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Original Article

DiBoS: Digital Twin and Beidou Precise Positioning Driven Intelligent Hoisting System with Fast Instant Networking

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Abstract:

To address the challenges of inaccurate guidance, low efficiency, and high safety risks in highway and bridge hoisting operations, this study develops a digital twin-based intelligent guidance system. Integrating multi-sensor fusion, coordinate transformation, attitude calculation, and 3D visualization technologies, the system realizes simulated construction, on-site guidance, risk early warning, and construction review. This paper comprehensively presents the system design, hardware configuration, and experi- mental scheme, while implementing in actual hoisting construction (Huangpi-Xinzhou Section of Wuhan Metropolitan Area Ring Expressway). Based on the Unity platform, the system develops a 3D visualized crane construction guidance system. It uses Beidou terminals for precise positioning and collection of hoisting position information, and conducts real-time communication with the 3D software system. Meanwhile, it acquires auxiliary information with sensors such as video cameras and wind sensors (cameras are used to prevent personnel intrusion, and wind sensors are used to obtain wind conditions at the construction site). Experimental verification under multiple scenarios (open field, obstacle field, harsh weather, dual-crane operation) demonstrates centimeter-level positioning accuracy and real-time risk warning capability.

Keywords: Digital twin; Crane hoisting; Intelligent guidance; Multi-sensor fusion; Collision warning; Industry application

1. Introduction

Large-scale bridge construction, particularly steel box girder installation and bridge rotation, relies heavily on crawler cranes and truck cranes. During crane operations, accurate construc- tion guidance is crucial for improving construction efficiency and ensuring construction safety. Traditional methods of con- struction guidance have issues such as non-intuitive informa- tion and poor real-time performance [1, 2]. Traditional hoist- ing operations face critical limitations: (1) Inaccurate real-time guidance due to unintuitive 2D information presentation; (2) Low operational efficiency caused by manual path planning and repeated adjustments; (3) High safety risks such as collisions, crane overturning, and personnel intrusion due to complex on- site environments. (4) High labor costs (at least one commander is usually required near the target).

Notable accidents in recent years, such as the 2022 bridge hoisting collapse in Guangdong, highlight the urgency of im- proving hoisting safety. Digital twin (DT) technology, which establishes real-time mapping between physical entities and virtual models, provides a promising solution. By integrating multi-sensor data and intelligent algorithms, DT-based systems can realize real-time perception, dynamic simulation, and deci- sion support for hoisting operations [3].

There have been many applications and effect evaluation of intelligent hoisting-related technologies. In the Linyi Yellow River Bridge project, China Railway Construction Bridge En- gineering Bureau applied the innovative application system of digital twin integration management for the first time. Through precise computer control, this system solved complex techni- cal problems such as displacement and structural deformation that are highly likely to occur during the bridge incremental launching process. It slowly pushes steel box girders at 90cm per 20 minutes, moving them to above bridge piers and ulti- mately to the predetermined location [4]. Similarly, in smart construction site projects, the comprehensive tower crane man- agement system, integrating technologies such as gigabit opti- cal network, sensors, and data collection and storage. These in- clude real-time multi-party supervision, regional anti-collision, group tower anti-collision, anti-overturning, anti-overloading, real-time alarm, wireless upload and recording of real-time data, real-time video monitoring, and precise hoisting [5].

However, limitations remain: (1) Poor adaptability to com- plex environments (e.g., dense urban areas with GNSS in- terference). (2) High computational cost of collision detec- tion in complex scenes. (3) Lack of full-link integration of "simulation-construction-review" [6, 7]. This study addresses these gaps by developing a comprehensive DT-based system.

This project aims to develop an intelligent guidance system for highway and bridge hoisting operations based on digital twin technology. This system primarily addresses the chal- lenges of insufficient guidance, low efficiency, and high safety risks associated with crawler cranes and truck cranes used as hoisting tools during large bridge rotations and steel box girder installations. By integrating multi-sensor fusion technology, data fusion algorithms, and digital twin technology, the system enables real-time construction site perception, situation evolu- tion simulation, and operational decision support, thereby im- proving the efficiency and safety of hoisting operations. The main contributions are as follows:

- We implement a digital twin module in the system with BIM model for simulated hoisting, and real-time hoisting guidance.
- We propose to use several Beidou terminals attached on the selected locations for precise positioning and import the positions into 3D system on real time for guiding the construction.
- We design an instant networking deployment method for enabling fast data transmission of collected data from mul- tiple hybrid nodes, e.g., Beidou terminals, wind sensors, and video cameras.

The rest of the paper is organized as follows: In Section 2, related work is reviewed. We present the preliminaries in Sec- tion 3. Section 4 describes the proposed scheme, followed by Section 5 performance evaluation. We conclude the paper in Section 6.

2. Related Work

Domestic research on digital twin-based intelligent construc- tion has made progress. For example, studies have combined BIM and IoT to establish digital twin models for prefabricated component hoisting risk control, realizing real-time informa- tion collection and path planning. Improved RRT algorithms have also been used for intelligent path planning of mobile cranes to enhance planning efficiency and safety [8,9,10]. However, existing research still has shortcomings: insufficient real-time collision detection, single early warning methods, low integration of guidance instructions, and lack of complete solu- tions covering simulated construction, on-site construction, and review.

Smart hoisting systems have evolved from single-sensor monitoring to multi-technology integration [11, 12]. China Construction Eighth Engineering Division successfully applied the unmanned tower crane technology in Huangdao District, Qingdao. This technology combines advanced industrial op- erating systems and intelligent control software, and integrates technologies such as 3D digital modeling, automatic path plan- ning, high-stability communication, and active obstacle avoid- ance, realizing automatic hoisting operations without manual intervention. The task can be completed with only two sig- nal riggers performing simple positioning via remote controls [13, 14]. This system utilizes lidar and visual AI technolo- gies to achieve seamless connection of perception, recognition, control, and decision-making, and possesses the capabilities of autonomous path planning, adaptive operation, and active ob- stacle avoidance. Compared with traditional manual hoisting, its operation efficiency has been improved by more than 15%, while the labor cost has been significantly reduced by over 60%. Researchers from Southeast University proposed an ar- chitecture for the unmanned intelligent hoisting system, which is divided into three functional layers: the perception layer, the decision-making layer, and the control layer. The perception layer relies on GPS and sensors, the decision-making layer is based on high-performance AI chips, and the control layer is implemented through relays, programmable logic controllers (PLCs), and other components. The system realizes decision- making through a neural network expert system and can adapt to complex environments [15]. In addition, the system uses deep learning algorithms to conduct real-time analysis of data during the hoisting process, predict the changing trends of the hoisting state, and adjust hoisting parameters in advance to en- sure the stability and safety of the hoisting process.

- **Unmanned Hoisting Technology**: China Construction Eighth Engineering Bureau applied unmanned tower crane technology in Qingdao, combining LiDAR and visual AI for autonomous path planning and obstacle avoidance, im- proving efficiency by 15% and reducing labor costs by 60%.

- **Intelligent Auxiliary Equipment**: Zoomlion developed smart attitude-adjusting spreaders and auxiliary hoisting robots, enabling automatic alignment and assembly of components without on-site personnel.

- **Digital Twin Integration**: China Railway Construction Bridge Bureau applied a DT-based fusion management system in the Linyi Yellow River Bridge project, solving displacement and deformation problems during bridge in- cremental launching.

2.1. Research Objectives and Contributions

The primary objective is to develop a digital twin-based intel- ligent guidance system for crane hoisting with simulated con- struction, on-site guidance, risk early warning, and construction review functions. The key contributions are as follows:

1. A multi-sensor integration framework combining GNSS, IMU, cameras, and meteorological sensors for compre- hensive on-site perception;
2. A coordinate transformation method adapting to Unity's left-hand system and engineering right-hand system;
3. A multi-scenario experimental scheme verifying the sys- tem's stability and accuracy under complex conditions;
4. Comparative analysis with industry cases to quantify the system's efficiency and safety improvements.

3. Preliminaries

3.1. Digital Twin

Digital Twin (DT) refers to a multi-dimensional digital rep- resentation of physical entities, processes, or systems that inte- grates multi-disciplinary data (e.g., geometric structure, phys- ical properties, operational history) and multi-scale simulation models. It establishes a bidirectional real-time mapping and dynamic interaction mechanism between the physical world and the virtual space [16, 17]. Originating from the "Mirrored Spaces Model"proposed by Professor Michael Grieves in 2003, the concept was formally named "Digital Twin" by the U.S. Air Force Research Laboratory in 2011 and has since evolved into a core enabling technology for intelligent engineering and smart manufacturing.

In the context of intelligent hoisting systems and bridge con- struction projects, DT plays a pivotal role as a core technical framework: It integrates high-precision spatial position data from RTK systems, structural stress data from sensors, and op- erational data from hoisting equipment to construct a virtual mirror of steel box girders, piers, and hoisting machinery. During the hoisting process, the DT system realizes real-time vi- sualization of the girder's movement trajectory, simulates me- chanical responses under complex loads, and predicts potential collisions or structural risks [18].

3.2. Real Time Kinetic Positioning

Real-Time Kinematic (RTK) positioning is a high-precision satellite navigation technology derived from Global Navigation Satellite System (GNSS) carrier phase differential positioning. It realizes real-time dynamic positioning with centimeter-level to decimeter-level accuracy by establishing a wireless commu- nication link between a reference station (with known precise coordinates) and a rover station (the positioning target), and performing carrier phase data synchronization and differential calculation [19].

The core principle of RTK lies in the elimination of com- mon errors (e.g., satellite clock error, ionospheric delay, tropo- spheric refraction) through the differential processing of GNSS observation data [20]. The reference station continuously re- ceives satellite signals, calculates the error correction informa- tion based on its known coordinates, and transmits the data to the rover station in real time via communication modules (such as radio, 4G/5G, or Wi-Fi). The rover station combines the received correction data with its own observed carrier phase in- formation to resolve the integer ambiguity of the carrier phase quickly and accurately, thereby determining the real-time three- dimensional coordinates (longitude, latitude, and altitude) of the target.

3.3. Coordinate Transformation and Attitude Calculation

The coordinate system in the Unity system is a left-handed system. When converting the ENU coordinate system (a right- handed system: X = East, Y = North, Z = Up) to the Unity co- ordinate system (a left-handed system: X =

Right, Y = Up, Z = Forward), the core lies in addressing axis mapping and rotation direction conversion. First, convert the GNSS coordinates to Gauss projection, where the central longitude of the projection can use the coordinates of local control points. Then, convert the projected coordinates to a left-handed system. For convert- ing ENU to the XZY (Unity) coordinate system, direct mapping can be adopted, specifically: Unity.X = ENU.E (East → Right, direct assignment), Unity.Y = ENU.U (Up → Up, direct assign- ment), Unity.Z = -ENU.N (North → Forward, sign inversion to adapt to the left-handed system).

Figure 1: System overall architecture

4. System Design

4.1. Overall Architecture

The system consists of four modules: *Surveying and Map- ping (preparation work)*, *3D Visualization Platform*, *Sensor Communication*, and *Algorithm Module*, deployed on a main server and an operation guidance terminal (tablet). The overall architecture is shown in Fig. 1.

As shown in this figure, we leverage 5G for seamless com- munication to integrate data from multiple advanced sensors, including Inertial Measurement Units (IMU), and cameras, en- abling precise and safe hoisting operations. A GNSS reference station is installed at a stable location on-site, it receives sig- nals from global satellite systems (e.g., GPS, BDS, Galileo) and provides high-precision differential correction data (supporting RTK technology). This ensures centimeter-level positioning ac- curacy for all on-site GNSS receiver.

Multiple GNSS receivers are mounted on key parts of the crane (e.g., main body, boom, hook) and hoisted components to capture real-time position data. An IMU is integrated with the crane's core control unit to measure angular velocity, linear ac- celeration, and attitude (heading, pitch, roll) at high frequency (> 100Hz). This compensates for GNSS signal interruptions or delays in dynamic scenarios (e.g., boom rotation). A "GNSS + Camera" integrated device is deployed on the crane or site perimeter. The camera captures real-time video of the hoisting area (supporting 1080p full HD resolution), enabling visual ver- ification of component alignment and obstacle detection. The GNSS module attached to the camera synchronizes spatial co- ordinates with video frames, linking visual information to the digital twin model. As for aerial surveying, a drone is equipped with a high-resolution camera and GNSS receiver, the drone conducts pre-construction site scanning to generate a 3D dig- ital twin model of the terrain, buildings, and obstacles. Dur- ing operations, it can also provide an aerial overview of the hoisting process, assisting in path optimization and risk identi- fication. For communication and data transmission, 5G serves as the system's unified communication backbone (500m cover- age), addressing the need for high-bandwidth, low-latency data exchange between distributed devices.

4.1.1. Surveying and Mapping

Firstly, we do on-site surveying and mapping. We use equip- ment such as RTK to conduct on-site surveying of the experi- mental site, establish an on-site coordinate system, and create on-site 2D maps and 3D models.

1) Use Continuously Operating Reference Station (CORS) to measure no fewer than 4 control points on-site. These control points should be distributed as evenly as possible around the construction site, and the WGS84 coordinate system shall be adopted.

2) Establish the on-site coordinate system: Take the center of the 4 control points as the coordinate origin, and establish an on-site plane rectangular coordinate system using Gauss pro- jection. The coordinate system can be rotated according to the layout direction of the site, and information such as the rotation angle shall be properly saved. After confirming the on-site co- ordinate system, measure the coordinates of the 4 control points in this on-site coordinate system.

3) Create on-site 2D maps: Use surveying equipment such as RTK or total stations to measure and draw on-site 2D maps under the on-site coordinate system. The maps must include the boundaries of passable areas, the positions of hoisting targets, the deployment positions of cranes, etc.

4) Establish on-site 3D models: Adopt methods such as ground-based or UAV (Unmanned Aerial Vehicle) 3D laser scanning to build on-site 3D models. If the on-site environment is relatively simple, equipment such as RTK or total stations can also be used to measure the 3D contours of on-site build- ings, etc., and then draw on-site 3D maps in drawing software such as CAD.

There are 4 types of 3D models required for the system to work:(1) Scene models: These include the terrain, landforms of the hoisting site and buildings outside the operation area, mainly serving an aesthetic purpose. (2) Crane models: These refer to the crane models used for hoisting operations, with a maximum of 2 units. They support joint adjustments such as rotation and telescoping of the crane boom, and are generally in FBX format. (3) Component models: These are the build- ing components to be hoisted, such as box girders, which con- tain information including the installation base point positions of the monitoring GNSS. (4) Other models: These cover other necessary models, such as the completed parts of construction buildings, other structures in the hoisting operation area, and materials. They come with coordinate information and may af- fect the hoisting path.

4.1.2. Coordination Conversion

During the actual hoisting process, due to the constraints of various conditions, it is difficult to pre-plan the installation po- sition of GNSS on the box girder and achieve accurate corre- spondence with the model. Consequently, the target position coordinates for hoisting cannot be obtained. In this project, the rigid body transformation method is adopted to calculate the accurate target coordinates of the actual GNSS installation po- sition. Firstly, we calculate the coordinate transformation rela- tionship between the current position and the target position of the box girder to be lifted. The steps are as follows:

1) Obtain the target coordinates of the 4 corner points of each box girder in the Unity scene. For each box girder *m*, obtain the Unity coordinates of its 4 corner points at the preset position in Unity in advance: $C\_PBU_m^T = \{CP_i^{UT} \mid i = 1, 2, 3, 4\}$.
2) Measure the coordinates of the 4 corner points of the component to be lifted on-site: $C\_PBG_m^O = \{CP_i^O \mid i = 1, 2, 3, 4\}$.
3) Coordinate transformation. Convert $C\_PBG_m^O$ to Unity coordinates through the global transformation relationship $H_U^O(t)$: $C\_PBU_m^O = \{CP_i^{UO} \mid i = 1, 2, 3, 4\}$.
4) Calculate the coordinate transformation matrix. Calculate the transformation matrix M_O^T from the coordinates of the 4 corner points $C\_PBU_m^O$ in the current Unity scene to the hoist-ing target position $C\_PBU_m^T$. Where $C\_PBU_m^T = C\_PBU_m^O M_O^T$.

Therefore, $M_O^T = (C\_PBU_m^O)^{-1} * C\_PBU_m^T$.

Next, We calculate the expected target coordinates of the ac- tual GNSS installation position on the box girder to be lifted. The steps are as follows:

(1) Obtain the coordinates of the GNSS installation point. Convert the current coordinates of the GNSS installation point $G\_PBG_m^O = \{GP_i^O \mid i = 1, 2, 3\}$ to the Unity coordinate system coordinates $G\_PBU_m^O = \{GP_i^{UO} \mid i = 1, 2, 3\}$.

(2) Calculate the coordinates of the hoisting target point. Cal- culate the expected target position of the current GNSS installation point $C\_PBU_m^T = \{CP_i^{UT} \mid i = 1, 2, 3, 4\}$. through the transformation matrix, as $C\_PBU_m^T = C\_PBU_m^O * M_O^T$.

4.1.3. 3D Visualization Platform

(1) 3D Model Reading and Writing

Read 3D models of the construction site, including the construction site 3D scene, crane model, hoisting component model, building model, and personnel model. Among them, the crane model shall include components such as the main unit, boom, hoisting rope, and hook; these components can move in- dependently according to the position and posture monitored by sensors.

(2) Collision Detection

Use Unity's built-in collision detection algorithm to detect in real time the collision between moving models (crane, compo- nents, personnel) and other models. The function of setting a collision buffer zone shall be supported.

(3) 3D Model Display and Interaction

Display 3D models on demand, with a selection function; different states shall be displayed through special effects such as colors. It shall support setting whether the selected model participates in collision detection, as well as moving or rotating the model. Additionally, it shall support interactive addition of waypoints, and functions such as setting the eye position of the main view, the observation point position, and the field of view.

(4) Information Display

Display data from various sensors, including position, pos- ture, speed, position difference, video images, and meteorolog-ical information. It shall have functions for setting data display selection, font, color, and display area. Display the entire scene in a top-down view, and support switching the display area with the main view.

(5) Communication and Guidance

The system establishes seamless communication with multiple GNSS and IMU sen- sors to acquire real-time position and attitude data of the crane and its components, interfaces with multiple video cameras to transmit and display camera feeds synchronously, dynamically updates the position and attitude parameters of the crane and components in the 3D model in real time based on the latest sensor data to achieve accurate digital-physical synchroniza- tion, precisely calculates the 3D distance deviation and angular deviation between the current position of the lifted component and the target installation position and intuitively presents these deviations on the main interface (e.g., via numerical readouts or color-coded indicators), and generates data-driven guided con- struction instructions based on the deviations, such as ”Raise X meters” or ”Turn left X degrees”, to provide clear operational guidance for on-site construction personnel.

(6) Risk Early Warning

Based on the monitoring data from various on-site sensors, issue risk early warnings in the form of pop-up animations com- bined with sounds. That is, 1) Trigger alarm animations and sound alarm beeps according to different types of risks. 2) De- sign different warning indicators for various risk types, includ- ing but not limited to: collisions between hoisting objects and vehicles, personnel intrusion, crane tipping, boom bending (or breaking), hoist rope slippage, and adverse weather (wind, rain, snow). The early warning scenarios include but are not limited to: collision between hoisted objects and vehicles, personnel intrusion, crane overturning, boom bending (fracture), hoisting rope slipping, and severe weather (wind, rain, snow).

Algorithm is shown in 1. First, target parameters are acquired from the 3D model, involving reading the 3D scene of the con- struction site, crane model, hoisting component model, building model, personnel model and other relevant models. Then cur- rent parameters are obtained from real-time monitoring equip- ment, including the positional information of the crane, jib, hoisting rope, hook and other components. Next, deviations are calculated, which covers coordinate system transformation and attitude calculation. Finally, the deviations are converted into guidance instructions, such as lifting/lowering instructions, movement instructions, rotation instructions and so on.

The p-axis denotes the left-right direction, the q-axis repre- sents the front-back direction, and the r-axis corresponds to the up-down (vertical) direction in the hoisting scenario. $dp_{,cur}$ is the current distance difference on $x-axis$ direction, and $dp_{,tar}$ is the target one. The Algorithm first retrieves target relative dis- tances $L'[x, y] = [dp_{,tar}, dq_{,tar}, dr_{,tar}]$ (corresponding to the three- axis target distances between fixed and moving Beidou posi- tioning points) from the 3D model M of the hoisting scene, where S_{fixed} denotes the set of fixed Beidou reference points on the construction site and S_{moving} represents the set of moving Beidou positioning points mounted on the hoisted component. It then enters a core iterative loop: at each iteration, the algo- rithm reads real-time 3D coordinates $[pj, qj, rj]$ of all points in $S_{fixed} \cup S_{moving}$, waits for the preset data refresh interval T_{update}, calculates the current relative distances $[dp_{,cur}, dq_{,cur}, dr_{,cur}]$ be- tween each fixed-moving point pair, and computes the posi- tion errors $\Delta p = |dp_{,cur} - dp_{,tar}|$, $\Delta q = |dq_{,cur} - dq_{,tar}|$, and $\Delta r = |dr_{,cur} - dr_{,tar}|$. If all computed errors are within the pre- defined tolerable error threshold Δ_{tol}, the algorithm marks the process as converged, outputs the ”HOISTING

COMPLETED” command, and terminates; otherwise, it generates axis-specific hoisting adjustment commands (left/right for the p-axis, back- ward/forward for the q-axis, and lower/hoist for the r-axis) based on the comparison between current and target distances, and repeats the loop until all errors meet the tolerance require- ment.

Algorithm 1 Real-Time Hoisting Comparison & Distance Hoisting Command Generation Algorithm

Require: M: 3D model (target relative distances $L'[x, y]$),
S_{fixed}: Fixed Beidou points (non-moving),
S_{moving}: Moving Beidou points (on hoisted component), T_{update}: Data refresh interval (s),
Δ_{tol}: Tolerable error (> 0, m)
Ensure: Direct hoisting adjustment/completion commands (executable)
for all $L[x] \in S_{\text{fixed}}, L[y] \in S_{\text{moving}}$ **do**
  Retrieve $L'[x, y] = [d_{p,\text{tar}}, d_{q,\text{tar}}, d_{r,\text{tar}}]$ from M
end for
converged ← *false*
while *converged* = *false* **do**
  for all $L[j] \in S_{\text{fixed}} \cup S_{\text{moving}}$ **do**
    Read $L[j] = [p_j, q_j, r_j]$ (real-time 3D coordinates)
  end for
  Wait T_{update}
  all_errors_within_tol ← *true*
  for all $L[x] \in S_{\text{fixed}}, L[y] \in S_{\text{moving}}$ **do**
    $d_{p,\text{cur}} = L[x].p - L[y].p$, $d_{q,\text{cur}} = L[x].q - L[y].q$, $d_{r,\text{cur}} = L[x].r - L[y].r$
    $\Delta_p = |d_{p,\text{cur}} - d_{p,\text{tar}}|$, $\Delta_q = |d_{q,\text{cur}} - d_{q,\text{tar}}|$, $\Delta_r = |d_{r,\text{cur}} - d_{r,\text{tar}}|$
    if $\Delta_p > \Delta_{\text{tol}} \vee \Delta_q > \Delta_{\text{tol}} \vee \Delta_r > \Delta_{\text{tol}}$ **then**
      all_errors_within_tol ← *false*
    end if
  end for
  if *all_errors_within_tol* **then**
    converged ← *true*
    Output HOISTING COMPLETED
    Continue;
  end if
  for all $L[x] \in S_{\text{fixed}}, L[y] \in S_{\text{moving}}$ **do**
    $d_{p,\text{cur}} = L[x].p - L[y].p$, $d_{q,\text{cur}} = L[x].q - L[y].q$, $d_{r,\text{cur}} = L[x].r - L[y].r$
    if $|d_{p,\text{cur}} - d_{p,\text{tar}}| > \Delta_{\text{tol}}$ **then**
      Output $\begin{cases} \text{MOVE LEFT} & d_{p,\text{cur}} > d_{p,\text{tar}} \\ \text{MOVE RIGHT} & \text{else} \end{cases}$
    end if
    if $|d_{q,\text{cur}} - d_{q,\text{tar}}| > \Delta_{\text{tol}}$ **then**
      Output $\begin{cases} \text{MOVE BACKWARD} & d_{q,\text{cur}} > d_{q,\text{tar}} \\ \text{MOVE FORWARD} & \text{else} \end{cases}$
    end if
    if $|d_{r,\text{cur}} - d_{r,\text{tar}}| > \Delta_{\text{tol}}$ **then**
      Output $\begin{cases} \text{LOWER} & d_{r,\text{cur}} > d_{r,\text{tar}} \\ \text{HOIST} & \text{else} \end{cases}$
    end if
  end for
end while
Termination: Hoisting completed

4.1.4. Engineering Management

We provide full-life-cycle project management:

• Guided project creation (input engineering information, sensor configuration, coordinate system parameters);

• Data storage and playback (sensor data, commands, warn- ings) with time-based retrieval;

• Automatic report generation (simulation, implementation, review reports) compatible with Office formats.

GNSS positioning and trajectory data adopt the NMEA-0183 format, which mainly stores information such as GPGGA and GPRMC, with a frequency of 1Hz. The hoisting guidance playback video adopts the H.264 format and is encapsulated in MP4. It can be saved in segments of 1 hour each to facili- tate quick indexing. Also, the experimental summary report is saved in DOCX or PPTX format.

4.1.5. Sensor Communication

We set up the 5G network using free5GC, which runs on HP x86 server with Ubuntu 18 and connected to the eNB via an Ethernet cable. The eNB, equipped with an antenna, communi- cates with mobile terminals over a wireless channel.

The network system components are shown in Fig. 2:

Fig. 2a shows the card reader and syscocom sim card. The SIM cards information includes international mobile subscriber identity (IMSI), subscriber key (K), and opera- tor code (OPC). For example, IMSI = 208930000000001, K = '8baf473f2f8fd09487cccbd7097c6862', and OPC = '8e27b6af0e692e750f32667a3b14605d'. Fig. 2b shows a cell station, which operates on Band 7 and has a bandwidth of 10MHz. The antenna has a 35dB gain, providing a coverage range of about 100m.

The Huawei USB dongle is shown in Fig. 2c. This device supports 3G/4G connectivity and communicates with the net- work via a USB interface. It comes pre-installed with SIM cards that we have pre-programmed. The information contained in these SIM cards is identical to the information registered in the 5G core network.

5G supports multi-protocol data transmission:

1. GNSS/IMU: TCP server for NMEA-0183 data parsing (position, time, attitude).

2. Cameras: Software Development Kit (SDK) integration for RTSP/HTTP video streaming, supporting screenshots. Set video parameters, receive and display video images, and support taking screenshots and saving them as image files.

3. Meteorological sensors: Wireless reception of wind speed, temperature, and humidity data.

4.2. Implementation Details

All core algorithms are implemented in C# scripts/standard DLLs:

(1) Coordinate Conversion Tool (CoordTools.cs)

It provides geographic information processing functions such as coordinate system conversion and azimuth calculation, and is a core tool class of the project. It uses parameters of the 2000 National Geodetic Coordinate System to achieve high-precision coordinate conversion calculations.

It has some key classes and interfaces as follows:

• *CoordTools*: Provides a static method GetAzimuth to cal- culate the azimuth between two points for determining di- rections.

• *IProjectionConversion*: Defines a projection conversion interface, including methods for mutual conversion be- tween longitude-latitude coordinates and plane coordi- nates.

- *ProjectionConversion*: Implements the Gauss projection conversion algorithm, supporting 3-degree zone and 6- degree zone projection modes. Its main functions in- clude: *GetBLFromXY*: Converts Gauss plane coordi- nates to geodetic coordinates (longitude and latitude) *GetXYFromBL*: Converts geodetic coordinates (longitude and latitude) to Gauss plane coordinates.

(2) Serial Communication Module (SerialPort Directory)

It is responsible for serial communication with external GNSS devices, including receiving, parsing, and processing GNSS data.

It has some key classes and interfaces as follows, supporting JSON format serialization and deserialization:

- *GGA Class*: Parses and processes GGA sentences in the NMEA protocol, containing information such as time, lon- gitude, latitude, and elevation.

- *POSCheck Class*: Manages the coordinate and attitude in- formation of 3 GNSS points on the box girder, and calcu- lates the yaw angle, pitch angle, and roll angle.

- *SPGNSS Class*: Implemented in a singleton pattern, re- sponsible for reading and processing serial port data, pars- ing GGA data, and converting it to the Gauss coordinate system.

(3) GNSS Data Playback Module (GNSSPlayback.cs)

Its main function is to load and play back GNSS log data, used to simulate the real-time data output of GNSS devices.

(a) Sysmocom SIM card (b) 4G base station (c) Dongle device

Figure 2: Hardware devices for fast networking system

- *BoardcastEpoch structure*: Stores multiple GGA data at a specific time point.

- *LoadBoardcastItem method*: Loads GGA data from log files and organizes them by time.

- *GetPOS method*: Obtains current GNSS position informa- tion at time intervals, and calculates speed and attitude an- gles.

Besides, we implement a thread-safe singleton pattern base class, ensuring thread safety using nested classes and static con- structors. Classes such as SPGNSS in the project implement singletons based on this (Singleton.cs). We also extend the Sys- tem.IO.Directory class, providing more flexible file retrieval ca- pabilities and supporting conditional filtering. In IniHelper.cs, we finish reading and writing of INI files by calling Windows API through P/Invoke, used for configuration management.

5. Experiment

5.1. Evaluation Indicators

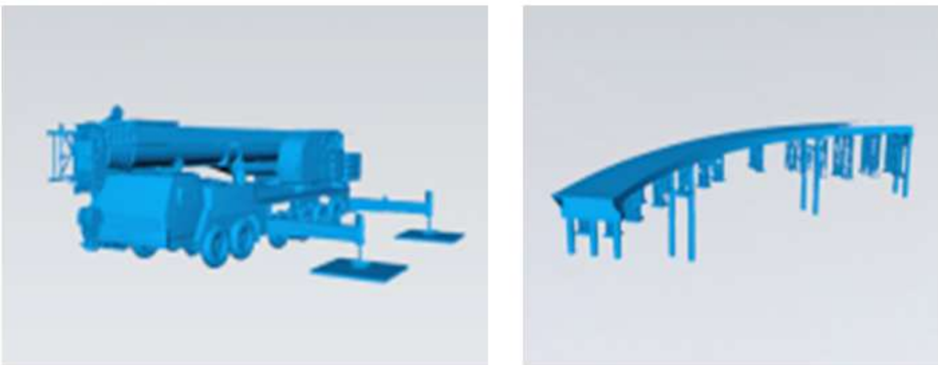
The indicators are as follows:

Table 1: Experimental evaluation indicators

Indicator	Requirement
Positioning accuracy	Horizontal/Vertical error <2/3cm
Data processing delay	<0.5s
Visualization frame rate	>30fps
Warning response time	<1s
System stability	7/24h continuous operation

5.2. Setup

The experimental setup's hardware configuration and in- stallation were engineered for high-precision crane opera- tion/component positioning monitoring and reliable data trans- mission. Key hardware included survey-grade GNSS termi- nals (multi-constellation support, RTK accuracy: 1cm+1ppm horizontal/1.5cm+1ppm vertical, 1–20Hz adjustable update rate, 4G/5G/5G/NTRIP communication, <30s cold start), high- stability consumer-grade IMUs (gyroscopes: ±500°/s range, $XY < 4.0/h/Z < 3.0/h$ zero bias instability; accelerometers: ±6g range, $XY < 20\mu g/Z < 40\mu g$ zero bias instability, -40°C to 85°C operating temp), IP66 cameras (1080p/30fps, 5G/PoE), and 10-inch 5G tablets (Huawei/Mi, universal bracket).



(a) Crane model (b) Bridge model

Figure 3: Crane and bridge models

5.3. Unity System

5.3.1. Model Management

We present the crane and bridge models in Fig. 3, which serves as the preparation model for the system's Unity front end.

Fig. 3a shows a detailed 3D model of a mobile crane, ren- dered in blue. The model accurately reproduces the crane's structural features, including its multi-wheeled chassis, outrig- gers (deployed during hoisting operations to ensure stability), and the extended crane boom. It supports dynamic joint ad- justment functions such as the rotation and telescoping of the crane boom, enabling precise simulation of real-world hoisting movements. Typically formatted in FBX, it can serve as a dig- ital replica in virtual environments for testing operational sce- narios, planning paths, and detecting collisions. Fig. 3 presents a 3D model of a bridge structure, also rendered in blue. The model depicts various components of the bridge, such as bridge piers and prefabricated box girders (construction components to be hoisted).

5.3.2. Sensor Data Showing

We present a high-fidelity digital twin visualization, devel- oped in Unity in Fig. 4, depicting an intelligent bridge con- struction scenario with integrated GNSS precise positioning ca- pabilities. In the foreground, a yellow hoisting crane is actively engaged in lifting a steel box girder, which is being transported by a heavy-duty truck. The crane's operations are underpinned by real-time GNSS-based positioning, as evidenced by the data panel in the top-left corner. This panel displays critical posi- tional information: the project name is G-83, with the current coordinates of the hoisted component recorded as X: 42.6001, Y: 8.81002, Z: 416.042, and the target coordinates set at X: 44.2377, Y: 8.26879, Z: 397.303. The coordinate differences are calculated as X: 1.63768, Y: 4.45857, Z: -18.738, provid- ing precise guidance for the crane's movement to ensure the box girder is placed accurately at its designated location. The scene also showcases a partially constructed bridge, with multi- ple steel box girders already installed across the piers, while the remaining section awaits the current girder's placement. The surrounding environment is rendered with realistic terrain, in- cluding green fields, a body of water, and an adjacent highway, creating an immersive digital replica of the actual construction site.

Figure 4: System front-end with sensor data

5.4. Network Performance Results

Once configured, we fixed the location of 4G cell station and tested the network performance. Firstly, we test the network latency and jitter under different distances.

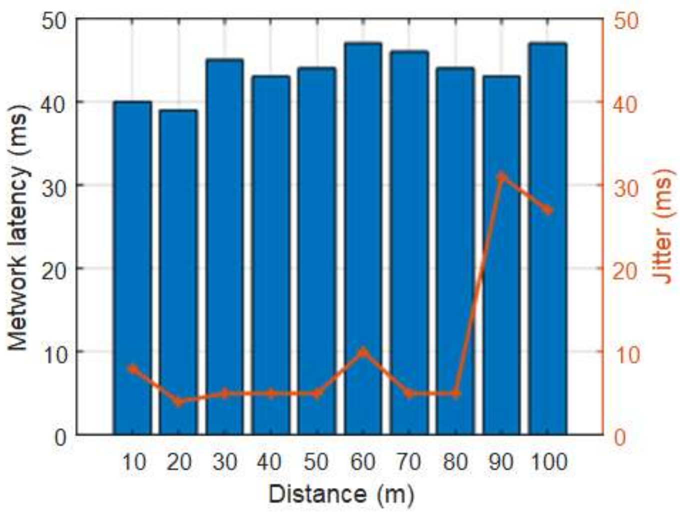


Figure 5: Network latency of different distance.

As shown in Fig. 5, the network latency results are all below 50ms with an average of 40ms when phones are 10m-100m away from the cell station. The network jitter remains stable under 10ms when phones and cell station are 10m-100m apart. When phones and cell station are far away from 90-100m, the network latency remains relatively stable. However, the net- work jitter are increasing significantly, up to 25ms-30ms. Over- all, our 5G NSA real testbed delivers latency below 50ms and maintains low network jitter of 5ms within an 80m coverage range.

Then, we measure the uplink and downlink throughput under different distances.

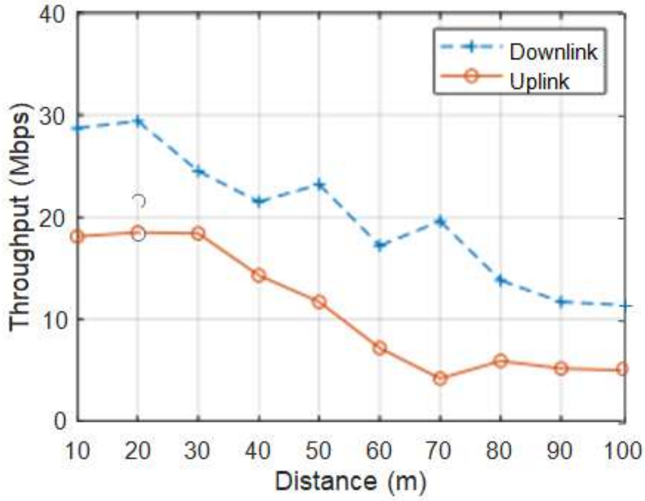


Figure 6: Network throughput of different distance.

As shown in Fig. 6, with increasing distance, both up- link and downlink throughput gradually decrease. The uplink throughput starts at 20M bit per second (bps) and declines to 5Mbps, while downlink throughput starts at 30Mbps and drops to 10Mbps as the distance increases from 10m to 100m. There- fore, our 4G real testbed supports uplink throughput of up to 20Mbps and downlink throughput of 30Mbps. For optimal per- formance, it is recommended to use mobile devices within a 70m coverage range.

5.5. Real-world Deployment

Fig. 7 presents the real-world deployment of the digital twin- based intelligent hoisting system in the Huangpi-Xinzhou Sec- tion of Wuhan Metropolitan Area Ring Expressway project, consisting of two subfigures that illustrate key on-site hardware configurations and operational scenarios.

Fig. 7a shows the on-site remote operation and data acqui- sition setup. A 5G-enabled tablet (serving as the operation guidance terminal) is deployed to realize remote control of the crane, with real-time display of sensor data (e.g., position, at- titude, and risk alerts) synchronized from the system's 3D vi- sualization platform. The setup eliminates the need for on-site commanders near the hoisting target, reducing labor costs and safety risks.

Fig. 7b depicts the multi-sensor deployment on the hoisted steel box girder. Multiple high-precision GNSS receivers are mounted at key positions of the box girder to capture centimeter-level real-time positioning data via RTK technology. Supplementary sensors (e.g., IMUs for attitude measurement, wind sensors for meteorological data, and integrated GNSS-camera devices for visual verification) are also installed, form- ing a comprehensive perception network to support digital-physical synchronization and risk early warning of the digital twin system.

(a) Remote control and data collection

(b) GNSS and other sensors deployed on box girder

Figure 7: Real-world deployment

6. Conclusion

This study presents a digital twin-based intelligent guidance system for crane hoisting, integrating multi-sensor fusion, coor- dinate transformation, and 3D visualization. The system's mod- ular design enables simulated construction, on-site guidance, risk early warning, and construction review. Detailed hard- ware configuration and installation guidelines ensure practi- cal applicability. Multi-scenario experiments verify centimeter-level positioning accuracy, real-time performance, and reliable risk warning. Comparative analysis with industry cases con- firms the system's superiority in efficiency and safety improve- ment. This research provides a technical solution for intelligent and safe hoisting in bridge construction, with broad application prospects in civil engineering.

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