate force, the DT model can estimate this, for instance, when the fingers could not support the appropriate contact forces due to the problem in its modelled stiffness and damping components. Hence, the failed aerial robot system is introduced into the DT model and simulate the reaction of the failed aerial robot system with the same motor of gripper input.

7. Conclusions

Aerial techniques are recently implemented in payload transportation instead of traditional ground platforms. Practical examples of aerial payload are generally implemented by aerial robotics. PDT supports monitoring in the real-time process of aerial payload transportation. Hence, faults can be immediately diagnosed during aerial robot flight. The required impedance between the fingers of the gripper can be obtained using an impedance controller based on the emerging mass of the payload and the model of the gripper fingers. In the impedance controller, MPD approach tracks the position of the interactional point between the fingers of gripper and payload. Tracking the position of the interactional point between the fingers of gripper and payload, inside the impedance control, is achieved using MPD approach. The developed PDT offered a model for on-board predicting where interaction with the unknown payload and aerial robot dynamics can be informed. Beside this, the results showed the ability of the introduced PDT to foretell the conditions of the forces acting on the payload which helped to predict the situation of aerial manipulation process.

8. Future Work

This study provides a way of diagnosing failure in aerial payload transportation by DT; however, there are limitations that recommendations for future work can be addressed. The study focused on on-board diagnostic process and off-board diagnostic process was not considered. Including cloud can provide further insights on applying DT within the Internet of Things in aerial robotics. While the diagnostic process was considered from the interactional forces between the fingers of the gripper and the payload, the effect of path of flight and orientation of the aerial robot is not considered in this study and can be recommended to be taken in consideration in future work. Furthermore, additional study is required to explore the benefits of DT in aerial transportation.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Research Article

Simulation Analysis of 4G/5G OFDM Systems by Optimal Wavelets with BPSK Modulator

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LTE (Long-Term Evolution) is one of the appropriate technologies to sever the requirement of the IoT (Internet of Things) together with mobile UE (User Equipment), because of priority services, high data rate, low latency, etc. LTE has received OFDM for the transmission because it meets the necessity of LTE-like range flexibility and empowers the cost gainful responses for the wide carriers. LTE offers big-data values, allows spectrum reframing, reduces cost, etc. We proposed a 4G/5G adopted OFDM based on the multi-equalizer and BPSK (Binary-Phase Shift Keying). The BER (Bit Error Rate) of the system is reduced through the optimal wavelet coefficient at the transmitter side. This optimal wavelet coefficient is obtained by applying a DWT (Discrete Wavelet Transform) to the input signal through a BFF (Binary Firefly) algorithm. The serial to parallel process is carried out through the BPSK modulation. At last, the multi-equalizer like MMSE (Minimized Mean Square Error) and MLE (Maximum Likelihood) is applied to the OFDM model to reduce the BER. The system is analyzed using the parameter like SER (Symbol Error Rate), spectral efficiency, MSE (Mean Square Error), and BER. The proposed methodology provides a better outcome than the other existing approaches.

1. Introduction

Smart IoT devices function as an important part of our lives unless any direct human intrusions. LTE is acting as a powerful technological solution for the broadband wireless approach networks and fast-improving data traffic needs from UEs and IoT devices because of its high data rate assist and another key characteristic. But, finding a small signal at additive white Gaussian noise (AWGN) from a small compression rating without signal reproduction is an enigmatic object [1]. Substantial recognition of the signal and authorization of modulation as a moderate part of the signal were given further attention as a defamation measure. Different approvals have been proposed step by step [2]. OFDM (orthogonal frequency division multiplexing) signals are examined as a procedure of numerous sovereign random signals [3]. The applications of remote signals are GBS-denied, and areas are taken as of late, owing to the practically universal immediacy in many structures [4]. To utilize a directional antenna, we use a hypothetical route to the transmitter we got the orientation signal legitimately as of the transmitter [5]. Here, the transfers are used to get the signal transmitted by the basis hub. The studies on the exhibition of hand-off helped OWC (RAOWC) display that it can widen strained transmitter the inclusion of strength and improve the heartiness of outlook imparting longer-extend distorting channels.

The information of transmission pace is extended normally using higher recurrence carriers, and microwave and millimeter-wave signals are taken as an example [6]. By figuring flex and progress, wavelet transform can multi-scale improve the signal. In the time area change, the signal to the wavelet space with the final goat that the vast majority of the signal vitality collected in barely any wavelet coefficients taken as an estimate [([7, 8]]. This wavelet coefficient is playing an important role in the domain of information which can able to process by using short-extend radio innovation that is considered an additional component for worms to increase with no web association. To control the malevolent signals in WSN and to shield it from infections and maggots, we need a solid security component [9]. The major problem in several frameworks is signal detection whereas the measurable signal handling technique is mostly utilized for the signal detection process [10]. The problem in the signal improvement is normally defined as the forecast problem which predicts the clean signal from the noise signal [11]. The major threats to the remote sensor are LTE signaling attacks whereas in the MIMO-OFDM framework, the signal discovery problem is observed as a component acknowledgment problem that is not included in the plan of conventional signal recognition [([12, 13]]. These issues are rectified by transmitting the neural signal obtained from the embedded cathodes to the outside unit [14].

2. Related Works

In 2017, Hassani et al. [15] had proposed Multitask Wireless Sensor Network (MWSN) for joining the LCMV Beamforming, DOA Assessment, and disseminated hub-Specific Signal Amplification. The low-position guess of the ideal signal was integrated with the grid based on the disseminated signal estimation method. Moreover, diverse signal preparing and undertaking were identified with the help of appropriated algorithm which helps to reduce the similar assets. Thereafter, the presented algorithm was utilized in the remote acoustic sensor organize circumstance along with numerous sources and it was efficient for the hypothetical results.

In 2016, de la Hucha Arce et al. [16] have presented a generalization for the utility of sensor signal. Here, a greedy method was utilized to track the bit that is assigned to the sensor. In addition to that, comparison of computational cost with available LMMSE (Linear Minimum Mean Squared Error) estimator is carried out.

In 2014, Chi and Li [17] have presented a waveform strategy based on the OFDM (Orthogonal Frequency Division Multiplexing) signal to eradicate the resolution conflict in medical ultrasound imaging. This method reduces the range side-lobe level of the signal to -96 dB and the peak side-lobe level is reduced to -80 dB.

In 2016, Zheng and Kostamovaara [18] have examined the statistical properties of ADC through AWGN (additive Gaussian noise) input. Digitization is achieved through a 2-level comparator rather than the multi-bit ADC when there is a large average.

In 2016, Hwang et al. [19] had presented an SDR (Software-Defined Ratio) method to establish the cross-platform LTE VSA (Long-term Evolution Vector Signal Analyzer). This method does not utilize the costly off-the-shelf VAS and it is separated into SA (Signal Acquisition) hardware as well as PC-based CS (Core Software). Here, the CS represents the SA control function and the process of the received LTE signal.

In 2014, Jerjawi et al. [20] have analyzed the LTE SC-FDMA (Long-term Evolution Single Carrier-Frequency Division Multiple Access) signals and the second-order cyclostationarity of the LTE SC-FDMA. Here, the investigation was carried out through the cyclostationarity-based detection algorithm, whereas the outcome obtained from the cyclic autocorrelation function is applied to the signal detection. The presented algorithm yields better performance for various channel constraints.

In 2015, Hwang et al. [19] have presented an ASI (Automatic Signal Identification) algorithm for recognizing the LTE and GSM signals. This algorithm is based on the pilot-induced second-order cyclostationarity. It provides a low signal-to-noise ratio without the channel estimation as well as the frequency and time synchronization process [T. [21]].

3. Proposed Approach: 4G/5G OFDM Systems Analysis

By utilizing the DWT method to the transmitter side of the OFDM system, the input signal's BER (Bit Error Rate) value can be lessened. Meta heuristics algorithms are utilized to enhance the DWT coefficients such as Haar, Daubechies, and Symlet. For the serial to parallel progression, improved coefficients and the BPSK are utilized, whereas, on the receiver side, the AWGN (adaptive white Gaussian noise) channel gets demodulated and decomposed transform technique is employed to the signals. The effectiveness of the presented approach is validated through the performance metrics such as BER, MSE, SER, and spectral efficiency.

3.1. OFDM System

(a) OFDM is considered a fine-tuning and multiplexing. Usually, multiplexing indicates the self-governing signal of several systems

(b) In an OFDM system, a multiplexing process is employed for the received signals and these signals are considered the sub-set of one essential signal

(c) In the autonomous channel, signal is the first segment and later it is multiplexed to generate the OFDM bearer

3.2. LTE with OFDM Model. MIMO – OFDM system is incorporated with the 4G, 5G broadband because of the advancement in MIMO like it can transfer the different signals through several antennas, whereas the OFDM channel splits the channel radio into the closely spaced sub-channels to deliver the signals at high speed. The LTE-OFDM structure is shown in Figure 1.

3.3. LTE-OFDM Transmitter. A transmitter includes the sub-carrier mapping, modulator-baseband, backward Fourier change, parallel-serial transformation, CP (cyclic prefix), and a computerized to-simple converter which are adopted by the DPSK modulator.

3.4. LTE-OFDM Receiver. OFDM collector includes a parallel-to-serial converter, analog to digital converter, RF segment, Fourier change, equalizer, CP remover, identifier, and sub-bearer de-mapper. The utilization of modulation types is based on the noise signal ratio of the received signal. The modulation signals are mapped to the subcarrier and its transfer through an IFFT. These modulations are also utilized to store control data of every subcarrier.

3.4.1. DWT in the Input Signal. The input signal is declined within time recurrence and that is depicted through DWT. The extraction processes of the transform wavelet are carried out through two steps. First, the signals are decomposed based on the distinct recurrence sub-groups. Second, the split-up signal of a specific recurrence sub-group is evaluated under numerous constraints. For $s(t)$ signal, the varaition in wavelet with $\delta m, n(t)$ wavelet is given as follows

$$D(m, n) = \int_{-\infty}^{\infty} s(t).\delta m, n(t)dt. \quad (1)$$

The input signal is passed through the channels like high pass and low pass then the signals are separated by the wavelet filters into two sub-band called high-pass sub-band and low-pass sub-band. These sub-bands are again classified into two units and this process is repeated till an appropriate stage. The outcome of the low-pass channel is referred to as the estimated coefficient whereas DWT is used to eradicate the attribute from the various signals. There are numerous elective wavelets; some of the wavelet utilized in the presented work are given below.

(1) Haar Wavelet

(2) Daubechies Wavelet

(3) Symlet Wavelet

(1) (1) Haar Wavelet Transform Coefficient. The two-dimensional Hor bandwidth is taken into account to carry out a filtering step, because it reduces the BER and computational duration, whereas m_t is expressed as follows.

$$m_t = H_t \omega_t, \quad (2)$$

where t represents the info signal and ω_t denotes the Haar wavelet transform.

In the initial stage, the AA1 is decomposed, and this process is continued. Every stage of the wavelet includes two advanced channels and a downsampler which is depicted in Figure 2. HP$[t]$ is a discrete mother wavelet and it is referred to as a high-pass channel whereas, LP$[t]$ is referred to as a low-pass channel and $\downarrow 2$ represents the subsampling. In the initial stage, the AA1 is decomposed, and this process is continued. The mean estimation of the detail coefficient is defined by making the detail coefficient as normal.

$$d[c_t] = \sum c_t, \quad (3)$$

where Δ_{c_t} represents the incentive means of estimation coefficient.

The standard deviation of the detail coefficient is evaluated through the square foundation of the mean worth.

$$\sigma_{c_t} = \sqrt{d[c_t] - (d[c_t])^2}, \quad (4)$$

where σ_{c_t} represents the standard deviation of estimation coefficient.

(2) (2) Daubechies Wavelet Transform Coefficient. The variation in the Daubechies wavelet is defined comparably through the Haar wavelet variation. The basic qualification between the wavelets incorporates the representation of scaling signal and wavelets. In the variation of the Daubechies wavelet, the scaling signal and wavelet have long backing which means it generates a contrast as well as midpoint and that utilizes a few more qualities from the signal. For each wavelet group, the orthogonal multiresolution generated by the balancing task $\omega(t)$ is examined as follows.

$$\omega(t) = \sum_{n=0}^{N-1} c_n \omega(2x - n), \quad (5)$$

where $(c_0, c_1, \cdots \cdots c_{N-1})$ a group of genuine numbers is referred to as scaling cover or succession.

(3) (3) Symlet Wavelet Transform Coefficient. It is one of the members of the dB frequencies family and is proposed by Daubechies. It compares the features of two wavelet members. It is referred a "sym" and later it is denoted through the quantity of evaporating minutes.

3.4.2. Optimal Coefficients Selection Using BFF. Firefly algorithm was proposed by Yang in the year 2007. This algorithm is inspired by the behavior and the flashing pattern of the fireflies. This algorithm is a metaheuristic population-based approach. The short and rhythmic flashes generated by the firefly are observed, whereas the pattern of the male and female fireflies is varied for each other. Fireflies communicate through bioluminescence which is a glimmering design [22]. FF contain certain benchmarks and they are as follows:

(i) Fireflies are unisex; therefore, the attraction process does not depend on firefly sex

(ii) The attractiveness of the fireflies is directly proportional to the brightness of the fireflies so if the

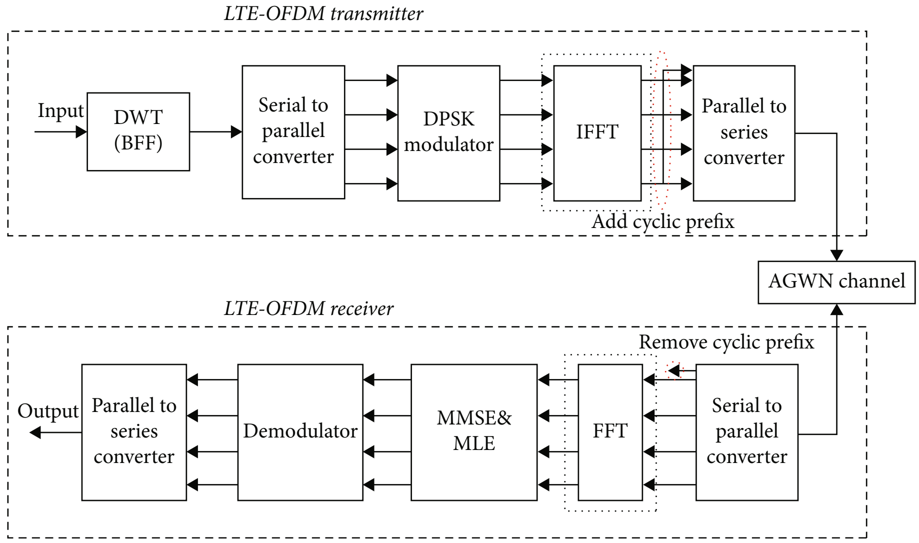

Figure 1: Structure of LTE-OFDM.

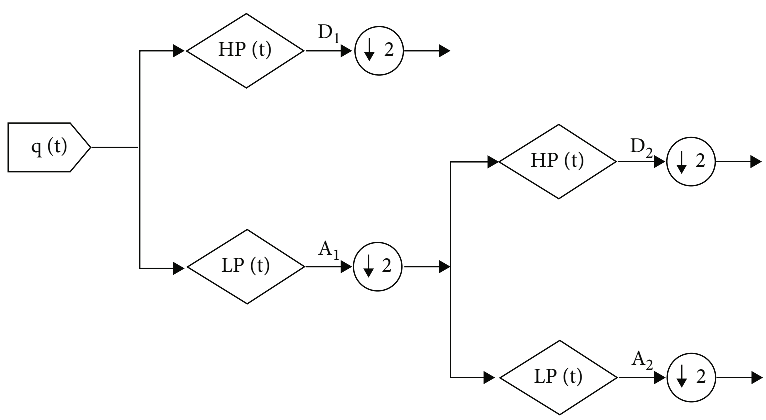

Figure 2: DWT decomposition.

begins

Fireflies population is initialized in the form of binary D_i ; $i = 1, \cdots n$

Intensity of each firefly is computed, T_i

co-efficient of light absorption is estimate,

While $t <$ Max_*generation*

For $i = 1 : n$; $j = 1 : n$

If $T_j > T_i$

Firefly i move towards j in d- dimensions

end if

Attractiveness varies with distance through $\exp^{(-\lambda d^2)}$

New solution is found and the brightness λ *is updated*

end for j

end for i

estimate best current coefficients then rank the fireflies

end while

authenticate the optimal coefficient

end

Algorithm 1: BFF Algorithm

attractiveness and brightness decrease, then the distance between the flies is increased [23]. The files with less brightness attract the flies with more brightness. If the firefly did not get the brighter one, then it moves randomly

(iii) The landscape of the objective function is used to define the fireflies' brightness

(1) (1) Binary Firefly. The firefly algorithm is handled through the binary structure. The consequence of this activity ranges from 0 and 1. After the application of the binarization technique, the appropriate 0 or 1 is obtained.

Step 1. Firefly population is initialized that is the coefficient of DWT $D_i = D_1, \cdots D_n$ is initialized, where $D_i = 1, ,. \cdots n$; here, n specifies the absolute number of the coefficient. Here, the values are transferred in the form of binary and the choices are revised to generate a firefly swarm with the required size. The length of firefly space is equal to the absolute coefficient. The firefly population measures resolve the optimal coefficients.

Step 2. The light force intensity of the firefly is measured in this phase. Here, the wavelet coefficient is evaluated through the fitness function.

Step 3. The estimation of target role in each FF is recognized through the light intensity of the compared FF. The firefly with fewer magnificence is pulled in and the light intensity is expressed as

$$T_i = T_{i0} e^{-\lambda r2}, \quad (6)$$

where T_{i0} represents the attractiveness with $r = 0$ and λ represents the coefficient of absorption, which controls the light force reduction.

Step 4. Every firefly includes an engagement which are used for the enhancement of the firefly constraint.

$$\tau = \tau_0 e^{-\lambda r2}, \quad (7)$$

where τ_0 indicates the quality of engaging at attr = 0.

The separation of fireflies a and b at positions a_p and b_q are characterized as follows:

$$r_{ab} = \sqrt{\sum_{f=1}^{d} \left(a_p^f - b_q^f\right)^2}, \quad (8)$$

where a_p^f indicates the f^{th} spatial coordinate's segment and d indicates the quantity measurements. At last, the progress of a firefly a is forced to the alternative in an attractive manner and it is indicated as

$$A_p^{f+1} = A_p^f + \tau\left(A_b^f - A_a^f\right) + \sigma\left(\text{rand} - \frac{1}{2}\right), \quad (9)$$

where A_a^{f+1} indicates the situation of firefly in the next generation.

A_p^f indicates the present situation of firefly A_a.

$\tau(A_b^f - A_a^f)$ represents the engaging quality.

$\sigma(\text{rand} - 1/2)$ indicates the random parameter σ and rand.

Step 5. The above process is continued until the optimal coefficient is obtained.

The BER of the input signal is reduced by selecting the optimal coefficient; after that, the input is transmitted to the LTE-OFDM transmitter. Then, the signals that are processed through the transmitter are explained in the further section.

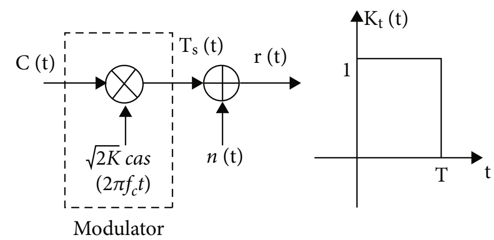

Figure 3: BPSK modulator.

3.5. BPSK Modulation Technique. BPSK is a two-phase balanced scheme in which two varied phase states in the transmitting signal are indicated through the zero's and one's in the double message. Figure 3 depicts the structure of BPSK modulation and Figure 4 illustrates the BPSK demodulation structure. The carrier is expressed as follows,

$$B(t) = P \cos(2\pi f_c t), \quad (10)$$

where P indicates the 1Ω load resistor's sinusoidal carrier peak estimation, whereas the power dispersed is expressed as follows,

$$R = 1/2P^2. \quad (11)$$

In the binary adjustment, two signals with antipodal produce the base error probability through the additional parallel signal arrangement. The probability of the error is reduced by allowing multiple waveforms to broadcast the data. The transmitting signal is characterized through $K(t)$ and it is expressed as follows

$$K_T(t) = \begin{cases} 1 & 0 \le t \le T \\ 0 & \text{otherwise} \end{cases}. \quad (12)$$

$$c(t) = \sum_{l=-\infty}^{\infty} c_l K_T(t - lT)\,;\, c_l \in \{+1,-1\}, \quad (13)$$

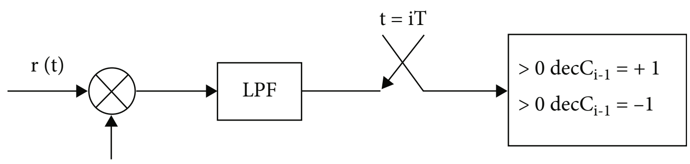

FIGURE 4: BPSK demodulator.

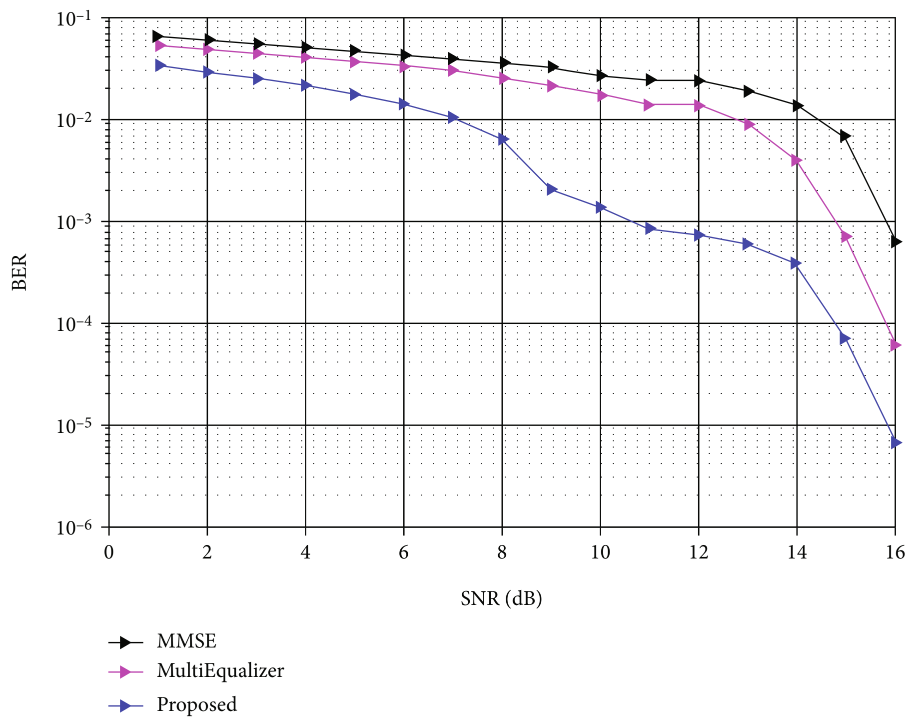

FIGURE 5: Comparison of 4G/5G OFDM with OFF methods based on BER.

where $c(t)$ indicates the waveform information which includes an interminable succession of pulses with time T and height 1.

The signal that are transmitted are represented as,

$$T_s(t) = \sqrt{2K} \sum_{l=-\infty}^{\infty} c_l \cos(2\pi f_c t) K_T(t - lT),$$
$$T_s(t) = \sqrt{2K} \cos(2\pi f_c t + \varphi(t)), \quad (14)$$

where $\varphi(t)$ indicates the waveform stage and K represents the signal force.

The energy of each transmitted piece is given as follows:

$$E = KT. \quad (15)$$

The AGWN presence provides the optimum recipient for BPSK, whereas the LPF (low-pass channel) is integrated with the baseband signal that is transmitted. The reaction is denoted as $j(t) = K_T(t)$. The yield of low-pass channel is given as follows

$$Y(t) = \int_{-\infty}^{\infty} \sqrt{\frac{2}{T}} \cos(2\pi f_c \tau) h(t - \tau) r(\tau) d\tau. \quad (16)$$

The capacity of the BPSK signal's data transfer is decreased through the separation process, whereas in the off-state, the capacity of the data transfer is reduced to $1/T$. After the modulation process, the input taken from the source encoder is grouped into a log2M bits cluster by the S/P (Serial to Parallel) converter, where M indicates the digital modulation plan size which is utilized by every subcarrier. Here, n number of O_m symbols is generated. After that, the signals are plotted to the IFFT container [26] and these IFFT bins are relays on the symmetrical sub-transporters of the OFDM signal. Therefore, the communication of OFDM is expressed as follows:

$$O(l) = \frac{1}{l} \sum_{k=0}^{l-1} O(k) \exp\left(\frac{j2\pi kl}{L}\right). \quad (17)$$

By using the N-point FFT function, the unique signal of the recipient is reduced and it is expressed as follows:

$$Y(k) = \sum_{k=0}^{l-1} y(n) \exp\left(\frac{-j2\pi kl}{L}\right) + Z(k), \quad (18)$$

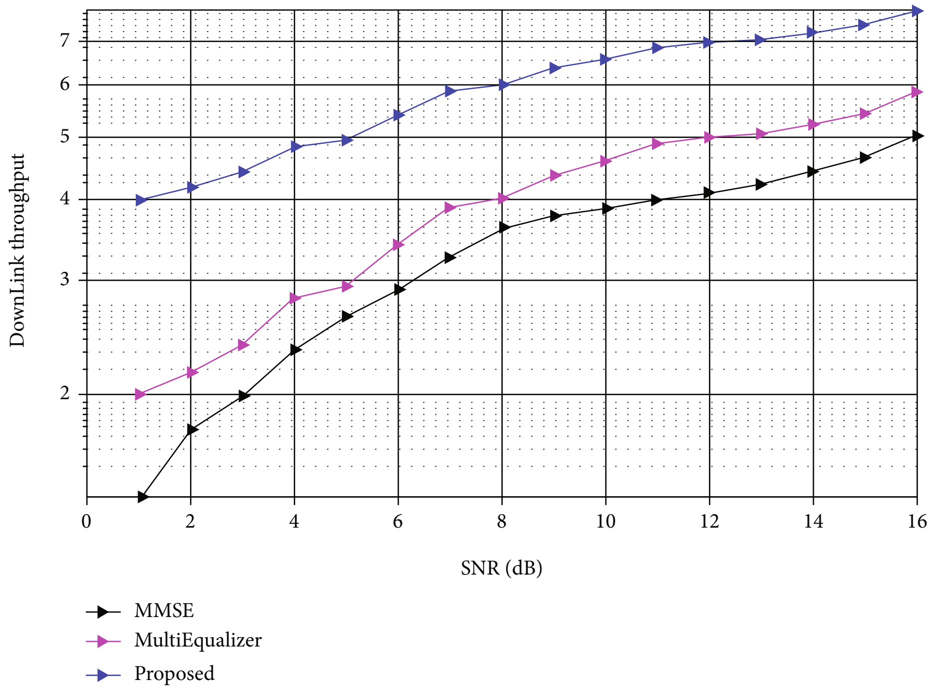

Figure 6: Comparison of 4G/5G OFDM with existing methods through DLT.

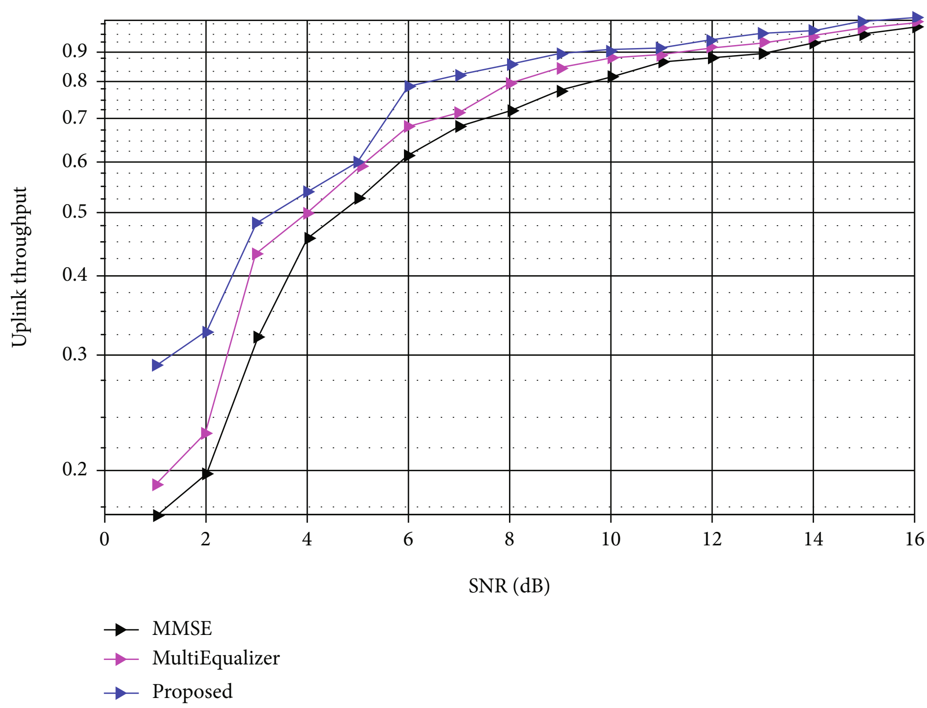

Figure 7: Comparative analysis of 4G/5G OFDM with OFF approach through ULT.

where $Z(k)$ is the AWGN that exists in the channel and compares to the $F(k)$ samples of FFT.

3.6. AGWN Channel. In the process of channel acknowledgment, the AGWN channel is a widely utilized numerical model. Here, the main source for the troubling impacts at the recipient side is taken as warm commotion. The white Gaussian clamor is added by the AWGN channel to the signal. This is expressed as follows:

$$r_s(t) = T_s(t) + G(t), \tag{19}$$

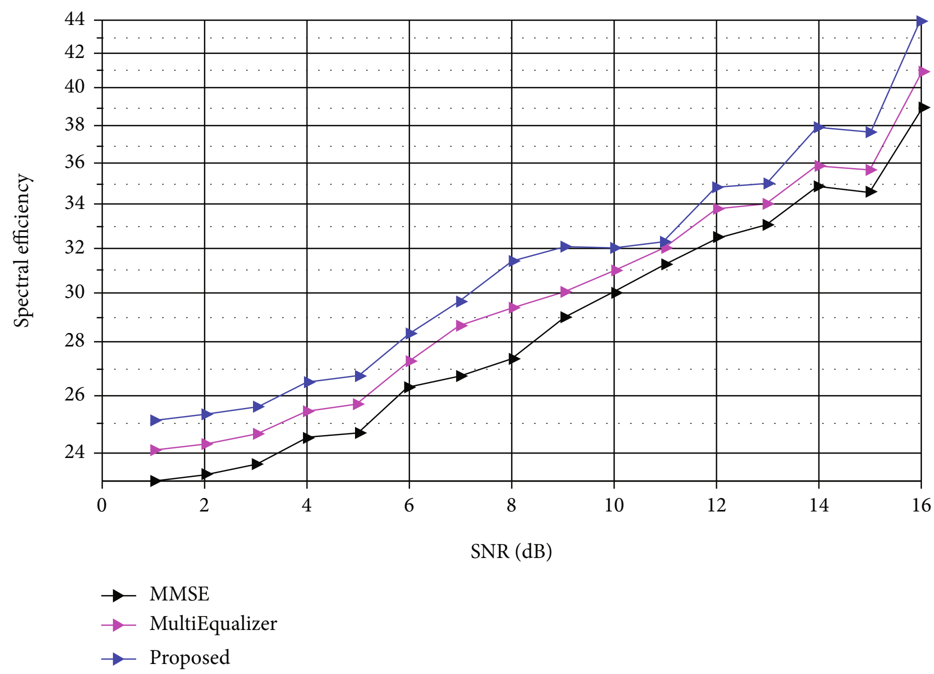

Figure 8: Comparative analysis of 4G/5G OFDM with existing method in terms of spectral efficiency.

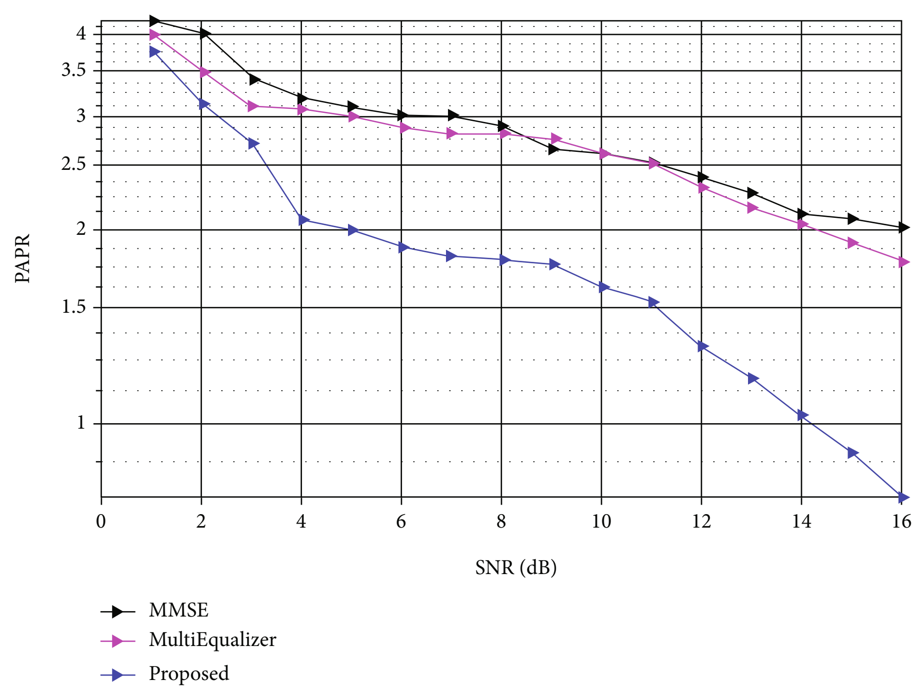

Figure 9: Comparison of 4G/5G OFDM with existing method in terms PAPR.

where $r_s(t)$ and $T_s(t)$ represent received and transmitted signal whereas $G(t)$ indicates the white Gaussian noise that is added to the AWGN channel. Moreover, Gaussian appropriation is employed for the noise test, and its function of thickness $P_d(x)$ with fluctuation σ^2 is given as follows

$$P_d(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\left(x^{-m2}\right)/2\sigma^2}. \quad (20)$$

For example, the negative impacts of the multipath are reduced through transmitting the signal with shortest path to the multipath channel with high data rate.

3.7. Multi-Equalizers for BER Reduction. The traditional OFDM recipient normally supports the inverse procedure of transmission. Here, the OFDM recipient utilized the multi-equalizer to

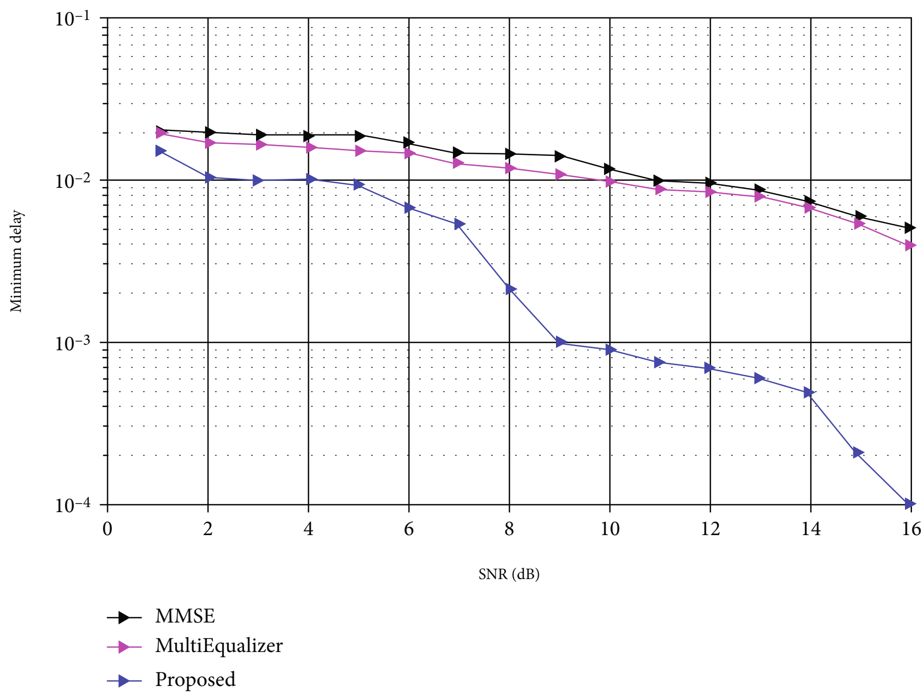

Figure 10: Comparative analysis of MSD for 4G/5G OFDM with existing method.

retrieve the signals which enhance the attributes of BER and retain better SNR.

3.7.1. MMSE (Minimum Mean Square Error) Equalizer. The MMSE arrangement includes various coefficients in which numerous coefficients are located for each example time to limit the error between the balanced and perfect signals. The MMSE recipient is utilized to diminish the average estimation error that occurs in the transmitted symbol. The capacity of the error estimation is communicated using the constraint (21).

$$e[t] = g[t] \otimes h[t], \tag{21}$$

where $e[t]$ indicates the blunder at test time t, and g and h represent the column and segment vector of measurement, respectively, whereas g reserves the coefficient of the equation and h limits the received test. t denotes the cycles in the equalizer or time count.

3.7.2. MLE (Maximum Likelihood Equalizer). The MLE is more supreme than BER and is known as an elective approach when the PMF or PDF are recognized in the circumstance. This approach compares every signal that is received for selecting the probability. The MLE is expressed as follows

$$\text{MLE} = \text{argmin}\|h(y) - Vx\|^2, \tag{22}$$

where $h(y)$ indicates the input signal. Here, the recipient diverges the vector and potential arrangement of the received signal whereas the ML equalizer evaluates the channel impulse response. The performance of the system is improved by periodically recognizing the signal rather than expanding the multifaceted nature. The MMSE-ML noise equalization reduces the BER of the LTE-OFDM signal.

4. Experimental Results

This research work is implemented in the MATLAB platform version 2015A with system configuration of i5 processors containing 4GB RAM. The main objective of the work is to reduce the BER (Bit Error Rate) through 4G/5G adopted OFDM. This reduction is carried out by selecting optimal wavelet coefficients through BFF (Binary Firefly) algorithm. Here, some other performance metrics like up and downlink throughput, minimum delay, and SNR are taken into account for the performance evaluation. The outcome of the exhibited work is applied to improve the productivity of the presented approach.

The above Figure 5 depicts the graphical representation of the comparative analysis made but the proposed 4G/5G OFDM and the OFF method. The parameter taken for the analysis is SNR and BER. From the analysis, the BER of the proposed method gradually decreases than the other existing technique.

The above Figure 6 depicts the graphical representation of the comparative analysis made but the proposed 4G/5G OFDM and the existing technique. The parameter taken for the analysis is SNR and downlink throughput (DLT). From the analysis, the DLT of the proposed method gradually increases when compared to the other existing technique.

The above Figure 7 illustrates the comparison of the proposed technique with multi-equalizer and MMSE. From the analysis results, the proposed method reduces the BER and error rate and improves the spectral efficiency, ULT, and DLT when compared to the other OFF techniques.

The above Figure 8 illustrates the comparison analysis of the proposed method with the multi-equalizer and MMSE in

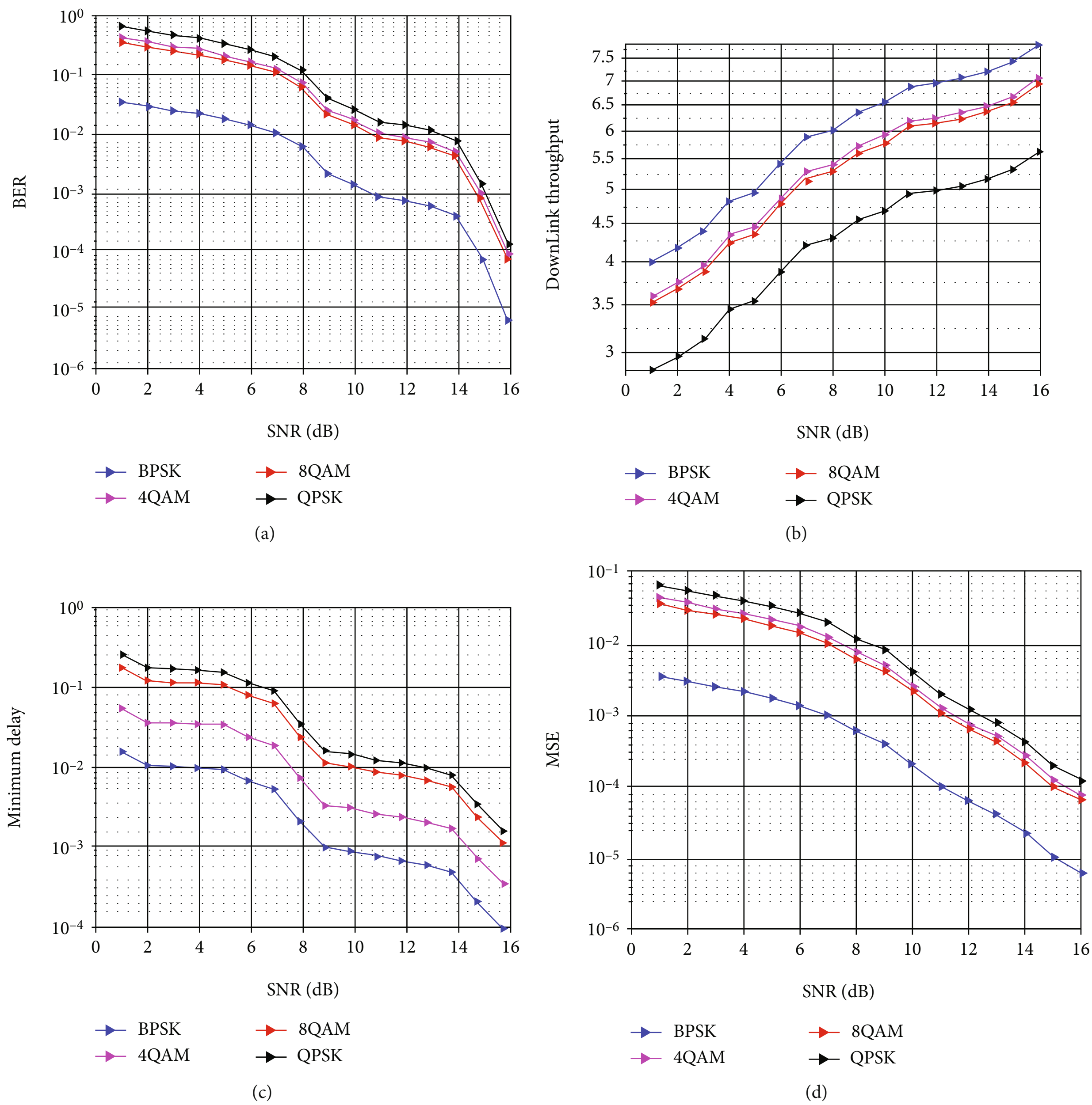

FIGURE 11: Continued.

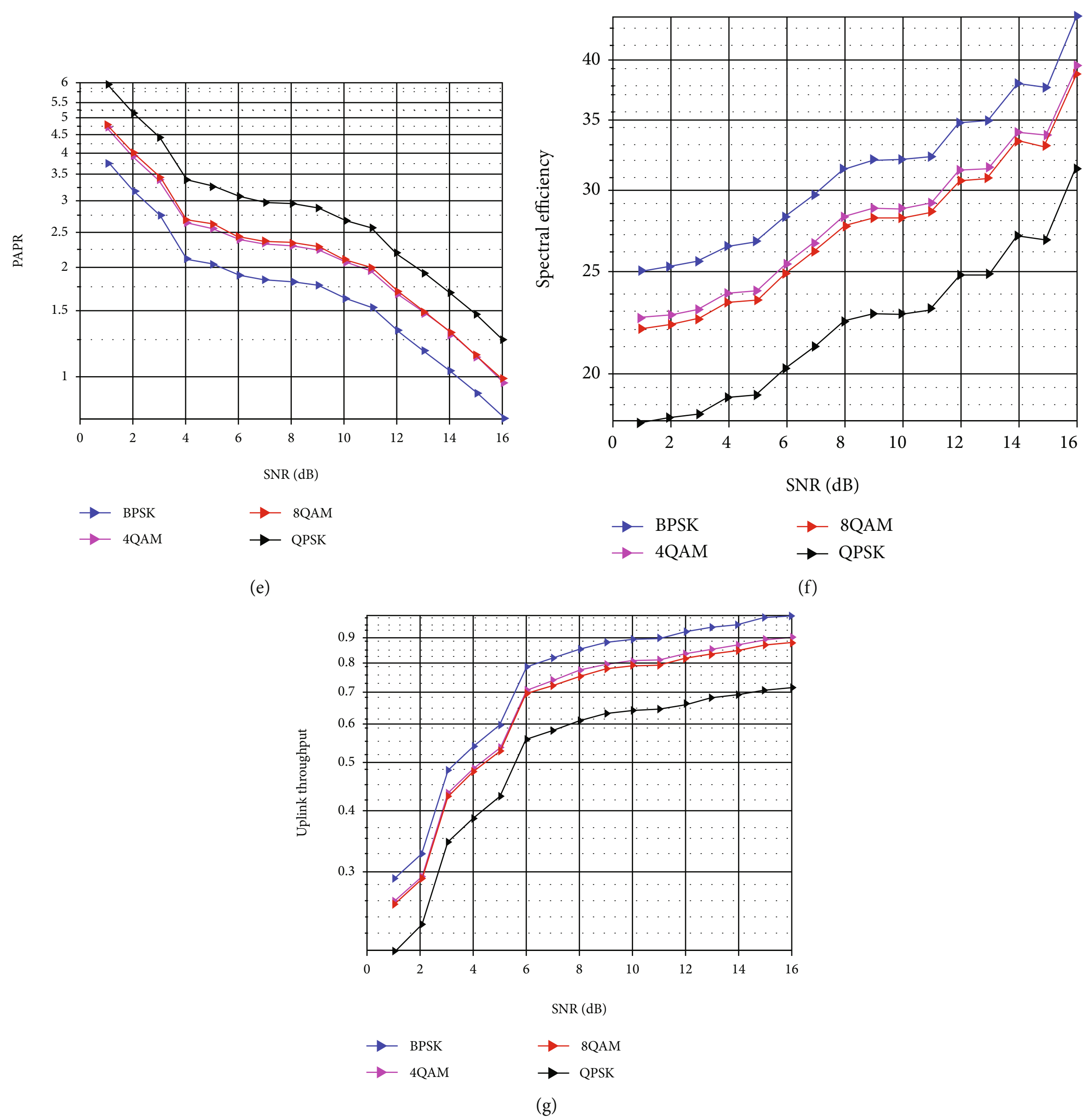

Figure 11: Comparative analysis depending on various modulators in terms of (a) BER, (b) DLT, (c) minimum delay, (d) MSE, (e) PAPR, (f) spectral efficiency, and (g) ULT.

terms of SNR-based spectral efficiency. As a result of the analysis, the spectral efficiency of the proposed methods is gradually increased when compared to the existing method.

The above Figure 9 illustrates the comparison of the proposed technique with the multi-equalizer and MMSE in terms of PAPR (Peak-Average Power Reduction). The analysis result shows that the proposed technique minimizes the delay when compared to the other existing technique.

The above Figure 10 illustrates the comparative analysis of the proposed method with multi-equalizer and MMSE. From the analysis results, the proposed method reduces the BER and error rate and improves the spectral efficiency, ULT, and DLT when compared to the other OFF techniques.

Figure 11 illustrates the comparative analysis of various modulators such 4QAM, 8QAM, and QPSK with the BPSK in terms of BER, downlink as well as uplink throughput, minimum delay, spectral efficiency, MSE, and PAPR. The simulation results indicate that the proposed BPSK reduces the noise interference and error BER and provides an accurate decision than the other modulators.

5. Conclusion

This research work mainly focused on the reduction of the BER value of the OFDM model which relies on the LTE-based IoT. Here, the proposed framework encircles through the BPSK when there occur contrasted with additional adjustment plots under AWGN (Additive White Gaussian Noise) channel. The performance of the DWT-OFDM through BPSK provides some specific unique properties which rely on other balance approaches. Therefore, BPSK is the most suitable application with low-speed communication. The input signals are simulated through various wavelets such as biorthogonal, Haar, Symlet, and Daubechies. The simulation is carried out through the MATLAB platform. The simulation results yield the optimal wavelet coefficient based on the plan which also provides the minimum average BER.

Data Availability

The data used to support the findings of this study are included within the article. Should further data or information be required, these are available from the corresponding author upon request.

Disclosure

It was performed as a part of the Employment of College.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Research Article

A Critical Evaluation of Procedural Content Generation Approaches for Digital Twins

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Procedural content generation (PCG) of terrains is one of the main building blocks for creating an automated and real-time virtual world. This study provides and in-depth review of the different tools, algorithms, and engines used for the PCG of terrains for the PCG of digital worlds; we focus especially on terrain generation but address also the main issues related to build structures and characters. It is important to know that the PCG of terrains can be implemented in a multidisciplinary scenario, for instance, modeling of games, simulating industrial maps, urban and rural planning of developments, government, and nongovernmental agency improvement plans. Many problems in current approaches were identified from the literature, where most of the researches studied were merely throwaway prototyping based, i.e., proof of concept-based systems, and were not tested in the real environment. Also, genetic algorithm-based PCG of terrains lack multiple features such as roads and buildings. The virtual cities generated through different engines were lacking a realistic look and feel. Terrain generation through multiobjective evolutionary algorithms (MOEAs) is investigated, and it is deemed the usage was restricted to the gaming domain and not extended to other fields. Findings suggest that the correctness of generated terrain is a big issue in the automatic generation of terrains. Thus, a focus on the automated correctness check is required. Other important content generation in video games such as structure generation and character generation has been extensively studied, and the techniques are analysed in the further sections of this research work.

1. Introduction

A digital twin is a computer software that creates simulations based on real-world data to forecast how a product or process will perform. To improve the output, these applications may use the Internet of Things (Industry 4.0), artificial intelligence, and software analytics. These virtual models have become a standard in contemporary engineering to drive innovation and enhance performance, thanks to advancements in machine learning and elements such as big data [1]. In brief, having one may help improve strategic technological trends, avoid expensive breakdowns in physical objects, and test processes and services utilizing superior analytical, monitoring, and predictive capabilities.

Human society has evolved in terms of disruptive technologies for breaking the long-held business rules using business process reengineering (BPR) [1]. One of the most significant disruptive technologies used by software developers is designing and implementing virtual worlds and their simulation and modeling content. Electronic games consume a significant part of our daily time, especially in urban areas where the Internet is available and access to game-playing hardware and software is available. The World Economic Forum estimated the gaming industry's revenue to be approximately USD 165 billion in 2020 [2]. It has been roughly 62 years since the computer gaming industry began during the late 1950s, with the first game's creation named "Tennis for Two" by physicist William Higinbotham [3]. Since then, electronic computer games have progressed, improved, and grown. Games are influenced by social norms and values, human views, and relationships, and most importantly, it has helped the game-playing community, content creators, and developers to understand the advancements in computer technologies. The 1970s saw the introduction of arcade games and gaming consoles. Personal computers were introduced in 1975, targeting niche markets. The gaming industry was still working on introducing new games and ideas for this technology's public use. In the 1990s, the personal computers were mass-produced, and hence, the home gaming consoles rapidly increase. The acceptance of home gaming came with the development of the first-person shooter game [4]. The continuous and rapid growth of the industry and incorporation of 3D content has made the video gaming industry phenomenal in size [5]. As such, the demand for exciting content design and generation has increased. The gaming industry's content creators and developers are coping with meeting the demands of these high-end users. These users are always eager to look for undiscovered exciting and challenging content within the minimal time possible and less cost incurred.

The technology advancements and high-end computational power availability have resulted in the game-playing community becoming very choosy and cautious in adopting a game. Video game developers and content creators always struggle with content production in terms of quantity and quality. Manual efforts and labours increase production costs and the time to deliver to the market. In game production, the content creators and developers use various tools to produce exciting content like Maya [6] and Unity 3D [7]. The game developers must create a virtual world for the game and create various types within that world along with interactive stories and playable levels. The whole process needs to be scalable [8] and cost-effective for the producers of games and the whole gaming community. Content generation for video games has been a critical concern for video game developer and producers. The journey from manual content creation in video game development to content creation through algorithms has been challenging. The researchers have been trying a mix of ideas from pure manual content creation to mix and automated content generation [9].

In video and electronic games, procedural content generation (PCG) creates the gaming world's content in an automated manner, using algorithms. The content can range from playing characters, nonplaying characters, storyline, and puzzles to the ecosystem and environment, which create the ambiance and feel [10] of the storyline being played. Thus, to generate many contents, the PCG mechanism is used. There can be several reasons and purposes for using such content generation methods. The approach can reduce the duration and cost of the content generation process [11], achieving the right time-to-market and affordable content. Also, exciting and unpredictable content to the game's users is aimed at increasing the fanbase and playtime. According to Freiknecht and Effelsberg's definition [12], "procedural content generation is the automatic creation of digital assets for games, simulations or movies based on pre-defined algorithms and patterns that require a minimal user input."

According to Merriam-Webster's [13] definition, terrain refers to a geographic area or a piece of land with physical features, which tend to erode. When it comes to electronic video games, simulations, or videos, then terrain or virtual terrain is considered virtually. A virtual world resembles an actual physical terrain or product of pure imagination and fantasy or even a mix of both. Virtual terrain modeling and generation are crucial in games and simulations and training applications [14]. The goal is to create a terrain that is as per the requirements with minimal effort and keeping the element of surprise and interest intact. Virtual terrain in gaming is a stage set where the story and its characters work together in a coherent and immersive manner to create an exciting experience. The gaming environment's terrain adds value to the story and increases the interest level of the players, and an example could be tropical or urban terrain.

Auto terrain generation is one of the critical factors that can significantly reduce the cost and efforts involved in developing a new electronic game. Cost and time are not the only factors that are of concern to the game developer and designers. It is also vital that the content is exciting and unpredictable to keep the audience and gaming users engaged. Apart from the electronic gaming domain, the interesting uncharted and unpredictable content generation is a critical factor in simulation and virtual training systems.

According to Hecker [15], "the game based on random generation will build the content based on the predefined elements that the developers hard coded" and "the game based on procedural generation which create original content itself for the player of explore or use." These can be used to generate elements of a game. For example, in the game "Binding of Isaac," random generation is used, whereas in the games like Minecraft and Terraria, procedural generation is used. The most important terminology in procedural generation is the noise, also known as the Perlin noise. Perlin noise is a procedural texture primitive, a kind of gradient noise used by visual effects artists to make computer images seem more realistic. Although the function seems to be pseudorandom, all its visual features are the same size. In terrain generation, the first step is to create a horizon with hills, valleys, and mountains. To create this, an offset is introduced which will create patterns to make the terrain more interesting. To shift this offset randomly, Perlin noise is used to introduce the variation in the terrain. The offset can be shifted up and down or left or right to create smoother and more realistic terrains like mountains, hills, and valleys. The same principle can be used in 3 dimensions to generate caves by using two sets of noise generators in two axes. The intersection of each point in space will be the new point that defines the height or depth in 3D space.

The gaming industry and other niches are also keen on utilizing modern technology trends to achieve their virtual and automated content generation [16]. For instance, the tourism industry has explored the virtual tourism concept [17]. Virtual tourism might be the only method of sightseeing and tourism in the future in case there are pandemics such as COVID-19. Such an approach may apply to various domains where social gathering and mobility are restricted [18]. Urban planning and landscape designing are time-consuming and expertise-oriented jobs are critical for humanity's future. Also, top academic universities teach architecture design and urban planning [19] involving virtual terrains for the planning phase. The industry-leading solution providers in GIS and urban planning also provide solutions [20] that help the urban planner and architects. PCG can help them to rapidly build terrain plan with minimal effort while remaining focused on the desired goals. Virtual terrains are practical in mission-critical domains where the usage of existing tools and machines is not feasible. Therefore, pilots trained by using a simulator are comparatively cheaper as compared to being trained multiple times in actual scenario [21].

The virtual terrain is a crucial component of the virtual world. Such terrain is applicable for games or any other virtual world or any other applicable niches. According to the findings, the accuracy of created terrain is a major concern in the automated production of terrains. As a result, the automatic correctness check must be prioritised. Other key content generation methods in video games, such as structure creation and character generation, have been widely investigated, and the approaches are discussed in the following sections. Nonetheless, manual terrain generation is a time-consuming and tiresome job and requires enormous effort and cost. Therefore, automated terrain generation is needed when we need a reduction in time and cost to deliver. It can also help in desired terrain generation with more minor or no input requirements. This work will study the previous work done in the field of procedural terrain generation. The last section concludes the paper and future directions to the research in the same domain.

2. Terrain Generation

According to Yin and Zheng [22], the users can naturally place terrain features through the Parametrically Controlled Terrain Generation (PCTG) method. It can be achieved by making sketches and adjustable parameters that can easily be understood while controlling the terrains' generation process. It is pertinent to state about the importance of procedural generation of terrains that the terrain's synthesis is widely applied in simulation training, moviemaking, and computer games. Experimental results have shown that the use of terrains is very efficient [23]. The gaming industry is increasingly focusing on procedural content generation methods, according to Frade et al. [24]. Considering the high degree of unpredictability of the procedural algorithms employed in video games, the gamers are expected to perform several tests and simulations to obtain an effective procedural system.

2.1. Procedural Terrain Generation. Players in computer gaming can easily be modelled by using AI agents while at the same time producing gameplay data [25]. The agent employed is capable of shooting and moving different gaming scenarios. Moreover, the terrain developed is specific to game content and is being implemented in video games. Technically, the automated generation of terrains in computer gaming makes the development of computer games cheaper and thus reduces the designer's work. It also enriches the experience of the player by continuously offering new game content. The work employs a turn-based 2D shooting game and emphasizes designing a gameplay-driven terrain generation in Scorched Earth. The features of the game also entail trajectory projectiles for gravity management. After every turn, the player can estimate the shooting angle and the projectile power for firing. Players can also avoid hitting the terrain when they estimate the correct shooting angle. Players also have the possibility of moving the tanks so that they can position themselves while shooting.

Procedural generation is a way of producing data algorithmically rather than manually in computers, usually by combining human-generated materials and methods with computer-generated randomness and computing capacity. It is frequently used in computer graphics to produce textures and 3D models. It is used in video games to automatically generate enormous volumes of material. Smaller file sizes, more content, and unpredictability for less predictable gameplay are some of the benefits of procedural generation, depending on the implementation. A subset of media synthesis is procedural generation.

PCG is an important technique for computer game development that is likely to become even more important in the future, both offline, for making the game development process more efficient (designing content such as environments and animations now consumes a large portion of the development budget for most commercial games), and online, for increasing replay value, ad revenue, and other benefits.

According to [26], Procedural Content Generation for Games (PCG-G) is tough since the generator must produce material, adhere to the artist's limitations, and provide players with intriguing examples. The paper discusses a six-layer taxonomy of game content: bits, space, systems, scenarios, design, and derived, and highlights various potential research possibilities in PCG-G.

The paper [27] describes how customized levels for platform games may be produced automatically. By developing models that predicted player experience based on level design elements and playing behaviors. These models are built using preference learning and are based on questionnaires given to participants after they complete various stages.

The paper summarizes the procedural game level generation by developing

(1) more accurate models based on a much bigger data set

(2) a system for adjusting level design parameters to specified players and playing styles

(3) assessment of this adaptation mechanism using both algorithmic and human players

In the paper [28], a search-based procedural terrain generation is defined, and the aim was to investigate what can and cannot be achieved by the approaches that go by that name and highlight some of the field's key research problems. The paper further discussed the correlation between search-based and other different types of procedural content generation methods.

DTL (Dungeon Template Library) [29] is a software library tool used to generate rougelike and terrain generation based on procedural generation.

THREE.Terrain [30] is an engine working on the procedural generation method which is used for terrain generation using Three.js 3D graphics library.

We classify the work done in procedural terrain generation into mainly four categories based on the algorithms' nature. These categories are as follows:

(1) Genetic algorithm-based approaches

(2) Engine-based classification approaches

(3) Multiple objective-based approaches

(4) Other approaches

2.1.1. Genetic Algorithm-Based Approaches. Designers may generate terrains depending on their aesthetic sentiments or desired characteristics using the Genetic Terrain Programming approach, which is based on evolutionary design using genetic programming. This method develops Terrain Programs (TPs), which can produce a family of terrains—-different terrains with the same morphological properties. The Interactive Genetic Algorithm (IGA) used for terrain generation means those algorithms where human evaluation or fitness test is needed. A nonspecialist can use the IGA in the generation of rapid terrains [31]. Additionally, graphics engines can allow terrains to be specified using more than 800 floating-point parameters. However, the increasing number of floating-point parameters can overwhelm nonspecialist users. The design of an auto terrain generation system (TAGS) is discussed in this research. TAGS is specifically based on the implementation of the IGA and addresses complicated procedural technique issues. The proposed design implements user preference, thereby exploring the multidimensional parameter space for satisfying aesthetic and user intuition. A semiautomatic technique with computer-aided modeling and physics-based modeling can be an innovative work. The combination of these techniques will reduce the aspects of the user input and, at the same time, promote high-quality output. Walsh and Gade [31] suggested that TAGS has been proven merely as a proof of concept. A more controlled study with unbiased users, a large sample of users, and many features are needed to acquire accurate results. Many features are not included, such as roads and buildings in the terrain generation, which makes the generated terrains unrealistic.

Wheat et al. [32] introduced a PCG method for generating 2D game difficulty levels tailored to a particular gamer's skills. Dynamic difficulty adjustment (DDA) technique, based on genetic algorithm, helps attract a larger gamer group by generating numerous levels. The study emphasizes game content's procedural generation, precisely dynamic game level difficulty on 2D platformer games. The study is specific to the game developed and not generalized. Only four parameters were considered in the study, along with a small number of participant sample. The results are suggestively requiring further study and research.

2.1.2. Engine-Based Classification Approaches. Rhalibi et al. [33] applied procedural methods to the 3D game environment by producing dynamically different game levels with random and user-selected constraints. The work is deemed not to have been tested by an actual company for evaluation. A web application development in Java programming language was part of the study, and future incorporation of artificial intelligence agents is intended to arrange the game world.

Dynamically generating structures such as cities with varied building structures by using PCG is among the current gaming industry approaches, as discussed by Greuter et al. [34]. In combination with algorithms, pseudorandom numbers produce a variety of buildings and streets, creating an impression of a city. The cities, however, are not as realistic because most of them are office skyscraper-type buildings without houses, factories, and schools, i.e., small buildings. During the rendering process, the building occluded by others is not needed to be drawn.

2.1.3. Multiple Objective-Based Approaches. A procedural generation of maps using a real-time strategy (RTS) game was developed by Lara-Cabrera et al. [35]. Kohonen network was used for evaluation purposes. A multiobjective evolutionary algorithm (MOEA) was utilized to evolve maps and to categorize the distance to bad or good in the training set. User involvement is entirely focused on aesthetics only and not on the playability in the games. In other domains, e.g., urban planning or city designs, other factors are emphasized, i.e., aesthetics related to the urban planning or landscaping norms.

Component-based generation of terrain can be achieved by selecting features from available ones having specific attributes. Such technique has been achieved for software product line shown by Khan et al. [36]. Thus, a multiple-level user's defined objective can be used as a selection criterion for the terrain's components or features to generate it automatically for various purposes. The approach is not specifically for terrain generation instead for software product line generation. However, based on the feature's selection algorithms, terrains can be generated as per the user's set objectives.

2.1.4. Other Approaches. This section summarizes different terrain generation approaches which do not fall in the categories of previous sections. It is essential to generate the procedural contents dynamically [37]. Role-play game (RPG) is a popular genre for many gamers. The procedural content generation (PCG) reduces the design efforts and the time for game development. The researchers in [37] employed a machine learning approach to predict the type of player using the Bayesian network and produce suitable game content but with low accuracy. One possible reason was that the generation occurred in a semiautomated manner. Also, there was no access to the source code of the study's target game, limiting achieving the desired accuracy. The study worked on predefined role-playing game (RPG) elements rather than randomly generated elements and components.

Game development is cumbersome and complex, where the development of terrain, environment, objects, and characters needs to happen [38]. De Carli et al. [38] stated different methods and techniques, i.e., classical and current about PCG, suitable for game development for producing terrains, coastlines, rivers, roads, and cities. Such a method may assist in reducing the cost of game development. This study also clarifies assistive and nonassistive methods for content generation and mainly focuses on cost reduction using nonassisted methods for content generation.

Roberts and Chen [39] introduced a novel machine learning PCG approach called "learning-based procedure content generation (LBPCG)," which can produce vigorous content for the gamers with a lesser interruption while the game is being played. However, user testing results were not rigorous to predict the effectiveness and satisfiability of the proposed framework. The research work predominantly focused on the computational efficiency in online content rather than the generation of quality content. Content categorization is based on the developer and their prior knowledge of the user's preferences. Also, the approach is not economical.

Luo et al. [40] proposed a data-driven scenario generation framework for game-based training. For scenario evaluation, the time of the event is necessary to be considered. Integration of simulation, training model for content evaluation of the game, and AI player modeling was the paradigm's primary goal. The generated model of scenarios does not include persistent objects within the generated virtual environment. As per this study, the framework only works on the set of commands and does not accept open inputs in the form of open text, for instance.

Quality assurance and effective control for the designers are the two significant challenges in PCG [41]. Super Mario Bros (SMB) was used in the case study to demonstrate the effectiveness of interaction between rule-based and learning-based methods for generating game levels. The merger was proved to be effective in producing quality and controllable game levels. Undesirable content is removed using rules known as constructive primitives (CP). The learning-based approach is prone to potential errors and hence needs to be further researched.

Since it is hard to match the accuracy and quality of a handcrafted design with the PCG, Shaker et al. [42] designed a fitness function for SMB levels via a grammatical evolution algorithm. Player experience has not been incorporated in the fitness evaluation mechanism. To ensure playability, the grammatical evolution generator produces levels with less density.

Smith et al. [43] worked on a launchpad to create an autonomous level generator based on rhythm and pace for 2D platformers. Two parameters, i.e., quality assurance and designer control, were introduced by the launchpad generator. The core focus was on performance; hence, the addition of complex components resulting in complex levels will slow down the performance.

Another game level PCG, based on generating character-sequence levels, was developed for "Angry Birds" by Jiang et al. [44]. Two methods, i.e., pattern-struct and a preset model, were used for constructing the "funny quote PCG" for different levels. The structures are evaluated based on a fitness function, which considers several important structural aspects, i.e., the number of pigs and blocks. There is a need for a mechanism to test the generated levels for playability and involve player experience and emotions in the generation process. Common problems in the procedural content generation of terrains are shown in Figure 1.

Training on short datasets, a lack of adequate data, parameter tweaking, and other issues plague the PG machine learning technique [9]. Most procedural content generation techniques (PCG) do not include assessment, and designers establish the goals. Automated generation, artificial intelligence-assisted design, maintenance, analysis, and data compression are some of the applications for PCGML. The suggested study focuses on autonomous generation, which combines the algorithms and the fitness function to develop game material without human input. Video games are a popular kind of multimedia that requires a wide range of machine learning techniques. In general, game design necessitates that the game's level be both playable and attractive [10]. Simultaneously, there is no universally accepted method for standardizing datasets and evaluating performance in game design difficulties.

The 3D nonassisted PCG method was developed for 3D-canyon scenes by De Carli et al. [45] based on noise-generated heightmaps. K-means is a supervised assistive method [46]. A nonassisted mean shift algorithm and image operations were used to portray a canyon design. However, improvements are needed to ensure that the generated design is realistic by incorporating credible textures, vegetation, and other objects.

Table 1 summarizes and tabulates the different algorithms and software used for generating terrains for game levels.

2.1.5. Procedural Terrain Generation Software's and Its Applications. Terrain generation and procedural terrain generation are in the market and industry for quite some time. There are various software and applications that exist to generate terrains in various formats. The generated terrains later can be exported into several compatible formats for the target. This study also investigates different generation software available in the market. However, there is insufficient scholarly data and information about most of the tools and applications. The information gathered is categorized according to the criteria of open source/closed source, 2D and 3D support, export or output, input controls as having graphical user interface or command line interface, and scripting. This

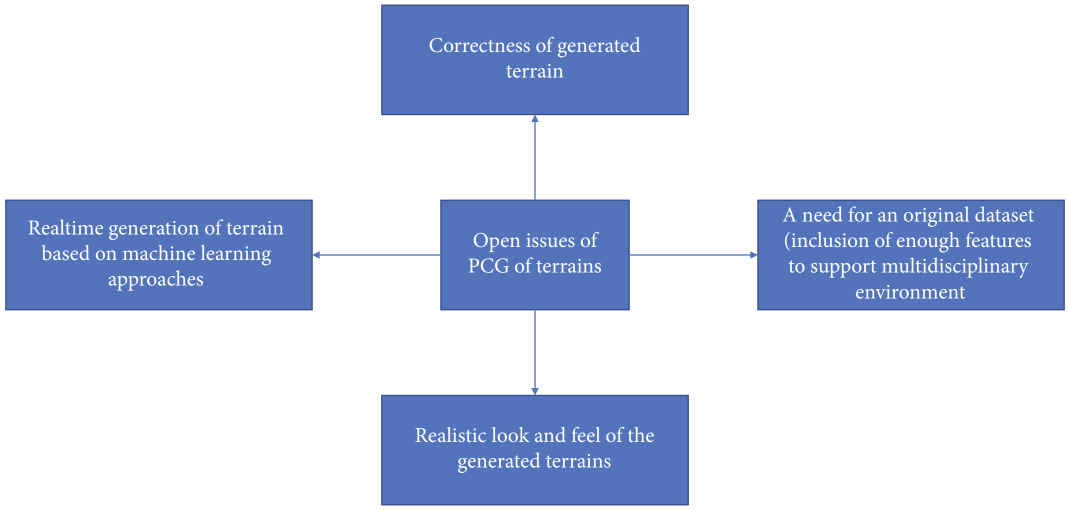

Figure 1: Common problems found in the PCG of terrains.

Table 1: Tabulated summary of the terrain generation algorithms.

Reference	Algorithm	Characteristics
[47]	Fractal noise, e.g., Perlin noise	Interpolation discontinuity of the second-order and nonoptimal gradient calculation
[48]	Midpoint displacement algorithm	The midpoint-displacement model for mountains now includes a squig-curve model of a river's path
[49]	Diamond-square algorithm	Terrain height is generated at random from four seed values organized in a grid of points, covering the entire plane in squares
[50]	Simple collision algorithm	Texturing and creating lifelike textures
[51]	Squarified treemap algorithm	In a two-dimensional region, show tree structures
[52]	Intent-driven partial-order causal link (IPOCL) planning algorithm	It solves the constraints of traditional causal dependency planners
[53]	Long short-term memory (LSTM)	Generation of simulated and original game levels and human level trajectories
[54]	Multidimensional Markov chains	The state space of a Markov chain that simulates the behavior of a system is frequently infinite in several dimensions
[53]	Autoencoder CNN algorithm	Heuristic approach for generation of terrains of all kinds

study also attempts to gather information about the underlying algorithms used in terrain generation within the applications.

Based on the study, the applications show that most procedural terrain generation tools are either standalone terrain generators and editors or part of a complex application, i.e., features as a plugin. In either case, the user requires prior knowledge of terrain generation and tweaking. Also, if the generated terrain is not as per requirements, the user may edit the content. Terrain generation in addition to manual verification for correctness is the key to such tools. This approach may be feasible for the domain experts but not for a user with limited knowledge about terrain generations. For instance, an urban planner that is not technically profound using terrain generation tools may expect less manual intervention with the tool concerning terrain editing. The urban planner's interest will be that a city environment is generated with correct measurements and necessary utilities and modalities with minimal or no corrections.

There exists a tool for terrain generation supported by different engines. There is information about open-source and closed-source software for terrain generation, 2D and 3D capabilities, export formats, the algorithms used, and the user control for the generation of the terrain, i.e., graphical user interface based or command-line interface. There is few open-source software that exists which can offer full support for 2D and 3D. Also, there is barely any information about the algorithms used (only a few share that info), while almost all have support for the graphical user interface to generate terrains.

Figure 2 shows the interface for the World Machine terrain generator. It provides manual controls and editing features for terrain generation and modification.

The interface for "Artifex Terra 3D" is shown in Figure 3, where it allows terrain editing in real time based on the heightmap. It also has texturing capabilities.

The EarthSculptor tool has an easy-to-use user interface, as shown in Figure 4. It is also a real-time heightmap editor

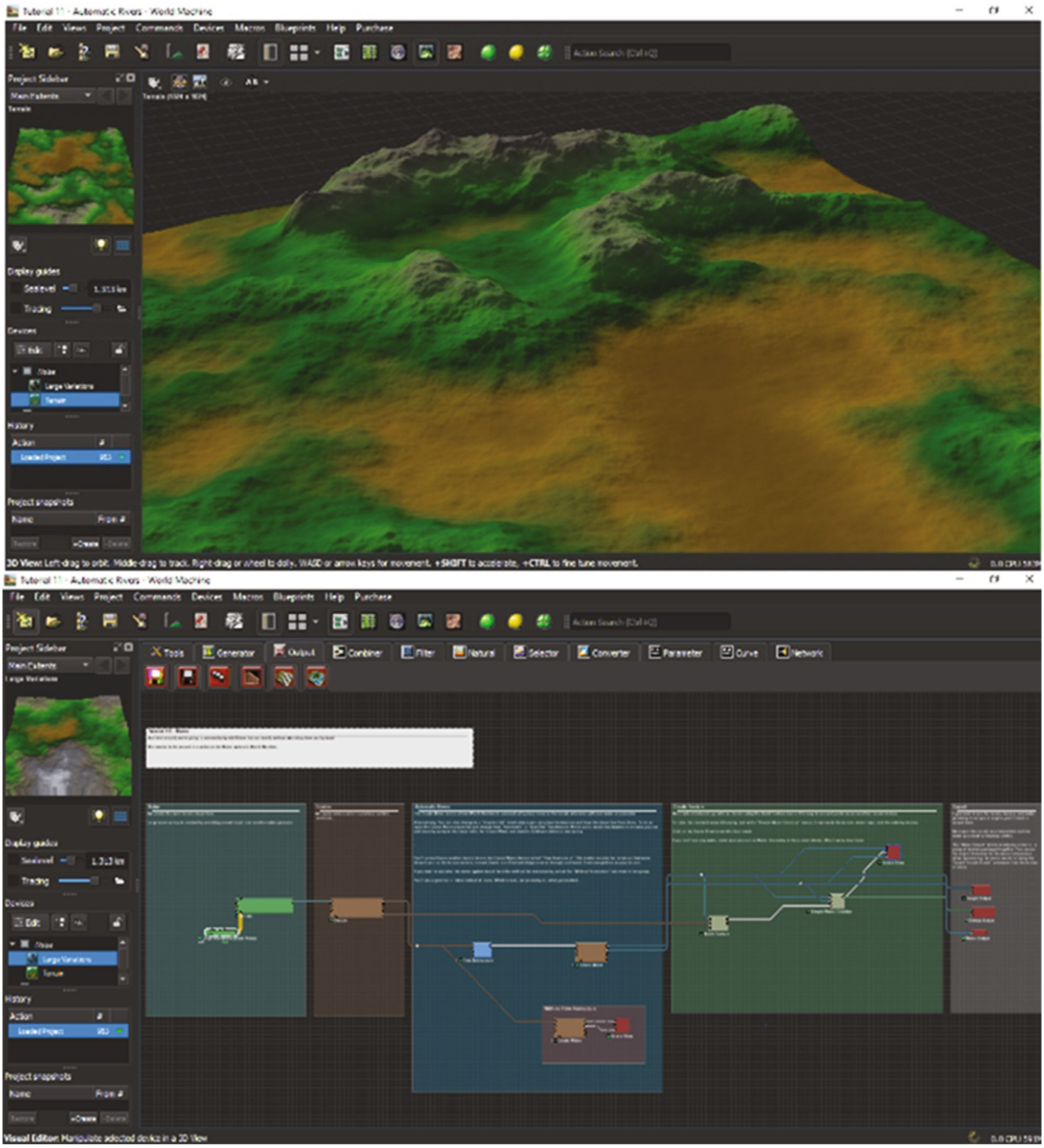

Figure 2: World Machine: terrain generator/editor.

that can generate terrains for various purposes in other target applications.

2.2. Random Terrain Generation. Random number generators generate a predictable, periodic series of pseudorandom numbers [55]. There are two kinds of random number generators:

(1) Computer software pseudorandom number generators (pseudorandom number generators) are software versions of random number generators. They do not create random numbers. Instead, they replicate actual randomness by simulating the selection of a value using algorithms

(2) Hardware random number generators (HRNG) are a kind of random number generator that uses a physical mechanism rather than an algorithm to generate random numbers. Thermal noise, photoelectric noise, diffraction grating noise, and other quantum

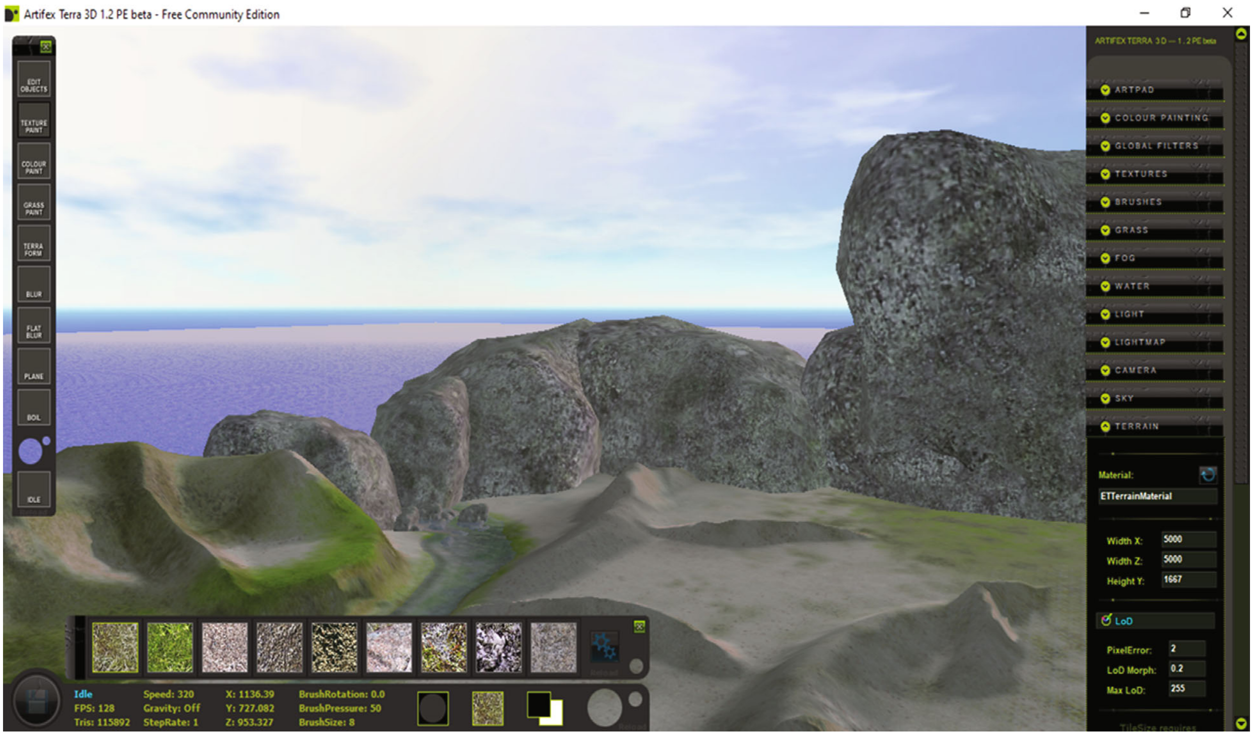

Figure 3: Artifex Terra 3D.

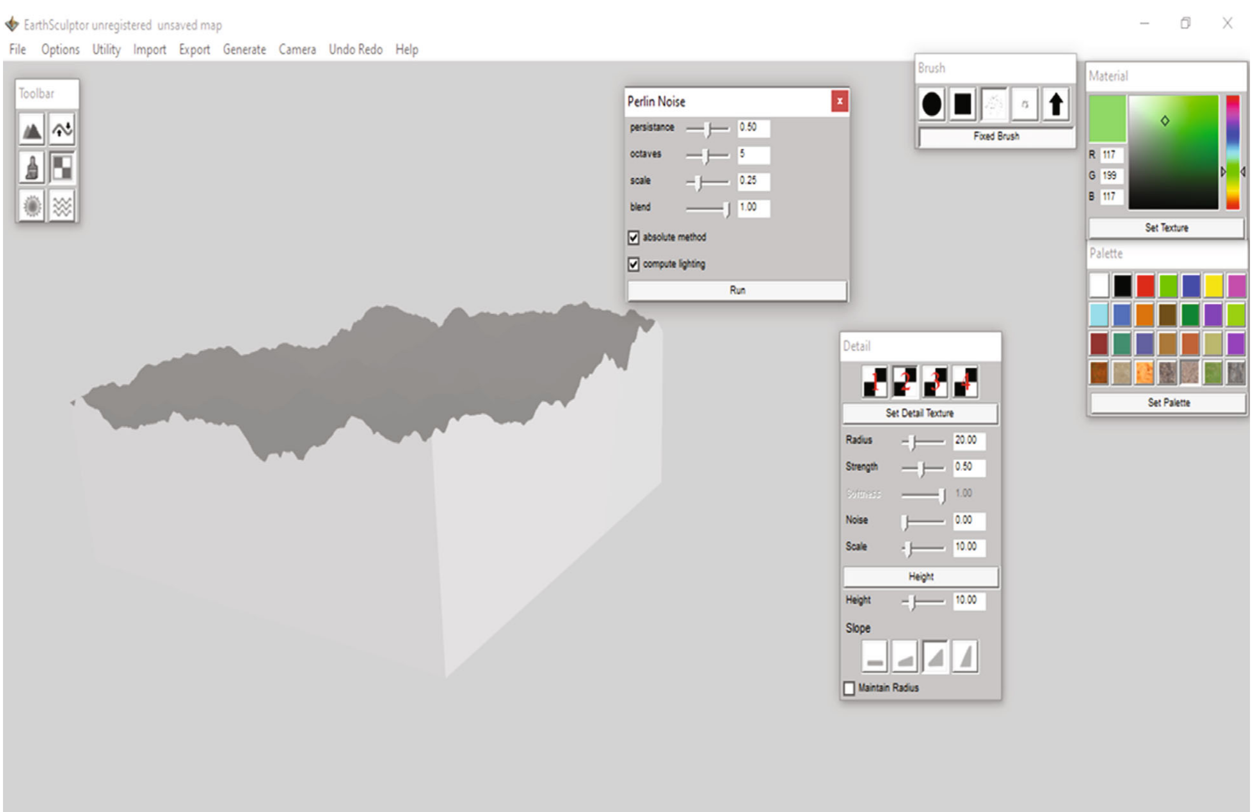

Figure 4: EarthSculptor.

processes are examples of tiny occurrences that produce low-level, significantly unpredictable "noise" signals

According to the paper [56], the uplift model, a novel and simple-to-implement terrain generator, is described in this study. It is based on the geology hypothesis of crustal deformations caused by uplifts. The eventual net impact of a series of uplifts on the Earth's surface is an average of the effects of each uplift at each location on the terrain. The application of this natural model results in a highly realistic-looking effect in the produced terrains. The model has six parameters that enable for a wide range of landscape types to be generated. Comparisons are performed with various terrain creation algorithms that are already in use. Averaging causes the surface to erode, whereas fractal surfaces are spiky and more suited to extraterrestrial planets.

In the paper [57], the suggested terrain model relies on a height-field representation that has been enhanced with materials and hardness data. The Poisson Faulting method, which was originally employed to create fractional Brownian surfaces, is the technique's starting point. The fault line generator's step function was changed with a circular one in the update. The resulting geometry was used to classify materials and calculate the hardness of the terrain model. The finished model was created by eroding geometry in accordance with the materials and their hardness data.

As per the paper [58], the goal of the authors is to apply the fractal dimension idea to assess the quality of raster digital elevation models (DEM). Most DEM evaluation approaches, which consist of calculating a global accuracy with respect to a reference, ignore artefacts generated by digitizing and sampling. They offered a method for computing fractal dimension based on the fractional Brownian motion model and utilized this model to highlight certain artefacts in digital elevation models.

Terrain generator [6] is a software based on random level terrain generation as a game that combines art and programming to create a natural-looking landscape. Slopes, soil, trees, cliffs, water, and other natural features may all be found in terrain. Stamping and pen techniques are frequently used to make them, and they are classified as games, simulations, and art. Simple 2D textured blocks to sophisticated 3D terrains are all possible.

3. Structure Generations

With the advancement in the gaming industry and the need for large quantity of content, the two most crucial parts of organic generations are as follows:

(1) Building generators

(2) Structure generators

The most popular procedural content generation (PCG) application is the generation of structures, cities, and buildings. "Citygen" [59] is a city generator system which generates the modern city's urban geometry. The system can develop the entire structure and system for roads and footprints of buildings with an input of just the terrain model. This system can then be used to place the buildings automatically or manually. There are several city generation techniques, they are as follows:

(1) Geometric rule-based systems

(2) L-systems

(3) Agent-based systems

(4) Template-based systems

(5) Split grammars

The methods described above show how to create collections of structures or even entire towns, but there have also been attempts to construct building interior "floor plans." The project, LaHave House, uses shape grammars to produce floor layouts. Based on player movement and positioning, a system that produces office building rooms in real time was created. Martin [60] investigated a graph-based technique in which rooms are treated as nodes and connections between rooms are treated as edges, with user-defined limitations such as room count and room function.

PCG approach has been effectively applied to generate numerous game contents, i.e., textures, geometric models, animations, and even sound clips [61]. PCG techniques for terrain elevation, water elements, vegetation, road networks, and urban environments are discussed in detail by Smelik et al. [61].

Tutenel and Bidarra [62] created a rule-based system that uses a semantic database to identify room kinds, and entities can form associations with their near neighbours. The concepts in this research were greatly influenced by Tutenel et al. [63], who tested a restricted rectangular L-growth algorithm that generated fully connected rooms for buildings. In a rectangular-growth-based technique, Camozzato et al. [64] procedurally create floor layouts using a hand-drawn building façade as input. Guo and Li [65] developed a system that creates multilevel structure floorplans using a combined method of agent-based search and optimization.

The methods to generate buildings can be bifurcated into two parts:

(1) Floor plan generation

A basic restricted growth algorithm is used to produce the floor layout. The original inspiration for utilizing this as a floor plan generator came from Tutenel et al.'s [63] L-shaped restricted growth technique. Unlike their technique, this one does not expand in a rectangle pattern, instead using a single block as the natural granular unit in Minecraft.

(2) External wall generation

The system then begins the process of constructing the external walls after the floor design has been produced. This is accomplished by employing a technique known as Cellular Automata (CA), which is derived from a family of algorithms known as Cellular Automata (CA). CA is employed in this system to self-organize the placement of solid blocks and glass panes, resulting in unique structural external walls. This system employs neighbour summation, which means it is less concerned with neighbour states and more concerned with the total of those states. If the block is a window, it is a 1, and if it is a solid block, it is a 0. Because each block has four neighbours in addition to itself, the sum of the states can be anything between 0 and 5. At wall start-up, a matrix representing the building's height at width/depth (depending on which wall is being created) is generated at random, with solid blocks accounting for 75% of the wall and glass blocks accounting for 25%.

4. Character Generation

Both the characters and the setting in video games are vital in establishing a feeling of immersion for the player. Although each figure may be created by hand to make them seem more lifelike, filling a gaming world with more than 100000 individuals makes the process intrinsically complicated. In such circumstances, developers must consider adding new technologies to automate and speed up their development cycle. The procedural element of PCG is where the knowledge of how to make something (the generative part) is put into action to generate the desired sort of content [55]. That implies there is a need to build up a system that can be given a certain set of instructions, ideally parametrizable, and will return a specific outcome. Using a modified style-based generative adversarial network (StyleGAN), a form of neural network, a novel approach for procedurally generating Nonplayable Characters (NPCs) in video games has been offered. The most cost-effective way for gaming content creation is PCGML, which stands for Procedural Content Generation with Machine Learning. It is used to cut production effort and conserve storage space. Their method combines PCGML with StyleGAN to create NPCs that were distinct in both look and behavior. Character creation is influenced by the attributes or features, resulting in a diversified and engaging gaming environment for the players.

Developers utilize the DCG to overcome a major issue in the video game development cycle: time. These algorithms are used by game developers to shorten the time it takes to produce a game or aspects of it. Real-time strategy (RTS) is a video game genre in which players must take control of safe regions of a map and remove their opponents' assets (e.g., towers, buildings, and shelters). The Multiplayer Online Battle Arena (MOBA) is a subgenre of this genre that enables two teams to battle against each other online. In general, maps are static, and the amount of material accessible to players is continually increasing as the game grows. Due to design challenges caused by the newly additional content, game designers must spend an increasing amount of effort while creating these games. In addition, the topography of MOBA game levels is built on heightmaps, which are well-suited to the use of generative algorithms [28].

The role-playing game (RPG) format is used to create characters in MOBA games. This approach determines a character's strengths and weaknesses based on a set of values. They have a level value that is a direct representation of how the learning process works, in which a character may acquire experience points by doing certain activities. Then, when they achieve a particular number of points, their character is promoted to a higher level, thereby making it stronger, resulting in a more experienced person.

There are also a set of qualities that specify things like hit points (the amount of damage a character can take before dying), damage resistance, and magical damage. These characteristics determine how effectively a character succeeds in various scenarios. Characters are divided into classes based on their level and qualities. Classes specify the collection of abilities that a character may have [29]. These are unique powers that a character may utilize to help them in battle and accomplish various special acts.

5. Role of Procedural Generation in Digital Twins

We may want to populate the digital twin with organic or inorganic matter. This is where procedural generation would help. The information from the sensors is unaltered whereas the surroundings, buildings, avatars, and extra objects can be generated using the procedural generation techniques as mentioned in this research [28]. Procedural generation is a means of producing data algorithmically rather than manually in computers, usually by combining human-generated materials and methods with computer-generated randomness and processing capacity. It is extensively used in computer graphics to produce textures and 3D models [29].

6. Conclusion

Based on the investigative literature findings, it is deemed that plenty of work has been done in the terrain generation domain. However, many research types remain open and offer opportunities for improvement in PCG of terrains for modeling and simulations. The PCG of terrains can be implemented in a multidisciplinary scenario for modeling games, industrials maps, urban and rural planning of developments, government, and company improvement plans. The critical finding identified through the literature is that many research studies are merely proof of concept and were not tested naturally. It was found out that genetic algorithm-based PCG of terrains lack multiple features such as roads and buildings. The cities generated through different engines were lacking a realistic look and feel. Terrain generation using MOEA is also analysed, where the application is restricted to the gaming domain and not extended to other fields. The correctness of generated terrain is also a significant challenge in the automatic generation of terrains; thus, a focus on the automated correctness check is essential. The modern user's current technological and aesthetic requirements demand fast, exciting, and quality content generation. The content, which can be playing on nonplaying content, must be usable. Hence, procedural generation methods are the best candidates for terrain and game content generation, quick, exciting, and usable. This research study has highlighted the different genres in the domain ranging from terrain generation, level generation to complete city, and virtual world generation. Therefore, it is recommended that further research work is necessary to evaluate the autogenerated terrains on aesthetics of users, e.g., of different ages, cultures, and preferences. At the same time, the validation of the generated terrain must also be verified for correctness. Indoor localization sensor combinations that include the software necessary for sensor data fusion in addition to the hardware should be employed. Processing systems, scenario-live-simulations, and digital shop floor management result in a procedural mix that must be followed. The capacity to constantly give all subsystems with the most up-to-date status of all essential information, procedures, and algorithms is critical to the digital twin.

Data Availability

All the data are included within the article, and no external data were used to support this study.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Research Article

Monitoring System for the Construction of Arch Cover Method Subway Station Based on DT and IoT

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Aiming at the problems of safety and monitoring beyond the existing experience in the construction of the subway stations with arch cover method in Dalian, China, combined with the real-time monitoring requirements of intelligent construction status, a multi-information construction monitoring system based on digital twin(DT) and Internet of Things(IoT) is proposed, and the digital twin 3D architecture is established. First, on the basis of the IoT monitoring experience of tunnel, the installation plan of the automatic monitoring device of the arch cover method subway station is clarified, and the sensor arrangement is carried out. Then, based on the Revit platform, the establishment of the main structure model of the station and the BIM parametric modeling technology of the sensors are realized, and the monitoring properties of the sensors are expanded. Finally, through the design of the BIM database and in the form of secondary development, a BIM-based construction information visualization monitoring system is established to realize the correlation between the sensor model and the monitoring data and achieve the effect of information visualization query and color change early warning. The system was initially applied at Shikui Road Station of Dalian Metro Line 5 and achieved good results. The system can intuitively reproduce and accurately describe the subway station construction status, which provides an advanced technical means for the informatization and visualization management of the construction of arch cover method subway stations.

1. Introduction

In recent years, subway construction has been increasing day by day, and the geological conditions faced by engineering construction have become more and more complex [1]. Especially, the upper and lower hard geological environments, such as Dalian, Qingdao, and other coastal cities in China, bring challenges to the construction of the underground excavation subway station [2]. The emergence of the construction technology of the arch cover method solves the problem of upper and lower hard strata faced by subway construction [3–6]. However, the arch cover method also faces a complex geological environment and conversion procedures, which are beyond the existing experience in the past. How to ensure construction safety has become an important issue of concern [7, 8].

There have been some reports on the study of the safety of subway station construction. Yu et al. [9] illustrated the surface settlement characteristics of subway station construction in the shallow-buried soft ground using the pile-beam-arch (PBA) approach of the shallow tunnelling method. Kim et al. [10] investigated the correlation between comfort level and brainwaves in a real-world environment. Avci and Ozbulut aim to describe and summarize the results of a Threat and Vulnerability Risk Assessment (TVRA) study designed for a generic subway station complex [8]. Chen [11] presents a combined construction technology that has been developed for use in underground spaces. It can be seen that most of the existing related research reports involve the design and construction of subway stations, and there are few reports on the automatic monitoring of subway station construction.

The monitoring information can reflect the safety status of the project, which is the main basis for the safety early warning in the tunnel construction process [12, 13]. At present, the monitoring and measurement of geotechnical engineering are gradually developing from single information to multiple information, from manual monitoring to IoT monitoring [14–16]. Gómez et al. address the implementation of a Distributed Optical Fiber Sensor system (DOFS) to the TMB L-9 metro tunnel in Barcelona for Structural Health Monitoring (SHM) purposes as the former could potentially be affected by the construction of a nearby residential building [17]. Wang et al. studied an improved method for the accurate measurement of sensors and wireless transmission bands suitable for complex tunnel environments. [18]. Hou et al. presented a method for sensing tunnel cross-section deformation based on distributed fiber optic sensing and a neural network [19]. Compared with manual monitoring, the IoT monitoring is more frequent and the data is more accurate and reliable. However, both manual monitoring and automatic monitoring are faced with the problems of large amount of monitoring data, complicated monitoring result information, and difficult management.

In recent years, technologies such as the Big Data (BD) [20], Artificial Intelligence (AI) [21], and the mobile Internet have developed rapidly. Through the deep integration of information technology and civil construction, the Cyber-Physical Systems (CPS) [22] and Digital Twin (DT) technology [23] in which physical space and information virtual space interact and integrate have become research hotspots in intelligent construction. The civil construction process is changing from the binary system relationship of "human-physical system" in traditional construction to the ternary system relationship of "human-information-physical system" in intelligent construction [23–27], which has become a trend. It is generally acknowledged that Michael W. Grieves' product lifecycle management model is the origin of DT in 2002 [28]. DT applications are emerging with the recent development of the IoT; both technologies share the same nature—connecting physical artifacts and their digital counterparts [29]. In modern cities, digital twins can be built to integrate spatiotemporal data of the life cycle of tunnels to analyze the potential causes and effects of anomalies in civil structures or electromechanical equipment, which will provide reasonable and feasible countermeasures to guide and optimize operations and maintenance (O&M) management [30].

There has been some progress in method visualization and computer vision techniques for detailed internal structures [31, 32]. Lundeen et al. [33] realized autonomous perception and modelling construction robot to adapt to construction objects in emergencies and presented two construction component model fitting techniques. Akula et al. [34] realized real-time monitoring for drilling process hazards by processing and incorporating point clouds from 3D imaging technologies into the drilling process. However, these proposed methods have not been proved in more complex conditions. The DT's development in this field is in its infancy [35]. Building Information Modelling (BIM) technology is a way of realizing digital twin [36]; it is also a research hotspot at the forefront of the current civil construction field and can realize the management and analysis of the whole life cycle of the project in a 3D visualization way, which has been gradually popularized and applied to many geotechnical engineering fields in recent years [37–39]. Costin et al. presented a literature review and critical analysis of BIM for transportation infrastructure [40]. Bueno et al. proposed a novel method for automatic rough registration of BIM models and as-built scan data called the "4-Plane Congruent Set" (4-PLC) algorithm to achieve construction quality and schedule control [41]. Lee et al. aimed to propose an integrated system of BIM and geographic information system (GIS) to improve the performance of current maintenance management system [42].

The current research on digital twin and BIM technology has achieved fruitful results, but the applied research combining monitoring and digital twin (DT) on the construction of subway station are still rare. Compared with the traditional underground engineering, the subway station with the arch cover method faces more complex geological and structural conditions, and the safety problems are more prominent. How to combine the characteristics of the underground excavation station with the arch cover method and combine the DT technology with the real-time monitoring of the subway station construction has important engineering significance. Based on the application background of Dalian Metro Line 5 Shikui Road Station, this study firstly determines the IoT monitoring plan for the underground excavation station with the arch cover method according to the structural characteristics. Then, the parametric modelling technology of the structure and sensors of the arch cover method station is studied, the monitoring information in the database is associated with the relevant BIM model in the form of secondary development, and a multi-information monitoring system based on BIM is developed, which provides a new method for tunnel construction information management.

2. An Integrated Framework for Digital Twins and IoT

2.1. The Characteristics of Arch Covered Subway Station. The subway station arch cover method is based on the PBA method, replacing the side piles with large arch feet, so that the main bearing capacity is attached to the rock foundation, and under the protection of the early buckle arch, the main structure is completed by the reverse method or the forward method [7]; the construction sequence of the arch cover method is shown in Figure 1.

The arch cover method absorbs the engineering experience of the early construction, improves the multispan structure into a single-span large-span structure, and replaces the original design with a supporting structure system of large arch feet and double-layer initial support. The column arch structure in the middle of the building makes full use of the self-stability of the surrounding rock and is supplemented by temporary support to ensure the safety of the structure. The number of pilot tunnels after optimization is significantly reduced, the construction process is simplified, and the number of temporary supports and joints is also reduced, which overcomes the disadvantage of poor integrity caused by alternative construction and is conducive to the improvement of the overall waterproof performance of the structure. After the removal of

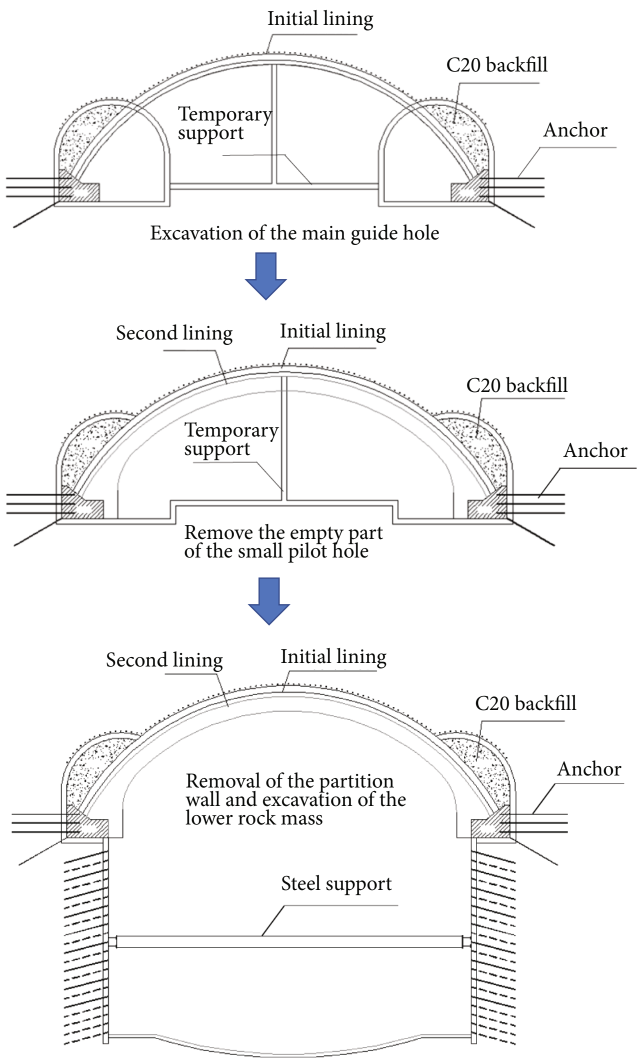


FIGURE 1: Construction steps of the arch cover method.

the double-layer initial support and temporary support, the secondary lining of the arch shall be constructed first, and the construction of the lower main structure shall be carried out under the protection of the secondary lining structure. Compared with other construction methods, the working space is significantly expanded, which is conducive to the construction of large machinery and equipment, and plays a significant role in shortening the construction period and improving the work efficiency.

At present, the existing research on the construction method of arch cover method recognizes that the construction time, structural strength, and construction quality are the key to the construction of arch cover method; however, the mechanical characteristics of arch construction have not been deeply studied; there is not enough research on the appropriate application timing and bearing capacity of the arch cover, resulting in a poor grasp of the application timing. It is essential to strengthen the monitoring of the construction of the arch. For this reason, this paper plans to establish a digital twin 3D monitoring system for the construction of subway stations.

2.2. The Information Composition of Digital Twin 3D Monitoring System. Based on the DT technology of the construction process of the subway station with the arching method, it is oriented to the needs of the construction attitude and safety control of the underground space excavation of the subway station. Condition data fusion display provides a more intuitive, more comprehensive, and more accurate visual monitoring method for intelligent production of subway station construction. At the same time, on the basis of data analysis, the DT monitoring system can integrate data monitoring functions for safety monitoring, construction sequence safety analysis, and support dynamics based on data inversion and improve the monitoring level of intelligent working faces.

Based on DT technology, the construction data-driven monitoring system of the arch cover method subway station obtains the system basic design data and real-time driving data from the geological body excavation, supporting structure, and supporting sensors and conducts modelling and analysis processingthrough the technologies of three-dimensional virtual display and human-computer interaction, the analysis results are provided to construction managers.

The information composition is shown in Figure 2, which mainly consists of 4 parts: (1) the physical entity is the geological body and supporting structure of the subway station construction; (2) the virtual entity is the digital twin of the virtual subway station construction; (3) service data is on-site information, including real-time equipment space attitude data, operating condition data, control command data, and historical data; and (4) feedback decision support system includes intelligent decision support and analysis systems.

The specific relationship is as follows: the arched subway station (physical entity) is the object to be monitored; the virtual entity is the underground station model established based on the basic information of the physical entity, including basic data such as geological information and design information. There is mapping of the three-dimensional virtual space, that is, the digital twin of the subway station; the service data is the data obtained from the on-site sensors of the subway station that can express the safety state and working condition of the surrounding rock supporting structure on site and realize the three-dimensional model of the virtual excavation space. The action-driven and working condition data are dynamically displayed; the auxiliary decision support system (DSS) is the basis for the feedback construction decision of the digital twin model.

2.3. Digital Twin 3D System Framework. Figure 3 shows the platform architecture of the digital twin 3D monitoring system for station excavation. In view of the monitoring characteristics and requirements of the construction of the subway stations with an arch cover method, based on the digital twin technology of the construction excavation process, combined with the three-dimensional virtual display technology, the design and development are designed to realize the real-time three-dimensional display of the station excavation, the three-dimensional real scene fusion of the working condition data, and the monitoring of the operation data. Management and abnormal state alarm are the main functions of the monitoring system for intelligent construction. In the digital twin

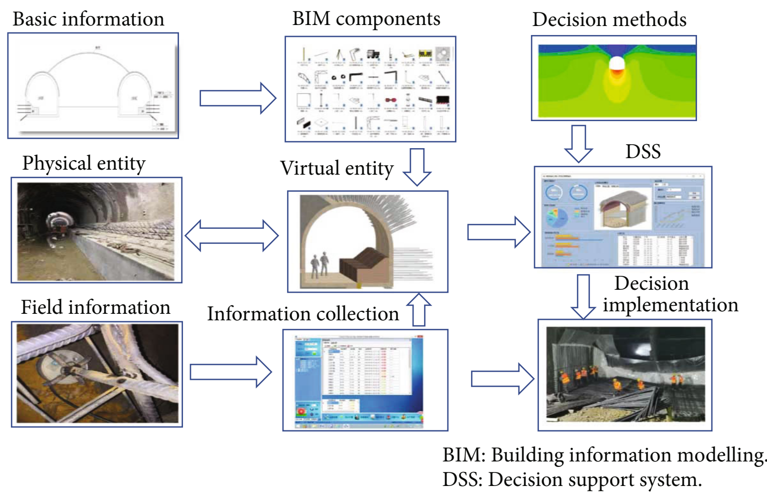


FIGURE 2: The monitoring system information of arch cover method subway station.

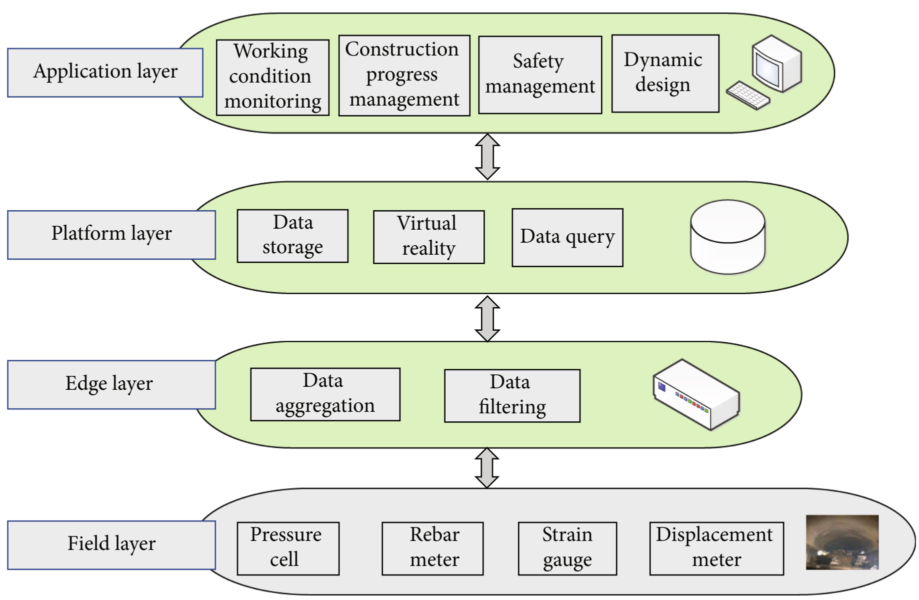


FIGURE 3: Structure of monitoring system based on digital twin.

3D monitoring system for the construction of the arch cover method station, data is driven throughout. According to the data from collection to application display, it can be designed as a four-layer model architecture of site layer, edge layer, platform layer, and application layer and data collection. It can realize data collection and transmission, data analysis and functional design, human-computer interaction, and other functions in turn.

2.4. Data Collection and Transmission. The Internet of Things (IoT) collection and transmission system for the construction of the arch cover method station was developed. Sensors are arranged for the most critical information in tunnel monitoring, such as top arch settlement, surrounding rock deformation, and steel arch structural stress. Considering the harsh characteristics of the underground engineering environment, the protective structure is used to overcome the damage to the sensor caused by groundwater and blasting disturbance. The monitoring results of the sensor terminal are collected through the vibrating wire data acquisition instrument. In addition, the data acquisition box also includes a wireless module for short-distance transmission and a power supply system. A data transmission box is set up near the tunnel face, and the data collected from each monitoring section is transmitted to this box via the wireless module and then uploaded to the internet by the general packet radio service (GPRS) system inside this structure. The database is accessed through the server to achieve remote acquisition of monitoring data, and on this basis, the data is decoded and the results are released in multiple terminals. Figure 4 shows the data transfer process.

Data acquisition is mainly obtained through reliable sensors and control systems in the station structure and is realized by the field layer and the edge layer. Field-level equipment is not only the physical entity and monitoring object mapped by the digital twin but also the data source of the system. The

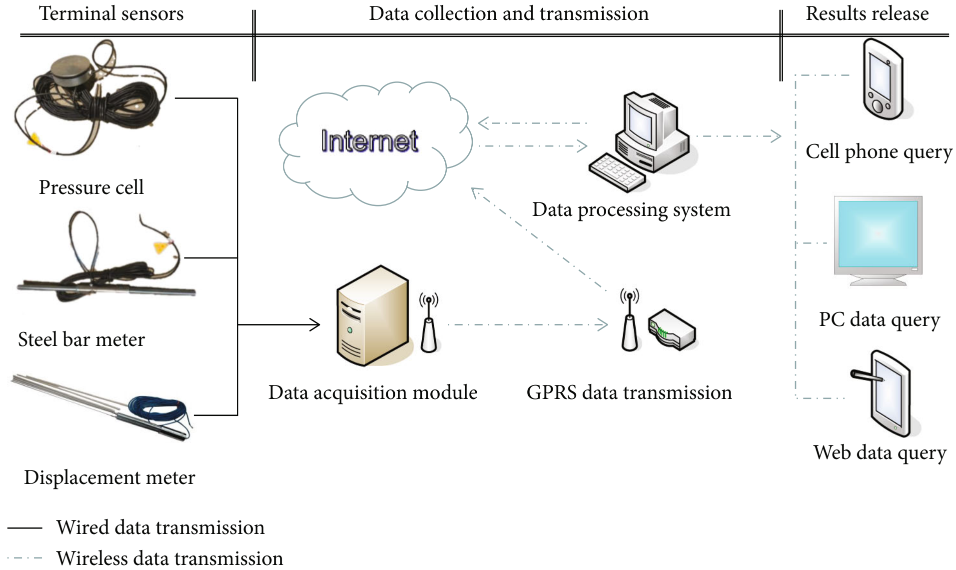


FIGURE 4: Information flow chart of IoT of metro station.

excavation structure and process conversion of subway stations are relatively complex. Here, the main monitoring of the arch cover structure involving relatively large safety risks is carried out. Pressure cells, rebar meters, strain gauges, and displacement meters are used to design and develop edge nodes to conduct on-site data collection. The edge nodes aggregate and filter the collected data, extract and transmit the valid data to the upper platform for data processing. The edge node terminal communicates with the sensor and the intelligent centralized control system through fieldbus, industrial Ethernet, and other communication methods to obtain data, process and archive it, and transmit it to the digital twin monitoring system database for storage by means of network communication. Figure 5 is the interface of server IoT information collection, which can collect data through the network IP address corresponding to the virtual serial port.

Sensors and data acquisition instruments are used to collect monitoring data, the communication module transmits data remotely through mobile phone GPRS, and the server sends acquisition commands to the edge layer acquisition box. After receiving the data, analyze and postprocess the data. The collection interval can be set, and the channels and sensors of the collection module can be added. The collection operation modes are divided into manual and automatic. You can also check whether the collection status is normal through collection monitoring.

3. Virtual Model and System Development

The digital twin 3D monitoring application platform is oriented to users. Through 3D model display, data, and model fusion display, data analysis, the process, status data, and analysis results of subway excavation construction are reproduced in the virtual space, and the construction process is interactively provided.

3.1. Construction of the Station BIM Model. The development of the digital model mainly includes three aspects: the construction of the station model, the parametric modelling of the lining structure and sensors, and the definition of the sensor monitoring attributes. Revit is a platform for building modelling; although family libraries such as walls, columns, floors, and infrastructure related to buildings are provided in the structural template, these components clearly cannot be used in the modelling of the subway station. The structural features and internal structure of the arch cover subway station are complex. Therefore, based on the modelling method of the platform, this paper independently creates a component family library for the station and realizes the 3D visualization of the subway station by assembling it in the project template. This section takes the metric conventional model as a template, draws a 3D model through operations such as elevation selection, extrusion, and lofting, and edits size parameters and professional attribute parameters to establish subway station parametric component models. After importing the parametric station components in the family library into the project, define the elevation, adjust the assembly position with the commands in the toolbar, such as rotate, move, and array, and change the size parameters of the family components, and the professional attribute parameters of the instance subway station, in turn, realize the assembly of various components such as the subway station lining, inverted arch filling, and anchor rods and finally complete the construction of the overall model of the station. The 3D digital model of arch cover method construction is shown in Figure 6.

Multivariate information monitoring involves the arrangement of various types of sensors, so it is necessary to add monitoring sensor models based on the establishment of the overall station model. However, when building sensor models, there are many problems, such as large number, many types, different positions and angles, and many repetitive tasks. In this regard, this article uses the method of Revit secondary development

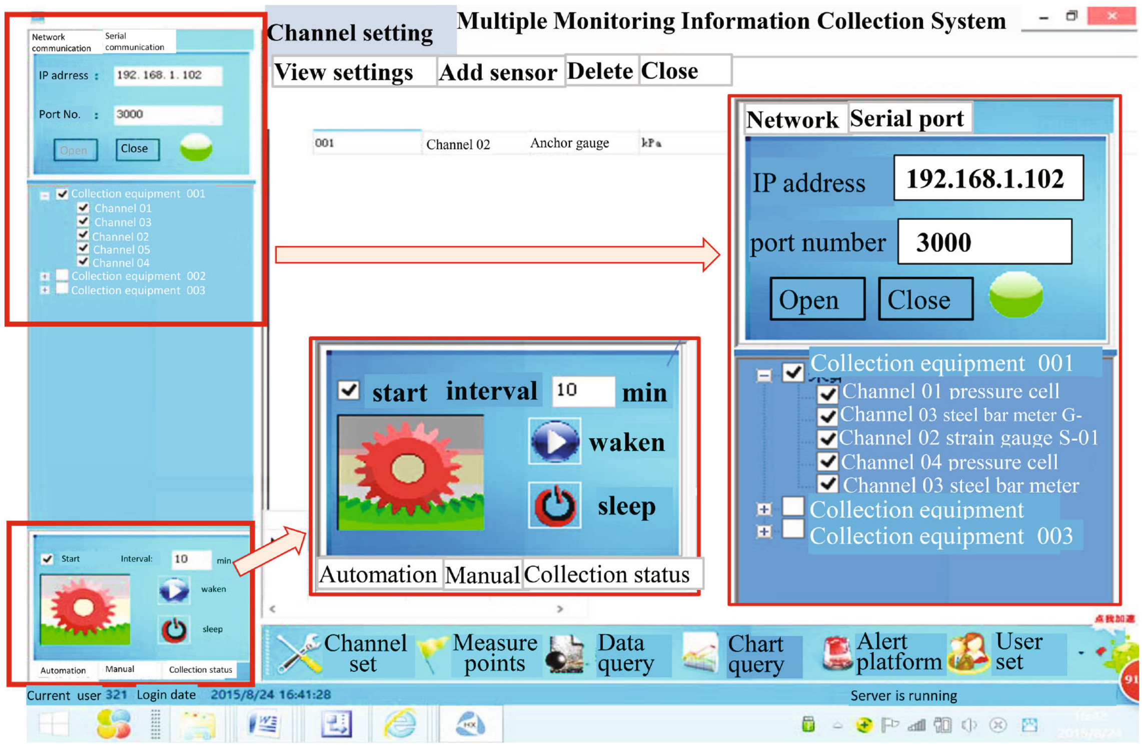


Figure 5: The interface of IoT information collection.

to write an automatic modelling program, and input the position parameters such as radius and angle into the specified position in the secondary development form, and the sensor model can be automatically generated efficiently and accurately without manual modelling. The programming process is as follows: using VisualStudio2019 as the platform and using C# language to build Windows Form applications. Reference the revitAPI.dll and revitAPIUI.dll dynamic link libraries in the compiler; establish external interfaces through IExternalCommand; IExternalCommand is a command that implements external extensions, including the Execute function.

The external command calls the Execute function to realize the external interface connection and uses the IExternalEventHandler to add external events, uses the transaction in revitAPI to call the created sensor component, and assembles it at the specified position by offset, rotation, etc. Run the parametric modelling form written through secondary development on the Revit platform, enter the corresponding position parameters, and place the sensor 3D family library model, as shown in Figure 7; enter the position radius and angle into the steel bar meter parameter input box; and the model appears automatically.

For example, input the parameters of strain gauge sensor and earth pressure box sensor, and the corresponding sensor family model can be obtained. The established arc and sensor models are shown in Figure 8.

Therefore, to realize the mapping between the monitoring information and the Revit entity model, it is necessary to expand the sensor properties. The Industry Foundation Class(IFC) standard is a computer-processable building data representation and exchange standard. The IFC extension method is used to define the monitoring attributes of BIM sensors. Establishing the mapping relationship between each member of the tunnel monitoring information and the IFC attribute set is the premise of realizing the IFC expression of the tunnel monitoring information. This paper associates the corresponding fields of monitoring information by extending the IFC attribute set, expresses the monitoring information parameters with appropriate attribute values, and associates the corresponding sensor entity attribute set and BIM 3D model. IFC standard description of the monitoring information is shown in Figure 9. The sensor is represented by the IfcSensor entity, and the type of the sensor is included in the enumeration type IfcSensorTypeEnum, which is expressed by the PredefinedType attribute of the entity IfcSensor. The specific monitoring information is represented by IfcProperty and multiple IfcProperty constitute the definition of a property set, that is, IfcPropertySetDefinition. Property sets are associated with sensors through IfcRelDefinesByProperties.

According to the requirements of the monitoring task, select the appropriate IFC attribute value to establish the expression of the corresponding monitoring data; usually select the appropriate attribute in the IfcPropertySetDefinition attribute set to establish the association, such as sensor number, measuring point number, monitoring value, monitoring time, and other information [43]. For the types of monitoring information missing in the IFC standard, IFC attributes should be extended, that is, by adding entity definitions or by extending them based on attribute sets.

3.2. Revit Secondary Development Method. The existing visualization models of tunnel construction management are mainly aimed at the numerical simulation of the tunnel

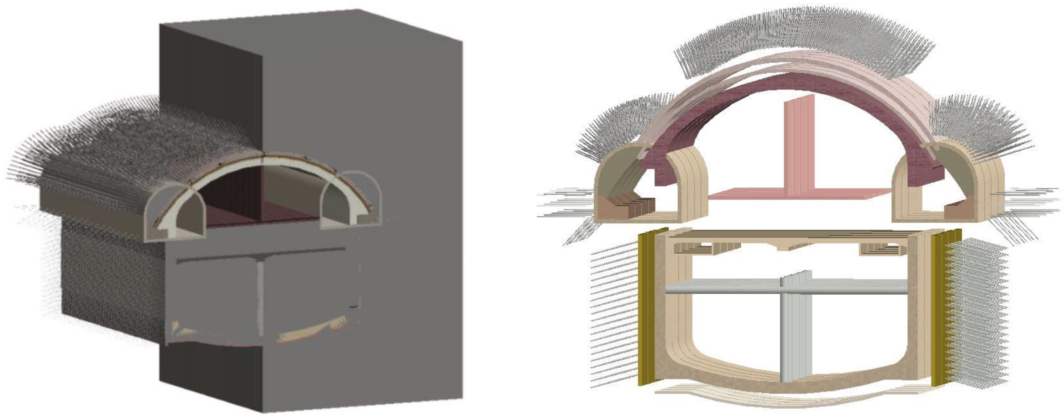


FIGURE 6: 3D digital model of arch cover method construction.

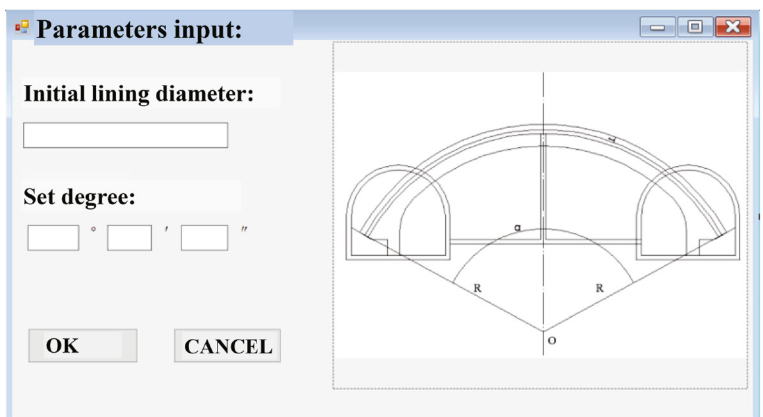


FIGURE 7: Parameter input box.

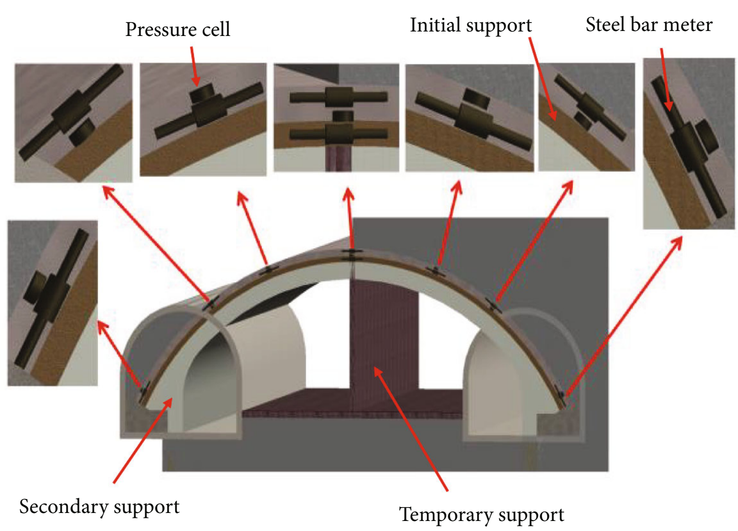


FIGURE 8: The model of arch cover and sensor.

construction process [6] and management information system for operation and maintenance [30]. Compared with the previous models, the model proposed in this paper needs to be oriented to the decision-making of the complex construction process of the arch cover method, integrates a variety of information and analysis methods, and has stronger functional requirements. Specific functions include time series prediction and early warning algorithm, subway station construction step visualization, AHP-FCE-based subway tunnel construction risk assessment algorithm, geological parameter inverse analysis

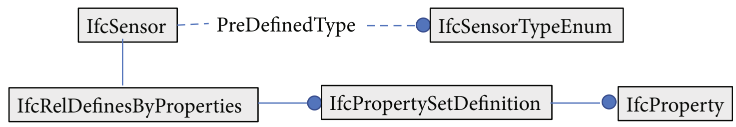


FIGURE 9: IFC standard description of the monitoring information.

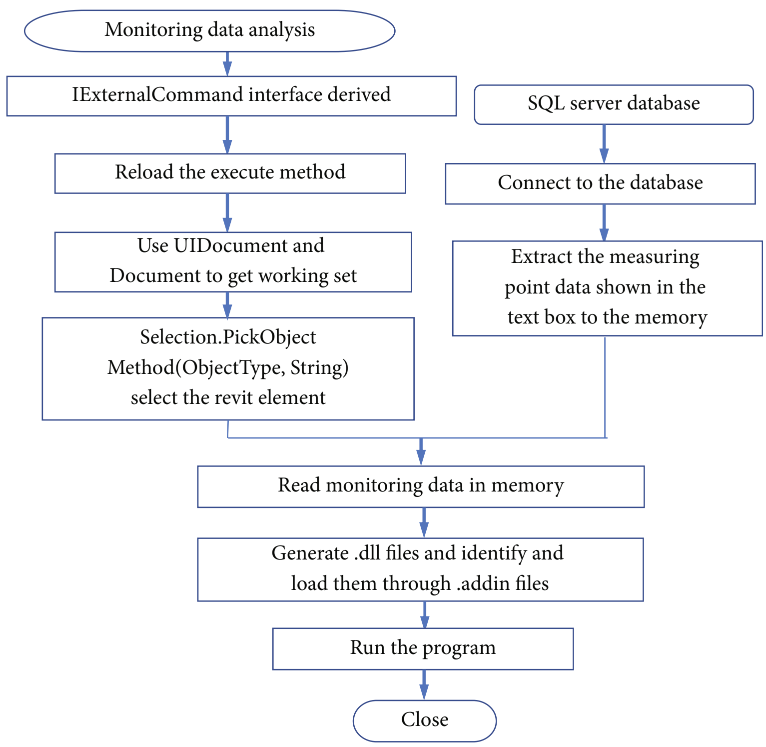


FIGURE 10: BIM model and monitoring information associative development flow chart.

algorithm, and particle swarm-based construction parameter optimization algorithm. The model in this paper represents the geological information, surrounding rock information, support information, construction progress information, personnel information, and other attributes of the subway station BIM through IfcProperty in the IFC physical file. This information is also stored in the SQLserver database at the same time. A digital twin-based multi-information monitoring platform is established through the secondary development of Revit. Using the Microsoft.NET Framework4.6 structural framework, the program is compiled through the C# language, and the RevitSDK2018 is used to make the program run in Revit.

Taking monitoring data information as an example to introduce the information integration technology of BIM, the BIM model and monitoring information associative development flow chart is shown in Figure 10. Firstly, create a new class library or form, add the IExternalCommand external interface, call the Execute method, write a function command to traverse and read the Id property of each component, and associate it with the database. Then generate a file with a suffix of.dll, load it into Revit through the Add-In Manager interface, and complete the Revit secondary development process. Furthermore, load the execute code to obtain all attributes of the model, and obtain the unique ID of the component with Revit.UI.Selection through the topology relationship of the component, define the SQL data connection parameters and create a connection instance. When the database is connected, define the database adapter and data set, create the DBOoperate database operation object, execute the database operation instruction, realize the filtering of the data fields in the sensor attribute table, and use the foreach statement to identify the primary key field row by row. After the primary key field is identified, other fields corresponding to the primary key ID in the data table are called out and output to the dataGridView to realize the query function of clicking monitoring data.

On this basis, by adding the DundasChart control, a complete basic chart structure is established, and by setting the Series-related properties, the monitoring data corresponding to the measurement point number in the database is screened, so that the data is generated in the form of a graph, and the history is realized. The DataGridView control supports the standard Windows Form data binding model, making the data presentation very simple and intuitive. With the help of Revit API and C# language, the monitoring data table query is realized. For example, the typical programming language is as follows:

3.3. Design and Realization of the System. The multi-information monitoring platform based on digital twin is combined with the database to realize the intuitive display of multi-information monitoring by the dome method. The

```
string sqlstr3 = "select Sensor ID, Sensor type, Measuring point number, Monitoring value,Unit, Temperature, Monitoring time,
from monitoring data table where(Measuring point number ='" + comboBox2.Text + "')order by Monitoring time desc";
DataSet ds = database.getSet(sqlstr3, " monitoring data table ");
dataGridView1.DataSource = ds.Tables[0].......
```

Code 1

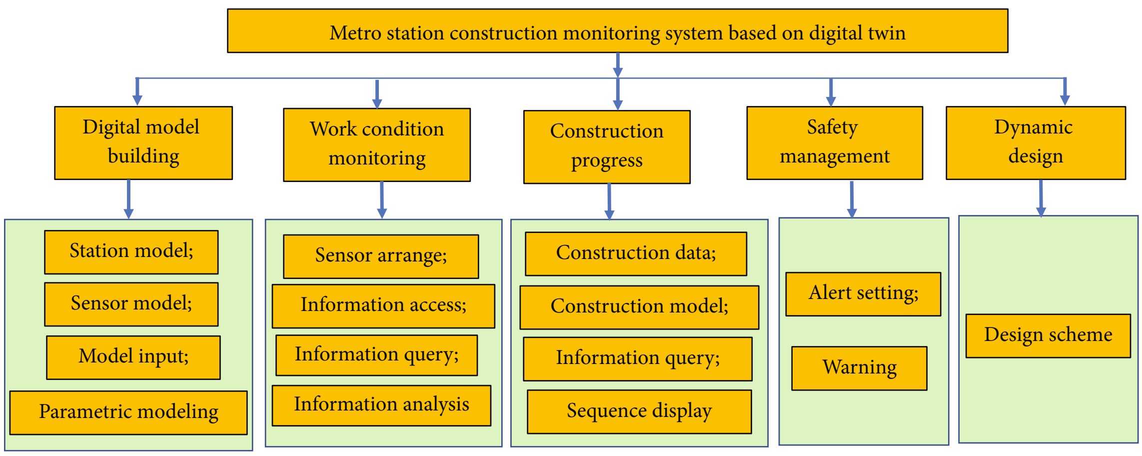


Figure 11: Functional block diagram of the system.

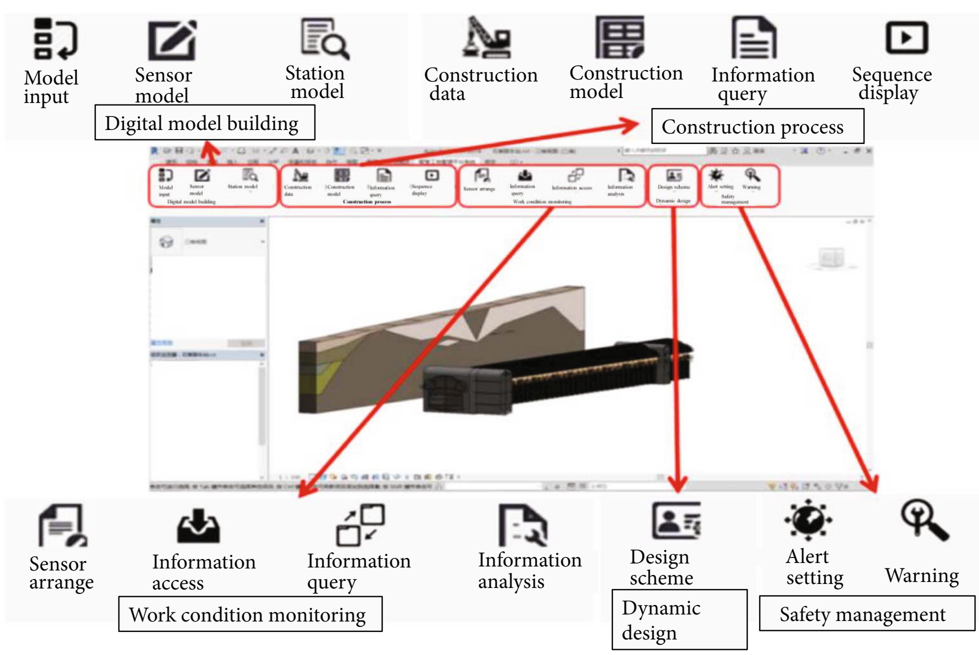


Figure 12: Multisource information subway station construction monitoring system based on digital twin.

functional planning of the developed multi-information monitoring platform based on digital twin is mainly divided into five parts, as shown in Figure 11. The five functional modules are digital model establishment, working condition monitoring, construction progress, safety management, and dynamic design. Firstly, the multi-information monitoring scheme of the underground excavation station with the dome-cover method is established, and the sensors are arranged to realize the acquisition of monitoring sensor data such as the earth pressure box. Then, by means of parametric modelling, the establishment of the main structure model of the station and the sensor model of the Internet of Things is completed.

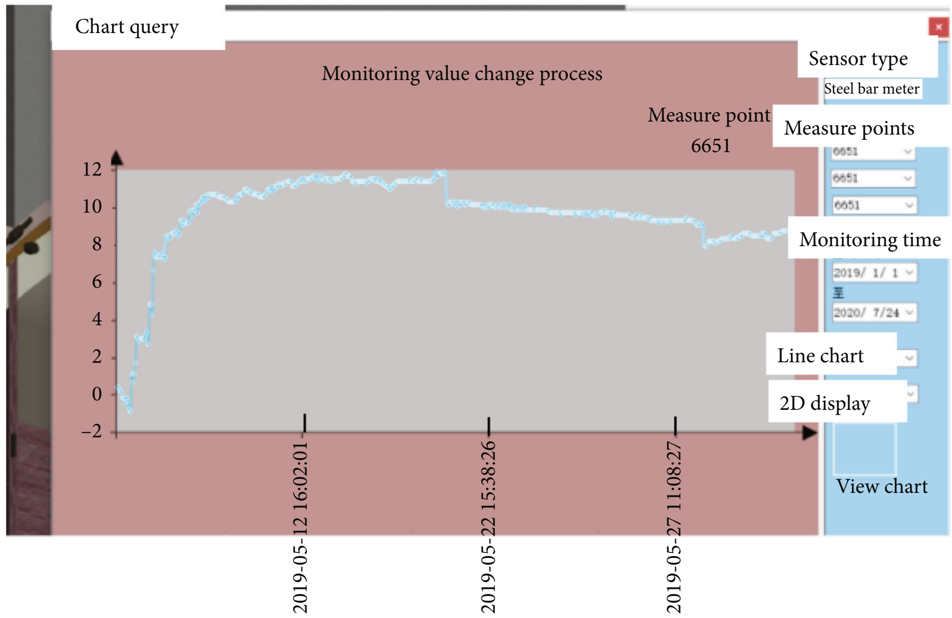


Figure 13: Historical graph.

Finally, based on the Revit platform, the monitoring data in the SQL database is linked with the relevant sensor models in the form of secondary development.

The BIM core modelling software Revit is used as the development platform, and C# is used as the basic development language to build the Revit API secondary development environment. According to the Revit secondary development process, the monitoring information visualization plug-in program was developed, and the BIM-based dynamic analysis information system function menu of the arch cover method subway station was developed in the Revit software interface. During development, the two methods of OnStartup() and OnShutdown() are mainly overloaded by external applications to complete the creation of the toolbar Ribbon Tab and the drop-down button PushButtonData. The function menu creates Ribbon Tabs called digital model establishment, work status monitoring, construction process, safety management, and dynamic design, as well as PushButtons corresponding to different function programs.

Through the interaction of monitoring information and models, functions such as automatic warning, graphic display of monitoring data, data analysis, real-time roaming, and information sharing are realized, which effectively improves the visualization level of monitoring information and the function of analysis and decision-making. The system interface is shown in Figure 12.

Digital model building menu includes submenus of model input, sensor model, and station model; construction process menu includes the submenus of construction data, construction model, information query, and sequence display. Work condition monitoring menu includes the submenus of sensor arrange, information access, information query, and information analysis. The menu of dynamic design includes the submenus of the design scheme. The safety management menu includes the submenus of alert setting and warnings.

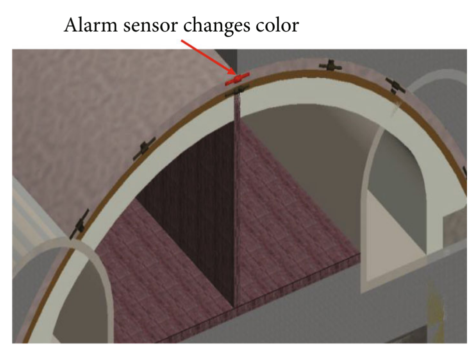
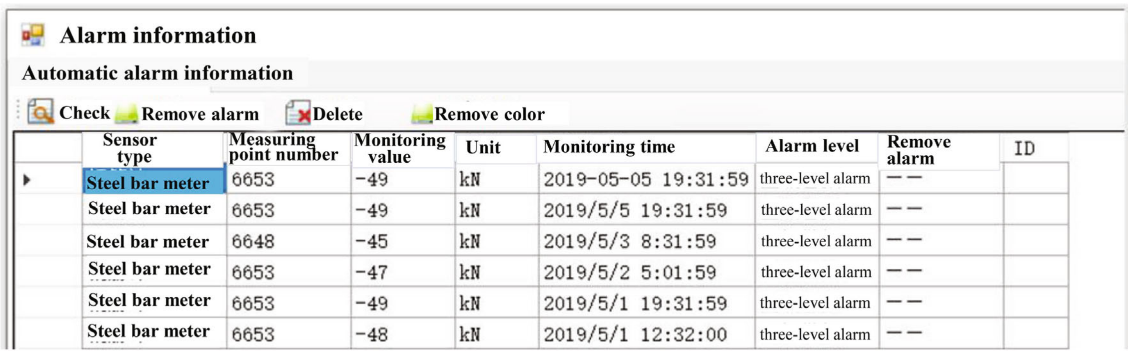


Figure 14: Color-changing display of virtual sensor alarms.

4. Case Study: Dalian Subway Station Application

4.1. Project Overview. The subway station, named Shikui Road station, is located in Dalian, China, on the north side of the intersection of Jiefang Road and Shikui Road and is arranged along Jiefang Road in a north-south direction. The terrain in the site fluctuates greatly. The absolute elevation of the ground within the station is 32.8-40.0 m, which is low in the South and high in the north. There are dense residential and commercial areas around the site, with large road traffic flow; many pipelines laid under it and in the air, which is a dense area of people and traffic flow.

The construction of Shikui Road station is carried out by arch cover method; that is, the upper arch cover is excavated first and reinforced by the initial support and a temporary middle support. After the temporary support is removed, the arch secondary lining structure is molded. Due to the complex construction process and the large number of process conversion times and joints, the secondary lining



Alarm information

Automatic alarm information

Check | Remove alarm | Delete | Remove color

	Sensor type	Measuring point number	Monitoring value	Unit	Monitoring time	Alarm level	Remove alarm	ID
▸	Steel bar meter	6653	-49	kN	2019-05-05 19:31:59	three-level alarm	——	
	Steel bar meter	6653	-49	kN	2019/5/5 19:31:59	three-level alarm	——	
	Steel bar meter	6648	-45	kN	2019/5/3 8:31:59	three-level alarm	——	
	Steel bar meter	6653	-47	kN	2019/5/2 5:01:59	three-level alarm	——	
	Steel bar meter	6653	-49	kN	2019/5/1 19:31:59	three-level alarm	——	
	Steel bar meter	6653	-48	kN	2019/5/1 12:32:00	three-level alarm	——	

FIGURE 15: Early warning sensor data output.

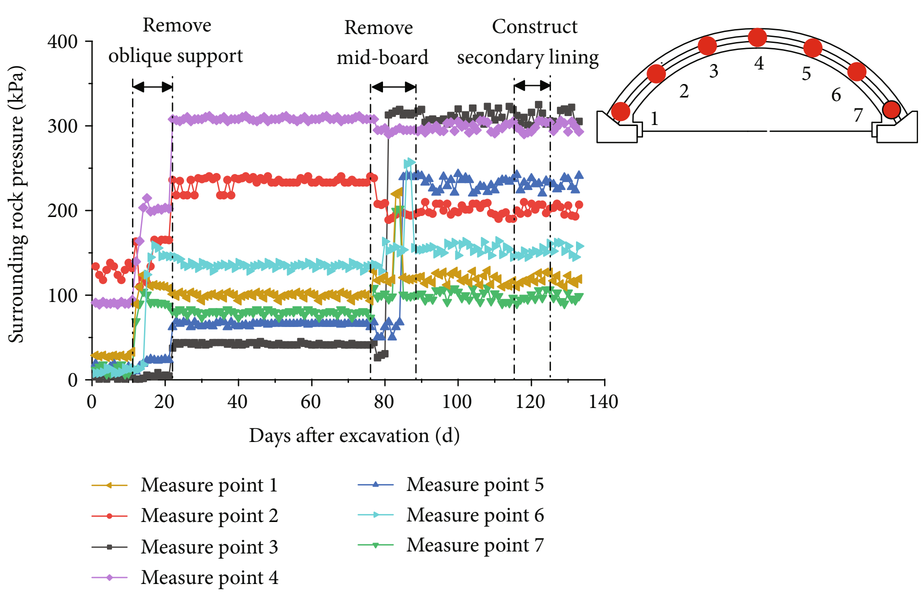


FIGURE 16: Pressure monitoring results of the initial lining on the first layer.

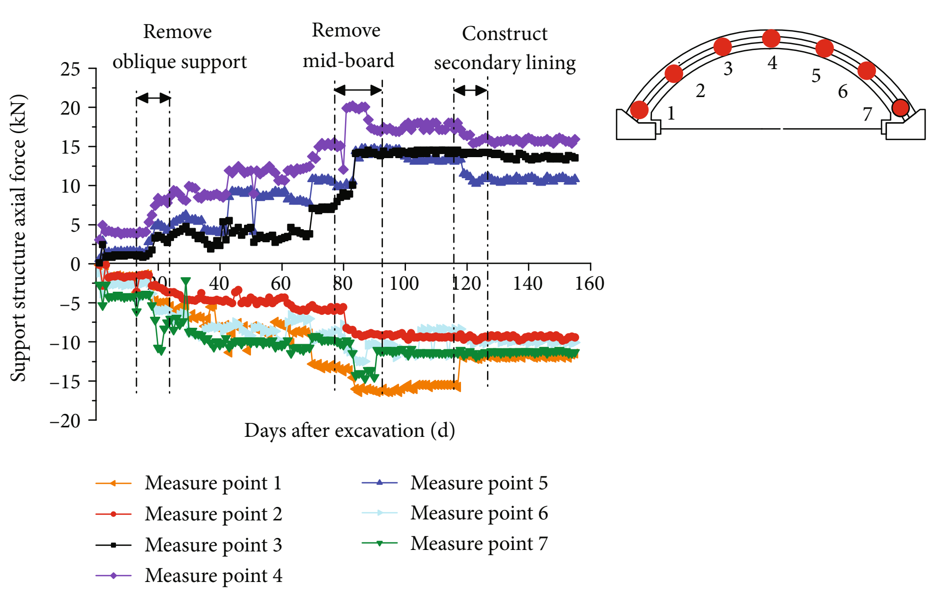


FIGURE 17: Internal force monitoring results of the initial lining on the first layer.

structure is constructed alternately, which is prone to structural safety problems. The excavation and support of pilot tunnel construction shall be carried out in the order of down first and then up side first and then middle. After the construction of the upper part is completed, the lower half section shall be excavated by drilling and blasting method in order, and the initial support shall be constructed in time. After the side wall is completed, the inverted arch shall be formed. Due to the complexity of the on-site construction structure and procedures, it is necessary to fully consider the problems that the excavation of the subway station may cause changes in the pressure and axial force of the surrounding rock of the vault. During the construction process, timely feedback information should be based on the monitoring and measurement results. To guide the design and construction and adjust the support parameters and construction methods in time, it is essential to collect multiple information on the Internet of Things in subway stations in real time.

4.2. Sensor Arrangement and Mapping Implementation with Modelling. According to the actual construction situation and requirements of the site, the terminal sensor for monitoring is prepared and installed at the arch cover according to the engineering requirements. The sensors include earth pressure cells, steel bar gauges, strain gauges, and settlement gauges, which are to be buried in the arch cover, and the pressure cells are located between the surrounding rock and the primary support. The rebar gauges are located on both sides of the upper and lower rebars of the arch, and the strain gauges are located at the partition wall. Seven monitoring points are set for each section, which are, respectively, embedded in the tunnel centerline and at 30° and 60° on the left and right sides of the tunnel centerline, and are arranged symmetrically on the arches. Real-time acquisition of data of subway stations is realized through the installed automation equipment.

In addition, through secondary development, the monitoring data is associated with the sensors of the BIM model. Figure 13 is a historical graph of a monitoring point. Click "Alarm" in the development function panel, as shown in Figures 14 and 15; the program will filter the monitoring data associated with the sensor model. When the monitoring data of an associated sensor exceeds the preset safety value, the program will output the corresponding excess data. The overlimit data corresponds to the element ID. Clicking the color-changing display button can change the color of the model corresponding to the overlimit data and display it intuitively in the Revit platform to realize the early warning function.

4.3. Real-Time Data Acquisition and Analysis of Station Excavation Process. Since the monitoring data laws of all sections are basically the same, take K6+467 as an example for analysis. The mechanical response of different supporting structures to the construction process is shown in Figure 16. The "constructed the secondary lining" is marked in Figure 16 which means that the secondary lining structure forms an effective support strength. It is shown that the force of the first layer initial lining structure has two transitional rises, which are located in the removal process of the oblique support and the midboard. From Figure 16, the largest increase point is at the

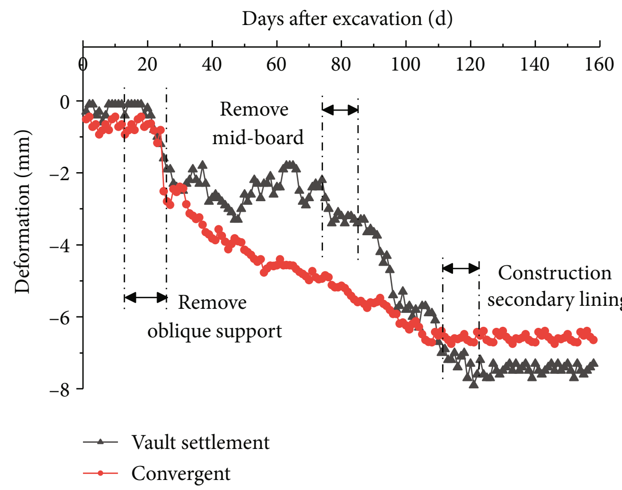


Figure 18: Tunnel deformation monitoring results.

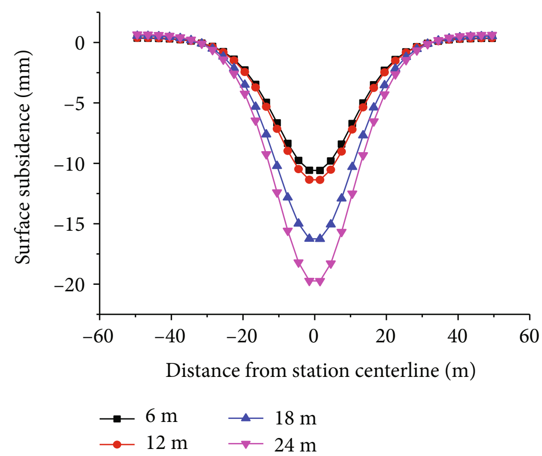


Figure 19: Surface settlement curve.

left shoulder (measure point 3), which increases by 260 kPa after the midboard is removed. The pressure on the vault position (measurement point 4) increased by 206 kPa after the oblique support was removed, and there was no significant change when the midboard was removed thereafter. The reason for this phenomenon is that this monitoring point is located directly above the middle plate. As the main support point, the force balance is quickly reached when the oblique support is removed, so there will be no significant pressure changes in the subsequent construction.

As shown in Figure 17, the internal force of the first layer initial lining reflected by the steel bar meter does not show a significant sudden change point. The upper parts of the structure (measure points 3, 4, and 5) are under a maximum tension of 20 kN, while the middle and lower parts (measure points 1, 2, 6, and 7) are under compression with a maximum pressure of 17 kN. After the secondary lining is formed, the internal force of the first layer initial lining decreases by 5 kN, and then it forms a joint supporting body with the second layer initial lining and the secondary lining structure.

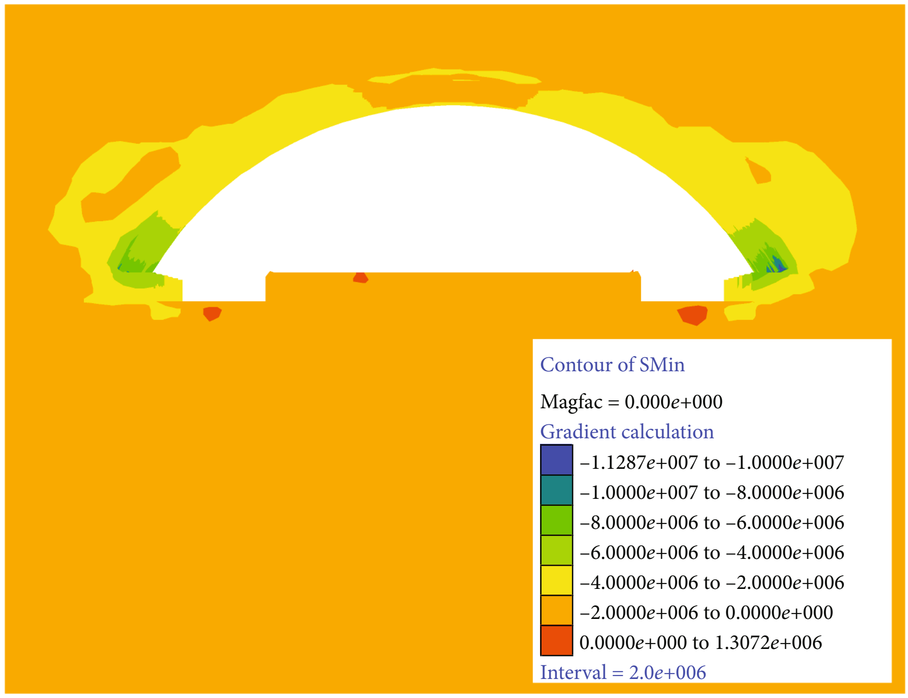


Figure 20: Minimum principal stress diagram after the temporary support is removed.

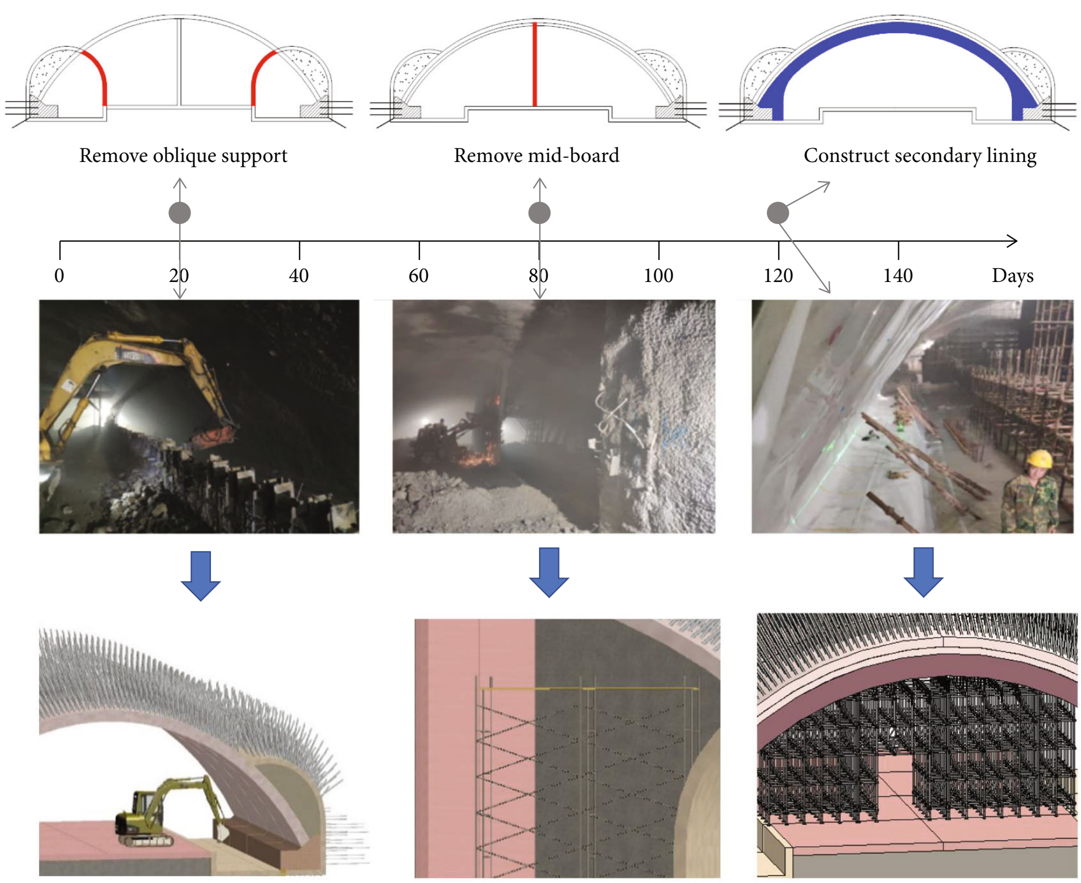


Figure 21: Key construction steps.

Figure 18 shows that the oblique support and the mid-board effectively limit the displacement growth after the excavation of the main tunnel. However, when these two kinds of temporary support structures are removed, the settlement of the vault and the convergent displacement around the cave will increase continuously for a period of time.

The above monitoring data reflects the stress change law of the construction of the arch cover method station, indicating that the timing of temporary support removal is crucial. Through the interaction law of the surrounding rock support, it can also reflect the surrounding rock geological parameters, to guide the construction to ensure the safety of the project.

4.4. Construction Control Based on Data Analysis. During the construction process of the underground excavation subway station, based on the self-developed multi-information collection technology of the underground excavation subway smart construction site, based on the monitoring data, the inverse analysis of the surrounding rock parameters was carried out, and the data obtained from the actual inspection of the project was used as the control value [44]. The mechanical parameter group obtained by inverse analysis is $E = 1.3$ GPa, $\mu = 0.24$, $c = 0.2$ MPa, $\varphi = 38.16^\circ$, and $t = 0.1429$ MPa. Based on the inverse analysis of surrounding rock parameters, the numerical simulation of each construction step of the arch-cap method is carried out, and it is concluded that the excavation of the middle pilot tunnel, the dismantling of the bracing, and the construction of the arch cap are the key processes affecting the settlement. The numerical simulation results show that the removal of the temporary support in the construction of the arch cover method has a great influence on the stability of the support structure, and the selection of the removal length of the temporary support is particularly critical. Therefore, during the construction process, it can be dismantled in sections, and the temporary support and the middle partition can be removed crosswise. The demolition area next door shall be pre-reinforced and other measures to ensure the safe construction of the project.

In order to select the most reasonable removal length of the middle partition, based on the identified stratigraphic parameters, the subsidence of the surface subsidence vault under different lengths of the removal of the middle partition was analyzed by numerical simulation. The original design plan determined that the demolition length of the temporary support was 6 m, and the demolition lengths of the middle partition were selected as 6 m, 12 m, 18 m, and 24 m for analysis. The ground surface settlement curve is shown in Figure 19. It can be seen from the figure that during the demolition process, the subsidence of the ground surface is symmetrically distributed with the vault as the center line, and the maximum subsidence of the ground surface occurs at the center line of the subway station. When the demolition lengths are 6 m, 12 m, 18 m, and 24 m, the corresponding maximum settlements are 10.59 mm, 11.37 mm, 16.26 mm, and 19.74 mm, respectively. In the demolition stage of the middle wall, it is determined that the demolition length of the middle wall will be 12 m for construction.

The stress distribution of the surrounding rock after the completion of the main pilot tunnel construction and the removal of the temporary support in the key construction steps is analyzed, and the results are shown in Figure 20. It is shown that, after the dismantling of the temporary support, the stress distribution of the rock around the cave has changed significantly, and the compressive stress value of the arch has increased, but the stress distribution of the entire arch is relatively uniform. In the lower part of the excavation face, the rock mass is uplifted due to the excavation and unloading, and a small part of the tensile stress concentration occurs.

Then, the excavation spacing of the pilot hole, the construction sequence of the substructure, and the construction of the steel support were optimized based on numerical calculation. The excavation spacing of the tunnel face was optimized from 30 m to 20 m. The physical and digital models of key procedures of the arch construction are shown in Figure 21. This optimization scheme has achieved good construction results.

5. Conclusion

To provide a solution for the construction monitoring of the dome method station, this research develops an automatic multi-information monitoring system based on DT and IoT. The developed system can be used to monitor the construction process of the arch cover method station, which is essential to ensure construction safety management. It not only shows the designed IFC extension and DT's station excavation construction model application but also facilitates the research progress as follows:

(1) A new station construction decision-making framework based on DT and IoT is established; furthermore, a multi-information monitoring system for subway stations based on BIM is developed to realize the visual query and early warning of monitoring data corresponding to each sensor model. The monitoring data time-history curve can be drawn to facilitate the automation of the construction decision-making process

(2) The 3D model of the subway station with the arch cover method established by Revit software intuitively shows the main structure of the station and the location of the sensor and realizes the intuitive expression of the engineering construction structure. Through the parametric modelling of the secondary development, the modelling efficiency is improved, and the monitoring information integration and expression are realized by extending the sensor attributes

(3) The IFC extended data integration structure based on the construction of the arch cover method station is designed, the monitoring data is managed through the IFC attribute set and the SQLSERVER database, and the storage, exchange, query, and update of the heterogeneous construction data are realized

(4) The developed system was initially applied to Shikui Road Station of Dalian Metro Line 5, and the expected visual expression effect was obtained. The method in

this paper provides an advanced technical means for the information construction management of the arch cover method subway station. The results show that the provided solution realizes the continuous condition monitoring of the construction process of the arch-cap method and helps in the safety evaluation and the dynamic adjustment of the construction plan in the construction management

The digital twin monitoring technology can provide an effective means for realizing the construction of the arch cover method station. This research promotes the application of DT technology in the construction of complex underground projects and promotes the intelligent construction technology of subway stations, thereby contributing to the knowledge system. The intelligent construction of subway stations is a process of continuous development. Future work will focus on three main avenues of research:

(1) Due to the complexity of the structure of the large-section underground excavation station, further improvement is needed in the equipment supporting sensors; especially the research and development of anticorrosion and anti-interference sensors such as laser ranging and grating fiber sensors is required

(2) The next stage of work should further establish a comprehensive analysis and prediction algorithm based on the additional information on the digital twin and improve the numerical analysis model to better realize the two-way mapping between the digital world and the physical display and help managers make more accurate decisions on station construction

(3) The digital twin realizes the virtual-real interaction and coevolution of station construction. At present, it is only suitable for a single station project. With the advantages of emerging technologies such as web, GIS, 5G, and blockchain, a more complete and powerful digital twin can be further built, forming a smart construction system for unified management of multiple station projects

Data Availability

All data, models, and code generated or used during the study appear in the submitted article.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Research Article

A Modern Approach towards an Industry 4.0 Model: From Driving Technologies to Management

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Every so often, a confluence of novel technologies emerges that radically transforms every aspect of the industry, the global economy, and finally, the way we live. These sharp leaps of human ingenuity are known as industrial revolutions, and we are currently in the midst of the fourth such revolution, coined Industry 4.0 by the World Economic Forum. Building on their guideline set of technologies that encompass Industry 4.0, we present a full set of pillar technologies on which Industry 4.0 project portfolio management rests as well as the foundation technologies that support these pillars. A complete model of an Industry 4.0 factory which relies on these pillar technologies is presented. The full set of pillars encompasses cyberphysical systems and Internet of Things (IoT), artificial intelligence (AI), machine learning (ML) and big data, robots and drones, cloud computing, 5G and 6G networks, 3D printing, virtual and augmented reality, and blockchain technology. These technologies are based on a set of foundation technologies which include advances in computing, nanotechnology, biotechnology, materials, energy, and finally cube satellites. We illustrate the confluence of all these technologies in a single model factory. This new factory model succinctly demonstrates the advancements in manufacturing introduced by these modern technologies, which qualifies this as a seminal industrial revolutionary event in human history.

1. Introduction

The term "industrial revolution" is defined as major changes to industrial processes due to the introduction of new technologies. Looking back on previous industrial revolutions helps us understand the genesis of the fourth industrial revolution. Technology was always used to support industrial processes. The water wheel and water turbines can be considered as the precursors of the first industrial revolution [1]. These were used for many "industrial purposes" such

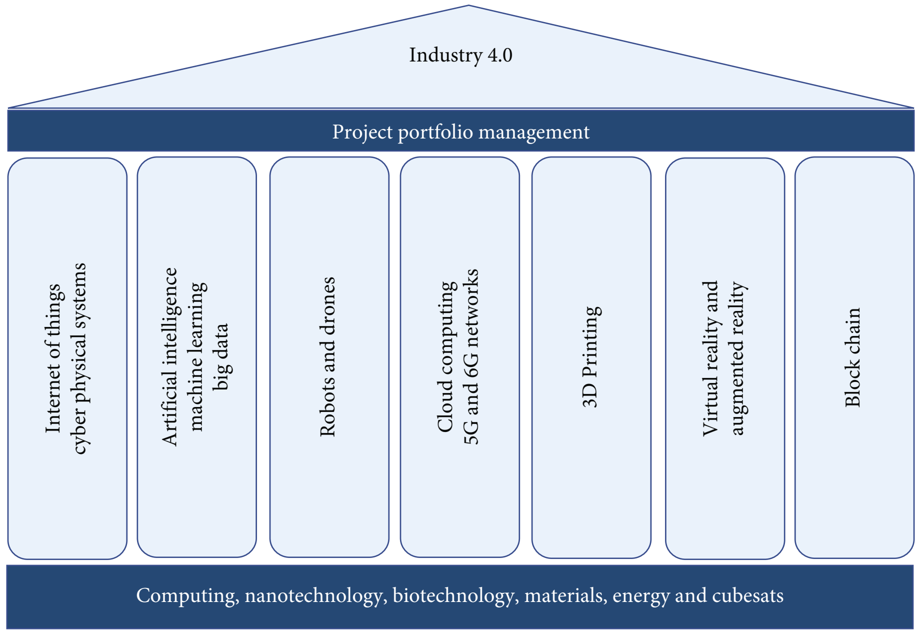

FIGURE 1: The pillars of Industry 4.0.

as lifting devices, grid grains, sawing, and more [1]. This continued to the early stages of the first industrial revolution, until the use of coal and steam. The first industrial revolution, 1760 to 1830 [2] happened when Watt's steam engine and other steam-powered machines were introduced to the manufacturing process [2]. This led to the increased production at lower costs that initially allowed Britain and later other European countries to play an important role in 18th century trade [2]. The trains also make their appearance during the first industrial revolution as another use case of the steam engine [3]. Unlike the first industrial revolution, which was initiated by advancements in a single field, the second was a result of multiple technological breakthroughs. It included advancements in fertilizers, electricity, and transportation [4]. It was initiated by the introduction of the gas- and air-based internal combustion engine developed in 1859 [4]. However, it was made commercially available towards the end of the 1870s, which marks the beginning of the second industrial revolution. It was the time when cars started becoming commercially available and used for transportation [3, 4]. The third industrial revolution started in the 1960s, and it was based on electronics and automation. Its main achievements were robots and computers [5]. The evolution of computers played a very important role in the 4th industrial revolution. The term fourth industrial revolution was first mentioned in Germany, during the "Hannover Fair" in 2011 by Kalus Schwab [6]. However, it was introduced to the public at the World Economic Forum 2015 [6]. Industry 4.0 is an era of cyber physical systems [5]. According to [6], the main areas are AI, robotics and ML, nanotechnology, biotechnology, quantum computing, blockchain, Internet of Things (IoT), 3D-printing, and others.

In this work, we will look behind the curtains and present the pillar technologies of Industry 4.0. It is not yet clear how quantum computing has impacted or will impact Industry 4.0 as it has not yet proved its potentials, but we can consider the advancements in computational processing power as an equivalent replacement. It is also believed that 5G and 6G networks as well as virtual and augmented reality play an important role in Industry 4.0. Figure 1 summarizes our view of Industry 4.0 from a multidisciplinary point of view.

There are many technological advancements in many areas but the ones that played the key roles were computing, nanotechnology, biotechnology, materials science, energy, and CubeSats. In this research, we identified seven pillars of Industry 4.0. That includes cyber physical systems and IoT, AI, ML and big data, robots and drones, cloud, 5G and 6G networks, 3d printing, virtual and augmented reality, and blockchain. These technological advancements have a huge impact on project portfolio management that has transformed the business to take advantage of all these opportunities as well as manage challenges and risks.

The rest of this paper is structured in the following way. Section 2 includes the foundation technologies where the pillars of Industry 4.0 were based. Section 3 identifies the technologies that are the seven pillars of the fourth industrial revolution. Section 4 presents the modern project portfolio management. Section 5 provides an example of how all these technologies could be applied to a model Industry 4.0 factory, in order to help the readers to realize the impact of modern technologies in the fourth industrial revolution. Finally, Section 6 concludes this paper.

2. Foundation Technologies of Industry 4.0

2.1. Computing. ML and modern advanced AI techniques utilize data in order to produce control decisions, such as simulations, forecasting, and many more outputs that made the Industry 4.0 possible. Most of these algorithms and their theoretical backgrounds were available before but the main difference nowadays is the amount of available data and the advancements in the computational power of modern machines. AI and ML applications utilize the modern central processing units (CPUs) and/or dedicated general-purpose graphics processing units (GPUs) in order to process their data. Over the last decades, the advancement of CPUs followed Moore's Law [7] which states that the amount and transistors in the CPUs are expected to double every two years. Even if this does not correspond to such improvements over the actual performance (applications execution time, etc.) which depends on many parameters which is an indication of the increase in computations power of modern machines. Another computing hardware that played an important role in Industry 4.0 is the GPU. GPUs were originally intended to allow computers to deal with higher quality graphics, and they included instructions to support that at the hardware level. Later, however, it was found that these instructions could be used to do the processing for other types of applications such as ML, key generation, and searches in blockchains, and more. Modern GPU-based solutions are faster and consume less energy than even some high-performance computing (HPC) clusters [8]. Recently, GPU-based solutions found their way to real-time cyberphysical systems [9], which play an important role in applications of Industry 4.0. Commercially available solutions with embedded GPUs like NVIDIA Jetson Xavier AGX [9] offer profound benefits to robots, drones, and other smart/intelligent machines of Industry 4.0.

2.2. Nanotechnology. The term nanotechnology defines the scientific field dealing with the establishment of materials, devices, and systems by manipulating matter and transforming it at nanometer length scale. The result in itself is not necessarily limited to nanoscale but can range at micro or macroscale. A particle of nanometer range (a billionth of a meter) that can be noncrystalline, an accumulation of crystallites, or a single crystallite is categorized as nanoparticle. Performing targeted interventions at the nanometer length scale provides the opportunity to alter the properties and control individual atoms and molecules. In this way, physicochemical, mechanical, electrical, optical, and magnetic properties are being altered, thus providing the ability to come up with innovative products and processes. Therefore, nanotechnology has the potential to revolutionize various technologies in industrial sectors like medicine, automotive and aerospace industry, renewable energy, information technology, and environmental science.

Undoubtedly, the majority of the ongoing research around Industry 4.0 has to do with progress in software and data algorithms [10]. In this automated and interconnected environment of Industry 4.0, nanotechnology plays a vital role. The sensors themselves can greatly benefit from nanotechnology. Sensors incorporating nanomaterials feature increased sensitivity and process ability, thus, minimizing the error margin of the data that they acquire and subsequently feed algorithms and other processes. Sensor robustness is another topic where nanotechnology can assist researchers. Often, demanding operating environments (increased corrosion, temperature, alkalinity etc.) can damage the sensors that will no longer be able to provide accurate data. The use of nanomaterials in the production of sensors can make them chemically inert and robust, broadening the fields of their potential use in environments that were considered not applicable beforehand [11]. The area of quantum computing is another Industry 4.0 field that strongly benefits from the use of nanotechnology. In this case, the use of semiconductor nanomaterials allows increased processing speed and more secure data transmission. Both the aforementioned elements are highly desired characteristics in the context of Industry 4.0 [12].

Another field where nanotechnology can be incorporated within the IoT context is in creating a network that combines different components using communication protocols at nanolevel. The term "Internet of Nano Things" (IoNT) is used to describe such a network. It is still an area considered under development that has great potential for telecommunication and medical fields. Relevant examples can be outdoor field-based applications, where there is a need for remote sensing, or for acquiring measurements within the human body [11]. In conclusion, conventional technologies in the fields of data acquiring and transferring, cloud computing, and data processing are still able to support current needs. However, in the continuously evolving context of Industry 4.0, nanotechnology can assist in shifting to smaller system architectures that will also feature greater processing and data acquiring capabilities.

2.3. Computational Biology and Biotechnology. After the completion of the human genome project in 2003 [13, 14], which was carried out using 'first generation sequencing' or Sanger sequencing technology, there was an emerging need for a cheaper and faster alternative solution to sequence the human genome. High-throughput genomic sequencing technologies, such as next-generation sequencing (NGS) or massively parallel sequencing, emerged that allow the rapid sequencing at low costs of full genomes, many samples of a certain genomic region from different individuals to detect low-frequency mutations or quantification of the abundance of fractions of a genome [15–19]. High-throughput sequencing has myriad applications in many fields such as medicine (e.g., understanding the mode of transmission of infectious agents and precision personalized medicine) [20, 21], forensics (i.e., identifying individuals based on their unique DNA profiles) [22], agriculture (i.e., genetically modified crops and genetically engineered animals) [23, 24], and environmental monitoring [25].

In 2005, the first commercial NGS platform was developed by Roche. Meanwhile, more sequencers were developed by different companies, and the existing ones were improved [26]. The costs associated with NGS continued to drop remarkably. The lower costs allowed scientists to launch the 1000 Genomes Project (or 1KGP), a coordinated international research effort to create an integrated catalogue of human genome variation [27]. The completion of the 1000 Genomes Project (1KGP) project in 2015 [28, 29] would be impossible using first generation sequencing. As of today, whole human genomes can be sequenced in less than a day for less than 1000 dollars.

Recently, ultrarapid genome sequencing enabled clinicians to diagnose rare genetic diseases in five patients in an average of eight hours [30].

The advent of high-throughput technologies in molecular biology resulted in the production of an overwhelming amount of raw, unprocessed biological data, which have to be processed and interpreted in a way to obtain biologically meaningful information. This has led to the emergence of the field of computational biology and bioinformatics which merges cutting-edge software and hardware technologies towards efficiently handling the accelerated generation of biological data. Computational biology constitutes an integral part of the fourth industrial revolution, 4IR [31].

Computational biology and bioinformatics methods are widely applied to genome annotation [32], a very complicated process, consisting of numerous steps. Genome annotation includes the (i) identification of the locations of individual genes and all of the coding regions in a genome, (ii) determination of key features of the sequences (e.g., active sites), and (iii) identification of functional and regulatory elements.

In the postgenomics era, there is an increasing amount of generated biological sequences, the experimental characterization of which is unattainable. If sequences similar to an unannotated sequence can be found in databases for which experimentally verified structural and functional information is available, then the structure and function of the novel sequence can be inferred. Bioinformatics methodologies are utilized to search the sequence (nucleotide or protein) databases for sequences similar to the new ("query") sequence; a process called database sequence similarity search or homology search [33]. In addition, the sequence-structure gap is widening between the number of proteins with experimentally defined structures and proteins with unknown structures. As a result, the most efficient alternative to experimental methods is to use computational and bioinformatics tools to assign structure to a novel protein based on its amino acid sequence [33].

Discovering useful knowledge from the biomedical literature poses a great challenge, given the plethora of published documents (containing information collected from scientific experiments or high-throughput experimental studies) available in premier bibliographic databases such as MEDLINE/PubMed. To address this issue, many bioinformatics tools have been developed for detecting, extracting, and processing biomedical terms through automated text mining [34, 35].

Furthermore, computational methods are employed for the analysis of multiomics Big Data, that is, very large "-omics" (e.g., genomics, transcriptomics, proteomics, epigenomics, and metabolomics) data generated from high-throughput experiments. To this end, relevant datasets are retrieved from public data repositories, processed, integrated, and interpreted, to extract meaningful information [36].

Complex biological networks are widely used to depict the associations of one or more bioentities (genes, proteins, hormones, etc.) and, also, integrate, visualize, and interpret multiomics data [37, 38]. Network-based computational approaches enable the modeling of biological processes and systems [39, 40]. The emerging potential of computational methods for identifying pharmaceutical targets suitable for drug design must be highlighted. Computational tools can facilitate drug target identification, drug candidate screening, as well as the discovery of novel compounds with improved pharmacological and biochemical properties for drug development [41, 42].

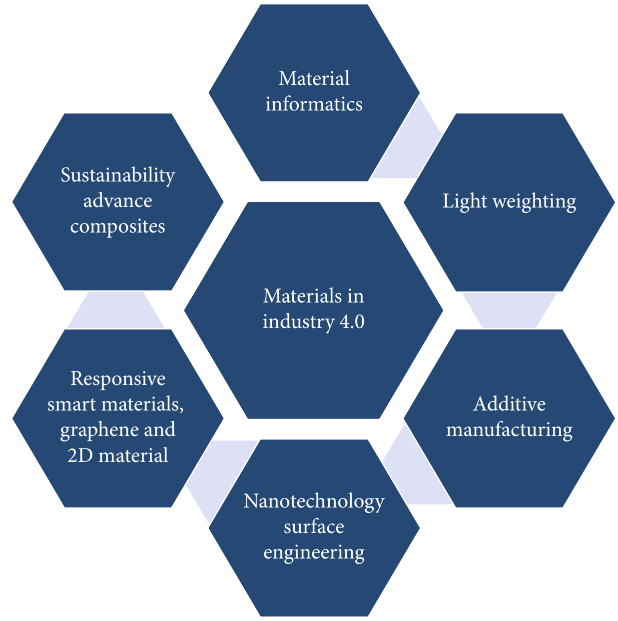

Figure 2: Materials in the context of Industry 4.0.

2.4. Materials. Materials used in Industry 4.0 applications must be able to withstand the high demands that the aforementioned applications place on them. Advanced composites and responsive (smart) materials are required for novel applications that have to be compatible with emerging manufacturing technologies like 3D printing and CNC milling. Assisted by the immense progress in fields like nanotechnology, such materials must exhibit properties like lightweight and elevated mechanical properties while being sustainable both in their production and general life cycle. In the context of circular economy, products made by such materials should be designed and manufactured taking into account such considerations [43]. Figure 2 depicts such material cases in the context of Industry 4.0.

The case of graphene and other 2D materials is a characteristic example of materials developed and used in the context of Industry 4.0 [44]. Graphene represents a novel, new material category exhibit only one-atom thickness, hence, named two-dimensional (2D) materials (they are characterized as 2D since they extend solely in two dimensions: length and width; as the material exhibits one-atom thickness, the third dimension (height) is considered to be zero). The development of silicon semiconductor technology in the late 1960s to early 1970s considered a breakthrough in the field of electronics. Devices like microprocessors enabled the development of computers and smartphones just by downscaling the physical size of circuits and wires to the nanometer scale. Nowadays, materials like graphene and other relevant 2D materials offer unlimited prospects of advancing in device performance at the atomic limit. Also, the parallel use of 2D materials with silicon chips is very promising in terms of achieving great advances in silicon technology.

The use of such innovative materials allowed towards broadening the horizons of existing manufacturing technologies, i.e., while 3D printing technology is considered to be one of the most advanced manufacturing techniques of our time [45], innovative raw materials allowed its transformation from 3D to 4D printing [46, 47]. 4D printing is the process by which a 3D printed object changes its geometry structure in response to external energy inputs like temperature, light, or other environmental stimuli. It is done with the help of a "smart material" with shape memory properties. Such materials are distinguished from ordinary 3D printing materials by their thermomechanical and other material features, which allow them to change shape.

2.5. Energy 4.0. The fourth industrial revolution has been impacted by the advancements in the energy sector, which are most prominently seen in energy storage, smart grids, and renewable energy. Any device (e.g., a robot, a drone, and a wearable) that can operate only for a few minutes is of limited use. The advancements in energy storage such as batteries allow the Industry 4.0 devices to operate for sufficient time in order to be useful in their operating environment. On the other hand, the new information communication technologies (ICT) introduced during Industry 4.0 created new energy distribution and management technologies.

2.5.1. Energy Storage. The decoupling from fossil fuels has made batteries the main technology for storing electricity. Minimizing the size, weight, and cost while increasing the energy capacity of the batteries has been one of the main drivers of Industry 4.0 [48]. Lithium and its polymers are the de facto standard for mobile devices such as mobile robots and mobile phones. The main advantage of such batteries is that they are small, lightweight, and can be easily recharged. There are two types of lithium batteries, lithium-ion and lithium iron phosphate [49]. They both have trade-offs in terms of the amount of energy density, supplied voltage, charging rate, and discharging rate.

In terms of energy density, lithium-iron outperforms iron phosphate. Lithium iron phosphate has lower voltage (approximately 3.2 V) compared to lithium-ion (in the range 3.6 V-3.8 V). On the other hand, the charge rates of both above batteries are equivalent. The discharge rate is the biggest trade-off factor that should be taken into consideration when we need to select Li-irons or Li-polymers. The discharge rate of Li-polymer is higher than Li-irons. Nevertheless, lithium iron phosphate is still the best choice for many applications due to its capability [49].

2.5.2. Smart Electricity Grids. Smart electricity grids depend on sensors and smart switches for monitoring and controlling the power distribution to smart factories, buildings, and cities. The data collected by sensors can be used for triggering automatic alerts and responses to incidents (such as diverting power from one sub grid to another), power consumption prediction, and prediction of possible issues before they occur [50]. Their advanced management capabilities allow them efficient energy management and control, leading to higher and more dependable power outputs at lower prices for the consumers [50].

2.5.3. Renewable Energy. Green technologies and procedures were first launched in the 1960s as part of the industrialized world's environmental movement [51]. Green technologies enable businesses and manufacturers to implement green processes into their operations, reducing the environmental effect of their operations. The scope of green processes (operations) in Industry 4.0 includes everything from product development to product lifecycle management, as well as environmental practices like eco-design, clean production, recycling, and reuse, all with the goal of lowering costs associated with product production, distribution, use, and disposal. Renewable energy can be obtained from various sources such as sun, wind, and biomass. The energy of the sun can be used directly in various industrial applications for numerous processes such as water desalination, improved oil reform, and food production. The other way that the energy of the sun can be indirectly investigated is by storing it in solar cells to produce the required electricity of driving Industry 4.0 [52]. Photovoltaics' growth is incredibly dynamic across the world and varies greatly by nation. A total of 629 GW of solar power has been installed throughout the globe by the end of 2019 [53]. In industries that are constructed in urban areas, turbines are an effective solution to generate electricity in Industry 4.0. For the industries that are located near big rivers, hydroelectric power approaches can be used to generate electricity for Industry 4.0 [54]. Biomass energy is the best solution to generate energy from plants and animals in food industries. In this type of energy, the burning of the biomass is implemented to generate electricity [55]. Renewable energy also plays an important role in terms of sustainability.

2.6. CubeSats. A CubeSat is a small satellite that has a cube shape of size 10 cm^3 and weight 1 Kg [56]. Compared to the traditional satellites, CubeSats are lower cost, lightweight, and much smaller, setting the basis for the new applications. There are more than 6500 in orbit, and their number is increasing rapidly [57]. Some of the main companies that are involved with the launching of these satellites include NASA, SpaceX, and many companies that are producing CubeSats. A CubeSat can work in swarm behavior to reach billions of global targets. Besides this, CubeSat swarm enhances the autonomous locative, data rate, measurements, and temporal settling of the global targets [58]. Referring to these features, CubeSat is the essence of Industry 4.0 future. CubeSat technology will enable the development of new commercial dealings between various industries [59]. It can be applied to enhance communications between IoT devices [60], work together with drone communications [61], take photos of different locations of earth and space, climate research, and weather predicting, and collect sensor data from space [59]. The CubeSat is expected to play a crucial role in the application of current technologies which will assist in making dramatic changes to the technologies that lead the fourth industrial revolution.

3. The Pillars of Industry 4.0

3.1. Cyberphysical Systems. Cyberphysical systems (CPS) integrate sensing, computation, control, and networking into physical objects and infrastructure, allowing them to communicate with one another and with the Internet. IoT and industrial wearable IoT devices are two major examples of cyberphysical systems.

3.1.1. Internet of Things (IoT). The IoT is a network of cyberphysical objects or "things" that are integrated with sensors, software, and other technologies that allow them to communicate with other devices and systems via the Internet. The complexity of these devices ranges from simple household items to major industrial equipment.

Industrial automation and control systems (IACS) have generally been maintained apart from standard digital networks, such as those found in commercial information and communication technologies (ICT). When communication is required, a zoned design is implemented, with firewalls and/or demilitarized zones separating the core control system components from other components. IACS is undergoing architectural changes as a result of the implementation of "IoT technologies, including increased connections to industrial systems. Industry 4.0 relies heavily on the IoT as it has a wide range of applications in the monitoring of industrial and service systems. By permitting increased performance, this technology offers up new and inventive industrial opportunities [62]. The main capacity of the IoT is to gather and distribute data via Internet-connected equipment and gadgets. The primary components of this technology are software, hardware, and network connection enabling data manipulation and collecting. In the sector of manufacturing, the IoT fosters disruptive innovation. Industries see an increase in efficiency during product manufacturing when this technology is properly applied. Manufacturing is done at a lower cost and with fewer mistakes. A typical IoT architecture includes the following three layers [63].

(1) Device layer: architects determine how devices interact with communications networks to link and interconnect in a structure at the device layer

(2) Communications layer: systems utilize protocols to transmit actionable data at the communications layer

(3) Semantic layer: the semantic layer gives the system meaning and context, and it recognizes system elements in the context of business objectives

The primary aim of IoT is automation, and it is a key component of "smart" ecosystems such as smart buildings and factories. The key intersecting point of Industry 4.0 and IoT is connected devices, smart factory grids, and heavy machinery. IoT is advancing the notion of manufacturing excellence by playing a critical role in every industrial operation and significantly enhancing it. Industry-specific IoT is the best match technology since it delivers meaningful results by integrating information and operational technology for processes [64].

IoT technology is considered to be the missing part of CPS realization. CPS technology has been treated either as a wirelessly connected embedded systems domain or as a system modeling domain. Unfortunately, this distinction of attitudes results in two different theoretical spaces aiming to act as a common world. The answer for this barrier is coming to be given from the Industry 4.0 technology of digital twins [65, 66]. According to it, real-time data acquired by embedded IoT-based sensors from real-life physical systems are delivered to a computerized digital system in order to feed with critical information a digital instance, the so-called digital twin. The digital twin aims to reflect the physical system (physical twin). In this context, model-based systems engineering (MBSE) can be supported to deliver better systems, processes, and services design and development [67]. Computer-aided design (CAD), computer graphics, modeling, simulation, and data analytics are some of the key technologies that their use in the digital space can have a tremendous impact on the models' improvement and ultimately the increase of knowledge for the physical systems. Thus, location-aware, and environment-sensitive cyberphysical systems can be studied and developed and help in this way the establishment of a unified, data-driven, and user-directed, federated-based learning space. Such a space will enable Industry 4.0 to blossom and develop the preconditions of getting closer to the next revolution, the Society 5.0. IoT is going to have a multitrillion US dollar contribution to the global economy in the next decade [68]. On the other hand, it also poses the risk of privacy and data security as all the people, devices, and equipment are all connected to the Internet in the present scenario. However, while this technology provides us with greater access to data through the cloud, it also provides opportunities for hackers to get access to networks and exploit the user's data.

3.1.2. Industrial Wearable IoT Devices. Wearable IoT devices are machines with sensors, output devices, processing and connectivity capabilities that can be attached to the human body. Examples of such devices are smart watches, glasses, and so on. Over the past decade, the use of wearable devices has expanded across a number of industries. Wearable gadgets help the Industrial Internet of Things (IIoT) to achieve increased productivity and efficiency [69]. Existing technologies, like radio frequency identification (RFID), have been integrated into garments, watches, goggles, and other protective gear for some years. The high-speed data networks that present in industrial premises provide an environment where wearable IIoT may flourish. The capacity to interact with a variety of sensor data is critical for wearable data-based devices [70]. How data is gathered and then utilized to make practical choices is an important aspect of how wearable technology will evolve across sectors.

The wearable sector is developing due to rising demand. There has been significant growth in the supply of these smart gadgets, particularly in the medical industry. More than 80% of customers throughout the world are open to using this sort of technology to track their vital signs and physical activity, among other things [71]. Wearables are not only for consumers; they may also be a lucrative prospect for companies. Processes have been optimized because of the use of IoT devices, making them more efficient and lowering costs.

Wearables in Industry 4.0 provide supply chains and manufacturers a tremendous chance to optimize and monitor the performance of their personnel on the shop floor, as well as provide more complete real-time data and alarms. They may also be utilized in preexisting device applications to allow portable device usage, such as inventory management and plant maintenance scheduling, all from the worker's wrist [72].

Field service technicians are another use case, since wearables make their outside work more convenient, allowing for quicker and more effective contact with customers as well as more agile movement. Wearable data may be used to influence company choices and improve staff skills and process effectiveness. These gadgets may also alert businesses to issues with their goods and services. This information may then be utilized to customize and adapt the product to the needs of the customer, as well as reduce the need for maintenance and repair.

Wearable gadgets are finding their way into our work settings at an increasing rate, from smart glasses with optical data collection and speech recognition technology to smart safety vests used at building sites to monitor and notify field workers when they reach predefined hazard-zones. From Industry 1.0 to Industry 4.0, robots progressively replace heavy physical labor and simple repetitive processes in terms of human operation and execution. Humans only need to work with machines in the human-centered-automation environment to perform nonreparative, complicated, and unpredictable processes, such as quality control and diagnostics.

The mechanistic, passive, and unidirectional methods of human-machine interaction have all been abandoned. Speech and gesture recognition technologies will enable humans to engage with machines in a more natural and intuitive manner. AI will enhance the human experience. Experienced frontend operators will make an increasing number of decentralized and real-time judgments [73].

Some of the most intriguing applications of wearables in Industry 4.0 are eSIM, reality smart glasses, and smart wearable vests [74].

The recent incorporation of Thales' eSIM in OPPO's new smart wristwatch is an excellent example. Cellular connections may be formed quickly and simply with the help of the eSIM. To create a cellular connection, smartwatches will often need to be linked to a smartphone. The watch is untethered using Thales' eSIM, giving customers seamless access to digital services. This kind of device independence may provide a raft of benefits in the context of wearable IIoT, the most notable of which being off-site process monitoring. Wearable linked devices may also be tiny and light, since there is no need for a hefty SIM card—both of which are criteria for widespread adoption of wearable technology [75].

Users may engage with high-definition 3D material projected into their environment using reality smart glasses. In an industrial context, a physical environment that gives valuable information to organizations might be advantageous to their operations. Users may, for example, be working on a machine that needs maintenance instructions, which may emerge when they point their heads toward the machine. Smart glasses may enable employees to collaborate more effortlessly, much like remote work or visiting clients at their offices, since they can seamlessly share their workplace or real-time virtual environment with peers regardless of their physical location [76].

Wearable smart vests are form-fitting clothing made of rubberized materials that are meant to capture data points on employee movements and location while remaining undetectable to the naked eye. This allows you to acquire a better knowledge of where productivity failures occur so that you may better deploy workers throughout the day and eliminate mistakes on production lines. Furthermore, these vests may be employed for safety, particularly in high-risk areas of industrial production [77].

The concept of "Operator 4.0" has been proposed in the context of Industry 4.0 and is a skillful and intelligent operator who performs not only "cooperative work" with robots but also "work aided" by machines as and when needed—using a variety of human empowering technologies to achieve "human-automation symbiosis work systems." In terms of the drawbacks, the wearables are expensive, some wearables are not stand-alone and can also pose security and privacy issues.

In conclusion, wearable devices must have a variety of useful functions in addition to having qualities such as a distinctive product design, a comfortable fit, and portability. Modules, wearable devices, and interaction mode in industrial wearable system (IWS) must be changed to fulfil the various needs due to the variety of real-world production situations. An important study area is how to optimize the usefulness of IWS in various situations.

3.2. Artificial Intelligence, Machine Learning, and Big Data. The fourth iteration of industry can be described as a vast improvement in our understanding of the exponentially rising quantity of available raw data, which greatly impacts our productivity in many aspects. Focusing solely on industry, the raw data is collected from smart, interconnected robots, sensors, and other machines, as well as from people who are connected to the production process or benefit from it. The data is continuously generated from these entities, and its availability gives rise to the following question: "What do we do with this data now?" Given humanity's experience with vast quantities of data from other fields, the answer is usually that we can benefit from it by understanding it. The data itself is made available through the rise of smart devices, and the interoperability of the IoT and the Internet of People (IoP) which amalgamates it and prepares it for analysis and, more importantly, understanding.

Most of the difficulty is in making the data available, but the next obvious question is how do we understand it once we have it? More importantly, what does understand it even mean? This is addressed in the research field of big data analysis and can be broken down into the ability to find trends and patterns in data, associations between different data points, and to group and classify the actors that generate the data. One of the most famous examples of finding patterns in data came in the retail sales industry where Target Corporation developed a method of determining if a woman is pregnant based on changes in her consumer behavior. More precisely, if she started suddenly purchasing from a pool of items that were statistically linked to pregnant shoppers, then she would receive additional advertisements for other products linked to pregnancy. Shopping tendencies such as frequency and recency, as well as the size of typical purchases, can segment customers into separate groups [78] that can be approached differently from a marketing standpoint in order to maximize sales revenue.

ML has increasingly been used for a variety of large data applications, with notable success in modeling the future behavior of groups of actors based on previous actions. This has found applications in several prediction tasks, such as identifying predators in social media [79] and automatically evaluating the trustworthiness of trading partners based on their past behavior [80]. Additionally, ML has been very successful at extracting sentiment and meaning from text written by humans. Forums can be analyzed for general sentiment on a given subject, and this sentiment has been used to successfully predict such things as election results [81]. Financial markets have also been analyzed with various deep learning-based networks in order to be able to predict price movements of tradable assets.

These examples illustrate the potential power ML methods have in gazing into the future, identifying trends, and in general helping us understand the world around us through data analysis. This technology enables us to understand what people need, and when they need it, making inventories in factories more streamlined and easier to manage. The production chain between factories also becomes more easily manageable as more information becomes available to each link in the chain. These technologies are technologically advanced and proven; however, its efficacy will be advantageous only when large amounts of data are available in the context of Industry 4.0 multilayered datasets representing a wide range of data pertaining to subsystems is required. This leads to another area of research which is still in its nascent stage.

3.3. Robots and Drones. Drones and robotics are considerably impacting Industry 4.0, because of their advantage and ability to adapt various tasks in industrial fields such as maintenance, inspection, and transportation. Thus, companies have started to invest the features of drones and robotics within their flexibility to be integrated into (IoT) for perfecting Industry 4.0. Both robots and drones are mechatronic systems capable of performing autonomous tasks in a physical environment. The main difference between the two is that the term robots is more general and refers to both fixed location and mobile robots. Drones on the other hand can change their location. Another difference is that robots tend to have a higher degree of autonomy and rely less on human input. Drone with high degree of autonomy can be considered as mobile robots. It is not uncommon for drones and robots to work in the same environment.

Robotics is an essential part of Industry 4.0 that supplies comprehensive efficiency in the domain of manufacturing. Robotics intensifies automation sectors and implements jobs in a precise manner with lower cost. Robotics provide a doubtless positive mutation in the performance of Industry 4.0 when integrated within the IoT system to form a new technology called Internet of Robotic Things (IoRT) [82]. IoRT merges the benefits of IoT and robotic features to support Industry 4.0 with a new technology that can provide advanced services with automation approach [83]. Applying IoRT provides industry the ability of using the single, cooperative, and common realization of robotic things with implementing actions under complex and uncertain conditions [84]. In addition, IoRT supports the Industry 4.0 with outstanding services by implementing cloud and networked robots, named Robotics 4.0, rather than conventional robots. Robotics 4.0 is collaborative and cognitive robots which are applied in IoRT rather than the traditional ones. Robotics 4.0 enables close interaction within humans. In turn, both the human and robot workspace have been intersected to implement cooperative tasks. Besides this, Robotics 4.0 increases the level of flexibility in the manufacturing process. Compared with traditional robots, Robotics 4.0 has higher dexterity. From traditional robotics to Robotics 4.0, the operation of robots is directed to be automated instead of only actuated. An essential part of Robotics 4.0 and drones in Industry 4.0 is integrating their information to implement automated tasks. For example, a drone that is performing sky monitoring will order a robotic 4.0 to implement a required task for a specific situation [85]. The major drawbacks of industrial robots and the use of robotic systems in the industry are high initial investment, the ongoing and maintenance costs, and the lack of expert technicians and eliminating the entire labor workers.

Drones can be used in industrial tasks that are difficult or even dangerous to be implemented by humans. Some of these tasks are reaching far distances and working in dangerous regions. Drones can do many tasks with more accuracy than humans due to the ability of integrating various sensor types with the drone platform [86]. For instance, the particularity of equipping infrared and ultraviolet sensors with drones provide the ability of detecting defects precisely in the components of industry. Besides this, involving autonomous drones enhances the features of Industry 4.0 [87]. They operate all the days of week without stopping, do not need a big space, and can do various tasks during a single flight path [88]. Furthermore, implementing autonomous drones to Industry 4.0 is motivating the market into the new technology and enabling new innovations in maintenance operation, safety of employees, security, survey, and map planning [89]. This new technology adopted AI techniques to implement high level tasks such as ordering robots to do repair operations.

In conclusion, applying Robotics 4.0 and drones in the fourth-generation industry will provide a way of implementing complex tasks in advance. Another essential characteristic is Robotics 4.0/drones behavior to interact in a cooperative manner. The benefits of Robotics 4.0, drones, and integrated Robotics 4.0/drones in Industry 4.0 consist of enhancing tasks conditions, increasing productivity, providing safety, and supplying advanced solutions to complex operations. In the market, companies are competing to supply their new technologies in this field. The limited capability of the drone, not being able to carry heavy loads and process information with high speeds, legal limitations, and safety concerns are some of the major drawbacks of drones and aerial robots.

3.4. 5G/6G and Cloud Computing's Impact on Industry 4.0. Industry 4.0 as an industrial revolution is promoted due to the diversified and increased needs of human society. Recent trends show that humans envision having highly customized products, mobile industrial applications, and flexible production lines. These services were served through wired communications but the presence of sensors, robots, drones, and many other devices requires connectivity through wireless mode. Such a need could be met through the enhanced features of 5G/6G [90]. Instead of only relying on cloud-based infrastructure, 5G provides services for extremely heterogeneous vertical applications through network slicing and edge computing techniques [91]. Various aspects of current industrial requirements are tied with time-sensitiveness. Considering time sensitivity, 5G and beyond networks are expected to deliver such requirements effectively through their support for ultrareliable and low-latency communications. Integration of Time-Sensitive Networking (TSN) with 5G and beyond is investigated for QoS requirements [92].

Apart from time sensitivity and quick connectivity, industrial automation requires intelligent networks to consider the dynamic nature of the equipment, the network and the operators involved. Intelligent industrial 5G networks are expected to meet such precise requirements through domain specific knowledge [93]. Furthermore, the requirements of various diversified industries include latency, reliability, jitter-free, lower packet loss, and accuracy [94, 95]. Such stringent and precise requirements could be addressed through 5G nonpublic networks [95]. The combination of various recent technologies such as 5G connectivity, distributed edge computing, and AI in the form of 5G edge intelligence for vertical experimentation (5G-DIVE) was evaluated for its support for real-time autonomous navigation [96].

Supersmart societies consider humans as their center of development. In order to cater for human centric approaches, 6G considers a holistic approach. The presence of cyberphysical-social systems (CPSS) in 6G mobile networks supports recent applications like Tactile Internet and Internet of No Things through human intelligence instead of relying on ML [97]. Such futuristic approaches tend to enhance Industry 4.0 towards Society 5.0. Network-in-a-box (NIB) of 6G provides support for mission critical applications through personalized private network services. Industry 4.0 applications are expected to benefit from 6G-NIB to meet their stringent requirements [98].

The transition to Industry 4.0 is not smooth for different industries, as they have their own legacy devices, which are not smart in nature. One approach to handle this transition is through a cloud-based IoT platform [99]. Meanwhile, the presence of multitenancy and resource heterogeneity in cloud computing platforms could be a challenge for cloud-based applications. Industry 4.0 should consider these challenges along with other stringent requirements like latency-sensitiveness. The stochastic nature of inference time caused by heterogeneous million instruction per second (MIPS) in the cloud computing environments have to be taken care of through Industry 4.0 [100]. Quality of service (QoS) requirements of real-time IoT applications are difficult to be met through cloud-computing infrastructure due to communication latency and geographical distributions. Addition of fog computing to the cloud causes challenges in delivering services in a time-optimized way due to their heterogeneous, distributed, and constrained resource nature. Context-aware application placement policy could assist addressing these challenges in Industry 4.0-oriented applications (I4OAs) [101].

Enhancements of various aspects of cloud computing have also happened through adding intelligence to existing elements like cloud and edge. Such AI-based elements have been tested on various situations like scheduling, optimization, and forecasting [102–104]. Along with the addition of intelligence elements to the existing cloud infrastructure, network-related advancements like software-defined network (SDN) are added to the existing Industry 4.0 network environment to improve data transmission and quality of service [105, 106]. Physical obstructions impacting the connectivity, high rollout costs, and no rural access, causing severe battery consumption are some of the shortcomings of 5G Technology in Industry 4.0.

3.5. 3D Printing. 3D printing is one of the leading emerging technologies within the framework of Industry 4.0. The utilization and implementation of this technology, together with other technologies, are making the industry shift towards an integrated modus operandi where machinery (autonomous, interconnected, and intelligent), systems, and networks can exchange information and transfer the output to the systems of production management [106, 107]. Moreover, as a fabrication technique capable of transforming a 3D design into an item without human intervention, 3D printing features a fundamental role. In addition, the need for surrounding industrial infrastructure is eliminated; postprocessing operations are minimized, as well as raw-material waste and human presence. These are considered key factors that will have a true impact in the industry of the future.

Due to 3D printing, industrial complexes now have the potential to increase their flexibility and adapt to the needs of a demanding and constantly evolving market. Also, it enables all kinds of customized items to be fabricated without the presence of traditional manufacturing tools like molds. Likewise, 3D printing has a minimum environmental impact, which is a desired characteristic considering in the context of Industry 4.0 due to the importance of utilizing sustainable manufacturing processes with low resources consumption [108].

In the last decade, 3D printing equipment has become more versatile in terms of exhibiting portability and wide variety of materials availability. Due to the expiration of relevant patents in the 2010s, the 3D printing market has expanded rapidly, offering desktop 3D printers at affordable prices for individual users and SMEs (small-medium-enterprises) [109]. 3D printing technologies like FDM, SLA, and SLS are now available at desktop sizes and in a user-friendly package. Also, the availability of offered raw materials has rapidly increased. Thermoplastics, resin, and metal raw materials can nowadays be used by the technology, making the fabrication of customized items with tailored properties a reality [110, 111]. Build size constraints, limited materials, postprocessing, inaccuracies in the design and build, and copyright infringement issues are the drawbacks of the 3D printing technology.

3.6. Augmented and Virtual Reality. Virtual reality (VR) is an artificially generated alternative reality, which primarily utilizes 3D images and sound and may use additional input and output devices. [112] VR attempts to convince the person the artificial reality is the actual reality with the user interacting with elements in a "virtual world" which is invisible to others except to the user herself.

One of the key applications for VR is simulations. VR simulations place the user in virtualized settings, surrounded by similar controls of vehicles and other equipment. The idea is to simulate the actual vehicle or equipment usage in a virtual world, allowing users to experience nearly exact situations without its dangers. These types of VR simulations require specialized equipment that sometimes have comparable size to the actual vehicles they mimic [112].

Nowadays, most VR applications will use equipment such as VR headsets. VR headsets are wearable technology which consist of the head-mounted helmets that provide 3D vision and surround-sound audio. The latest headsets will have gyroscopes and accelerometers to track the users head movement, creating a sense of immersion that blinds them from the outside world. Devices such as the Oculus Rift and Oculus Touch provide the user with the means to control, interact, and be immersed in a virtual world [113].

VR currently has many applications that include but are not limited to training, education, simulation, data collection, advanced remote control, social research, psychology research, and entertainment [114].

Virtual reality has evolved over the years by mixing other forms of interface technology such as touch screens to lead to what we can term as "mixed reality" (MR). In MR, the user can actually see a mix between virtual or artificial reality with the real world. This has led to the development of augmented reality. Augmented reality (AR) is a visualization technique that overlays visual artifacts, such as text, images, and other interactive media material, over a reality view acquired by a device's camera. [115]. AR systems work via image recognition that "look for target images." Once a target image is recognized, a virtual object is activated, and further virtual interaction can be conducted by the user. AR can be applied from mobile phones to specialized head mounted displays [116].

Current applications of AR include visualization of information, simulation, environmental interaction, communication, collaboration, and potentially more. Due to the high availability of mobile phones, AR technology has an incredible potential reach. It can be seen applied mainly in museums [117]. However, other points of information such as libraries and shopping centers have also started to utilize AR for various applications.

The delivery of information and a virtual experience that does not put the user at harm is one of the great advantages of utilizing VR, MR, and AR. Information is delivered while providing an immersive experience to simulate an actual situation. In today's world of IR 4.0, the delivery of such experience and information is essential as we move forward with the integration of the other aspects of IR4.0. "Augmented reality (AR) currently plays an important role in undertaking the challenges in integrating technologies to expedite the march towards Industrial Revolution 4.0 (IR 4.0)" [118].

Even though the previous statement focuses on AR, recent developments have also pointed to further growth for virtual reality and mixed reality in general. The development of "the Metaverse" provides a huge opportunity for further research and development for AR, VR, and MR on ways to experience this virtualized world [119]. A future where we may have a totally virtual universe to live our lives in alongside our current reality will require the development of the other supporting pillars and contribute heavily to the growth of Industrial Revolution 4.0. Motion sickness, ethical concerns, nausea, dizziness, and lack of privacy are some of the many disadvantages of the AR and VR technology [120].

3.7. Blockchain. The technology known as blockchain is a shared, distributed ledger (system of records), which is immutable, and quickly provable to contain authentic transactions between parties [121]. Anyone can participate as verifier of transactions, or "miner," where "mining" is incentivized with rewards that come in the form of the coins that belong to the network being mined. Bitcoin is the world's first and most popular cryptocurrency by market capitalization. Although early cryptocurrency networks were designed to be able to transfer information in the form of numbers between parties, recently, any type of information can be transmitted. Therefore, it is now possible to securely and immutably transfer images, video clips, documents, and any other forms of digital media. Several recent research works present blockchain as one of the technologies which enable and empower Industry 4.0 [122–125]. Blockchain can boost and normalize the process of data collection, decentralize the tremendous effort involved in examining and analyzing industrial data, and drive the most useful judgments and decisions based on the learning achieved from the aforementioned operations [126]. Production processes become very trackable, as every step can be documented on a block chain, and errors are easier to identify. With the aid of faster computation power, better intelligent machines, smaller sensors, and more affordable data storage, Industry 4.0 allows for efficient, adequate, individualized, and customized production at an affordable cost [127].

The wealth of a market is measured by the flow of the transactions in the market network. Via the ledger,

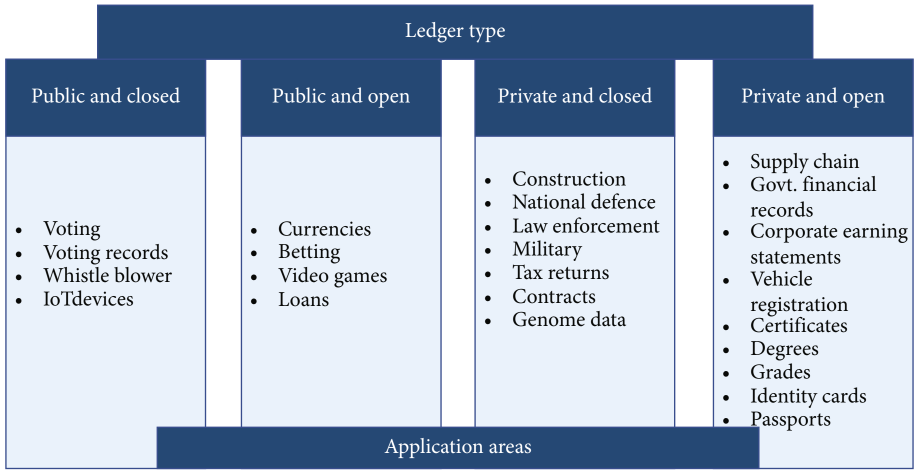

Figure 3: Ledger types and their application areas.

transaction information is attainable to all authorized participants; this feature creates trust, transparency, and a steady business relationship. IBM Food Trust is an example that demonstrates how blockchain is used to maintain quality control and inspect every step of the food production system [128].

Different types of applications can be built on top of the distributed ledger. The nature of the application determines whether a public or private ledger should be used. A clustering of ledger types against their corresponding applications [126] is shown in Figure 3.

Transactions can be very basic, where one party sends information to another party, or they can be more complex, and involve sets of rules that must be satisfied for an event to be triggered. More complex transactions involving rules are called smart contracts, which can be described as digital versions of legal contracts [129]. Applications for smart contracts can be found in decentralized finance and loans, crowd financing, and wills and testaments. Not being a distributed computing system, high energy consumption for its functioning, data being immutable, and not being completely secure are some of the disadvantages of blockchain technology [130].

4. Project Portfolio Management

Industry 4.0 describes a plethora of developments which are expected to lead to a new industrial revolution that is fundamentally characterized by digitalization. To this, technologies such as AI, IoT, nanotechnology, space, robotics, blockchain, cybersecurity, and other emerging domains have a great potential to empower project management.

The applications of AI can fundamentally change the way projects are realized; setting new frontiers for forthcoming future challenges for the modern society and humanity [131] argued that among the changes that Industry 4.0 brings, project managers are also required to adapt to new needs and expectations in an attempt to foster the development of new ubiquitous technologies.

These new technologies have urged industries to embrace a more versatile organizational capability of adopting more agile and hybrid practices [132], readapting their processes around customer-obsessed value delivery. In effect, this has an impact on overall enhanced customer experiences which impacts the organization's profitability sustainability and digital future footprint.

However, one of the greatest challenges in regard to the project management world is being able to deal with continuous and increasingly complex change(s) in an evolving global digital scene. Undoubtedly, AI can affect projects' design, development, structure, and execution, reshaping organizational digital capabilities.

For instance, the adaptation of an AI to project management, from planning to risk management, procurement, benefit realization (programs), collection, and information analysis achieves a more robust continuum of procedures, processes, and baselined policies. In turn, the application of actionable insights for future projects is useful, as it provides stakeholders with insights based on a range of data sources.

Moreover, AI can eliminate inconsistencies and complexity. Machines are not predisposed by psychological factors, socioeconomic greed, or grief such as bad days, subpar living standards, which are not tied to a family or relatives and are less, if at all, error prone. The whole picture is important to draw including, what, when, and how AI can give you that picture with real data analysis and optimize projects' performance with greater confidence.

The more digitally shaped an organization becomes, the greater the new value will be created in the economy. A proper and concise digital strategy in place can guide more businesses to modernize their digital capabilities, gaining a significant competitive advantage, and foster a business culture which focuses on the use of digital technologies leading to tangible and sustainable results [133].

Digital transformation as a key enabler for Industry 4.0 is rather notoriously difficult and complex, more so when linked to terms such as "digital disruption." The fundamental change brought to operations to deliver value faster, better, and safer to customers coupled by digital and technological advances at an organizational level is a challenge in itself. An approach to realize the benefits of a transformation requires commitment by both; the organization and individuals since the notion of one-sized-transformation-does-not-fit-all materializes rapidly.

Project managers and other key stakeholders need to realize that digital transformations are not purely technological ones rather part of the wider business transformation ecosystem; with culture becoming an instrumental pillar on the path to success. In other words, technology in Industry 4.0 acts as the tooling bandwagon to deliver on promised value. Therefore, technology can offer global businesses diversified potential to engage seamlessly and inclusively with others on the worldwide scene.

Overall, the use of AI in the project management domain can fundamentally change the way projects get delivered to achieve a common purpose. AI leverages the project data to drive strategic decisions with a greater understanding leading to better investments. This means delivering value to communities on the premise that the right type of work improves their experiences, at the right time and in the right way.

5. A Model Industry 4.0 Factory

The fourth industrial revolution differs from earlier ones in that it considers factories as cybersocio-physical systems. The physical system includes all the machinery, physical space, and physical resources. The social part includes all the people and processes. The cyberpart includes all computational parts such as AI and ML algorithms. Most Industry 4.0 technologies work across multiple levels of the cybersocio-technical stack, which includes human information systems and machines working together directly or via the Internet. To understand the impact of new technologies to Industry 4.0, we will introduce a model factory and give some examples of how the technologies introduced in this paper can maximize its potential. To that respect, consider a factory F, which requires resources $r1, r2, \cdots rn$ and produces a product p and subproducts sp1, sp2. Spm.

In order to successfully meet factory automation requirements, the concept of the IIoT can be applied in Industry 4.0 to get processes which are critical, robust, reliable, timely, and have close-to-zero latency. 5G networks will be applied to facilitate the operation of massive IoT deployments in order to deliver high bandwidth and reliability communications. The implementation of IIoT can positively affect the massive machine-type communication (mMTC) and ultra-reliable low-latency communication (URLLC).

Factory workers wearing wearables and automated technology, when used together, may assist businesses, and industries obtain data-driven visibility throughout the supply chain, increase productivity, and make the workplace safer. For example, using a smartwatch can allow workers to constantly monitor certain machines and receive messages or alerts on certain processes. Also, they can be called at any time if required.

ML and AI enables systems and algorithms to learn from their mistakes and improve over time. The model factory F is a digital factory that continuously monitors production and gathers data using smart devices, equipment, and systems. Advanced analytics are provided by this data collecting, enabling manufacturers to make more informed decisions.

It is possible for factory F to save money on health and safety expenditures by having fewer employees participate in potentially hazardous occupational activities, which will result in fewer accidents and less time off for their employees. Many robots require relatively little space to operate and may safely work alongside humans on production lines. The factory can downsize to cheaper workspaces as a result of the probable decrease in necessary space.

In the manufacturing industry, drones will be used for asset inspection, intracompany material and component movement, and inventory taking. Inspection and maintenance will be the most typical applications, as drones equipped with radar or laser scanners, infrared, or stereoscopic cameras can swiftly detect irregularities or issues in industrial equipment. It is especially important in areas like refinery, pipeline, quarries, and other major facilities, where human inspection is either unsafe or worthless due to limited access to all regions.

The existing mobile communication protocols of 2G, 3G, and 4G are being upgraded to 5G. The development of a mobile communications standard focusing on communications between sensors, devices, and machines in the IoT, as well as human digital connectivity, is referred to as 5G. With peak data transfer speeds of 20 Gbps, 5G is up to 20 times faster than 4G, can send data with a millisecond latency (essentially no delay), and is almost as reliable as cable data transfers, with up to 99.9999 percent dependability.

Additive manufacturing, in conjunction with other technologies, is promoting an evolution in the industry toward intelligent production, in which machines, systems, and networks can exchange information and respond to production management systems. 3D printing is important because it is a technology that can turn a 3D design into a product without the need for human intervention. Additionally, expensive tools and fittings are no longer necessary, resulting in reduced postprocessing, waste, and human involvement. Prototyping of new versions of product P and subproduct SP1, SP2, and SPn could also be done using 3D printing technology before production.

Manufacturing and quality control of all products and subproducts could be enhanced while reducing the cost using augmented reality. With the use of augmented reality, F could rely on cheaper junior workers in the assembly lines. The workers could wear augmented reality glasses that guide them on how to assemble P and SPs by understanding what the worker is doing and display the next step. Meanwhile, it could raise an alarm if something goes wrong. In that case, the worker could be connected with a more senior engineer who could also see what the work can see and support him with the help of visual artifacts.

Designers in the manufacturing industry can use virtual reality (VR) to replicate their design prototype or model. This enables them to correct faults at the first stage of manufacturing while also reducing production time and cost. This could be from a simple model of the production line to a digital twin that replicates the whole factory. That also allows the immersive training experiences for their staff, allowing them to practice real-world situations. Workers with demanding occupations may hone their talents away from the perils of the workplace. Because virtual reality is engaging and fascinating, learners acquire knowledge quickly and remember it longer. Virtual reality may assist in the creation of a shared virtual workplace that connects several individuals working on the same project. Users from all around the world will be able to view, visualize, and collaborate on the same virtual model. This may help coworkers communicate more effectively so that validation procedures can be completed without the need for a physical meeting.

Blockchain could aid the model factory by ensuring traceable provenance of all parts in the production and assembly lines. In its most basic form, blockchains can track the origins and final destinations of all parts in the manufacturing process, which will enable managers to easily identify products that contain a series of deficient parts from a particular production line.

Factory *F* includes many automations at different levels. Not only in the actual production but also at the management level. AI and ML can optimize the business processes, supply chain management, and even aid the marketing of the outputs. Automated rewards systems could be used to ensure fair benefits for the employees. That will enable the managers to reduce their micromanagement and focus more on macro and strategy levels, ensuring the long-term success of the organization.

A point that can be considered a drawback of factory *F* is that it will occupy significantly less people than a less-automated peer factory. The factory will require more highly skilled manpower but less workers overall.

6. Conclusion

Mechanical production based on water and steam power, mass labor and electrical energy, and electronic, automated manufacturing were the driving forces behind the first three industrial revolutions, correspondingly. The fourth industrial revolution ("Industry 4.0") is defined by its dependence on the usage of cyberphysical systems capable of communicating with one another and making autonomous, decentralized decisions in order to improve industrial efficiency, production, safety, and transparency. This is not the only technology that led to Industry 4.0. In this paper, we identified seven technology families that acted as the pillars of the fourth industrial revolution. IoT, AI and ML, robotics and drones, cellular wireless communications, 3D printing, virtual and augmented realities, and blockchain.

IoT is a network of devices with sensors, processing units, and other systems that have Internet connectivity. IoT is one of the essential pillars of the fourth industrial revolution due to its role in supporting the objective of digital transformation. AI and ML with the help of big data are able to make intelligent decisions at all production and management levels. Robots and drones are capable of performing simple to complex staff reliably, fast for a long period of time. Circular networks such as 5G and the soon to come 6G will offer high speed reliable connection to the Internet allowing the various devices to take advantage of high-performance remote resources from any lower power consumption device, anywhere within the coverage area. 3D printing can produce from prototypes to complex functional products. Augmented reality can enhance the reality of individuals with visual artifacts providing clues on the physical environment. This can enhance remote collaboration and reduce the need for physical presence. Virtual reality can also aid in many areas, such as training and remote control. Blockchain can reliably store information and trace the history of assets. The pillar technologies of Industry 4.0 are based on the advancements of computing, nanotechnology, biotechnology, materials, advancements in energy, and CubeSats. The paper used an imaginary Industry 4.0 model factory to show how all these technologies can be applied on a single production entity and their impact. The main drawback was that it can provide less jobs than a peer, less-automated factory.

The main limitation of this paper is that it only touched the surface of all the presented technologies and their applications. This was done, because the aim of this paper is to provide the readers with an understanding of all the technologies that compose the fourth industrial revolution. In the future, we plan to produce more focused papers that will discuss in more detail the impact and the risk of each of these technologies to the manufacturing process and the society.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Research Article

Healthcare Data Security Using IoT Sensors Based on Random Hashing Mechanism

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Providing security to the healthcare data stored in an IoT-cloud environment is one of the most challenging and demanding tasks in recent days. Because the IoT-cloud framework is constructed with an enormous number of sensors that are used to generate a massive amount of data, however, it is more susceptible to vulnerabilities and attacks, which degrades the security level of the network by performing malicious activities. Hence, Artificial Intelligence (AI) technology is the most suitable option for healthcare applications because it provides the best solution for improving the security and reliability of data. Due to this fact, various AI-based security mechanisms are implemented in the conventional works for the IoT-cloud framework. However, it faces significant problems of increased complexity in algorithm design, inefficient data handling, not being suitable for processing the unstructured data, increased cost of IoT sensors, and more time consumption. Therefore, this paper proposed an AI-based intelligent feature learning mechanism named Probabilistic Super Learning- (PSL-) Random Hashing (RH) for improving the security of healthcare data stored in IoT-cloud. Also, this paper is aimed at reducing the cost of IoT sensors by implementing the proposed learning model. Here, the training model has been maintained for detecting the attacks at the initial stage, where the properties of the reported attack are updated for learning the characteristics of attacks. In addition to that, the random key is generated based on the hash value of the data matrix, which is incorporated with the standard Elliptic Curve Cryptography (ECC) technique for data security. Then, the enhanced ECC-RH mechanism performs the data encryption and decryption processes with the generated random hash key. During performance evaluation, the results of both existing and proposed techniques are validated and compared using different performance indicators.

1. Introduction

Artificial Intelligence (AI) [1–3] is one of the modern and highly demanding technology used in many real-time application systems due to its enormous benefits of ensured security, ability to handle more complex data, reduced duplicates, and unknown threat identification [4, 5]. Also, the Internet of Things (IoT) [6, 7] is a kind of intelligent framework that helps to connect various sensors [8] and devices with the cloud for reliable data communication and transmission. The IoT applications have gained significant attention in many research fields with the benefits of increased efficiency and autonomous characteristics. In this system, the IoT device [9] can use various sensors to gather the data from the environment and transfer it to the connected devices, which passes the information to the cloud through wireless links. However, this process faces many security challenges [10, 11] by the vulnerabilities and harmful attacks against the network. Hence, security is one of the major concerns that need to be resolved in the cloud-IoT environment [12] to preserve confidential information's trustworthiness. In recent days, increasing the security of healthcare systems is highly demanded to protect the users' private and confidential information. For this type of application, AI technology is more suitable for improving the security of healthcare applications deployed in an IoT-cloud environment. Typically, there are different types of AI techniques that have been used in many application systems, which come under the categories of rule-based methodologies, machine learning techniques, and deep learning models. The general illustration of various AI techniques with their types is represented in Figure 1.

1.1. Motivation and Incitement. This research work intends to develop an intelligent AI-based feature learning methodology for predicting attacks in an earlier stage by training the features of the user data. Moreover, the random hash key is generated and incorporated with the ECC methodology for data encryption and decryption processes.

1.2. Research Gap. The conventional works developed different encryption and classification methodologies [13, 14] to ensure secure data storage and retrieval in the IoT-cloud domain. Generally, the encryption techniques [15] like Advanced Encryption Standard (AES) [16], Rivest Shamir Adleman (RSA), SHA-512, and Elliptic Curve Cryptography (ECC) have been widely used in many data security systems [17]. Moreover, it helps decrypt the raw data before storage and retrieval processes with guaranteed security [18]. Still, it faces the major problems of increased time consumption, high computational complexity, and slow processing at the time of key generation and authentication. Also, the classification methodologies [19–21] limit the issues of high error rate, inefficient prediction results, and delay in the process, which degrades the performance of the entire security system. In order to solve these problems, the proposed work is aimed at developing an intelligent security scheme based on AI technology for healthcare systems.

1.3. Contribution and Organization. The major contributions of this paper are as follows:

(i) To ensure the security of healthcare data stored in IoT-cloud, the Random Hashing (RH) technique is developed for generating the random keys used for data encryption and decryption

(ii) To establish the secured data transmission from IoT to cloud based on the user query input processing

(iii) To guarantee the secured data retrieval with attack detection and feature learning models, an Artificial Intelligence- (AI-) based Probabilistic Super Learning (PSL) mechanism is implemented

To assess the performance of the proposed PSL-RH technique, various evaluation metrics have been considered. Such as accuracy, precision, recall, key generation time, encryption time, and decryption time. The remaining portions of this paper are segregated as follows: the existing techniques used for data security and attack classification in cloud-IoT domain are reviewed with their advantages and disadvantages in Section 2. The detailed description of the proposed methodology is presented with its clear flow and algorithmic illustrations in Section 3. The performance analysis of existing and proposed data security mechanisms is validated and compared based on various performance measures in Section 4. Finally, the overall paper is summarized with its future scope in Section 5.

2. Related Works

This section discusses some conventional security mechanisms related to AI-based security schemes for IoT systems. Also, it investigates the advantages and disadvantages of each technique based on its working operations and characteristics.

Ghazal [22] developed an IoT framework incorporated with an AI system to ensure healthcare applications' security. The main aim of this paper was to safeguard the privacy and security of patients' data stored on the internet. For this purpose, the Deep Neural Network- (DNN-) based malware detection mechanism was deployed. This helps restrict the authenticated access to the cloud data to avoid unauthorized/malware activities. Also, the key authentication was performed based on the parameters of specific weight and bias values. In order to detect the malware and secure the recognized information, the sigmoid function has been estimated for training the set of extracted features. The key benefits of this work were reduced response time, increased delivery of packets, and minimal delay. Valanarasu [23] constructed a smart and secured IoT framework to increase the hospital environment's security. Here, some of the key policies and regulations of AI technique could be integrated with this framework, including accountability, transparency, data privacy, security, interoperability, and sustainability. Also, it is aimed at detecting the different types of attacks based on the host properties, information disruptions, and network properties. However, this framework does not utilize any specific methodologies for detecting the attacks on the network, which degrades the entire system's performance. Greco et al. [24] investigated the recent trends of IoT-AI systems to develop smart healthcare systems. Here, the three-tier architecture was constructed for designing the Internet of Medical Things (IoMT) systems by incorporating the functionalities of WBSN, field sensor networks, and cloud services.

Bharadwaj et al. [25] conducted a detailed study on various machine learning techniques used for the healthcare IoT (HIoT) systems, where the applications and constraints of each technique have been discussed. This work stated that the parameters like interoperability, reliability, bounded latency, privacy, and security must be satisfied for developing an efficient and secured IoT framework. Here, the different types of similarity matching techniques such as linear regression, logistic regression, K-means, discriminant analysis, and dimensionality reduction methods have been discussed with their operating functions. Based on this study, it is observed that the linear regression model is one of the suitable techniques for estimating the relationship between the dependent/independent variables. Zaman et al.

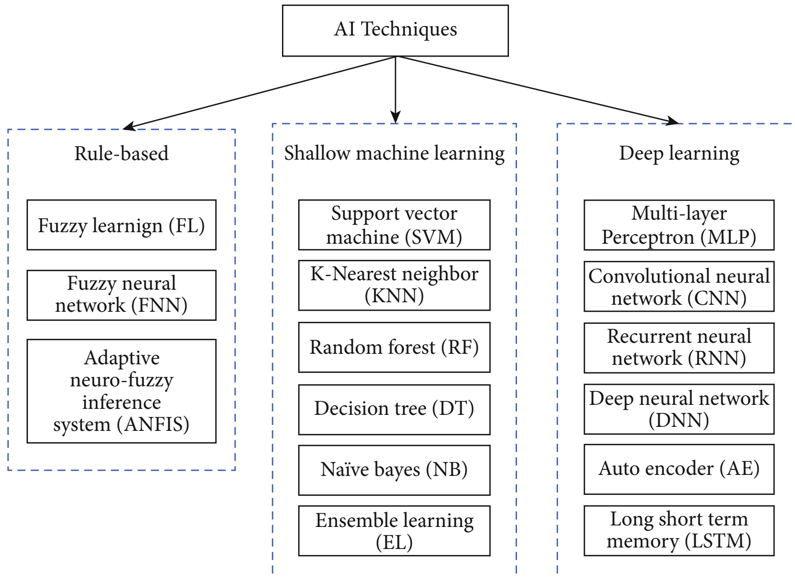

Figure 1: Various AI mechanisms used for security.

[26] presented a comprehensive survey related to various AI mechanisms used to improve IoT networks' security. This paper also discussed the major security challenges that exist in the IoT networks, which include the factors of confidentiality, availability, and source authentication. Amin et al. [27] designed a lightweight authentication protocol to increase IoT-enabled devices' security in the cloud environment. This work includes the processes of user/server registration and authentication. The motive of this system was to authenticate the users for providing access to the confidential information stored on the private cloud. The advantages of this framework were reduced computational and storage cost consumption. Nevertheless, it does not provide an optimal performance outcome regarding high reliability, attack detection, and misclassification rate.

Choi and Choi [28] developed an IoT-cloud security framework by using the context ontology model for identifying the system vulnerabilities. The key motive of this paper was to accurately detect the system intrusions and device vulnerabilities across the IoT-cloud environment by deploying an efficient security mechanism. In this model, the inference rules have been generated based on the pattern of attacks such as data sniffing, memory dump, software attack, and port access. However, this model is more complex for understanding, which requires categorizing the vulnerabilities based on the inference rules. Shen et al. [29] employed an efficient privacy preservation mechanism to ensure the IoT-cloud environment's security. Here, an integrated bilinear map and homomorphic encryption methodologies have been utilized for encrypting the data into an unknown format. Mo [30] suggested a secured data storage method by using an enhanced Ant Colony Optimization (ACO) technique. This paper mainly considers improving the load balancing strategy with optimized completion time for securely storing the data on the cloud. Here, the full-homomorphic encryption and reencryption mechanisms were deployed to store the data on the IoT-cloud in an encrypted format. In [31], the Advanced Encryption Standard (AES) mechanism was utilized to store healthcare data in an IoT-cloud environment securely. This type of encryption model generates the secret key for generating the ciphertext with multiple transformation rounds. The overall quality of this security system has been assessed based on the parameters of accuracy, latency, consistency, and QoS.

Riad et al. [32] implemented a Sensitive and Energetic Access Control (SE-AC) mechanism for improving the security of Electronic Health Records (EHRs) stored in an IoT-cloud environment. The main motive of this paper was to ensure both the privacy and confidentiality of the healthcare data by using the fine-grained access control mechanism. In order to validate the effectiveness of this mechanism, the encryption time, decryption time, storage overhead, and token generation time have been estimated. Guan et al. [33] investigated the data security and privacy issues in cloud computing and fog computing. Here, the major requirements of secured data storage have been discussed, including integrity verification, dynamic support, reduced overhead, access efficiency, authorization, and fine-grained access control. Zhu et al. [34] deployed a new cyber security framework for guaranteeing the privacy and security of healthcare systems. The main aim of this paper was to reduce the computational overhead of the security framework with the use of a machine learning approach. Kalyani and Chaudhari [35] employed an Optimal Homomorphic Encryption (OHE) scheme for increasing the sensitivity of data stored in an IoT environment. Here, the Deep Neural Network (DNN) technique was used for classifying the attack based on the optimal features. In addition to that, the Step Size Firefly (SSFF) optimization technique was also utilized for authenticating the key during the data encryption. Zaman et al. [26] presented a taxonomy of various AI-based security mechanisms used for IoT networks. The layer-wise security threats have been discussed with their attacking activities. The different types of AI technologies investigated in this paper were rule-based machine learning, deep learning, and shallow machine learning. Table 1 presents the review on various AI models used for improving the healthcare IoT data security systems.

Based on this study, it is analyzed that the AI and machine learning techniques are widely used for guaranteeing the countermeasures of IoT threats. These techniques have the ability to self-routine the operations that helps to increase the overall performance of the security system. Still, it limits with major challenges of overfitting problems, handling difficulties in large dimensional data, increased time delay, and data scarcity. In order to resolve these problems, the proposed work is aimed at developing an advanced AI-based security mechanism for enabling the secure data storage and retrieval of healthcare systems.

3. Proposed Methodology

This section presents a detailed description of the proposed methodology with its clear algorithmic and flow illustrations. The main motive of this paper is to securely store and retrieve the data from the IoT-cloud system by implementing an advanced AI technique, where the healthcare-based application system is considered. The original contribution of this work is that the proposed framework utilizes the AI-based Probabilistic Super Learning (PSL) model for efficiently managing the secure data transmission by identifying the properties/features of the data obtained from the IoT devices. The PSL technique is aimed at identifying both the normal and attacking activities with the updated set of features. Also, the PSL technique developed based on the AI model improves feature learning by updating the properties and characteristics of the attacks at each instant. In addition to that, the Random Hashing (RH) technique is utilized in the Elliptic Curve Cryptography (ECC) model for performing the data encryption and decryption processes, which guarantees the data security of both storage and retrieval.

The overall architecture and flow of the proposed AI-based security system are shown in Figures 1 and 2, respectively, which comprise the following stages:

(1) Data transmission from IoT to cloud

(2) User query input processing

(3) Attack detection and feature learning

(4) Secured data retrieval from cloud to user

At first, the users' sensor data has been obtained and encrypted before storing it into the cloud using the proposed RH technique. It is mainly used to encrypt and decrypt the original data based on forming a hash key generation matrix. Then, the AI security mechanism is applied to check whether the data is normal or attacked. Suppose it is identified as the normal flow. In that case, the data arrangement process is performed for storing the data in the cloud. If it is identified as an attack, it can be automatically reported to the firewall or routing system to block the attacks at the initial stage of processing.

Consequently, the training model has been updated with the help of PSL methodology, which updates the properties of the reported attack and arranges the features according to that. Here, the attacking classification is performed based on the updated properties/features of the data maintained in the training model. The user can enter the input query to access the required data during the query input processing. The AI-PSL methodology is used to validate whether the user is normal or an attacker based on the set of updated properties of the trained model. If the user is normal, the query request has been passed to the cloud storage, which provides the retrieved data in the decrypted format. Here, the RH-based decryption process is applied to decrypt the original information by generating the signature matching pattern. At last, the decrypted data has been displayed to the user with ensured privacy and security measures.

3.1. Data Security Using ECC-Based Random Hashing Technique. In this stage, the original data was initially encrypted before storing it into the IoT cloud using the RH technique. In many security application systems, ensuring data security is one of the demanding and challenging processes due to the large volume of data and complex formatting in feature arrangement. Typically, data security has been defined by the processes of secured data storage before encryption and data retrieval after decryption with the proper authentication for accessing the data. For this purpose, there are different types of data encryption, and decryption standards are developed in the conventional works, including AES, DES, RS4, and some other models. However, it has the significant disadvantages of increased time consumption for key generation and encryption, complexity implementation, and computational overhead. Hence, this paper utilized an Elliptic Curve Cryptography-(ECC-) based encryption mechanism [36] with the novel RH key generation technique. This ECC-RH is used to ensure data security based on the encryption and decryption processes. The ECC is one of the widely used encryption standards for increasing the data security of both IoT-cloud domains. In the proposed scheme, the key generation process of the existing ECC technique has been updated with the RH technique. Based on the input data stream with the hash value, the random key has been generated in this model, which is used for encrypting and decrypting the cloud data. The major advantages of using the random hashing-based ECC technique are as follows: the generated keys are small in size, fast encryption and decryption, reduced time consumption, and optimal bandwidth usage. However, it follows some composite computations for generating the hash function in order to ensure the increased level of security.

Initially, it takes the data streams I_n as input and produced the random key points R_V as output, which is used for data encryption and decryption. Here, the weight parameters w and temporary matrix q are initialized at first that are used for generating the hash key matrix. After that, the sequence of parameters such as S_1 and S_2 are updated with respect to each counter iteration as shown in the following:

Table 1: Review on existing models.

Authors and references	Method	Description	Advantages/disadvantages
Ghazal [22]	Deep Neural Network-(DNN-) based AI model	This work objects to improve the privacy and security of patients' data stored on cloud systems by using the AI-incorporated IoT framework.	Advantages: (1) Requires minimal response time (2) Increased delivery of packets (3) Reduced delay Disadvantages: (1) Computational complexity (2) Misclassified predictions
Valanarasu [23]	Smart and secured IoT framework using the AI model	The purpose of this paper is to detect the different types of attacks based on the host properties, information disruptions, and network properties.	Advantages: (1) Simple design (2) Minimal cost consumption Disadvantages: (1) It does not have any specific methodologies for attack detection (2) Increased error outputs
Bharadwaj et al. [25]	Healthcare IoT (HIoT) systems	It presented a comprehensive survey on various similarity matching techniques for securing healthcare data using IoT systems.	Advantages: (1) Ensured data privacy and security (2) Optimal performance Disadvantages: (1) Training model of features requires more time consumption
Zaman et al. [26]	AI model in IoT security	In this paper, a comprehensive review is presented related to various AI models used for IoT security systems.	Advantages: (1) AI models provide accurate prediction results (2) Efficient learning and training Disadvantages: (1) Deep learning models follow complex operating steps
Amin et al. [27]	Light weight authentication protocol for IoT security	This paper developed a light weight authentication mechanism for increasing the security of IoT-cloud systems with the help of the AI model.	Advantages: (1) Minimal computational and storage cost consumption (2) High efficiency Disadvantages: (1) Reduced reliability (2) Increased misclassification results
Riad et al. [32]	Sensitive and Energetic Access Control (SE-AC) mechanism	Here, the SE-AC mechanism is mainly developed for improving the security of Electronic Health Records (EHRs) stored in an IoT-cloud environment.	Advantages: (1) Reduced encryption and decryption time (2) Minimal storage overhead Disadvantages: (1) Increased token generation time (2) It does not have the ability to handle large dimensional data
Kalyani and Chaudhari [35]	Optimal Homomorphic Encryption (OHE) scheme	This paper utilized the OHE-DNN model for classifying the attack based on the optimal features.	Advantages: (1) Better convergence speed (2) Highly efficient Disadvantages: (1) More time consumption (2) Increased storage overhead

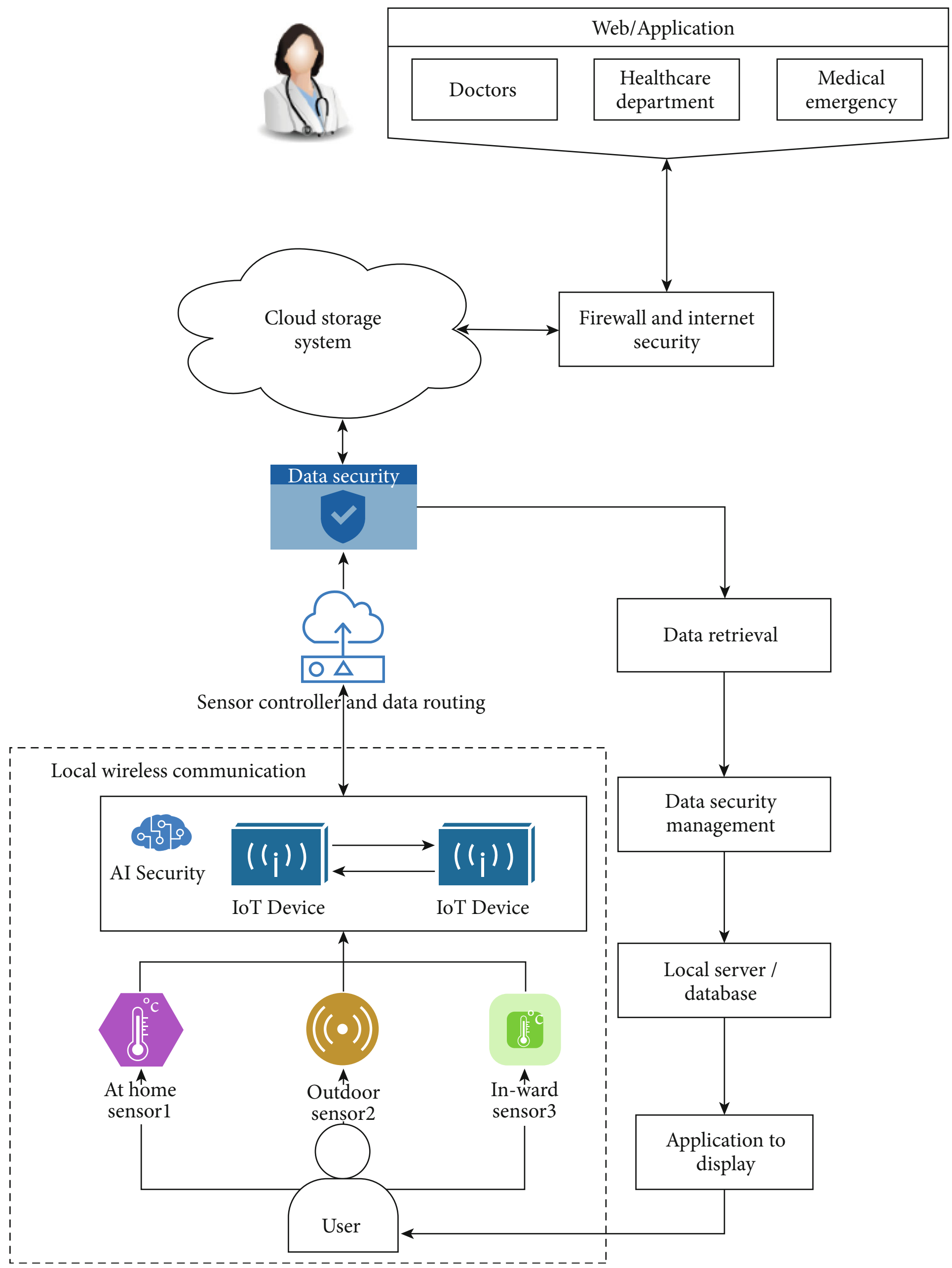

Figure 2: Architecture model of the proposed AI-based healthcare data security scheme in IoT-cloud.

$$S_1 = h_q(m) + (\mathrm{XOR}(A, B, C)) + (\mathrm{XOR}(D, E, F)) + w + k + ch + m, \quad (1)$$

$$S_2 = h_q(4) + h_q(m) + (\mathrm{XOR}(D, E, F)) + w + k + ch, \quad (2)$$

where $A = \{q[1][1:0], q[1][32:2]\}$, $B = \{q[1][12:0], q[1][31:13]\}$, $C = \{q[1][21:0], q[1][31:22]\}$, $D = \{q[5][5:0], q[1][31:6]\}$, $E = \{q[5][10:0], q[1][31:11]\}$, and $F = \{q[5][24:0], q[1][31:25]\}$.

Then, the signature pattern $h_q(x)$ is computed from the generated matrix as shown in the following:

$$h_q(x) = \begin{cases} h_q(x-1), & \forall x = \{2, 3, \cdots m-1\}, \\ S_1, & \text{if } (x == 1), \\ S_2, & \text{if } (x == 5). \end{cases} \quad (3)$$

Consequently, the count has been updated with respect to the size of matrix, and the estimated patterns are represented as follows:

$$ch = \mathrm{XOR}(\mathrm{AND}(q[5], q[6]), \mathrm{AND}(\mathrm{NOT}(q[5]), q[7])), \quad (4)$$

Input: Input data streams, I_n
Output: Random key points, R_V
Step 1: Initialize weight parameter as "w"
Step 2: Initialize the temporary matrix "q" as
$q' = \{q1, q2, \cdots qn\}$
Step 3: From this "q'" matrix, the sequence S_1 and S_2 parameters are updated and arranged for each counter iteration as represented in equations (1) and (2)
Step 4: Estimate the signature pattern $h_q(x)$ from the matrix by using equation (3)
Step 5: **For** $x = 2$ to $m - 1$ **loop**//loop run for 2 to "$m - 1$" size of "q'" matrix.
Update counter as counter ++.
Estimate the pattern such as ch and mj by using equations (4) and (5);
Update S_1 and S_2 for each counter update;
End loop "x"
Step 6: This cross computing generates the random key R_V for the memory storage which can be represented as represented in equation (6)

Algorithm 1: Data security using RH generation.

$$mj = \text{XOR}(\text{XOR}(\text{AND}(q[1], q[2]), \text{AND}(q[1], q[3])), \text{AND}(q[2], q[3])). \tag{5}$$

Based on this cross computing, the random key R_V is generated for storing and retrieving the data in cloud that is illustrated in the form of

$$R_V = h_q(\text{counter}). \tag{6}$$

The detailed algorithmic procedure of the random hash key generation process is illustrated in Algorithm 1 as follows:

3.2. PSL Algorithm. In this stage, the feature learning technique is mainly used for detecting the attacks by training the model based on the features of the matrix. The proposed PSL methodology extracts features from the IoT device. It is updated in the training data model with the categories of normal and attacking features. The PSL is developed as the feature learning model for matching the feature attributes with the database for spotting the attacks. The IoT device features are matched with this training model for identifying whether any attacking devices could try to access the data stored in the cloud during the data storage and retrieval process. If the access is legitimate, the normal flow of operations like data storage and retrieval has been performed automatically. If it is identified as an attack, it can be automatically reported to the firewall/routing device that blocks the access at the initial stage. Also, the features and characteristics of this attack are learned and updated with the available training model; then, the overall features of the training model have been entirely updated and arranged to the new attacking features. This trained model can be further used for the consequent data storage and retrieval processes for identifying and blocking the attacks. Hence, this type of AI-based feature learning helps enhance the system's security with accurate detection of attacks. Also, the AI-based attack learning process is carried out in this research based on the parameters of probabilistic distributional features. It identifies the multiple combinations of parameters for grouping and forming it to the cluster, ensuring a better prediction process. The PSL mechanism's key benefits are increased detection accuracy, ensuring data privacy, high security, minimal time consumption, and reduced computational complexity. These advantages are attained by performing AI-based feature learning with probabilistic features. The typical architecture of the PSL methodology with its matrix construction is depicted in Figure 3.

In this algorithm, the input data matrix M_{NID} is taken as the input for processing, and the predicted clustered results A_{ij}, R_{ij}, and C_{id} are produced as the output. Here, the availability and responsibility matrices are constructed at first with respect to the size of matrices S_i and S_j. Based on this, the initial clustering of data A_{ij} has been computed as shown in the following:

$$A_{ij} = \begin{cases} 0.5, & \text{if}\left(M_{\text{NID}}(i, j) \leq 0.5\right), \\ 0, & \text{otherwise}. \end{cases} \tag{7}$$

Consequently, the responsibility and availability matrices are constructed for computing the relevant vector R_{ij} as represented as follows:

$$R_{ij} = \left\{ \begin{matrix} M_{\text{NID}}(i, j) - A_{ij}, & \text{if}\left(A_{ij} \leq M_{\text{NID}}(i, j)\right) \\ 0, & \text{otherwise} \end{matrix} \right\}. \tag{8}$$

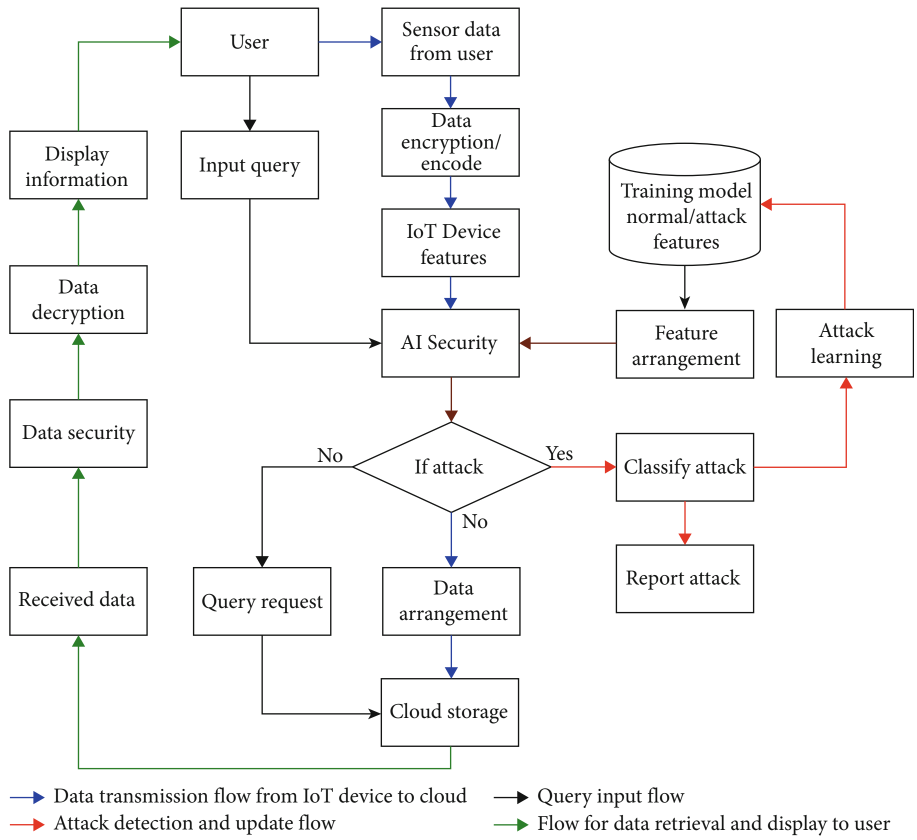

FIGURE 3: Overall flow of the proposed security system.

Then, the temporary matrix of R_{ij} is estimated and updated with the availability matrix, which is illustrated as follows:

$$\text{temp}_{Rij} = \begin{cases} \text{temp}_{Rij} + R_{ij}, & \text{if}\left(\text{temp}_{Rij} \leq 0\right), \\ R_{ij}, & \text{otherwise}, \end{cases} \tag{9}$$

$$A_{ij} = \begin{cases} 0, & \text{if}\left(\text{temp}_{Rij} < 0\right), \\ \text{temp}_{Rij}, & \text{otherwise}, \end{cases} \tag{10}$$

$$A_{ij} = \begin{cases} \text{temp}_{Rij}, & \text{if}\left(\text{temp}_{Rij} > 0\right), \\ 0, & \text{otherwise}. \end{cases} \tag{11}$$

Consequently, the exponential matrix is formed with the average of relevant vector based on the estimated list index, which is further updated in the list as shown in the following:

$$\text{Exp}m_{ij} = \begin{cases} 1, & \text{if}\left(A_{ij} + R_{ij}\right) > 0, \\ 0, & \text{otherwise}, \end{cases} \tag{12}$$

$$\text{avg}_{\text{idx}} = \frac{1}{x} \sum_{x=1}^{\text{size}(\text{Idx}_{\text{ls}})} R_{i(\text{Idx}_x)}, \tag{13}$$

$$\text{avg}_{\text{list}} \longleftarrow \text{avg}_{\text{idx}}. \tag{14}$$

Then, the related average avg_R of overall vector is computed by using the following model:

$$\text{avg}_R = \frac{\sum_{j=1}^{S_j} R_{ij}}{S_j}. \tag{15}$$

Moreover, the distance is estimated between the average lists and its related parameter is updated as shown in the following:

$$\text{dis}_{ls} = \sqrt{\text{avg}_{\text{List}}^2 - \left(\text{avg}_R{}^2\right)}, \tag{16}$$

$$\text{Update } C_{id} \longleftarrow \min\left(\text{dis}_{\text{ls}}\right). \tag{17}$$

Then, the clustered outputs are used to predict the classified L based on the minimum distance of parameters with relevancy levels. If the predicted clustered label is an attack, it is automatically blocked by the firewall, and the feature learning is carried out with the update of attacking features in the training model. Then, the updated model is further used for classifying the attacks for ensuring both the secure data storage and retrieval processes. Figure 4 shows the architecture model of the proposed PSL methodology.

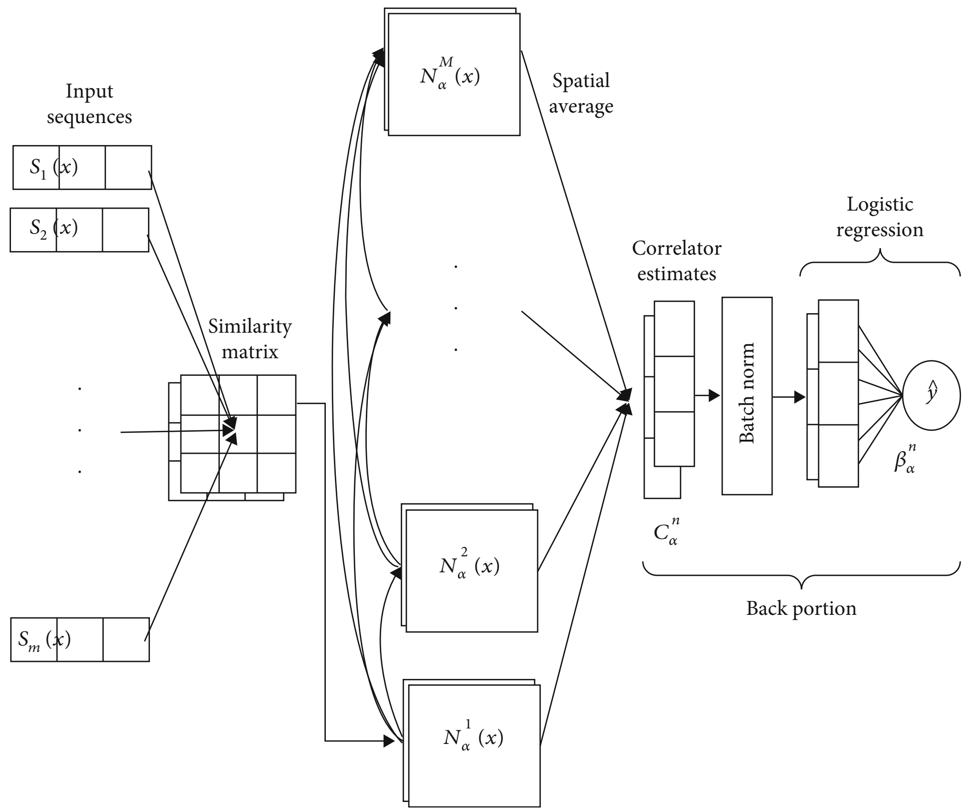

Figure 4: Architecture model of PSL methodology.

The detailed algorithmic steps involved in the proposed PSL-based feature learning model are illustrated in Algorithm 2 as follows:

4. Results and Discussion

This section evaluates the performance and comparative results of both existing and proposed security techniques based on accuracy, precision, recall, F1-score, Matthews Correlation Coefficient (MCC), encryption time, decryption time, delay, throughput, packet delivery rate, and computational time.

4.1. Performance Analysis of Existing and Proposed AI Mechanisms. Figure 5 and Table 2 depict the throughput rate of both existing [22] and proposed AI security mechanisms for various IoT devices. Typically, the system's output can be assessed in terms of bytes. The network's output depends highly on the transmission rate of connected devices. Then, the throughput is calculated based on the ratio of the total number of messages created by all nodes of a network and the total number of messages that are successfully received. Here, the existing Securing Things in the Healthcare Internet (ST-HIoT), Intrusion Detection System (IDS), Intelligent Face Recognition and Navigation System (IFR-NS), and Internet of Things-Artificial Intelligence System (IoT-AIS). Based on the results, it is observed that the proposed PSL-RH technique outperforms the other techniques with increased throughput value because the proposed framework enables reliable data transmission between the users and devices by accurately detecting the attacks based on the set of features.

Figure 6 and Table 3 show the delay of existing and proposed techniques with respect to a varying number of IoT devices. Typically, the delay of the network is estimated based on the maximum amount of time required by the data to reach its destination ultimately, and the data rate amounts to the maximum flows are segregated based on the delay. It is also defined by the term of latency between the request sent by the user and the response provided by the cloud server. From the analysis, it is proved that the proposed PSL-RH techniques consume minimum delay when compared to the other techniques. Because, in the proposed system, the users' input query has been processed by checking the features of the request at the initial stage based on the training model. So, it helps to reduce the delay of input query transmission and data retrieval processes.

Figure 7 and Table 4 depict the transmission rate of existing IoT-AIS and proposed PSL-RH techniques with respect to various devices. Here, the data transmission rate is assessed between the flow of data from IoT device to cloud and retrieved data from the cloud to user with effective attack detection. Compared to the existing model, the proposed PSL-RH technique attained an increased data transmission rate with high security. Due to the maintenance of the trained feature model, the attacks are identified and blocked at the initial stage, which helps to improve the data transmission rate of the proposed system. Figure 8

Input: Input data matrix [IoT sensor matrix (M_{NID})]
Output: Predicted cluster output A_{ij}, R_{ij}, and C_{id} and classified Label L
Step 1: Construct availability and responsibility matrices;
Let consider, S_i and S_j be the size of matrix (M_{NID})
And set $K = 2$;
Where NID – Node ID
For $i = 1$ to S_i
For $j = 1$ to S_j
Compute the initial clustering of data A_{ij} by using Equation (7);
End for j;
End for i;
Step 2: Construct and update the responsibility and availability matrices;
For $X_k = 1$ to k
For $i = 1$ to S_i
For $j = 1$ to S_j
Compute the relevant vector R_{ij} by using equation (8);
End for j
End for i
For $i = 1$ to S_i
For $j = 1$ to S_j
Let $\text{temp}_{R_{ij}} = 0$;
For $m = 1$ to S_i
$\text{temp}_{R_{ij}} = \text{temp}_{R_{ij}} + R_{im}$;
End for m;
Compute $\text{temp}_{R_{ij}}$ by using equation (9);
If $(i! = j)$, then
Estimate A_{ij} by using equation (10);
Else
Estimate A_{ij} by using equation (11);
End if
End for S_j
End for S_i
End for X_k
Step 3: Compute exponential matrix $\text{Exp}m_{ij}$ and the average A_{ij} of relevant vector R_{ij} based on the estimated list index avg_{idx} and update avg_{list} in the list by using equations (12) to (14);
For $y = 1$ to S_j
Compute the related average of overall vector avg_R by using equation (15);
Compute the distance list dis_{ls} between the average list $\text{avg}^2_{\text{List}}$ and the related parameter $\text{avg}_R{}^2$ by using equation (16);
Update C_{id} with the minimum of dis_{ls} as shown in equation (17);
End for y;

Algorithm 2: Continued.

Step 4: The classified label has been predicted based on the minimum distance of A_{ij}, R_{ij}, and C_{id} of these matrices, as
shown below:
$L = \min\,(A_{ij}, R_{ij}, C_{id})$
If (the predicted label L is normal)
Normal flow of data transmission can be enabled;
Else if (attack)
It can be automatically blocked by the firewall;
The learning features of attacks with its characteristics are updated in the training model as shown below:
$\text{UF} = \text{append}(A_F)$; //AF–attacking features in the trained model;
End if;

Algorithm 2: PSL-based feature learning.

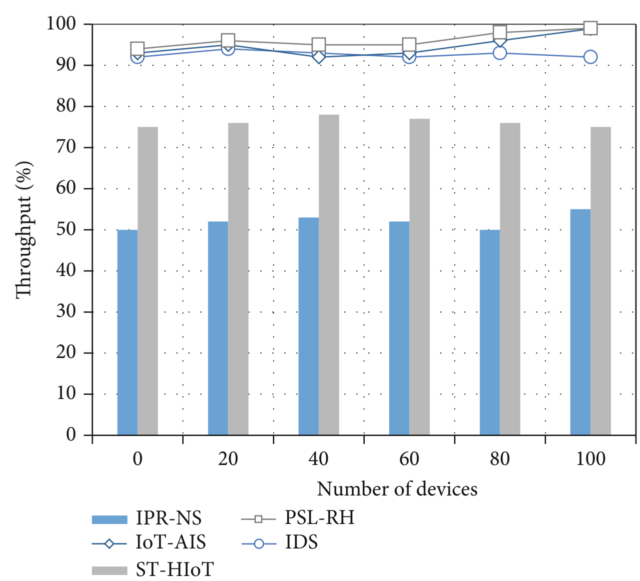

Figure 5: Throughput vs. number of devices.

Table 2: Throughput analysis of existing and proposed techniques.

Number of devices	IPR-NS	ST-HIoT	IDS	IoT-AIS	PSL-RH
0	50	75	92	93	94
20	52	76	94	95	96
40	53	78	93	92	95
60	52	77	92	93	95
80	50	76	93	96	98
100	55	75	92	98.9	99

and Table 5 compare the energy utilization level of both existing and proposed security mechanisms with respect to various devices. The energy usage of the network is assessed based on the communication delay of the IoT devices. These results also state that the proposed scheme requires minimal energy consumption when compared to the other technique.

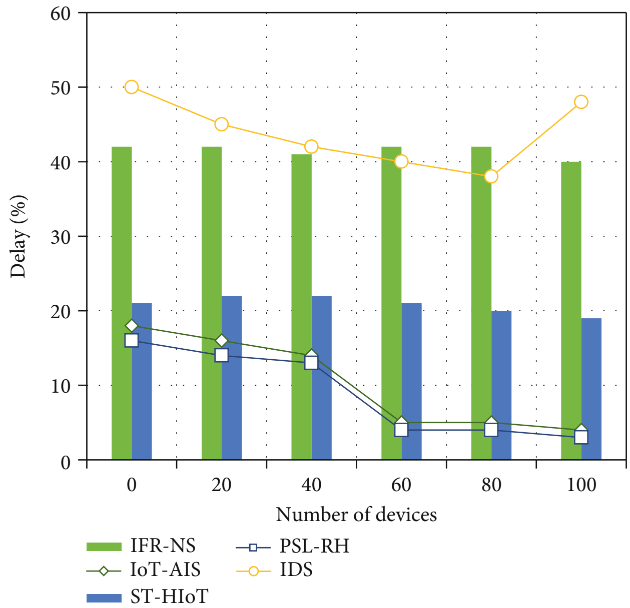

Figure 6: Delay vs. number of devices.

Table 3: Delay of existing and proposed techniques.

Number of devices	IFR-NS	ST-HIoT	IDS	IoT-AIS	PSL-RH
0	42	21	50	18	16
20	42	22	45	16	14
40	41	22	42	14	13
60	42	21	40	5	4
80	42	20	38	5	4
100	40	19	48	4	3

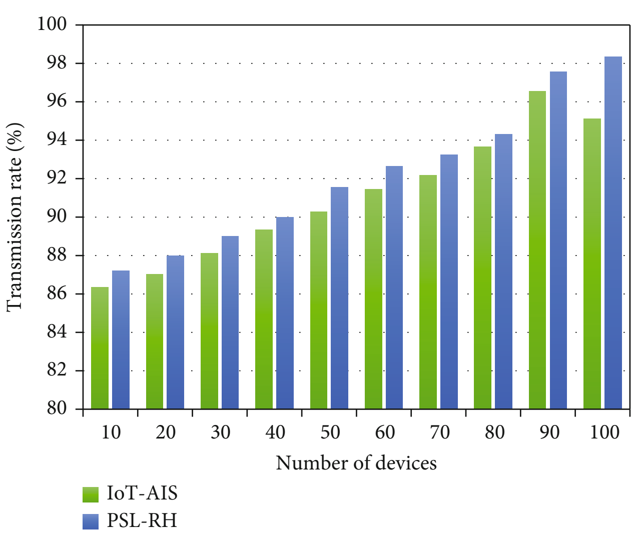

Figure 7: Transmission rate vs. number of devices.

Table 4: Transmission rate of existing and proposed techniques.

Number of devices	IoT-AIS	PSL-RH
10	86.34	87.21
20	87.02	88
30	88.13	89
40	89.33	90
50	90.27	91.56
60	91.45	92.64
70	92.18	93.25
80	93.67	94.31
90	96.56	97.56
100	95.11	98.35

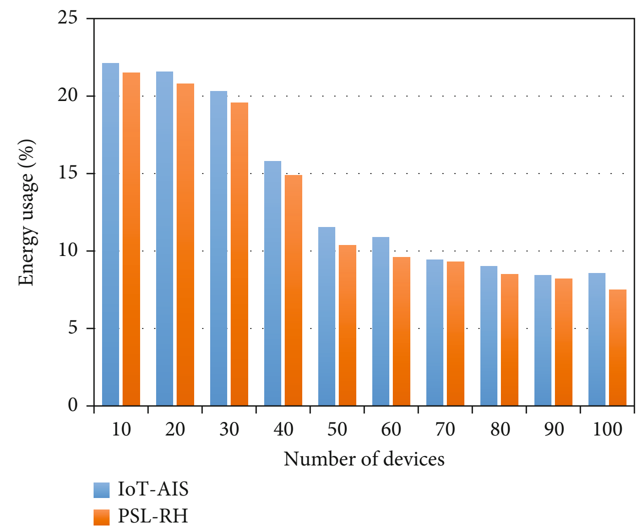

Figure 8: Energy usage vs. number of devices.

Table 5: Analysis of energy usage between existing and proposed techniques.

Number of devices	IoT-AIS	PSL-RH
10	22.11	21.5
20	21.56	20.8
30	20.32	19.56
40	15.78	14.9
50	11.52	10.36
60	10.89	9.6
70	9.45	9.32
80	9.02	8.5
90	8.44	8.2
100	8.56	7.5

Figure 9 and Table 6 compare the overall performance analysis of existing [37] and proposed attack detection techniques based on the measures of accuracy, precision, recall, F1-score, and MCC. Typically, the efficiency of the overall security system highly depends on the measures of accuracy, precision, and recall. Moreover, these measures are mainly computed to determine how the security scheme could actually predict the accurate values at the time of attack identification and prediction, which are calculated as follows:

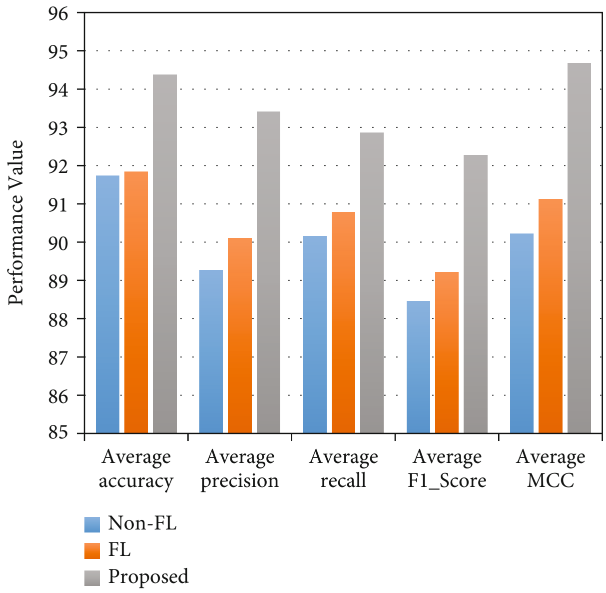

FIGURE 9: Overall comparative analysis of the existing and proposed techniques.

TABLE 6: Accuracy, precision, recall, F1-score, and MCC analysis.

Parameters	Methods: Nonfederated learning (non-FL)	Federated learning (FL)	PSL-RH
Average accuracy	91.73	91.846	94.377
Average precision	89.27	90.1	93.408
Average recall	90.15	90.785	92.861
Average F1_ score	88.46	89.207	92.274
Average MCC	90.22	91.127	94.672

$$\text{Accuracy} = \frac{\text{TP} + \text{TN}}{\text{TP} + \text{TN} + \text{FP} + \text{FN}}, \quad (18)$$

$$\text{Precision} = \frac{\text{TP}}{\text{TP} + \text{FP}}, \quad (19)$$

$$\text{Precision} = \frac{\text{TP}}{\text{TP} + \text{FN}}, \quad (20)$$

$$\text{F1-score} = \frac{2\text{TP}}{2\text{TP} + \text{FP} + \text{FN}}, \quad (21)$$

$$\text{MCC} = \frac{\text{TP} \times \text{TN} - \text{FP} \times \text{FN}}{\sqrt{(\text{TP} + \text{FP})(\text{TP} + \text{FN})(\text{TN} + \text{FP})(\text{TN} + \text{FN})}}, \quad (22)$$

where TP indicates the true positive, TN represents the true negative, FP defines the false positive, and FN represents the false negative. Based on these results, it is evident that the proposed PSL-RH technique provides improved performance results compared to the other learning techniques by accurately detecting and blocking the attacks based on the trained model of feature set.

Figure 10 illustrates the Receiver Operating Characteristics (ROC) analysis of both existing and proposed techniques with respect to varying True Positive Rate (TPR) and False Positive Rate (FPR). Here, the ROC of the learning models is computed for validating the performance of attack detection process under different thresholds. Based on this analysis, it is evident that the proposed PSL-RH technique provides an increased TPR, when compared to the other learning models.

Figure 11 and Table 7 show the information entropy analysis of both existing [19] and proposed techniques under different samples. Typically, the information entropy has been measured based on the randomness of information, which is mainly evaluated for estimating the average uncertainty level of ciphertext. This analysis shows that the RH incorporated with the PSL technique could efficiently improve the information entropy by generating the random hash points during key generation.

Figure 12 and Table 8 evaluate the maximum, minimum, and mean values of the Number of Data Unit Change Range (NPCR) and Unified Average Changing Rate (UACI) for both existing and proposed security mechanisms. These measures are computed as follows:

$$\text{UACI} = \frac{1}{X \times Y} \sum_{i=1}^{X} \sum_{j=1}^{Y} \frac{|A_1(i,j) - A_2(i,j)|}{255} \times 100, \quad (23)$$

$$\text{NPCR} = \frac{1}{X \times Y} \sum_{i=1}^{X} \sum_{j=1}^{Y} B(i,j) \times 100, \quad (24)$$

$$B(i,j) = \begin{cases} 0, & A_1(i,j) = A_2(i,j), \\ 1, & A_1(i,j) \neq A_2(i,j), \end{cases} \quad (25)$$

where $A_1(i,j)$ and $A_2(i,j)$ are defined as the gray values of two ciphertext data at points (i,j). From the evaluation, it is observed that the proposed PSL-RH technique provides improved theoretical values of NPCR and UPCI, when compared to the existing techniques.

4.2. Performance Analysis of Existing and Proposed Data Security Techniques. Figure 13 and Table 9 show the encryption time of both existing [38] and proposed data security techniques for the varying number of IoT devices, including ECC, RSA, IECC, and proposed ECC-RH. Generally, the encryption time is defined by the amount of time taken for encrypting the original data into ciphertext using the generated key. Similarly, the decryption time is defined by the amount of time taken for decrypting the cipher data into original format, which is evaluated for both existing and proposed techniques, as shown in Figure 14 and Table 10. Based on these comparisons, it is stated that the proposed RH technique integrated with the ECC data security

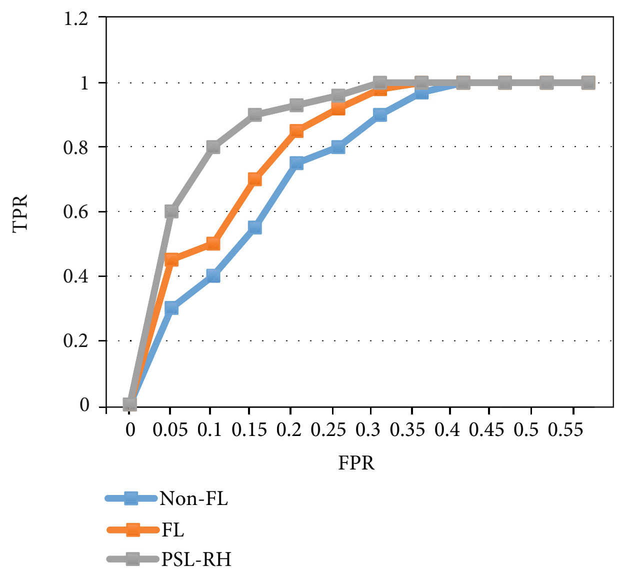

Figure 10: ROC analysis.

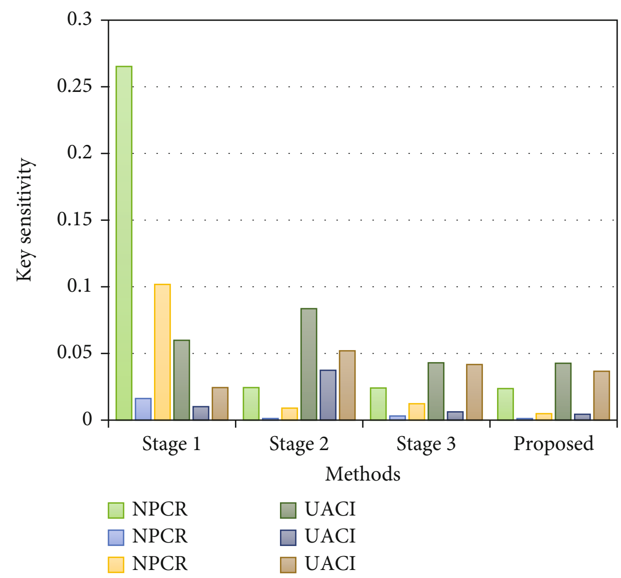

Figure 12: Key sensitivity analysis of existing and proposed techniques based on NPCR and UACI.

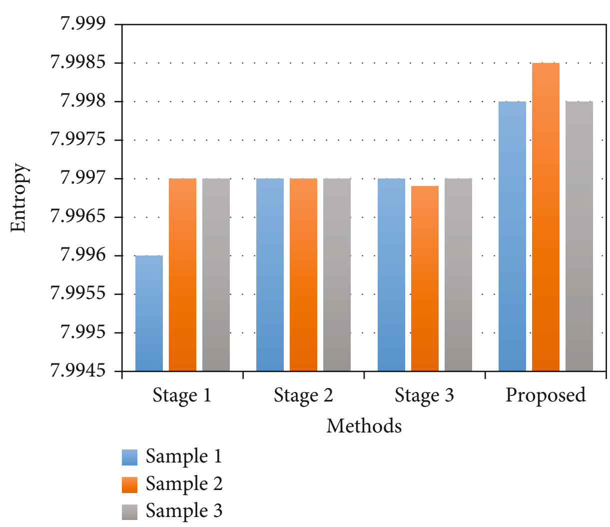

Figure 11: Analysis of entropy with respect to different samples.

Table 7: Entropy of existing and proposed techniques.

Data samples	Methods			
	Stage 1	Stage 2	Stage 3	PSL-RH
Sample 1	7.996	7.997	7.997	7.998
Sample 2	7.997	7.997	7.9969	7.9985
Sample 3	7.997	7.997	7.997	7.998

Table 8: Analysis of key sensitivity based on NPCR and UACI.

Parameters		Methods			
		Stage 1	Stage 2	Stage 3	PSL-RH
NPCR	Max	0.2653	0.0244	0.0241	0.02366
	Min	0.0162	0.0012	0.0031	0.001167
	Mean	0.1018	0.009	0.0123	0.004847
UACI	Max	0.0599	0.0836	0.043	0.042667
	Min	0.0101	0.0374	0.0062	0.0044
	Mean	0.0244	0.052	0.0417	0.036667

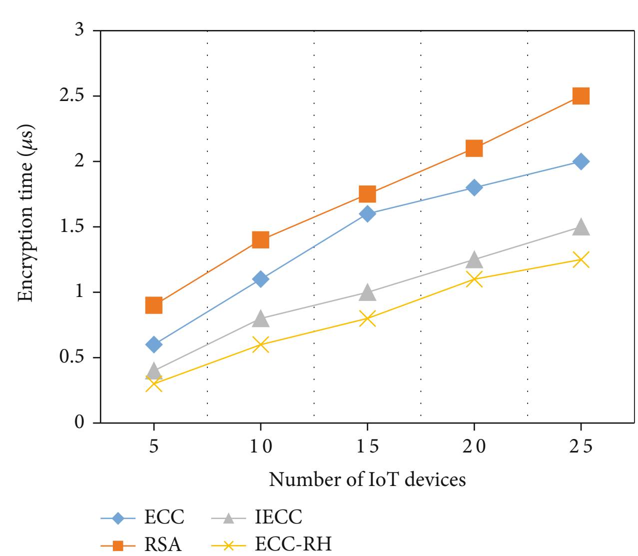

Figure 13: Encryption time vs. number of IoT devices.

mechanism requires reduced time consumption for both data encryption and decryption. In the proposed data security scheme, the random key is generated for the input data stream based on the data matrix's random hash value and signature pattern. So, it helps to speed up the processes of data encryption and decryption with reduced time consumption.

Table 9: Encryption time of existing and proposed techniques.

Number of IoT devices	ECC	RSA	IECC	ECC-RH
5	0.6	0.9	0.4	0.3
10	1.1	1.4	0.8	0.6
15	1.6	1.75	1	0.8
20	1.8	2.1	1.25	1.1
25	2	2.5	1.5	1.25

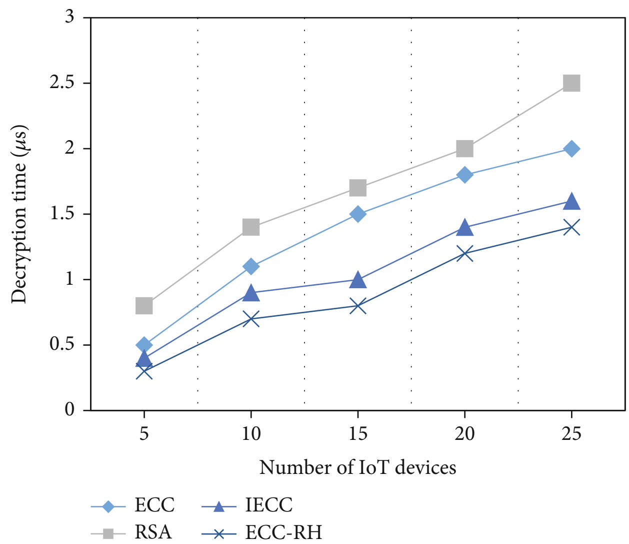

Figure 14: Encryption time vs. number of IoT devices.

Table 10: Encryption time of existing and proposed techniques.

Number of IoT devices	ECC	RSA	IECC	ECC-RH
5	0.5	0.8	0.4	0.3
10	1.1	1.4	0.9	0.7
15	1.5	1.7	1	0.8
20	1.8	2	1.4	1.2
25	2	2.5	1.6	1.4

Consequently, Figure 15 and Table 11 compare the encryption and decryption time of both existing Advanced Encryption Standard (AES), Ciphertext Policy Attribute-Based Encryption (CP-ABE), Modified CP-ABE (MPC-ABE) [39], and proposed ECC-RH techniques with respect to varying key size (bits). Then, Figure 16 and Table 12 show the decryption time of both existing and proposed data security techniques with respect to different key sizes. The obtained results depict that the proposed ECC-RH technique requires the minimal time consumption for both encryption and decryption, when compared to the other existing data security techniques.

Figure 17 and Table 13 show the average computation time of both existing and proposed data security techniques with respect to a varying number of users. Typically, the computational time is defined based on the amount of time taken by the system to fulfill the user request until the data retrieval is successfully completed. This analysis proves that the proposed ECC-RH technique requires the reduced computational time(s), when compared to the other data security mechanisms by completing the data storage and retrieval processes with increased speed and security. Then, it shows the improved performance rate of the overall AI-based security system deployed in an IoT-cloud environment.

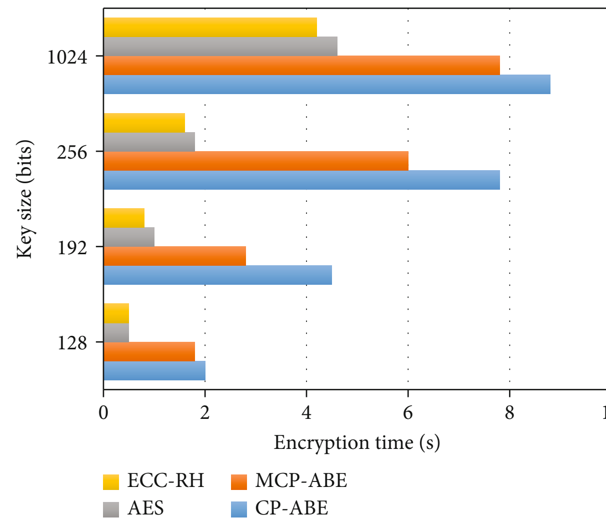

Figure 15: Encryption time vs. key size (bits).

Table 11: Encryption time of existing and proposed data security techniques.

Key size (bits)	CP-ABE	MCP-ABE	AES	ECC-RH
128	2	1.8	0.5	0.5
192	4.5	2.8	1	0.8
256	7.8	6	1.8	1.6
1024	8.8	7.8	4.6	4.2

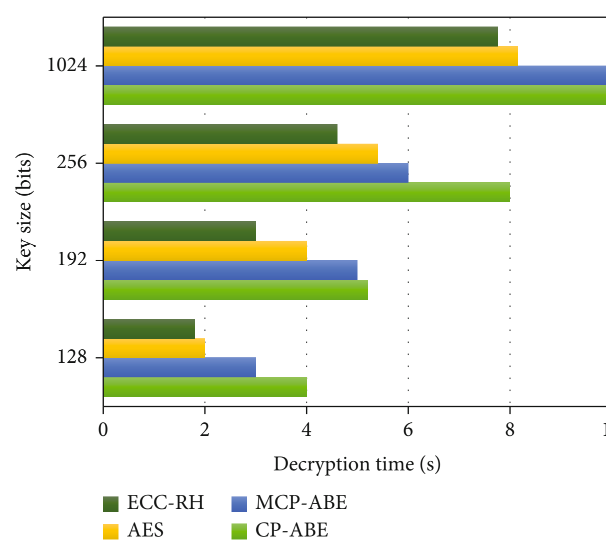

Figure 16: Decryption time vs. key size (bits).

Table 12: Decryption time of existing and proposed data security techniques.

Key size (bits)	CP-ABE	MCP-ABE	AES	ECC-RH
128	4	3	2	1.8
192	5.2	5	4	3
256	8	6	5.4	4.6
1024	12.2	10	8.2	7.8

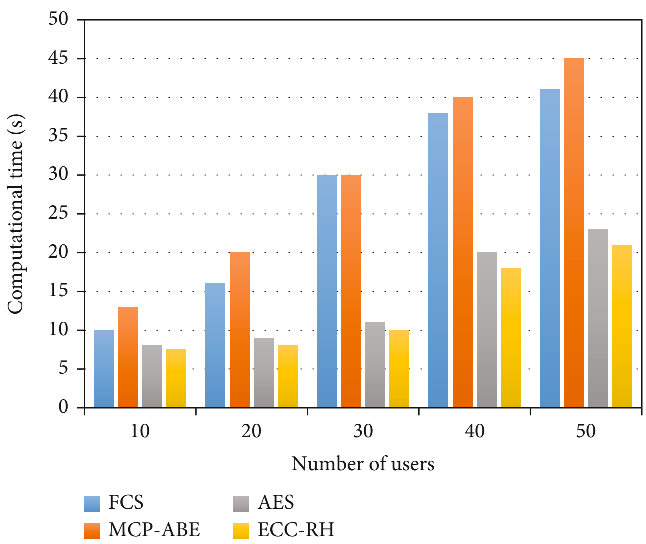

Figure 17: Computation time vs. number of users.

Table 13: Computation time of existing and proposed data security techniques.

Number of users	FCS	MCP-ABE	AES	ECC-RH
10	10	13	8	7.5
20	16	20	9	8
30	30	30	11	10
40	38	40	20	18
50	41	45	23	21

5. Conclusion

This paper presents an intelligent AI-based security system for ensuring the privacy and confidentiality of healthcare applications in an IoT-cloud environment. The main aim of this work is to enable the secured data storage and retrieval processes by implementing an advanced AI methodology. For this purpose, the PSL technique is proposed that intends to predict the attacks in an earlier stage. This ensures the healthcare application system's increased security by training the model with the set of learned features. Consequently, the RH-based key generation process is implemented and incorporated with the ECC mechanism for ensuring secured data storage and retrieval processes. The novel contributions of this AI methodology are that it maintains a trained data model with the set normal and attack features that help identify the attacks at the initial stage of processing. Also, it blocks the attack by reporting to the firewall and updates the trained model by appending the features and characteristics of the detected attack. Also, the data security process could be improved by generating the random key based on the data matrix's hash value and signature pattern. Then, this random key can be used for data encryption and decryption processes, which guarantees secured data storage and retrieval in an IoT-cloud environment. The significant advantages of the proposed AI-based security mechanism are reduced computational complexity, fast process, minimal time consumption, accurate attack detection, and optimal performance outcomes. The proposed AI-based security mechanism results are validated and compared with the existing feature learning, classification, and data security models using various evaluation metrics during the performance analysis. Based on the obtained results, it is stated that the proposed PSL-RH technique outperforms the other techniques with improved performance results.

In the future, this work can be extended by implementing the AI-based security framework to some other real-time application systems. Also, lightweight security models can be developed for ensuring the security of healthcare IoT data based on the processes of random key generation and trust agreement.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors have no potential conflicts of interest, such as financial interests, affiliations, or personal interests or beliefs, that could be perceived to affect the objectivity or neutrality of the manuscript.

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Research Article

Design and Implementation of Digital Twin-Assisted Simulation Method for Autonomous Vehicle in Car-Following Scenario

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The automated system replaces the driver, which makes autonomous vehicle to improve safety and convenience, so the market of autonomous vehicle is huge. However, the real-world application of autonomous vehicles faces many challenges due to the immaturity of automated systems. As a consequence, simulation verification plays an irreplaceable role in the application of autonomous vehicle (AV). Car-following is the most common driving scenario in mixed traffic flows, so it is essential to develop an appropriate and effective simulation method for AV. Combined with the existing AV simulation methods and digital twin (DT) technology, this paper proposes a DT-assisted method for AV simulation in a car-following scenario. The method makes the physical vehicle interact with the DT vehicle, and the DT vehicle can dynamically regulate the physical entities through real-time simulation data; the simulation verification can be displayed in the DT scenario to ensure the security of the simulation. Meanwhile, a DT-assisted simulation framework of AV is proposed, the framework includes physical entity components, DT components, and data processing and evaluation components. Besides, a DT-assisted simulation platform is developed base on Unity engine. Finally, the DT-assisted simulation of AV in the car-following scenario is implemented in field experiment. The experimental results show that the proposed method can be effectively conducted AV simulation in car-following, and the average of communication latency is 52.3 ms, which is smaller than the update frequency 15 Hz (66.6 ms) between DT-assisted platform and AV. The DT-assisted simulation method of AV proposed in this paper is applied in the car-following scenario, which effectively solves the challenges of car-following scenario simulation through virtual-real interaction.

1. Introduction

In recent years, AV has entered a stage of rapid development both in theory and technology [1]. Establishing safety of AV is a challenging endeavor due to the variety of conditions an AV has to operate in and the complexity of their system implementation, which is one of the important reasons why AV has not been applied in a large scale [2]. Hence, in the process of AV development, simulation verification plays an irreplaceable role. In particular, car-following is the most common driving scenario in mixed traffic flows, and it is very crucial to select an appropriate and effective simulation method for the car-following scenario. At present, the main methods of autonomous vehicle simulation include software-in-the-loop (SIL) [3], hardware-in-the-loop (HIL) [4], and vehicle-in-the-loop (VIL) [5]. SIL focuses on algorithm simulation verification, HIL focuses on algorithm and partial subsystem simulation verification, and VIL takes into account vehicle system and algorithm simulation. However, the vehicle can only move within finite degrees of freedom in the VIL, due to the physical vehicle on the wheel-hub. In addition, the interaction between the vehicle and the environment (e.g., wheels and the road surface) is all in the simulation platform. Closed road testing of AV is risky and costly.

With the advent of industry 4.0 era, the emergence of DT technology brings new applications in the field of AV simulation [6]. At first, Dr. Michael Grieves introduced the concept of DT equivalents of physical products in the product life cycle management executive course at the University of Michigan in 2003 [7], since DT can synchronize the running state of physical entities and realize real-time simulation test in the DT space. Otherwise, DT can dynamically regulate the physical entities through real-time simulation data form a closed-loop simulation test, so many researchers around the world begin to pay attention to the DT technology. Rasslkin et al. [8] constructed DT connecting physical entities and virtual models in the real world and assigned a special unsupervised prediction and control platform for the performance evaluation of the energy system for AV. Szalai et al. [9] proposed a hybrid reality simulation environment that integrates real vehicles into virtual environments and uses the hybrid reality environment to create a diversified test environment around real vehicles. Ge et al. [10] proposed a method of using DT technology to carry out AV test in extreme environment. In the simulation test environment of autonomous driving, the test of real AV under the virtual complex road scenarios can be realized by using the DT mapping. da Sliva et al. [11] introduced a novel concept called Cyber DT, which transfers the idea of the DT to automotive software for the purpose of security analysis, and DT is used to evaluate automotive security requirements through automated security requirement verification using policy enforcement checks and detection of security vulnerabilities.

The car-following scenario is one of the most common driving scenarios of AV. There are also many previous achievements in the simulation of AV in the car-following scenario. Wang et al. [12] proposed a new car-following model by using vehicle-to-everything technology. In the end, a case study was conducted in VISSIM to verify the proposed model. Osorio and Punzo [13] developed a simulation-based optimization methodology for the efficient calibration of car-following models of large-scale stochastic networks, and the methodology was verified by using AIMSUN simulator. These efforts focus on the validation of the algorithm and ignore the influence of other parts, so the results of these works may differ greatly from the actual scenario. Ma et al. [14] proposed an optimized control approach for cooperative vehicular platoon, and a HIL test was performed with Carsim to simulate a high-fidelity vehicle dynamic model. Zhou et al. [15] developed a hierarchical control strategy for vehicle stability; the HIL simulation test show that the effectiveness of proposed strategy. Ard et al. [16] experimentally demonstrates the effectiveness of an anticipative car-following algorithm by a VIL experiments. In the HIL simulation, virtual vehicle kinematics and dynamics models are used. In the VIL simulation, the physical vehicle is embedded into a virtual environment. However, this is quite different from vehicle-road interaction in the physical world, so the validity of the simulation results is questionable.

The DT technology and existing simulation method of AV in car-following scenario are combined, and we propose a DT-assisted simulation method for AV in car-following scenario in this paper. The main insights and contributions of this paper are as follows:

(1) A DT-assisted simulation method for AV in car-following scenario is proposed. This method uses physical vehicle to interact with the DT vehicle, which dynamically regulates the physical entities through real-time simulation data

(2) A DT-assisted simulation framework of AV is proposed, which is composed of three parts: physical entity components, DT simulation components, and simulation evaluation components

(3) The DT-assisted simulation platform is implemented based on Unity3D engine, including DT scenario, DT vehicle, and network communication module. Finally, a field experiment is implemented and verified the effectiveness of DT-assisted simulation method

The rest of this paper is organized as follows: Section 2 introduces the DT-assisted simulation framework. Section 3 details the DT-assisted simulation platform. Section 4 introduces the AV simulation in car-following by DT-assisted method. Section 5 details the real DT-assisted field implementation, and its results are analyzed in Section 6. This paper is ended in Section 7 with the conclusion and future work.

2. DT-Assisted Simulation Framework of AV

According to the characteristics of DT technology and the experience of previous researches, and a DT-assisted simulation framework for AV is proposed. As shown in Figure 1, the DT-assisted simulation framework includes three parts: physical entity components, DT simulation components, and data processing and evaluation components. The AV of physical entity components acquires real data by physical sensors, and the DT simulation components is used for simulation verification by DT vehicle in DT scenario. The data processing and evaluation components are used for data storage in the DT-assisted simulation platform. Virtual perception data is sent to physical entity components from DT components. According to the acquired virtual information, the AV implements decision-making and control. Each is described in detail in the following sections.

2.1. Physical Entity Components. The physical data acquired by the real sensor devices in the physical entity components is used to implement the digitizing process from the physical space to the DT space. As for the autonomous driving simulation test, the AV equipped with the autonomous driving controller runs in the real test field and obtains real-time data (position, attitude, fault, etc.) through on-board IMU, GNSS, and other sensor devices. At the same time, the real-time acquired data is transmitted to the DT simulation

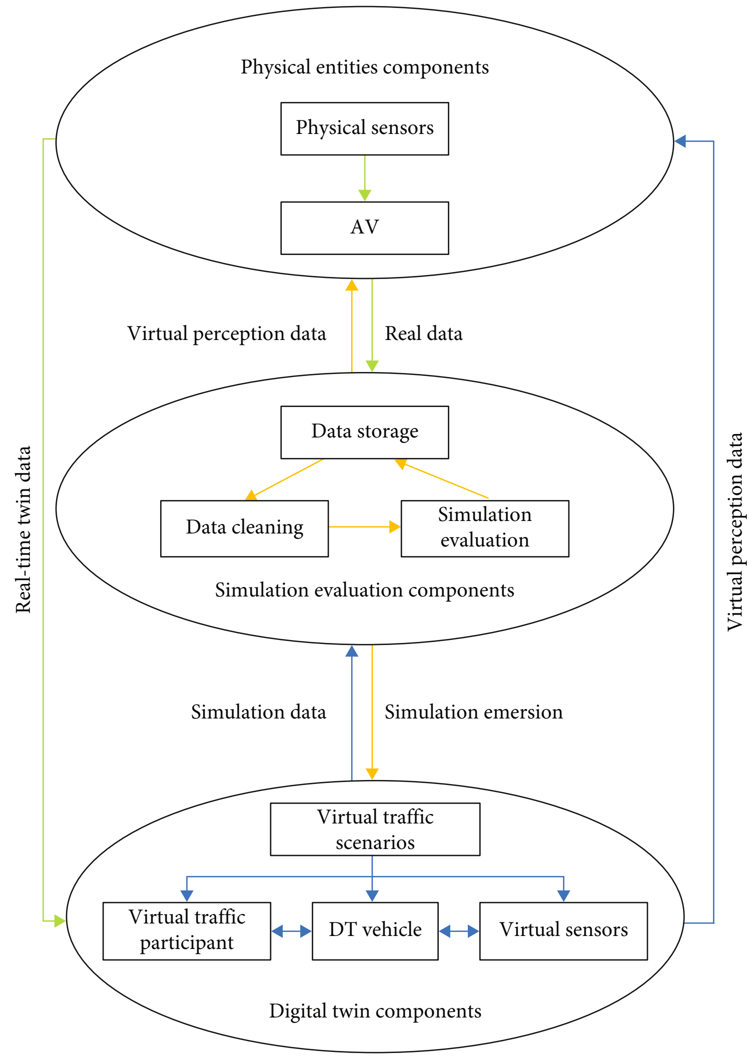


Figure 1: DT-assisted simulation framework for AV, the green lines represent physical entities data flow, the blue lines represent DT flow, and the yellow lines represent simulation evaluation data flow.

components through network communication module, so as to realize the interconnection between the DT vehicle and AV under test.

On the other hand, the real-time data acquired by the physical entity components is also transmitted to the data processing and evaluation components for data storage, which is convenient for historical data reproduction and simulation evaluation. The autonomous driving controller will also receive virtual perception information. After receiving the virtual perception data, the AV make decision and control through the real test field and the real vehicle actuator, so as to gain more accurate simulation results.

2.2. DT Simulation Components. DT simulation components are digital description of certain historical moment or current real-time state in the physical entities' components. The DT vehicle receives the real-time positioning data from real sensors in physical entity components and keeps the motion state of the DT vehicle consistent with AV at the appropriate frequency. The DT simulation components can provide repeatable and extreme simulation test scenarios, so the virtual sensors can sense the extreme scenarios information, and transmit the real-time dynamic simulation data to the data processing and evaluation components for data storage and data mining. The virtual perception information is fed back to the autonomous driving controller in physical entity components. At the same time, the DT simulation components is also used as visual module, which can observe the motion state, positioning information, and fault information of the physical vehicle through the DT vehicle.

2.3. Simulation Evaluation Components. The simulation evaluation components are the core part. In the process of DT-assisted simulation, the simulation evaluation components receive real-time data from the DT simulation components and the physical entity components for storage and mining. In addition, the data processing and evaluation components can perform simulation evaluation base on the real-time data fed back from the physical entity components and the simulation data fed back from the DT components. Besides, the simulation results are stored in simulation evaluation components, which can realize the rapid and convenient reproduction of dangerous accident scenarios and key simulation test process.

3. DT-Assisted Simulation Platform

At present, the mainstream simulation platforms of AV simulation are developed based on game engine. For instance, Carla was developed by Intel and Toyota based on Unreal4 [17], AirSim developed by Microsoft based on Unreal4 [18], SVL developed by LG based on Unity3D [19], and this AV simulation software based on game engine have good performance in the test process.

Unity3D has very efficient graphics rendering system, which can render realistic DT scenarios in real time. Besides, Unity3D can be developed on multiple platforms such as Windows, Linux, and Mac by using scripts such as C#. In addition, Unity3D can communicate with ROS through the TCP/IP protocol [20]. According to the characteristics of AV simulation test and DT-assisted simulation framework, this paper chooses Unity3D engine as the development platform. This part mainly introduces the implementation of DT-assisted simulation platform, including DT scenarios, DT vehicle, and network communication module.

3.1. DT Scenario. DT scenarios are particularly important for DT-assisted simulation test. As shown in Figure 2, the framework which is divided into two parts, the virtual environment and car-following scenarios. A virtual environment needs to reflect the characteristics of real environment from various aspects, so the virtual environment has high requirements for accuracy. Traditional 3D models are usually modeled by software such as 3DsMax, Blender, and Revit. However, those methods have the characteristics of low efficiency, long modeling cycle, and more manpower consumption and cannot meet the high-precision requirements of DT-assisted simulation test environment.

In this paper, ESRI City Engine, a three-dimensional city modeling software based on computer generated architecture rules, was used for integrated modeling. The ESRI City Engine can quickly create 3D scenarios from 2D data. At the same time, ESRI City Engine provides perfect support for ArcGIS, which enables the quick realization of high precision 3D modeling based on existing GIS data without conversion, shortens the construction cycle of DT environment, and ensures the high-precision requirements of the DT environment. The construction process of high-precision DT environment is presented:

(i) Step1: acquisition of L19 satellite image and elevation data. Then, import the downloaded elevation data into ArcGIS and project it into 3857 coordinate system, and import the satellite image into ArcGIS to carry out the vectorization of buildings and roads

(ii) Step2: the vectorized shp data and real materials in ArcGIS were imported into ERSI CityEngine, and integrated modeling was carried out based on the vectorized data. Then, the 3D model was fine-tuned according to the road parameters

(iii) Step3: FBX models exported from ERSI CityEngine are imported to Pixyz for automatic model optimization and lightweight

(iv) Step4: Unity3D generates a realistic and high-precision DT environment through high-definition render pipeline

For traffic scenarios, on account of that, the scenes of Unity3D is editable and extensible, and there are abundant resources in Asset Store; it is easy to simulate the traffic scenarios in the physical world. In addition, the traffic flow can also be controlled by the script to realize the traffic flow simulation of the AV. In the DT-assisted simulation platform, DT traffic scenarios can be designed according to simulation test requirements.

3.2. DT Vehicle (the Replica of AV). The DT vehicle is replica of AV, playing an essential role in the simulation test of AV. The model of DT vehicle can be divided into four levels: physical model, connection model, data model, and virtual model [21]. As shown in Figure 2, the process from the physical model to the virtual model is the digital process. The physical model of the DT vehicle is defined to describe the motion characteristics of the AV to be tested. The connection model of the DT vehicle is the key model to realize the synchronization between the AV to be tested and the DT vehicle. The connection model includes coordinate transformation and data format transformation. The connection model interconnects the five hierarchical models of the DT vehicle. The data model drives the virtual model to keep in sync with the behavior of the physical AV to be tested, and the data model of the DT vehicle is also used to define the normal working threshold of each device and realizes the function of fault diagnosis. The virtual model of the DT vehicle is the visual model of the AV to be tested. In addition, modularized data storage can be carried out through the data model, which is convenient for subsequent AV simulation evaluation.

3.3. Network Communication Module. The network communication module is the bridge between physical space and DT space, and it is also the basis of DT-assisted simulation test. DT components need real-time operation data in physical space to be driven, and physical entities also need feedback data from DT components to be dynamically regulated. Unity3D supports common communication protocols. Considering the advantages and disadvantages of various communication protocols, the DT-assisted simulation platform in this paper uses WebSocket communication protocol for data transmission. The DT-assisted simulation test in this paper can be carried out by local area network (LAN) or 5G communication. As shown in Figure 2, if LAN is adopted, the data in the autonomous driving controller is sent to the on-board wireless router through controller area network (CAN), which realizes data transmission with the AP of the test field and finally is sent to the DT-assisted simulation platform through the switch. If 5G is adopted, the data in the autonomous driving controller is sent to 5G-CPE through CAN, subsequently sent to the wireless router

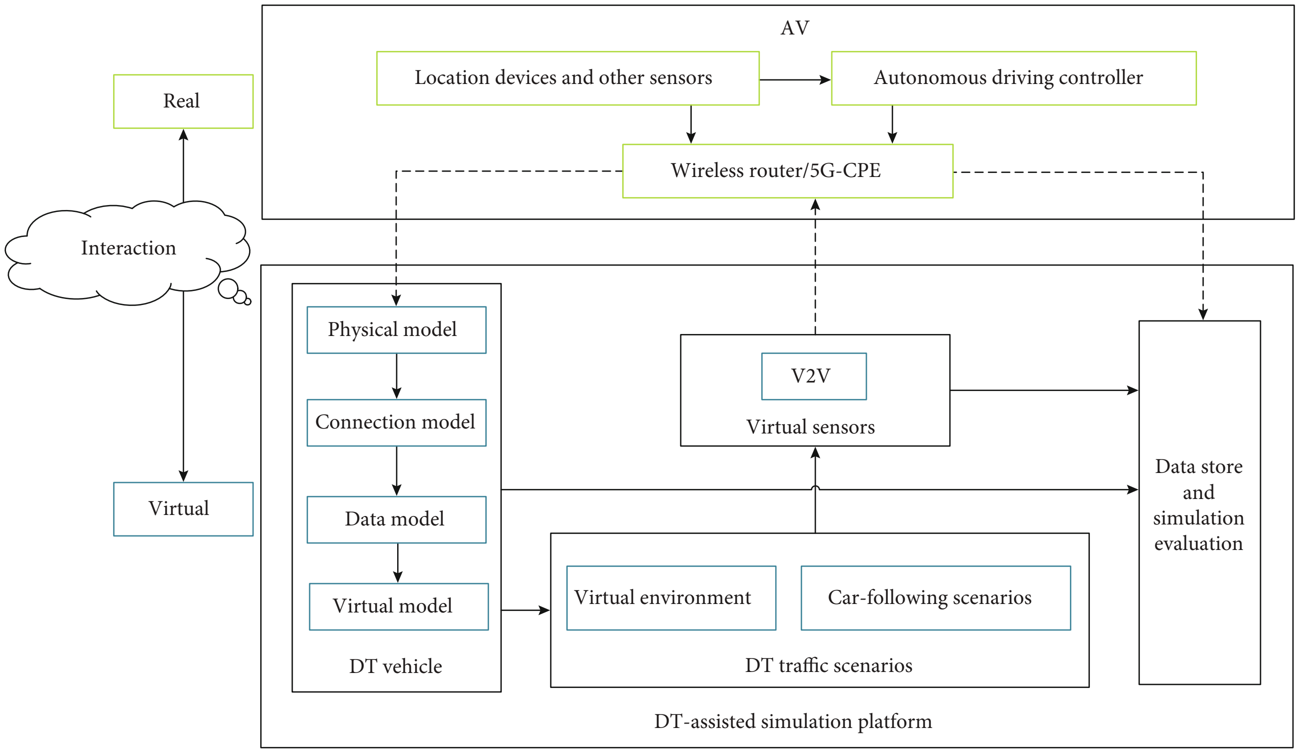


Figure 2: The implementation framework of DT-assisted simulation platform, the main components include AV, DT vehicle, and DT traffic scenarios. The dotted lines indicate the communication data flow between the real world and the virtual world, and the solid lines indicate the flow of communication data in the real or virtual world.

through the 5G base station, and finally transmitted to the DT-assisted simulation platform. The DT-assisted simulation platform uses the same communication link to feed back the virtual perception information to the AV to be tested. The two communication modes can be switched automatically according to the strength of the signal to ensure low latency of DT-assisted simulation test.

4. The AV Simulation in Car-Following Scenario by DT-Assisted Method

In the process of car-following, it is defined as a car-following scenario with potential risks when the leading vehicle suddenly conduct emergency brake with large braking deceleration in this paper. Under the circumstances, if the following vehicle does not have effective emergency braking strategy, it will lead to serious accidents. Therefore, in the face of potential risks in the car-following scenario, the effective simulation verification of collision avoidance strategy is an indispensable part in the development process of AV. Collision avoidance strategies in car-following scenarios can be divided into four methods: time headway (THW), time to collision (TTC), time to stop (TTS), and time to react (TTR) [22]. In the car-following scenario, the most commonly used method to evaluate the potential risk and rear-end collision is TTC [23–25]. TTC represents the time it takes for the following vehicle to collide with the leading vehicle from the current state of motion. In this paper, the TTC model adopts to verify the effectiveness of the DT-assisted simulation method.

4.1. The Statement of AV Car-Following. This paper only considers the two-car following problem in single-lane. As shown in Figure 3, the vehicle in front is called the leading vehicle, which is represented by a MV that is an manned vehicle in traffic flow. The rear vehicle is represented by the DT vehicle for the following vehicle and is also the replica of AV in the physical world. The DT vehicle and AV maintain real-time information exchange and status synchronization. In the DT scenario of DT-assisted platform, it is assumed that the following vehicle (DT vehicle) and leading vehicle (MV) use the communication mode of V2V to realize information interaction. The DT vehicle sends the real-time virtual perception information obtained from the MV, to the AV in the physical world. In order to simulate the potential risks existing in the scenario of car-following, MV have four random motion states, that is stationary, accelerated motion, uniform motion, and decelerated motion. In order to simulate the potential risks in the scenario of car-following, the MV with random possibility of emergency braking is designed.

In the DT simulation components, the DT vehicle receives the speed, acceleration, and position information of MV through V2V and calculates the distance information between the two vehicles according to the position of the DT vehicle. The acceleration and speed information of the two vehicles, as well as the distance between the two vehicles and the safe distance, and the TTC are calculated by collision

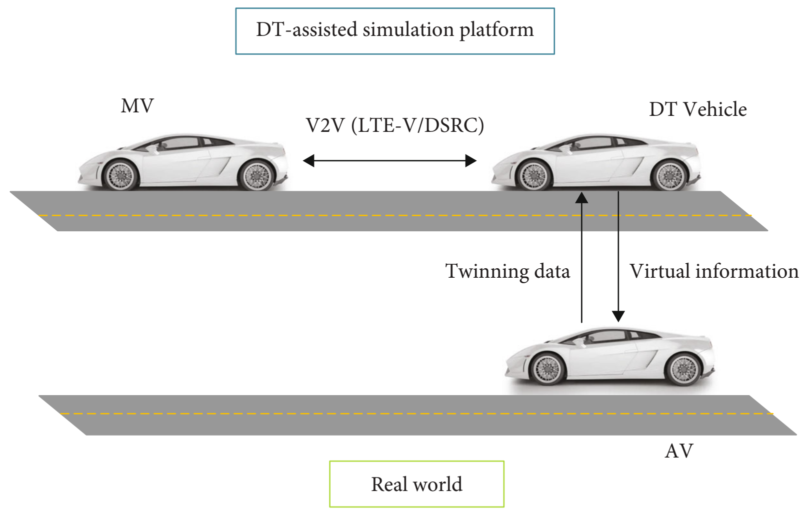


Figure 3: DT-assisted simulation for autonomous vehicle in car-following scenario, the vehicle in front is the leading vehicle (MV), and the vehicle in rear is the following vehicle (DT Vehicle), which interacts with AV in real-time.

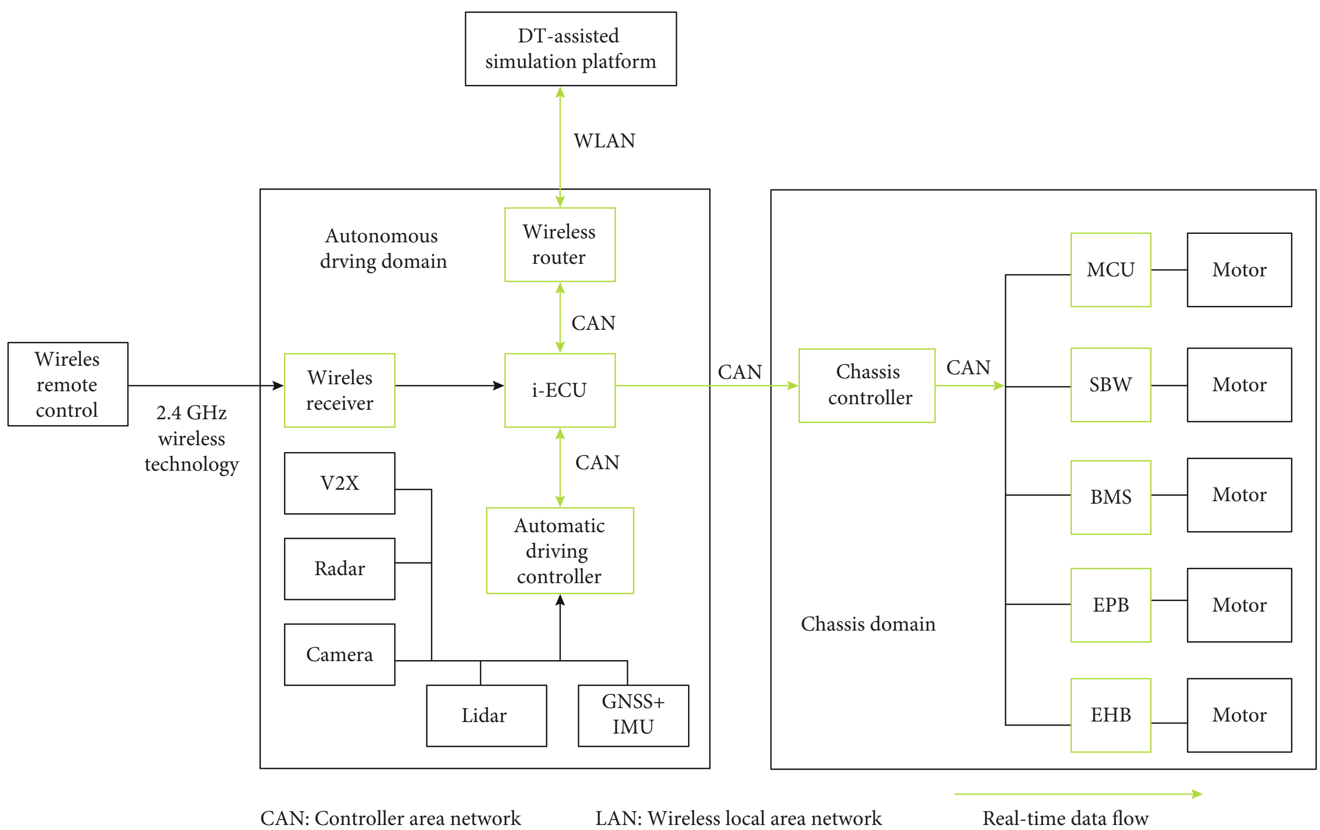


Figure 4: Topology of AV motion control module; it is divided into the autonomous driving domain and the vehicle chassis domain.

avoidance strategy. Different motion states of MV correspond to different TTC models. The same TTC model can be used when MV is in a state of uniform motion or at stationary, i.e. a_{MV} is equal to 0. When the MV is in the decelerating motion state, the potential risks need to be discussed separately. First, the two vehicles collided before the MV decelerated to stop. Second, the two vehicles collided after the MV stopped. If the relative velocities of between MV and DT vehicle are very small or zero, and the relative acceleration of both or the acceleration of DT vehicle is small, considering it to be a safe working condition for following vehicle, and TTC tends to infinity at this time. Since the larger TTC value has no real reference value, so the TTC value for this state is default to 30 s. If the TTC is less than 3 s, the output TTC is 3 s by default, indicating the risk of collision in the car-following scenario. Meanwhile, the MV

Input: 1. TTC: collision time calculated by collision avoidance strategy; 2. t_1: time threshold for collision avoidance warning; 3. t_2: time threshold for braking;
Output: 1. Flag1: the collision avoidance warning indicator; 2. Flag2: the braking indicator;

```
Initialization :
Flag1 ⟵0; Flag2 ⟵0;
if TTC>t1 then
    Flag1 ⟵0;
    Flag2 ⟵0;
end if
if t2< TTC ≤t1 then
    Flag1 ⟵1;
    Flag2 ⟵0;
end if
if 0 < TTC ≤t2 then
    Flag1 ⟵1;
    Flag2 ⟵1;
end if
return Flag1, Flag2
```

Algorithm 1: Motion control of AV in car-following scenario.

(a) (b)

Figure 5: Field implementation: (a) DT-assisted simulation platform of car-following test and (b) the AV to be tested drives at the test field.

and DT vehicles in the DT-assisted platform are assumed to be within the scope of V2V communication, and they interact and share information in real-time. At the same time, DT vehicle feedback the virtual perception information of MV to the AV in the physical world through the LAN in real time.

4.2. The Motion Control of AV in DT-Assisted Simulation. Longitudinal motion control of AV is closely related to the behavior of the car-following, and the longitudinal motion control module of the AV controls the vehicle to adjust its motion state (such as emergency braking) in time, so as to ensure the timely elimination of potential risks in the process of car-following. The control topology of AV can be divided into two parts: autonomous driving domain and vehicle chassis domain. As shown in Figure 4, the autonomous driving domain mainly consists of four parts: the autonomous driving controller, i-ECU, wireless router, and wireless receiver. The autonomous driving controller senses the surrounding environment and realizes the function of autonomous driving through V2X, Radar, Camera, LIDAR, GNSS, and other sensors. The chassis controller communicates with the (MCU) motor control unit, SBW (steer-by-wire), the braking system consisting of two parts, EPB (electronic parking braking system) and EHB (electronic-hydraulic braking system), and BMS (battery management system) through CAN.

Algorithm 1 is designed to conduct the collision avoidance warning and generate the longitudinal motion control command of the AV. According to the characteristics of AV and in the case of potential risks to ensure safety, the time threshold for collision avoidance warning is t_1 and the time threshold for braking is t_2. The values of t_1, t_2, and TTC are taken as the input of Algorithm 1. If the TTC is less than the set threshold t_1, the collision avoidance warning indicator (Flag1) changed from 0 to

1, and the AV will send collision avoidance warning messages. If the TTC is less than the set threshold t_2, the braking indicator (Flag2) changed from 0 to 1, and the braking command will be generated and sent to the vehicle chassis domain controller through the i-ECU module and then sent to the EPB or EHB module through the CAN, and the AV will actuate braking.

5. Real DT-Assisted Field Implementation

5.1. DT-Assisted Simulation Platform. According to the general framework of DT-assisted simulation test for AV proposed in this paper, the AV DT-assisted simulation platform has been developed. In this simulation platform, the high-precision model of the test field was established and realized the communication between the simulation platform and AV to be tested based on WebSocket protocol. In addition, the car-following scenario with potential risks is designed in the DT scenario. The relevant data and early warning information in the process of simulation test can be displayed in real time on the UI interface. As shown in Figure 5, the related data include leading vehicle motion state, collision avoidance warning information, AV operating state, and fault information and video. In the field implementation of AV simulation in the car-following scenario, the DT vehicle and MV play an important role in DT-assisted simulation platform. The DT vehicle model structure is consistent with the AV and it can interact with the AV in the physical world in real-time. Both of them have the same motion state and motion parameters. In the car-following scenario, MV is a virtual motor vehicle, which simulates the motor vehicle in the traffic flow.

5.2. Hardware Setup of AV Simulation in Car-Following. A 4-wheel steering AV is adopted in field implementation, of which length is 2.8 m, and width is 1.5 m. The AV has two sets of drive system, two sets of steering system, and a set of braking system, and it is also equipped with sensors such as lidars, millimeter-wave radar, and cameras. All the hardware equipment for field implementation included the following: DT-assisted simulation platform server, physical sensors, autonomous driving controller, and network communication devices.

5.2.1. DT-Assisted Simulation Platform Server. This module runs a DT-assisted simulation platform. As shown in Figure 6, the simulation platform server is equipped with Intel Core i9-10900K/i9-10900KF hybrid 3.7 GHz (10-core) CPU, 64G RAM, 1 TB SSD and 2 TB HDD, and GeForce RTX3090-24 G.

5.2.2. Physical Sensors. This module is equipped on the AV to be tested, and it is used to obtain real-time position, attitude, and speed data of AV. The above data is transmitted to the DT-assisted platform, and the DT vehicle can receive the real data and synchronize the motion state of the AV to be tested in real time. As shown in Figure 6, the Starneto Newton-M^2 inertial measurement unit (IMU) integrated navigation system is adopted in the implementation field, and the

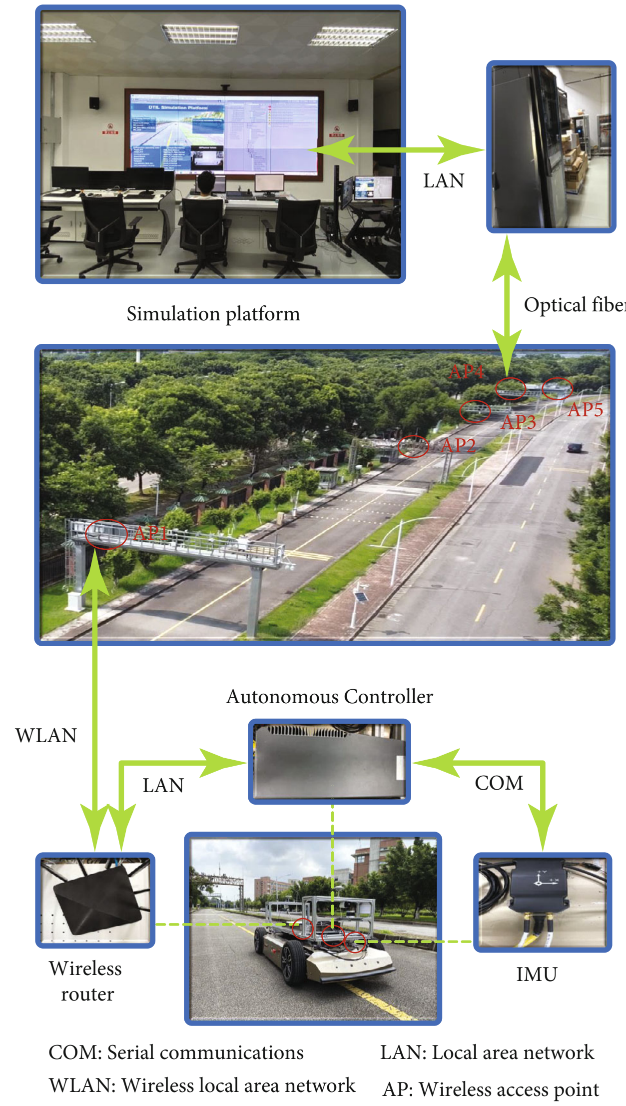


Figure 6: Hardware in field implementation, including DT-assisted simulation platform server, Starneto Newton-M2 INS, on-board wireless router, autonomous driving controller, and AP location in the test field.

Table 1: Parameters setup of car-following field implementation by DT-assisted simulation platform.

Parameters	MV(virtual)	AV
Initial speed	0 km/h	0 km/h
Maximum speed	20 ± 2 km/h	10 ± 2 km/h
Acceleration range	-8 ~ 2 m/s^2	-6 ~ 6 m/s^2
Initial distance	30 m	
t_1 threshold	10 s	
t_2 threshold	3 s	
Maximum TTC	50 s	
Interaction rate	15 Hz	
The length of test field	339 m	

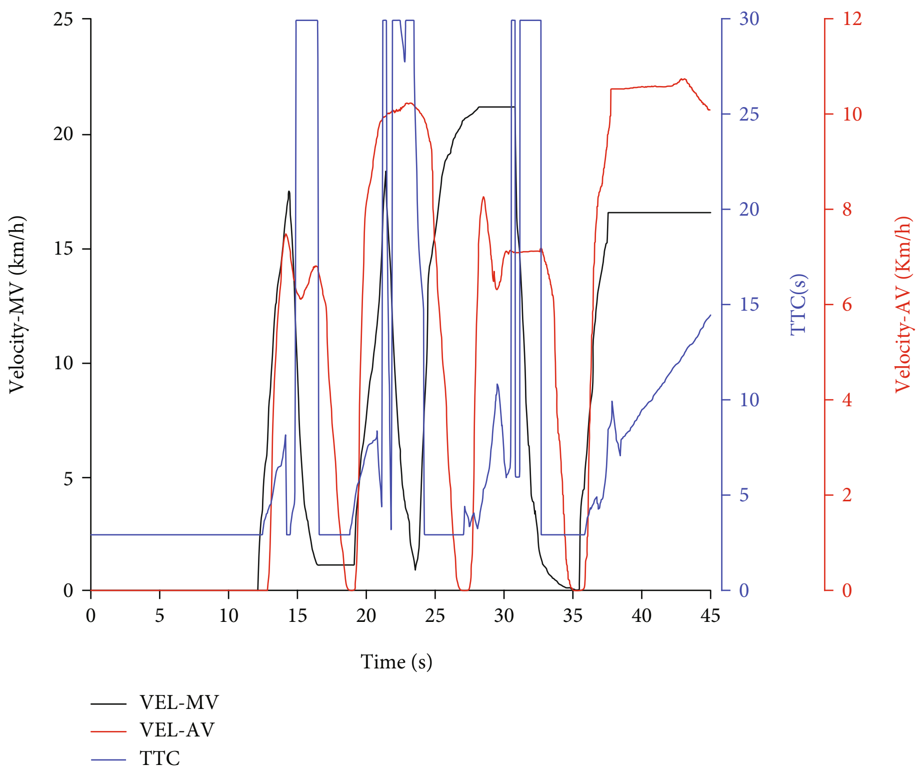


FIGURE 7: Speed and TTC changes in the car-following scenario of AV and MV, the blue line shows the real-time TTC curve, the black line shows the velocity change curve of MV, and the red line shows the velocity change curve of AV.

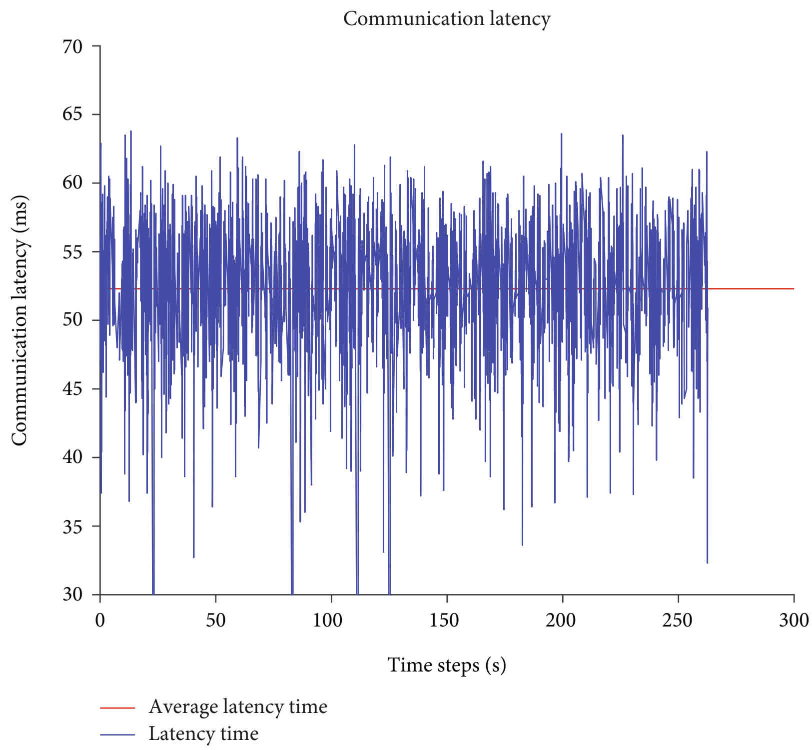
maximum data update frequency is 100 Hz. When the RTK mode is used and GNSS signal is good, positioning accuracy is 2 cm+1 ppm.

5.2.3. Network Communication Devices. As shown in Figures 6 and 5, APs are installed in the test field to ensure the full coverage of the LAN. The AV to be tested is connected with AP through on-board wireless router (as shown in Figure 6), when the vehicle passes the AP node, and it can automatically switch the AP node according to the signal strength. APs are connected with a DT-assisted simulation platform through a switch. The communication latency of the LAN is within a certain range, which meets the requirements of our field implementation.

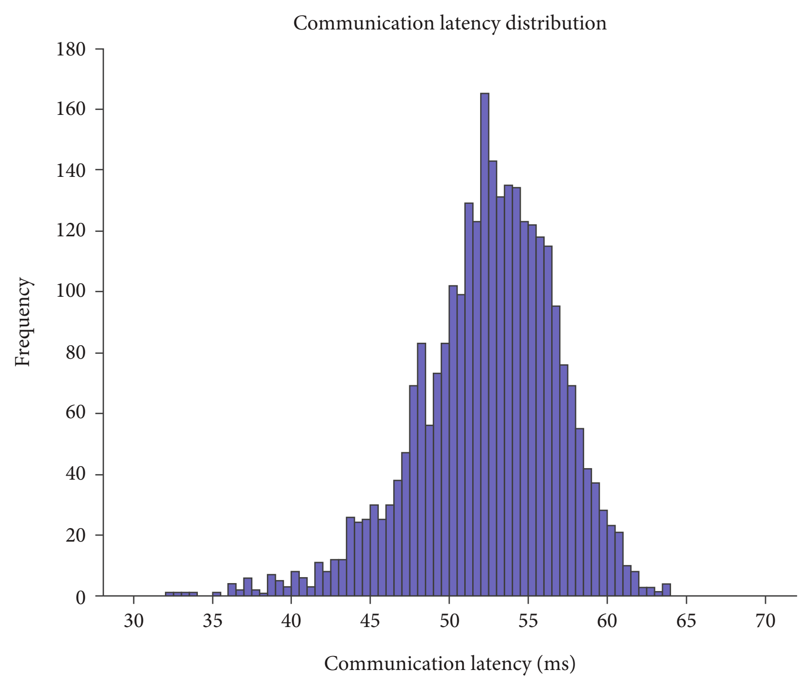
5.2.4. Autonomous Driving Controller. As shown in Figure 6, this module is the control center for the AV, and the collision avoidance strategy and autonomous driving algorithm runs in the autonomous driving controller. In addition, it has the ability of multisensor fusion, path planning, decision, and control. It is equipped with GTX2060s, 256 GB SSD, and 16 GB RAM. The autonomous driving controller is connected to the vehicle chassis domain via the i-ECU unit, realizing the motion control of the AV.

5.3. Field Implementation Plan of DT-Assisted Simulation. The test field is located in East Campus of Sun Yat-sen University, Guangzhou, China, and the total length of the test field is 339 m. As GNSS+RTK positioning data obtained from the INS receiver is the latitude and longitude information of the WGS-84 protocol, it is not conducive to realize the position synchronization between the DT vehicle in the DT-assisted platform and AV. So, this paper takes the longitude and latitude of the starting point as the origin and convert the longitude, latitude, and height data into Cartesian coordinate data. In each time step, the position, attitude, speed, and acceleration information of the AV to be tested is provided by the INS system and communicate with the DT vehicle in real-time through the LAN. In the DT-assisted simulation platform, a certain distance is maintained between the DT vehicle and MV at the initial moment, and DT vehicle sends the received MV virtual perception information (including localization, speed, acceleration, and yaw) to the autonomous driving controller through the wireless router on the AV. The autonomous driving controller will input the virtual information received in real-time into the autonomous driving controller to calculate the TTC, then input the TTC into the longitudinal motion control instruction generation algorithm.

In order to simulate more special and dangerous collision avoidance scenarios, MV may break in an emergency during the movement. The effectiveness of the collision avoidance strategy can be judged by the braking time and braking effect of autonomous vehicle. In addition, it can also be judged by the collision between the DT vehicle and MV in the DT scenario. Field implementation is shown in Figure 5. In order to simplify the test, both the DT vehicle and MV were kept in the right lane, and only longitudinal collision avoidance was considered, without lateral collision avoidance. As shown in Table 1, the initial velocity of MV and



(a)



(b)

FIGURE 8: Test result of communication latency between AV and DT-assisted simulation platform: (a) communication latency in continuous 300 s and (b) histogram of communication latency distribution.

AV is 0, and due to the short lane distance, the maximum speed of AV is limited to 10 ± 2 km/h, and the maximum speed of MV is limited to 20 ± 2 km/h. The forward collision warning time is 10 s, and the communication frequency of the MV and DT vehicle in the DT-assisted simulation platform is 15 Hz.

6. Result Evaluation

In this paper, the DT-assisted platform is verified by AV simulation in the car-following scenario. The field implementation by DT-assisted was carried out at 08:00 on June 27, 2021. The DT-assisted platform updates the status of

Table 2: The special value of the communication latency results.

Maximum	Minimum	Average	85^{th} percentile	100^{th} percentile
63.8 ms	32.3 ms	52.3 ms	56.5 ms	63.8 ms

the MV and the AV on 15 Hz. The effectiveness of the collision avoidance strategy can be evaluated according to the real-time velocity and TTC. The DT vehicle can reflect the state of AV in real time. On the other hand, in the process of DT-assisted simulation, DT vehicle needs to synchronize motion state of AV in real time and needs to feed back the virtual perceptual information to AV. In this work, if the communication latency is too large, which will lead to inaccurate simulation results, so the communication latency is particularly important in the simulation. The communication latency was also tested between AV and DT-assisted simulation platform.

6.1. Car-Following Simulation Result Evaluation. As is shown in Figure 7, for the first 12 seconds, MV stays stationary, and then, the leading vehicle speeds up. When there is no danger of collision between MV and AV, AV starts to speed up and keeps following the MV at 12.8 s. At 14.4 s, MV suddenly decelerates with a large acceleration. According to the collision avoidance strategy, there is a collision risk, and TTC reaches 3 s at 16.6 s. Therefore, AV adopts emergency braking to avoid collision with MV. At 19 s, MV accelerates with a large acceleration, and when the two vehicles enter the safe driving state, AV immediately accelerates and keeps car-following. At 21 ~ 30 s, MV changes dynamically in three motion states of deceleration, acceleration, and constant speed. Due to the high speed of MV, when MV decelerates at 21.4 s, TTC is maintained at a large value. At 23 s, the TTC value is equal to 3 s according to calculate by collision avoidance strategy, and AV begins to stop in an emergency. In the last period, AV calculates TTC in real-time according to the motion state of MV and estimates the emergency degree of potential collision danger in the car-following scenario according to the TTC value, so as to adopt appropriate collision avoidance strategies to maintain the following state.

The effectiveness of collision avoidance strategy based on TTC in the car-following scenario with potential risks is demonstrated by the DT vehicle in the DT-assisted simulation platform. If the DT vehicle collides with the MV, this indicates that the strategy running in the AV is defective. If the DT vehicle follows the MV at safe distance, there is no collision between the DT vehicle and MV in the DT-assisted simulation platform, which indicates that the strategy in the AV is valid. In this process, the DT-assisted method using the real kinematics and dynamics model of AV, which greatly improved the reliability of the simulation results and also improved the efficiency of the simulation under the premise of ensuring safety. In particular, the DT-assisted method reduces the risk of simulation.

6.2. Communication Result Evaluation. To verify the communication latency in the DT-assisted simulation method is within an acceptable range, the communication latency experiment is performed. In this experiment, the communication latency is defined as the difference between the time when the AV sends a message and the time when the AV receives the feedback message from the DT-assisted simulation platform. First, AV sends real data to the DT-assisted simulation platform and records the time t_1. After receiving the messages, the DT-assisted simulation platform will immediately send a message back to AV. When AV receives the feedback message, it records the time t_2 and the communication latency is $t_2 - t_1$. Figure 8 shows that communication latency in continuous 300 s and the histogram of communication latency distribution. As shown in Table 2, the maximum communication latency is 63.8 ms, the minimum communication latency is 32.3 ms, and the average communication latency is 52.3 ms. As shown in Figure 8(b), the results reveal that 85% of the communication latency is less than 56.5 ms, and 99% of the communication latency is less than 61 ms. In the field implementation, the communication frequency between the DT vehicle and AV is 15 Hz (66.6 ms), that is, the communication latency must be less than 66.6 ms to meet the requirements of DT-assisted simulation. According to the above communication latency test results, the maximum value is 63.8 ms less than 66.6 ms, which meets the requirement that DT vehicle can synchronize the motion state of AV smoothly to realize simulation in the car-following scenario.

7. Conclusion

The DT-assisted simulation method of AV is proposed in this paper, and the simulation platform is developed based on Unity3D. The AV simulation in the car-following scenario is implemented on the test field. The experiment results show that the DT-assisted method is effective within an acceptable communication latency. In the process of AV simulation, the real vehicle actuators and the vehicle directly interacts with the surface. Meanwhile, there is no need to consider vehicle kinematics and dynamics simulation, which can greatly improve the reliability of AV simulation. In particular, the DT-assisted simulation method can safely and efficiently implement simulation test that are difficult to complete in the physical world. There are many challenges in this paper. Firstly, since the physical world needs to be synchronized with the virtual world in real time, the accuracy of the DT scenario in the virtual world is critical. If the DT scenario is not accurate enough, the perception information outputted by the DT vehicle may be inaccurate. Secondly, if the DT-assisted simulation platform uses more sensors, huge amounts of data need to be transmitted between the virtual world and the real world, and it is difficult for general communication methods to meet the requirements. As a consequence, how to realize lightweight data transmission is an urgent problem to be solved.

Further, we need to continue to optimize the DT-assisted simulation platform and develop a method of lightweight data transmission for DT-assisted simulation. More virtual sensors need to be developed so as to realize AV simulation in various scenarios. On the other hand, the DT-assisted simulation method to reduce the communication latency as much as possible.

Data Availability

The experimental data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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