

A Digital Twin-Based Closed-Loop Deployment Framework for GNSS-Capable Smart Cones in Planned Traffic-Control Operations

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Abstract—Reliable deployment of temporary traffic-control devices is essential for planned traffic-control operations. However, conventional traffic cone deployment is often performed manually, which may introduce deployment uncertainties and expose workers to safety risks in high-traffic or high-speed environments. This paper proposes a digital twin-based closed-loop deployment framework for GNSS-capable smart cones. The proposed framework represents the planned traffic-control layout in a digital twin, generates smart-cone deployment tasks, receives GNSS feedback from deployed cones, and updates the observed layout accordingly. To support closed-loop operation, the proposed framework assesses deployment quality based on position, spacing, and topology consistencies between the planned and observed layouts. In addition, a deployment quality score is introduced to support correction or manual inspection decisions. A software-in-the-loop evaluation is designed to analyze representative uncertainties, including GNSS noise, placement deviation, missing cones, spacing violations, and topology deformation. The proposed framework provides a practical basis for transforming traffic-cone deployment from manual placement into a measurable, traceable, and auditable closed-loop process.

Index Terms—Digital twin, GNSS smart cones, closed-loop deployment, planned traffic-control operations, deployment quality assessment, intelligent transportation systems

I. INTRODUCTION

Temporary traffic control devices are widely used in planned traffic control operations, such as road maintenance, incident management, lane management, public-event traffic control, and temporary road closure. In these operations, traffic cones are deployed to guide vehicles, separate traffic flows, define restricted areas, and protect workers, responders, pedestrians, or event participants.

In conventional deployment, traffic cones are often placed manually according to a traffic-control plan, field experience, or on-site instructions. This personnel-based deployment can suffer from inaccurate placement, missing cones, inconsistent spacing, unintended displacement, and deformation of the planned layout. More importantly, when cones are deployed in live traffic, incident scenes, or crowded public-events areas, deployment personnel may be exposed to safety risks. These

limitations motivate the need for a measurable, traceable, and closed-loop deployment process.

Recent studies have explored digital twins (DT) for intelligent transportation systems, including traffic monitoring, prediction, simulation, adaptive control, transportation network optimization, and intelligent road inspection [1]–[3]. In parallel, smart work zones and connected temporary traffic-control devices have been investigated for sensor-based work zone safety, location reporting, work zone perception, and connected work zone management [4]–[6]. Automated and semi-automated work-zone systems, such as automated cone placement robots, have also been studied to reduce personnel exposure and improve operational safety [7]. However, existing studies have not sufficiently integrated traffic-control layout planning, smart-cone deployment task generation, deployment execution, GNSS-based layout feedback, and deployment quality assessment into a DT-based unified closed-loop framework.

This paper proposes a closed-loop digital deployment framework based on digital twins for GNSS-capable smart cones in planned traffic-control operations. In the proposed framework, a digital twin represents the planned traffic-control layout and generates deployment tasks, including target positions, cone identifiers, deployment order, and allowable placement tolerance. These tasks can be executed by smart self-deploying cones, automated guided vehicle (AGV)-based cone deployment carriers, or, in low-risk environments, human-assisted deployment processes. After deployment, GNSS-capable smart cones report their observed positions, and the digital twin updates the deployed layout accordingly.

By comparing the planned and observed cone layouts, the framework evaluates position, spacing, and topology consistencies and computes a deployment quality score to support correction or manual inspection decisions. The scope of this paper is limited to closed-loop deployment, while deployment-executor control, path planning, cone manipulation, semantic interpretation, driver warning generation, and traffic impact evaluation are beyond the scope of this work.

The main contributions of this paper are summarized as

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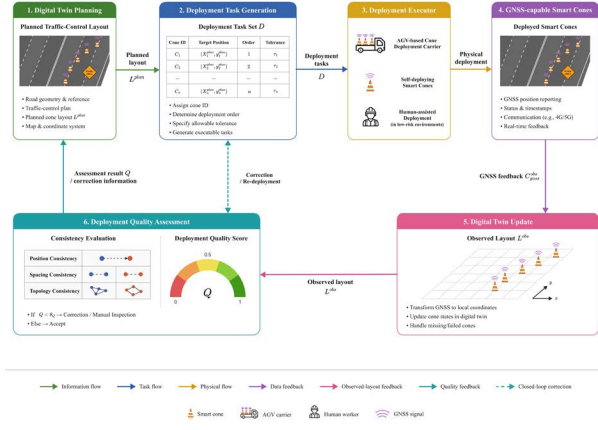


Fig. 1. Digital twin-based closed-loop deployment framework for GNSS-capable smart cones. The framework connects traffic-control layout planning, deployment task generation, deployment execution, GNSS feedback, digital twin update, and deployment quality assessment.

follows:

- We propose a DT-based closed-loop deployment framework for GNSS-capable smart cones in planned traffic-control operations.
- We model the deployment process as a closed loop consisting of layout planning, deployment task generation, deployment execution, GNSS feedback, digital twin update, and deployment quality assessment.
- We define deployment consistency metrics and a deployment quality score based on the position, spacing, and topology consistencies between planned and observed cone layouts.
- We design a software-in-the-loop evaluation to analyze representative deployment uncertainties, including GNSS noise, placement deviation, missing cones, spacing violations, and topology deformation.

II. SYSTEM MODEL AND PROBLEM FORMULATION

Fig. 1 illustrates the proposed DT-based closed-loop deployment framework for GNSS-capable smart cones. The framework consists of six functional modules: a digital twin planning module, a deployment task generation module, a deployment execution layer, GNSS-capable smart cones, a digital twin state update module, and a deployment quality assessment module. The objective of the framework is to transform a planned traffic-control layout into an executable deployment task, update the digital twin according to the GNSS feedback reported by the deployed smart cones, and evaluate whether the observed deployment satisfies the planned layout.

A. Planned Traffic-Control Layout

Let the planned traffic-control layout represented in the digital twin be denoted as:

$$\mathcal{L}^{plan} = \{p_i^{plan} \mid i = 1, 2, \dots, n\}, \quad (1)$$

where $p_i^{plan} = (x_i^{plan}, y_i^{plan})$ is the planned local coordinate of the i -th cone, and n is the number of cones in the planned layout. The planned layout may correspond to a temporary lane closure, lane diversion, pedestrian separation, restricted area, or other planned traffic-control configuration.

The local coordinate system is defined with respect to the target deployment area. In this paper, the transformation of coordinates from geographic coordinates to the local digital twin coordinate system is assumed to be available through map information or predefined reference points. All distance-based metrics in this paper are computed in the local digital twin coordinate system. Unless otherwise specified, $\|\cdot\|_2$ denotes the Euclidean norm.

B. Deployment Task Generation

Based on the planned layout, the digital twin generates a set of deployment tasks:

$$\mathcal{D} = \{d_i \mid i = 1, 2, \dots, n\}. \quad (2)$$

Each deployment task is defined as

$$d_i = \{c_i^{id}, p_i^{plan}, o_i, \tau_i\}, \quad (3)$$

where c_i^{id} is the identifier of the assigned smart cone, p_i^{plan} is the target deployment position, o_i is the deployment order, and τ_i is the allowable placement tolerance.

The set of deployment tasks $\mathcal{D}$ is assumed to be executed by an underlying deployment executor. This paper abstracts the executor as a task execution layer and does not address its motion control, navigation, or manipulation mechanisms.

C. GNSS Feedback and Observed Layout

After deployment, each GNSS-capable smart cone reports its observed state:

$$c_i^{obs} = \{c_i^{id}, lat_i, lon_i, t_i, s_i\}, \quad (4)$$

where lat_i and lon_i are the reported GNSS coordinates, t_i is the timestamp, and s_i is the cone status. The observed GNSS coordinates are transformed into the local digital twin coordinate system:

$$p_i^{obs} = T(lat_i, lon_i) = (x_i^{obs}, y_i^{obs}), \quad (5)$$

where $T(\cdot)$ denotes the coordinate transformation function. The observed deployment layout is then represented as:

$$\mathcal{L}^{obs} = \{p_i^{obs} \mid i = 1, 2, \dots, m\}, \quad (6)$$

where m is the number of smart cones successfully reported after deployment. In practical deployments, m may be smaller than n because of missing cones, communication failures, or unsuccessful deployment.

D. Deployment Quality Assessment Problem

Given the planned layout $\mathcal{L}^{plan}$, the set of deployment tasks $\mathcal{D}$, and the observed layout $\mathcal{L}^{obs}$, the deployment quality assessment problem is formulated as

$$Q = \Psi(\mathcal{L}^{plan}, \mathcal{L}^{obs}, \mathcal{D}), \quad (7)$$

where $Q \in [0, 1]$ denotes a deployment quality score. A higher value of Q indicates that the observed-cone layout is more consistent with the planned layout.

In this paper, the quality score is computed based on three aspects: position consistency, spacing consistency, and topology consistency. The corresponding consistency result is denoted as:

$$\mathcal{V} = \{C_p, C_s, C_t\}, \quad (8)$$

where C_p , C_s , and C_t represent position, spacing, and topology consistencies, respectively.

The overall closed-loop deployment process can therefore be summarized as:

$$\mathcal{L}^{plan} \rightarrow \mathcal{D} \rightarrow C_{gnss}^{obs} \rightarrow \mathcal{L}^{obs} \rightarrow \mathcal{V} \rightarrow Q. \quad (9)$$

If the quality score of deployment Q is lower than a predefined threshold θ_Q , the system marks the deployment as requiring correction or manual inspection. The generated correction information can be returned to the digital twin as the basis for a subsequent deployment update.

III. CLOSED-LOOP DEPLOYMENT AND QUALITY ASSESSMENT

This section presents the proposed closed-loop deployment and quality assessment method. After the digital twin generates the set of deployment tasks and the cones are deployed, GNSS feedback is used to update the observed layout. The quality of the deployment is then evaluated by comparing the planned and observed cone layouts.

A. Digital Twin Update after Deployment

Given the set of deployment tasks $\mathcal{D}$, the deployment executor places the assigned smart cones at their target locations. After deployment, the reported GNSS coordinates are transformed into the local digital twin coordinate system, forming the observed layout $\mathcal{L}^{obs}$.

Since some cones may fail to report their positions or may not be successfully deployed, we define the matched cone index set as follows:

$$\mathcal{M} = \{i \mid p_i^{plan} \in \mathcal{L}^{plan} \text{ and } c_i^{id} \text{ is matched in } \mathcal{L}^{obs}\}, \quad (10)$$

where the cone identifier c_i^{id} is specified by the deployment task $d_i \in \mathcal{D}$. Each matched cone has both a planned position and an observed position. The reporting ratio is defined as:

$$\rho = \frac{|\mathcal{M}|}{n}, \quad (11)$$

where n is the number of cones in the planned layout. A smaller ρ indicates missing cones, communication failures, or unsuccessful deployment.

B. Position Consistency

Position consistency evaluates whether each deployed cone is close to its planned target location. For each matched cone $i \in \mathcal{M}$, the position error is defined as:

$$e_i = \|p_i^{obs} - p_i^{plan}\|_2. \quad (12)$$

The average position error is computed as:

$$E_p = \frac{1}{|\mathcal{M}|} \sum_{i \in \mathcal{M}} e_i. \quad (13)$$

When no cone is matched, the deployment is regarded as a complete reporting failure and C_p is set to zero.

The position consistency score is defined as:

$$C_p = \rho \cdot \exp\left(-\frac{E_p}{\sigma_p}\right), \quad (14)$$

where σ_p is a scaling parameter for position tolerance. The reporting ratio ρ is included to penalize missing or unreported cones. Thus, C_p decreases when the deployed cones deviate from their planned positions or when some cones are missing.

C. Spacing Consistency

Spacing consistency evaluates whether the relative distances between adjacent cones are preserved after deployment. Let $\mathcal{E}^{plan}$ be the set of adjacent cone pairs in the planned layout:

$$\mathcal{E}^{plan} = \{(i, j) \mid i \text{ and } j \text{ are adjacent in } \mathcal{L}^{plan}\}. \quad (15)$$

For each adjacent pair $(i, j) \in \mathcal{E}^{plan}$, the planned spacing is defined as

$$d_{ij}^{plan} = \|p_i^{plan} - p_j^{plan}\|_2. \quad (16)$$

If both cones are matched, i.e., $i \in \mathcal{M}$ and $j \in \mathcal{M}$, the observed spacing and spacing error are defined as:

$$d_{ij}^{obs} = \|p_i^{obs} - p_j^{obs}\|_2, \quad (17)$$

and

$$s_{ij} = |d_{ij}^{obs} - d_{ij}^{plan}|, \quad (18)$$

respectively. The spacing violation penalty is defined as:

$$\phi_{ij}^s = \begin{cases} \mathbf{1}(s_{ij} > \theta_s), & i \in \mathcal{M}, j \in \mathcal{M}, \\ 1, & \text{otherwise.} \end{cases} \quad (19)$$

where θ_s is the allowable spacing deviation and $\mathbf{1}(\cdot)$ is the indicator function. The spacing violation ratio is computed as

$$R_s = \frac{1}{|\mathcal{E}^{plan}|} \sum_{(i,j) \in \mathcal{E}^{plan}} \phi_{ij}^s. \quad (20)$$

The spacing consistency score is then defined as:

$$C_s = 1 - R_s. \quad (21)$$

A higher C_s indicates that the deployed cones preserve the planned spacing more reliably.

D. Topology Consistency

Topology consistency evaluates whether the structural relationships of the planned cone layout are preserved after deployment. Compared with spacing consistency, topology consistency evaluates the vector deformation of the planned adjacency relations.

For each planned adjacent pair $(i, j) \in \mathcal{E}^{plan}$, the planned and observed adjacency vectors are defined as:

$$\mathbf{g}_{ij}^{plan} = \mathbf{p}_j^{plan} - \mathbf{p}_i^{plan}, \quad (22)$$

$$\mathbf{g}_{ij}^{obs} = \mathbf{p}_j^{obs} - \mathbf{p}_i^{obs}. \quad (23)$$

The topology deformation of the adjacency relation is defined as:

$$\Delta_{ij}^{topo} = \|\mathbf{g}_{ij}^{obs} - \mathbf{g}_{ij}^{plan}\|_2. \quad (24)$$

For each planned adjacent pair $(i, j) \in \mathcal{E}^{plan}$, the normalized topology deformation penalty is defined as:

$$\phi_{ij}^{topo} = \begin{cases} \min\left(1, \frac{\Delta_{ij}^{topo}}{\theta_t}\right), & i \in \mathcal{M}, j \in \mathcal{M}, \\ 1, & \text{otherwise,} \end{cases} \quad (25)$$

where θ_t is the tolerance to topological deformation. If either cone in the pair is missing, the corresponding adjacency relation is assigned the maximum deformation penalty. The normalized topology deformation score is computed as:

$$D_t = \frac{1}{|\mathcal{E}^{plan}|} \sum_{(i,j) \in \mathcal{E}^{plan}} \phi_{ij}^{topo}. \quad (26)$$

The topology consistency score is then defined as:

$$C_t = 1 - D_t. \quad (27)$$

A lower C_t indicates that the deployed layout may suffer from missing cones, broken cone sequences, disconnected boundaries, or topological deformation.

E. Deployment Quality Score

The overall deployment quality score combines the three consistency scores:

$$Q = w_p C_p + w_s C_s + w_t C_t, \quad (28)$$

where w_p , w_s , and w_t are non-negative weighting factors satisfying

$$w_p + w_s + w_t = 1. \quad (29)$$

In this paper, the weighting factors are treated as deployment-policy parameters. Unless a specific operational priority is given, equal weighting is used as the default setting, i.e.,

$$w_p = w_s = w_t = \frac{1}{3}. \quad (30)$$

This default setting avoids introducing task-specific bias into the prototype evaluation. In practical deployments, the weights can be adjusted according to operational requirements. For example, a task requiring strict placement accuracy may assign a larger w_p , while a layout that relies on continuous cone

sequences or restricted-area boundaries may assign a larger w_t . The score $Q \in [0, 1]$ represents the overall reliability of the deployed cone layout. A higher value of Q indicates that the observed deployment is more consistent with the planned traffic-control layout.

The deployment decision is defined as:

$$Decision = \begin{cases} Accept, & Q \geq \theta_Q, \\ Correction, & Q < \theta_Q, \end{cases} \quad (31)$$

where θ_Q is the minimum acceptable deployment quality threshold. If $Q < \theta_Q$, the digital twin marks the layout as requiring correction or manual inspection. The correction information can then be used to generate a subsequent deployment update task.

IV. PROTOTYPE AND SOFTWARE-IN-THE-LOOP EVALUATION

This section presents the prototype implementation and software-in-the-loop evaluation design of the proposed DT-based closed-loop deployment framework. The objective is to examine whether the proposed consistency metrics and deployment quality score can reflect representative deployment uncertainties in planned traffic-control operations.

A. Prototype Implementation

The software prototype implements four core software modules of the proposed framework: a digital-twin layout planner, a deployment task generator, a deployment feedback emulator, and a deployment quality assessment module. The digital-twin layout planner represents a planned traffic-control layout in a local coordinate system. The deployment task generator converts the planned layout into a task set $\mathcal{D}$, including cone identifiers, target positions, deployment order, and allowable placement tolerance.

The deployment feedback emulator generates observed cone positions to emulate GNSS feedback under representative deployment uncertainties. The deployment quality assessment module computes the reporting ratio ρ , position consistency C_p , spacing consistency C_s , topology consistency C_t , and the overall deployment quality score Q . If Q is lower than the threshold θ_Q , the layout is marked as requiring correction or manual inspection.

B. Evaluation Scenarios and Metrics

A baseline case and five representative deployment uncertainty scenarios are considered in the software-in-the-loop evaluation. These scenarios are summarized in Table I. The evaluation focuses on the relationship between deployment uncertainty and deployment quality. The main metrics are summarized in Table II.

C. Results and Discussion

In the software-in-the-loop evaluation, a planned layout with 20 cones was generated in the local digital twin coordinate system. The nominal cone spacing and task tolerance were set to 10 m and 0.3 m, respectively. Unless otherwise

TABLE I
SOFTWARE-IN-THE-LOOP EVALUATION SCENARIOS.

Scenario	Description
GNSS noise	Gaussian noise added to reported cone positions.
Placement deviation	Systematic layout shift with small jitter.
Missing cones	Randomly removed cone reports.
Spacing violation	Local longitudinal misplacement of selected cones.
Topology deformation	Local lateral displacement of selected cones.

TABLE II
DEPLOYMENT QUALITY EVALUATION METRICS.

Metric	Description
Reporting ratio ρ	Matched-cone ratio.
Position consistency C_p	Consistency of cone positions.
Spacing consistency C_s	Consistency of adjacent spacing.
Topology consistency C_t	Consistency of local adjacency vectors.
Quality score Q	Overall score for correction decision.

specified, $\sigma_p = 1.0$ m, $\theta_s = 1.0$ m, $\theta_t = 3.0$ m, $\theta_Q = 0.8$ and $w_p = w_s = w_t = 1/3$ were used.

Each uncertainty scenario was evaluated over 1000 random seeds. GNSS noise was modeled as zero-mean Gaussian noise with a standard deviation of 0.35 m. In the placement-deviation scenario, the cone layout was systematically shifted with small seed-based jitter. In the missing-cone scenario, 15% of the cone reports were removed randomly. In the spacing-violation scenario, a small subset of cones was locally misplaced along the deployment direction, causing abnormal distances to neighboring cones. In the topology-deformation scenario, a small subset of cones was laterally displaced to distort local adjacency-vector relationships without introducing unrealistic accumulated rotation.

As shown in Table III, different uncertainty scenarios affect different consistency metrics. The placement-deviation scenario mainly reduces C_p , while C_s and C_t remain close to one because the relative spacing and local topology of the cone sequence are preserved. The missing-cone scenario reduces ρ , C_s , and C_t , since missing cones break adjacent spacing and topology relations. The spacing-violation scenario mainly reduces C_s , showing that locally misplaced cones can be captured through adjacent spacing consistency. The topology-deformation scenario reduces C_t while keeping C_s almost unchanged, indicating that vector-based topology consistency can capture structural deformation that is not fully reflected by spacing consistency alone.

For example, a layout may preserve relative spacing but still be displaced from the planned target positions, or it may preserve adjacent distances while exhibiting local topology deformation. By combining position, spacing, and topology consistencies, the proposed quality score provides a more comprehensive assessment of the deployed traffic-control layout.

From a deployment-decision perspective, the quality score provides a compact criterion for correction. With $\theta_Q = 0.8$, the missing-cone and spacing-violation scenarios fall below the acceptable threshold, while the GNSS-noise case lies on

TABLE III
SIMULATED DEPLOYMENT QUALITY UNDER REPRESENTATIVE UNCERTAINTY SCENARIOS AVERAGED OVER 1000 SEEDS.

Scenario	ρ	C_p	C_s	C_t	Q
Baseline	1.000	1.000	1.000	1.000	1.000
GNSS noise	1.000	0.648	0.957	0.794	0.800
Placement dev.	1.000	0.557	1.000	1.000	0.852
Missing cones	0.850	0.850	0.716	0.716	0.760
Spacing vio.	1.000	0.771	0.710	0.827	0.769
Topology def.	1.000	0.779	0.998	0.834	0.870

the decision boundary. This suggests that missing reports and abnormal spacing should trigger correction or manual inspection, whereas increased positioning uncertainty may require closer inspection under stricter deployment policies. In contrast, placement deviation and topology deformation remain acceptable under equal weighting, but they affect different consistency components.

V. CONCLUSION

This paper proposed a DT-based closed-loop deployment framework for GNSS-capable smart cones in planned traffic-control operations. The proposed framework transforms a planned traffic-control layout into deployment tasks, receives GNSS feedback from deployed cones, updates the digital twin, and evaluates the deployment quality based on position, spacing, and topology consistencies. The software-in-the-loop evaluation examines representative deployment uncertainties, including GNSS noise, placement deviation, missing cones, spacing violations, and topology deformation. Future work will validate the proposed framework using physical deployment platforms and field experiments under different planned traffic-control scenarios.

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