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Optimal Camera Placement for Monitoring Safety in Metro Station Construction Work

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Abstract. Monitoring systems based on cameras are crucial for safety management of the high-risk activities common in the complex environment of metro station construction sites, and hence the need for a reliable camera network system. However, the number and locations of cameras are currently estimated according to the experience of managers/engineers, while the occlusion effect is rarely considered, resulting in weak coverage of 3D spaces in practice. To address this gap, a novel approach is presented to optimize the camera placements for 100% site coverage while considering the occlusion dynamics caused by sidewalls and supports during excavation in metro station projects. A case study of a metro station project is presented to demonstrate and validate the approach, with results showing that the optimized plans for camera placement have larger coverage than the original plan, and better performance in safety monitoring and controlling hazards. Optimized in this way, the plans for camera placement can help managers in effective planning and enhanced safety management of metro station construction sites.

Keywords: Safety monitoring, camera placement, optimization, occlusion, metro station construction, modified genetic algorithm.

Introduction

Metro station construction is a high-risk activity featuring lengthy durations, complex environments, and unforeseen risk factors (Ding and Xu 2017; Valipour et al. 2017). Research find that significant risks are obviously associated with inappropriate workers' acts or omissions of properly safety mechanisms, thus a stricter site management and surveillance is necessary (Edwards et al. 2008). A camera surveillance system, as a kind of sensor system of the Internet of Things, is now regarded an important aid to safety management (Teizer and Vela 2009; Skibniewski 2014, 2015). Camera systems can monitor construction areas in real time for 24 hours daily, record information, and detect safety hazards to guide managers/workers in taking appropriate measures and improving the safety performance (Abdelhamid and Everett 2000; Liu et al. 2016). For example, engineers can inspect such safety hazards as unsafe behaviors (e.g. walking on steel pipe supports or working without safety helmets) (Garrett and Teizer 2009; Yu et al. 2017; Ding et al. 2018) and unsafe material-machine-environment conditions (e.g. unprotected shafts or holes, or stacking materials at the edge of pits) (Perlman et al. 2014). This results in a more effective monitoring center, and improved recorded information to be sent to the site engineers for processing (Bohn and Teizer, 2009; Lu et al. 2015).

The placement of cameras is important in providing a maximum view field (Liu et al. 2016); however, this invariably depends on the experience of the managers/workers in estimating the number and locations of cameras needed, and takes little account of cameras being blocked by the occlusion of sidewalls and supports in the process of excavation. This risk may occur in any area of a construction site in a complex environment, and therefore, the full coverage of cameras is crucial for safety monitoring (Ding et al. 2011; Zhang et al. 2016). However, placing cameras based on experience to achieve the required coverage is difficult and seriously affects the role of video surveillance equipment in safety supervision in a complex metro station project (Murray et al. 2007). Camera placement on metro station construction sites has therefore become an urgent problem that requires a solution.

Camera placement is a typical optimization problem involving achieving an objective function and satisfying given constraints (Erdem and Sclaroff 2004, 2006; Liu et al. 2016). Previous studies discuss the problem from several perspectives, such as 2D floor surveillance (Yao et al. 2008; Nam and Hong 2012; Erdem and Sclaroff, 2006), 3D spaces (Murray et al. 2007; Yaagoubi et al. 2015; Albahri and Hammad 2017), and the use of a heuristic algorithm for optimization (Indu et al. 2009; Hsieh et al. 2011). However, these methods can produce imprecise camera coverage calculations as they fail to consider some of the elements that block camera visibility (Murray et al. 2007; Amriki and Atrey 2014; Liu et al. 2016). For metro station construction projects, the occlusions caused by sidewalls and supports are different from those in buildings or indoor floors because the monitoring area changes as the excavation work progresses, physically affecting the camera placement. Current approaches do not account for the effects of occlusion in metro station construction sites, as the coverage of a work area with cameras is impractical for 3D applications. Finding the optimal placement of cameras in metro station construction sites therefore involves creating a plan to meet the required coverage by considering dynamic occlusion with a minimal number of cameras.

This study presents an approach to modeling the camera placement problem by simultaneously considering dynamic occlusion to achieve 100% coverage in 3D space while minimizing the number of cameras. The decision variables, objective function, and constraints of the camera placement model are first defined and established. A case study is then provided to demonstrate and evaluate the efficiency and feasibility of the approach. The approach is intended to enhance camera placement planning in metro station construction with concomitant implications for improved safety management.

Besides, the proposed model is proved to be a non-deterministic polynomial hard (*NP-hard*) problem (Cole and Sharir 1989). To improve the search efficiency of the optimal solution, a genetic algorithm(GA)-based algorithm is developed. The GA is a biological evolution algorithm based on bionic principles that are used to find optimal solutions (Goldberg 1989). It simulates the natural process of genetic recombination and evolution, programming the parameters of a problem to be solved into a binary or decimal code, i.e., the gene. Several genes form a chromosome, and many chromosomes are operated by the steps of natural selection, crossover, and mutation through repeated iterations until the final optimization results are obtained. With the standard GA, the infeasible solutions are generated during the crossover and mutation for offspring population selection, which would increase the number of iterations and reduce search efficiency. In this studies, the standard GA is improved by modifying the infeasible chromosomes produced by cross mutations and transform them as feasible chromosomes. To evaluate the quality of the modified GA for solving cameras placement problems, the algorithm is compared with standard GA. Results verified that the developed GA has great performance in improving convergence speed.

Literature Review

Application of cameras systems in construction area

By inferring the objects' motion in each video frame based on the history of their appearance and location, the cameras can provide real-time visual information of construction sites. As a kind of sensor system of the Internet of Thing, the application of cameras in construction is promising due to simple operating conditions (e.g., none requirement in sensors and ID tags installing), commercial availability and low costs (Caldas et al. 2004). Camera network systems have been widely used in construction fields in recent years due to their capability of recording video information and other intelligent applications (Ryan et al. 2011; Yaagoubi et al. 2015; Liu et al 2016), such as, dynamic tracking of multiple equipment, personnel and materials in construction site (Brilakis et al. 2011; Zhu et al. 2017; Park et al. 2012), 3D reconstruction of construction job sites (Rashidi et al. 2013; Brilakis et al. 2011), etc. However, the technology is usually limited when the line of sight between the camera and the target object is obstructed by other objects and unfavorable environment condition such as weak illumination (Jog et al. 2009). In order to increase the surveillance coverage and save the cost, the research of camera layout is very necessary.

Layout of cameras

The camera layout must be determined before the start of construction to minimize modification costs, and the number of cameras required directly affects coverage. Achieving a predefined coverage of a given physical space while minimizing the number of cameras remains a difficult optimization problem (Erdem and Sclaroff 2006). Thus, camera placement has attracted numerous studies.

Erdem and Sclaroff (2006), for example, propose a camera placement algorithm based on a binary optimization technique, by converting the continuous domain (area) into a discrete domain (grids) and developing a 0–1 integer programming to solve the optimal camera locations, in which all discrete grid points in specific areas/lanes are monitored. However, this approach was based on a 2D building floor plan. Murray et al. (2007) have developed a procedure based on a geographic information system (GIS) to optimizing the coverage of security monitoring equipment in an urban environment. Occlusions, such as buildings, are static and easy to accommodate in establishing the coverage for equipment placement. Yao et al. (2007) extend the placement of cameras to consider not only coverage but also overlaps, to allow for automated tracking processes. However, their research was based on a 2D floor. Piciarelli et al. (2010) present an occlusion-aware camera configuration strategy to observe areas of high activity. These studies focus on finding the pan, tilt, and zoom parameters for each camera that lead to an optimal coverage of relevance maps. However, they do not provide the optimal locations of cameras in relevance maps. Chrysostomou and Gasteratos (2012), on the other hand, propose a bee-colony algorithm for designing a multi-camera layout to maximize coverage using a minimal number of cameras while considering static occlusion of the edges of an area; Nam and Hong (2012) design an optimal method for camera placement by considering the static spatial information and priorities of pedestrian paths in spaces; Yaagoubi et al. (2015) suggest a new Voronoi-based 3D GIS-oriented approach for surveillance camera network placement to achieve an approximately 100% coverage for a seaport area by considering the landscape of the monitored environment and influence of existing objects; Ahn et al. (2016) present a two-phase algorithm based on binary integer programming to solve the camera placement problem for large spaces but disregarding occlusions; while Albahri and Hammad (2017) propose simulation-based optimization of camera placement for the inside of buildings using the building information modeling (BIM) tool - the BIM being mainly used to define the inputs and visualize the results – but confined solely to the inside of buildings with static obstacles and floors.

Camera systems on construction sites minimize the workers' risks in the absence of their supervisors on the site (Teizer and Vela 2009). The videos recorded by these camera systems can then be analyzed for further safety management decision making. The *Technical Code for Video Surveillance on Construction Sites* (JGJ/T 292-2012) provides guidelines for the design, installation, acceptance, and maintenance of camera network systems; however, the code does not provide details of camera network placement. The characteristics of having occlusion, dynamic, and 3D spaces in metro station construction are different from the characteristics of indoor floors and obstacles (Liu et al. 2016), especially occlusion caused by sidewalls and supports that may block excavation during operation in a complex environment. Few publications focus on camera network placement in consideration of these special features of metro station construction sites, where a special model is needed to analyze and describe the camera layout problem.

An intelligent algorithm for camera layout optimization

Camera placement is a non-deterministic polynomial hard (*NP-hard*) problem (Cole and Sharir 1989), which means an optimal solution is difficult to find within a reasonable time, and optimization algorithms are necessary for obtaining solutions effectively or efficiently. In camera placement, the nonlinearity that typically arises for a set of candidate cameras cannot be computed as a linear combination of coverage optimization due to overlaps and occlusion. Many metaheuristic search algorithms, such as the *genetic algorithm* (GA) (David et al. 2007; Hengel et al. 2009; Yao et al. 2010) and particle swarm optimization (PSO) (Hsieh et al. 2011; Xu et al. 2013), are useful in such circumstances.

The GA is a metaheuristic optimization algorithm that mimics the process of natural selection through techniques inspired by natural evolution, such as crossover and mutation, which are based on genetic operators (Goldberg 1989). The process iterates until the stopping criteria are met, and the optimal individual in the last group is decoded as the near optimum solution of the problem. The generic GA represents solution binary vectors that are extremely convenient to use in the discrete formulas of camera placement problems, while PSO is mainly used to solve formulations with a known number of cameras (Xu et al. 2013). GA has been demonstrated to have advantages in handling complex nonlinear objectives coupled with large or poorly understood search spaces (David et al. 2007; Gandomi and Alavi 2012). Furthermore, GA provides a reliable balance between exploitation and exploration by using random processes and genetic operators (David et al. 2007). Chen and Li (2004), for example, develop a sensor placement graph for model-based inspection based on a GA approach; Indu et al. (2009) use GA to present the problem of optimizing camera placement to ensure the maximum coverage of areas by placing multiple cameras, with the camera parameters coded as a gene in a chromosome to represent an array of cameras, but do not discuss the GA performance due to the small size of the monitoring area; Hengel et al. (2009)

apply GA to camera placement for an arbitrary building; while Sreedevi et al. (2011) use a GA to solve the optimal camera placement problem, proposing a simple encoding mechanism on the basis of binary strings to represent the gene of the camera.

A GA-based solution to the camera placement problems in the context of metro station construction sites is difficult, as the GA used to search for optimal solutions for large-scale spaces requires much computing time (Goldberg 1989). Infeasible solutions are also often generated during crossover and mutation for offspring population selection in standard GA (Goldberg 1989, David et al. 2007). A common approach is to directly discard or introduce a penalty function to reduce the fitness value of an infeasible solution, which often resulting in more iterative computations (David et al. 2007). An alternative, adopted here, is to employ a *detection-patching* operator based on the greedy principle, to modify the infeasible chromosomes produced by cross mutations and transform them as feasible chromosomes to effectively improve convergence speed, and facilitate the search for global optimal solutions from large-scale computational solution spaces.

Methodology

The process of the approach is to optimize the camera placement problem is illustrated in Fig. 1. This can be divided into 1) construction of the camera placement model and 2) search for optimal solutions with the modified GA. Modeling the placement of cameras involves four steps: camera modeling, site scene modeling (defining monitoring area), camera visibility analysis, and objective function establishment. The modified GA is used to search for optimal solutions via initialization, reproduction, and the detection-patching operator. The parameters of the coverage, the number and locations of the cameras are output for optimal camera placement planning.

Camera placement optimization modelling

Step 1: Camera modeling

The three main types of video cameras are fixed perspective, pan–tilt–zoom (PTZ), and omnidirectional cameras (Erdem and Sclaroff 2004). A type of PTZ camera, the spherical video camera, is widely applied on metro station construction sites for safety surveillance management. The spherical video camera is an integration of cameras, an electronic platform, ball cover and decoder, of which the control signal can be sent to the control terminal to rotate the camera around the horizontal (tilt) and vertical (pan) axis zoom lenses. The horizontal range (h_r) is 0°–360°, and the vertical range (v_r) is −90°–+v°. Fig. 2 depicts the visual stimulus space. Cameras are also equipped with an adjustable focal length (zoom) that is limited within a certain range. For the sake of simplification, we assume that all points within a radius of a camera can be monitored and have the same resolution (Erdem and Sclaroff 2006). Assume L is the available camera range.

Step 2: Site scene modeling

Given space S and length × width × depth of $a' \times b' \times h$, we define the coordinate system, as presented in Fig. 3. Several activities (e.g., material processing, transportation, and hoisting) are performed on the ground, and other works (e.g., digging and concreting) are conducted by workers on the excavation floor. Thus, the monitoring area includes land (the *ABCD–A'B'C'D'* field) and pit areas (*A'B'C'D*) that constantly change throughout the digging operation (Fig. 3). Candidate positions can be provided to improve the search for optimal solutions from the candidate space by considering the available places for the camera layout (the ring field between *ABCD–A'B'C'D'*).

Step3: Camera visibility analysis

Point Qi (x_i, y_i, z_i) (i= 1, 2, …, n) is observed on the excavation floor and candidate camera Pj (xj, yj, zj) (j=1, 2,…, m). Fig. 4 shows the visibility analysis of the cameras. The excavation area is initially blocked by the sidewall, with the digging sequentially performed in the deep foundation. The cameras cover the area of M_{11}, M_{12}, M_{15}, and M_{16} on the ground and the area of M_{13}, M, and M_{14} on the excavation floor (Fig. 4). The erected concrete and steel supports also obstruct the camera view fields while the digging continues, as demonstrated in area *S* in Fig. 4. Therefore, the observed point Qi on each floor is required to determine whether any candidate camera can view the point.

Camera visibility analysis involves two steps: mesh division and observed matrix establishment. Mesh division aims to divide the monitoring area into meshes to represent the observed field. Given that the number of meshes is n, the coordinate of the center point (Qi) of the mesh can be computed based on the four points of the mesh; then, the observation matrix (A) reflecting the points on the observed floor that can be seen by the cameras under varied camera placement is constructed, as expressed in

$$A=\{a_{ij}\} \qquad (1)$$

where a_{ij}=(0,1); a_{ij} represents point Q_i that can be observed by candidate camera P_j in the camera placement plan j; a_{ij}=1 when the point can be observed, and a_{ij}=0 otherwise.

Step 4: Objective function and constraints

The camera placement problem aims to obtain maximal coverage with a minimal number of cameras and improve the utilization of given resources. Therefore, the objective function can be defined as the search for the minimum number of cameras while satisfying the constraint that the camera network systems cover the whole meshes in the construction area. The objective function and constraints respectively are

$$\min \sum_{j=1}^{m} x_j \tag{2}$$

$$s.t.\begin{cases} \sum_{i=1}^{n} \mathrm{a}_{ij} = n \times u\% \\ \mathrm{a}_{ij} = \{0,1\} \\ x = \{0,1\} \end{cases} \tag{3}$$

where x_j indicates the number of cameras in placement plan j, a_{ij} is whether point Q_i can be observed by camera P_j in plan j, a_{ij}=0 or 1 represents blocked and unblocked respectively, n is the total number of meshes, and $u\%$ is the coverage of the camera network system. Camera placement planning with the objective function and constraints can be created by searching for the optimal solution based on the heuristic optimization algorithm.

Modified GA for global solution search

As mentioned earlier, the infeasible solutions are generated during the crossover and mutation for offspring population selection in standard GA, which would increase the number of iterations and reduce search efficiency. In this study, by detection patching based on the greedy principle, the operator involved can modify the infeasible chromosomes produced by cross mutations and transform them into feasible chromosomes, which can significantly improve the convergence of optimal solutions from the solution space, especially large-scale computational solutions (Kumar et al. 2010). Based on the standard GA, the main steps of the modified GA for optimum solution search are:

- Step 1. *Coding*. The camera placement solution is encoded in the form of a string with 0 or 1, where 0 indicates no camera in the candidate position, and 1 denotes that a camera is mounted in this position. The length of the chromosome is m.
- Step 2. *Initialization*. The population size is set, and each initial population is detected to ensure the whole coverage of each chromosome until population N is obtained. The chromosome, as a feasible solution, is shown with a vector $X=(x_1, x_2, \ldots, x_j,)$, $x_j=\{0, 1\}$, $j=1,2, \ldots, m$.
- Step 3. *Crossover*. The chromosomes selected by exchanging genes from each of the two parent groups, are exchanged to produce a new individual. Each pair chromosomes have a possibility being exchanged to performing the crossover, the value of the possibility is set as Pc. According to Schaffer et al. (1989), the value of Pc is suggested 0.4 to 0.99.
- Step 4. *Selection*. The chromosomes are selected for the mutation offspring, replacing the original chromosome according to the fitness value. The fitness value for each population is evaluated using the coverage. The fitness function is Fit= $c_{max}-F(x)$ where c_{max} is a positive

number, which is longer than the length of the chromosome. The fitness value of the P_i chromosome is computed and ranked.

– Step 5. *Mutation*. The mutation is operated to generate the new offspring. Similar to the crossover, each chromosomes mutates as a certain probability, the value is expressed as P_m, which ranges from 0.0001 to 0.1 according to Schaffer et al. (1989).

– Step 6. *Detection-patching*.

1) Each chromosome of the new group is tested to determine whether it is a feasible solution based on the constraints; if it is infeasible, then the chromosome is repaired.
2) The repair method aims to develop a matrix integrated from the uncovered observed grid as the line and the value of gene 0 as the column.
3) The coverage of each population is computed when the gene value is 1, and then the populations are ranked.
4) The optimal gene position is selected and given a value ranging from 0 to 1. The detection-patching process is repeated until the chromosome is feasible as a solution.

The detection-patching operator transforms the infeasible solution into a feasible one, which promotes the optimal solution obtained from the global space. The operator accelerates the convergence of the iteration due to the number of operations in steps 3–6 being slightly reduced.

– Step 7. *Termination*. The iteration is stopped, and the optimal result is outputted. The optimal solution is obtained with the above steps when the solution fitness curve reaches convergence. The chromosome is outputted for problem solving.

Modelling of camera placement for metro station construction

Parameters of the cameras

Smart PTZ cameras are applied on the metro station construction site are. A DS-2DF7220IW-A produced by *HIKVISION* is used in Wuhan metro construction projects. We adopt this version to describe the camera network system. The focal length of the camera is 4.7–94 mm, 20×; the angle of view is 58.3–3.2; and the adjustment ranges are 0°–360° for pan and −10°–90° for tilt. The cameras are mounted on studs, maintained between 3 and 5 m high for the safety of the cameras and for ease of maintenance. A 50 m irradiation distance is suitable (L=50 m) given the requirement to observe the behavior and faces of workers,

Camera visibility analysis

For ease of explanation, the metro station construction site dimensions are $a' \times b' \times h$, and the excavation dimensions are $a \times b \times h$. Given L as the irradiation distance of cameras, the excavation floor is blocked by the support of the Dth floor, and d_1 and d_2 are the distances from the x- and y-coordinates to the edge of the foundation. Fig. 5 illustrates the monitoring area of the site.

(1) Definition of the candidate camera placement region

The identification of the candidate region for camera placement can significantly contribute to improving the search for optimal solutions from a defined available space. The area of the construction site can be divided into two parts: the ground and excavation floors. The ground floor is the first choice for the placement of the cameras because most of the activities in the excavation area could easily destroy the cameras. The cameras are laid out beside the protective fences around the foundation pit at a distance more than 0.5 m away from the edge to comply with the *Technical Code* (JGJ/T292-2012), as near the edge as possible to reduce the occlusion caused by the foundation pit sidewall, while considering traffic and task interventions. The candidate region for camera placement can then be obtained according to these, i.e., the edge area of the foundation pit and security fence (Fig. 3).

Definition 1. Given $\{P_j, j=1, 2, \ldots, m\}$ as the set of candidate cameras, T_j is the variable of the jth candidate camera location that indicates whether a camera should be installed; $T_j=1$ indicates installation, and $T_j=0$ indicates uninstallation.

(2) Mesh division of the monitoring area

A large number of observed points equate to a solution of discrete optimization that is close to the continuous global optimal solution. Nevertheless, relatively low-density sample points are generally sufficient to obtain a solution that is acceptably close to the optimal solution for the continuous problem. Mesh division is a widely used method to describe a region as a discrete point. Fig. 5 depicts the mesh division of the construction floor. The construction site is divided into a ground section and a pit section. In the ground section, cut every 2m from the edge to the center, take the actual length (or width) of the part less than 2m. The division of the pit section is also the same, and the middle side of the grid may be less than 2m. The shaded area indicates the excavation area and the number of each mesh from 1 to n, $i=1,2, \ldots,n$. By this mean, the four corner coordinates of grid i can be obtained, namely, (x_{ik}, y_{ik}, z_{ik}),where k=1,2,3,4. Q_i is defined as the center of mesh i, and is calculated based on the four top points of the mesh, i.e., Qi $(\sum x_{ik}/4, \sum y_{ik}/4, \sum z_{ik}/4)$.

Definition 2. Let $\{Q_i, i=1,2, \ldots, n\}$ be the set of observed mesh points. If the distance between P_j of plan j and Q_i is less than L and no obstacles block the observation of the candidate cameras, then the value of the observation variable $a_{ij} = 1$; otherwise, $a_{ij} = 0$. The observed matrix can be computed based on the visibility analysis. A special optimization model: namely, 0–1 programming provides a convenient way of representing this problem in matrix notation in terms of the set coverage problem (Wolsey 1998). Table 1 presents the observation matrix. The percentage of the total number of meshes observed by candidate cameras is the coverage rate of the camera network system.

(3) Camera visibility analysis

For the observed mesh point Q_i on the ground area, the coordinate of Q_i (x_i, y_i, h) and the candidate cameras P_j (x_j, y_j, z_j) must satisfy formula (4); thus, all meshes are covered by the camera placement plan, that is, $a_{ij}=1$ in the observation matrix.

$$\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2 + \left(h - z_j\right)^2 \le L^2 \qquad (4)$$

Point Q_i on the excavation area is blocked by the sidewall and support. Fig. 6 presents the observation of the camera system. Given the pth floor of supports and k supports in each floor, we simplify the supports into a rectangular plane to facilitate the description of the observations. If the x-axis range of the first support of the pth floor is $(x_{p1}, x_{p1'})$, then the kth support of the pth floor is (x_{pk}, $x_{pk'}$), and the value of the *z*-axis of the *p*th steel pipe support is h_1. The range of the x-axis of the *p*th floor support can be defined as S_p in

$$S_p = (x_{p1},\ x_{p1}') U (x_{p2},\ x_{p2}') \cdots U (x_{pk},\ x_{pk}') \tag{5}$$

We define the intersection point of line P_jQ_i and *p*th plane of the supports floor as V(x_p, y_p, z_p), which is computed by eqn (6), where h*p* is height of supports floor in the *p*th plane, e.g. in the case, h_1=20.6-0.4m=20.2m. R(x_c, y_c, z_c) computed by eqn. (7) is defined as the intersection point of line P_jQ_i and the plane of the ground floor. When P_j meets the demands of eqns (8)–(10), the observed mesh point Q*i* is observed by the candidate cameras P_j, and a_{ij}=1. The gray area can be observed in Fig. 8. Eqn. (8) displays the observed point within the monitoring distance. Eqns (9) and (10) respectively ensure that the meshes are observed by the cameras and not blocked by the sidewalls and supports.

$$\begin{cases} \dfrac{x_p - x_j}{x_i - x_j} = \dfrac{y_p - y_j}{y_i - y_j} = \dfrac{z_p - z_j}{z_i - z_j} \\ z_p = h_p, h_p \le \mathrm{h}, p = 1, 2, \ldots \end{cases} \tag{6}$$

$$\begin{cases} \dfrac{x_c - x_j}{x_i - x_j} = \dfrac{y_c - y_j}{y_i - y_j} = \dfrac{z_c - z_j}{z_i - z_j} \\ z_c = h \end{cases} \tag{7}$$

$$\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2} \le L \tag{8}$$

$$x_c \in (d_1, d_1 + a) \cap y_c \in (d_2, d_2 + b) \tag{9}$$

$$x_p \notin S_p, p = 1, 2, \ldots \tag{10}$$

Objective function and constraints of camera placement

Based on the visibility analysis of the camera network system, the camera placement aims to lay out cameras efficiently on the site in a way that they can cover the chosen work area. The optimal solution to this problem can be obtained via binary optimization over a discrete problem space. The idea is to satisfy the constraints with a minimal number of cameras to achieve full coverage on the construction site area and thereby create a camera placement plan. Thus, the objective function and constraints can be defined as

$$\min \mathrm{F}(T_j, t_i, a_{ij}) = \min \sum_{j=1}^{m} T_j \tag{11}$$

$$\text{s.t.} \begin{cases} \sum_{i=1}^{n} t_i = n \times u\% \\ T_j = \{0,1\} \\ a_{ij} = \{0,1\} \\ t_i = 0\left(\sum_{j=1}^{m} T_j a_{ij} = 0\right), i = 1,2,\ldots n \\ t_i = 1\left(\sum_{j=1}^{m} T_j a_{ij} \geq 1\right), i = 1,2,\ldots n \end{cases} \tag{12}$$

where t_i=1 indicates that mesh point Q_i can be observed by the cameras, t_i=0 otherwise; T_j=1 indicates that the candidate camera point P_j is mounted with a camera (j=1,2,…,m), T_j=0 otherwise; u% is the coverage of the camera system; a_{ij} =1 indicates that mesh point Q_i can be observed by the candidate cameras P_j in plan j; a_{ij}=0 otherwise.

The parameters of the cameras and objective function are input into the modified GA using *MATLAB* (*R2016b*), from which the optimal camera placement plan is produced, including the coverage, number of cameras, and positions.

Case study

Background

A Wuhan metro station construction project is used as a case study to demonstrate and verify the approach. The open cut method was used to excavate the station. Fig. 7 displays the sketch of the project. The size of the station excavation is 221.6 m × 29.6 m × 17.6 m (length × width × depth); there are 4 floor supports, and the first 24 concrete floor supports are 800 mm wide; the other steel pipe floors are 600 mm wide, and each floor has 72 supports; the floor supports are 16.6 m (z_1), 10.8 m (z_2), 6.8 m (z_3), and 3.2 m (z_4) wide; and the structure floor is 0 m (bottom slab), 8.8 m (medial slab), and 15.3 m (roof slab) high. The black outline in Fig. 8 (a) is the top view of the security fence. According to the established 3D coordinate system, the coordinates of the main angular points are O (0,0,0), A (0, 0, 17.6), B (273.2, 9.1, 17.6), C (273.2, 52.6, 17.6), D (0, 55.6, 17.6); A’ (15.7, 20.6, 17.6), B’ (237.2, 20.6, 17.6), C’ (237.2, 50.2, 17.6), and D’ (15.7, 50.2, 17.6). The original camera placement plan was created before construction commenced, and includes five cameras: No. 1 (20.5, 17.6, 20.6), No. 2 (232.8, 17.1, 20.6), No. 3 (221.1, 55.8, 20.6), No. 4 (104.7, 52.8, 20.6), and No. 5 (29.2, 54.2, 20.6).

Analysis of camera placement

The camera placement plan can be generated at any given time for any construction area being monitored during the construction process. Three typical phases are selected: comprising, the bottom slab, medial slab, and roof slab constructions, integrated with many activities that must be fully observed. The standard GA is used in the search for optimal solutions for comparison with the modified GA; one crossover point is selected as the crossover operator; and the parameter of P_c is given as 0.6, and P_m=0.01. The algorithms are run on the platform of a 3 GHz computer with 4 GB memory.

Fig. 8 shows the output, indicating that the modified GA obtains the optimum solutions quickly and performs better than the other algorithms. The same is true when obtaining a favorable solution through the contribution of the detection-patching operator.

During the *bottom slab* construction phase, the optimal camera placement plan is required to cover the bottom plate and ground construction area under occlusion. The candidate cameras of the optimal plan are searched, and the cameras' IDs are 7, 8, 12, 15, 17, 19, 21, 26, 28, 29, 34, 36, 42, 43, 45, 47, 51, 53, 55, 60, 62, 66, 69, and 72. Similarly, the *medial slab* construction area and ground field must be monitored while being blocked by the first floor and second steel pipe supports during the medial plate construction phase. The optimal camera placement plan includes 19 cameras, and the cameras' IDs are 11, 13, 16, 19, 21, 23, 25, 27, 31, 33, 43, 50, 54, 55, 59, 61, 63, 67, and 69. The optimal camera placement plan for the *roof slab* construction surveillance with 100% coverage comprises 14 candidates with IDs of 3, 12, 16, 24, 38, 41, 44, 51, 55, 57, 60, 63, 64, and 68. The position of these candidate points can be obtained based on the IDs.

The position, number of cameras, and coverage of the optimal plans are presented from the top view in Fig. 9. Fig. 9 (a)–(c) shows the optimal plans for camera placement for the bottom slab, medium slab, and roof slab phases. Fig. 9 (d) presents the original plan for camera placement.

Discussion

Camera coverage, defined as the observed area in relation to the entire monitored area, is an index that reflects the performance of camera placement. A total of 3504 meshes are distributed in the metro station construction area, with 1665 distributed in the excavation area and 1839 distributed in the ground area. The optimal plans obtained for the three phases achieve 100% coverage. The placement of the original five cameras shows the coverage situation for the three phases under occlusion caused by the sidewall and support during excavation (Table 3). The original plan does not meet the full coverage required in the ground area. This scenario is true for the excavation area under occlusion caused by the sidewall and supports.

Fig. 10 indicates a coverage of 80.34%%, 64.62%, and 46.12% for the 3 phases under the original plan. The sidewall and support significantly block visibility, and the coverage for the excavation floor is 70.0%, 54.8%, and 15.7%, which fails to meet the monitoring requirement. Considering the construction dynamics, we conclude that the number of cameras for the optimized camera placement plan for the three phases should be 24, 19, and 14 to achieve 100% coverage. This dynamic camera placement is consistent with the actual situation at the construction sites.

Different coverage requirements to the monitoring area can be satisfied by the plan based on the optimization model of camera placement. Table 3 presents the optimal camera placement plan under different coverage to reveal the relationship between the coverage and the number of cameras in support of planning before the commencement of construction work.

In order to validate the effect of the optimized camera placement plan on safety management, both the original and optimized camera placement plans were followed simultaneously on the same metro station. We recorded the safety hazards inspection by using the site's web-based camera video monitoring system and the "Quality and Safety Management System for Wuhan Metro". Two typical types of safety hazards were selected: comprising, 1) falls from a height (e.g. from unprotected outside edges of slabs or balconies, and unprotected shafts or holes) (Perlman et al. 2014), and 2) unsafe condition of materials, machines and equipment (e.g. materials piled at the edge of pits, and working with loose materials (blocks) at height) (Ding et al. 2018). These provide inspection objects for the monitoring system to ensure the cameras could view the macro and meso scene more clearly than the micro level on the site. Two engineers inspected the safety hazards using the monitoring system every day based on the camera placements of the original plan and optimized plan. The detected safety hazards were imported into the monitoring system, and the engineers on site handled the hazards to improve safety. The roof slab construction phase was chosen to show the different changes in safety hazard detection. Fig.11 shows the application of the camera video monitoring system, and Fig.12 represents safety hazards detection change between the two plans during one month.

As Fig. 12 indicates, the plan can help detect more safety hazards (81.1%) than the original camera placement plan (74.1%) initially, with the advantage diminishing as the hazards reduce over time. This is clearly due to the wider coverage of the optimized placement of cameras than that based on experience, and hence the detection of more safety hazards (Carter and Smith 2006). However, there were still some safety hazard occurrences due to the unreliability of worker behaviors and the complex environment of the metro station construction site, even with persistent inspections and modifications. Compared with current camera placement, however, optimization contributes to a more effective safety hazards inspection and safety management process.

Research Contributions

This study presents a novel approach to optimizing the placement of cameras on metro station construction sites by considering construction dynamics and the occlusion of deep foundations in 3D space. The occlusion identified comprises two types: 1) supports and 2) sidewalls. As the occlusion changes with excavation works, a visibility analysis model is established for optimizing camera placement problem consists of an objective and constraint function. The objective function to establish the minimal number of cameras needed and their locations, and the constraint function is for a 100% coverage of the monitoring area. An improved GA is introduced to search global optimal solutions. A case study is used to demonstrate and validate the usefulness of the model, comprising of three typical stages of station construction as the dynamic considerations, and the optimal camera placement plans (including the positions, numbers of cameras, and coverage) for these stages are obtained. In contrast to the original plan, with only 46.1%, 64.6%, and 80.3% coverage, the optimized plan has nearly 100% coverage. In term of safety performance, safety hazards detection shows that more hazards are detected and inspected with the help of the optimized plan than the original plan.

This study helps advance construction management knowledge and practice by (1) developing a model for camera placement in such complex environments as metro station construction sites, which can be applied to similar circumstances; (2) analyzing visibility by taking into account the occlusion caused by supports and sidewalls, rather than estimation based solely on engineer experience; (3) validating the system on an actual site, by achieving an optimal plan with nearly 100% coverage and to increase hazard detection and response rates for improved safety management. The work provides engineers with a quantitative decision tool for planning the placement of cameras on construction sites to help improve safety performance.

Study Limitations and Future Research

The contributions of the model for the placement of cameras in support of construction safety management are explained, however, there are some limitations to be addressed for future research in this area. Although the model identifies the optimal number and placement of cameras to obtain a full coverage of metro construction sites, catching micro actions or behaviors remains difficult due to limitations of camera monitoring distance and resolution. The micro actions consist of human slight movements (e.g., uncomfortable facial expression, no goggles when cutting, tools are not firmly fixed on waist and so on), machine subtle changes (e.g., piled machinery tilting, excessive excavation of soil and so on) and environment subtle changes (e.g., foundation pit cracking, sinking or bulging, displacement of the edge of the foundation pit and so on), which closely related to the safety of workers.

In addition, there is a need to design and optimize the automatic patrol path of video cameras according to the nature of the construction activities and the dynamics within construction sites. Further work is also needed of the appropriate role of safety managers in response to the increased identification of hazards in terms of safety monitoring, inspection, management, and possible interventions.

Besides, the proposed method is mainly devoted to optimizing the placement of cameras considering adverse environment conditions (e.g., the occlusion dynamics caused by sidewalls and supports and the 3D spaces characteristics of the foundation pit project). However, other environment conditions such as lighting and illumination, levels of occlusions, and sizes of jobsite, could also affect the cameras layout. It is necessary to valid the applicability of the proposed method under these conditions

Data Availability Statement

Data analyzed during the study were provided by a third party. Requests for data should be directed to the provider indicated in the Acknowledgments. Information about the *Journal*'s data-sharing policy can be found here: http://ascelibrary.org/doi/10.1061/(ASCE)CO.1943-7862.0001263.

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Figure Captions

Fig. 1. Process of the proposed approach to optimize camera placement
Fig. 2. (a) Visual space and (b) rotation of cameras
Fig. 3. Monitoring area of metro station construction
Fig. 4. Camera visibility analysis
Fig. 5. Mesh division of the construction area
Fig. 6. Camera view field analysis of deep excavation area
Fig. 7. (a) Metro station construction site, (b) 1-1 section view, (c) 2-2 section view
Fig. 8. Output based on the modified and standard GAs for (a) bottom slab, (b) medial slab, and (c) roof slab constructions.
Fig. 9. Coverage of optimal camera placement plan for (a) bottom slab, (b) medial slab, and (c) roof slab constructions; (d) placement plan of original cameras
Fig. 10. Comparison of the coverage between original and optimized plans (a) coverage for excavation floor, (b) coverage for ground floor, and (c) coverage for whole construction area
Fig. 11. Application of the proposed approach for camera placement optimization on metro station sites: (a) model of cameras on metro station sites; (b) interface of the web-based Quality and Safety management system for Wuhan Metro; (c) and (d) system used by engineers.
Fig. 12. Performance of the change of safety hazards detection based on original plan and optimized plan

Table. 1. Application of GA in camera layout optimization problem

Reference	Applications/Conclusions
Xu et al. 2013	The generic GA represents solution binary vectors that are extremely convenient to use in the discrete formulas of camera placement problems.
David et al. 2007	GA have advantages in handling complex nonlinear objectives coupled with large or poorly understood search spaces.
Gandomi and Alavi 2013	
Chen and Li 2004	Develop a sensor placement graph for model-based inspection based on a GA approach.
Indu et al. 2009	GA is used to present the problem of optimizing camera placement to ensure the maximum coverage of areas by placing multiple cameras, with the camera parameters coded as a gene in a chromosome to represent an array of cameras.
Hengel et al. 2009	GA is applied to camera placement for an arbitrary building.
Sreedevi et al. 2011	GA is used to solve the optimal camera placement problem, proposing a simple encoding mechanism on the basis of binary strings to represent the gene of the camera.

Table 2. Observation matrix

Meshes	Candidate camera points				
	1	…	*j*	…	*m*
1	1	…	0	…	0
…	…	…	…	…	…
i	0	…	a_{ij}	…	0
…	…	…	…	…	…
n	0	…	0	…	1

Table 3. Comparison of coverage between the optimal and original plans

Camera placement plan	Construction phase		
	Bottom slab (P)	Medial slab (M)	Roof slab (R)
Original plan			
Number of cameras	5	5	5
Coverage	46.1%	64.6%	80.3%
Optimal plan			
Number of cameras	24	19	14
Coverage	100%	100%	100%

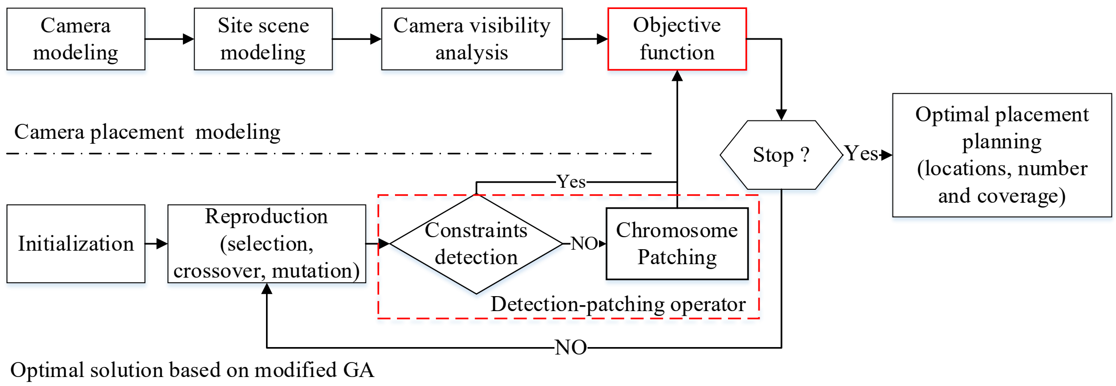

Fig. 1. Process of the proposed approach to optimize camera placement

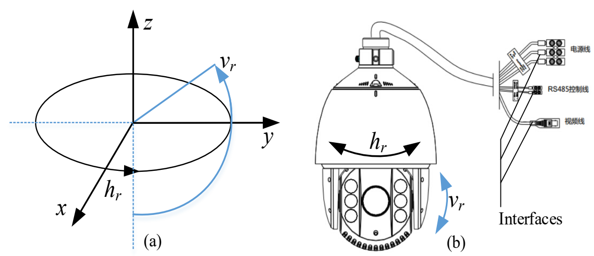

Fig. 2. Visual space (a) and rotation (b) of cameras

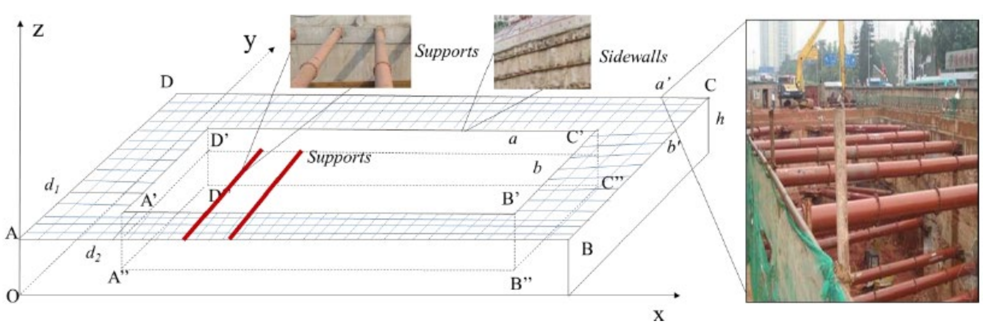

Fig. 3. Monitoring area of metro station construction

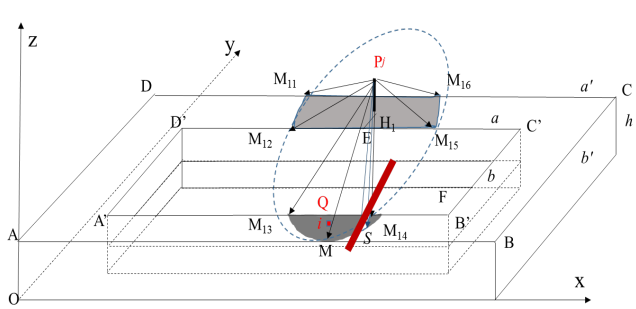

Fig. 4 Camera visibility analysis

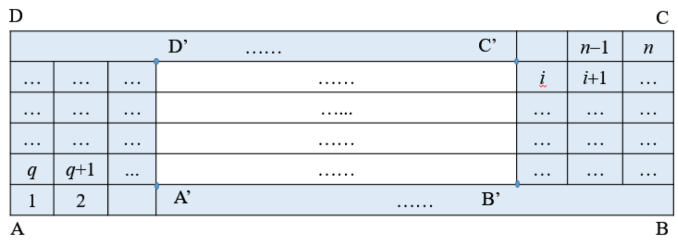

Fig. 5. Mesh division of the construction area

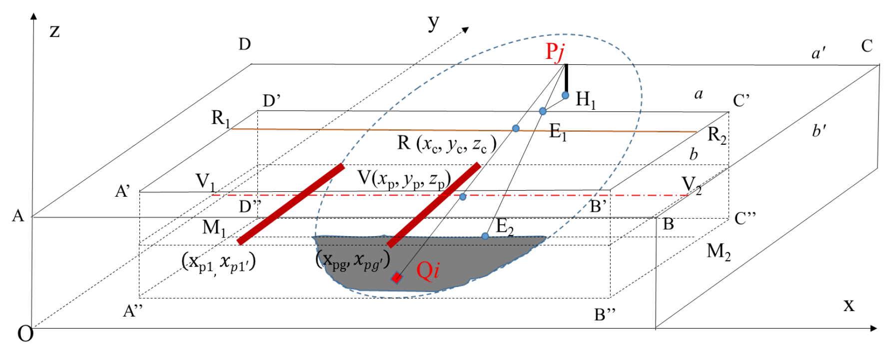

Fig. 6. Camera view field analysis of deep excavation area

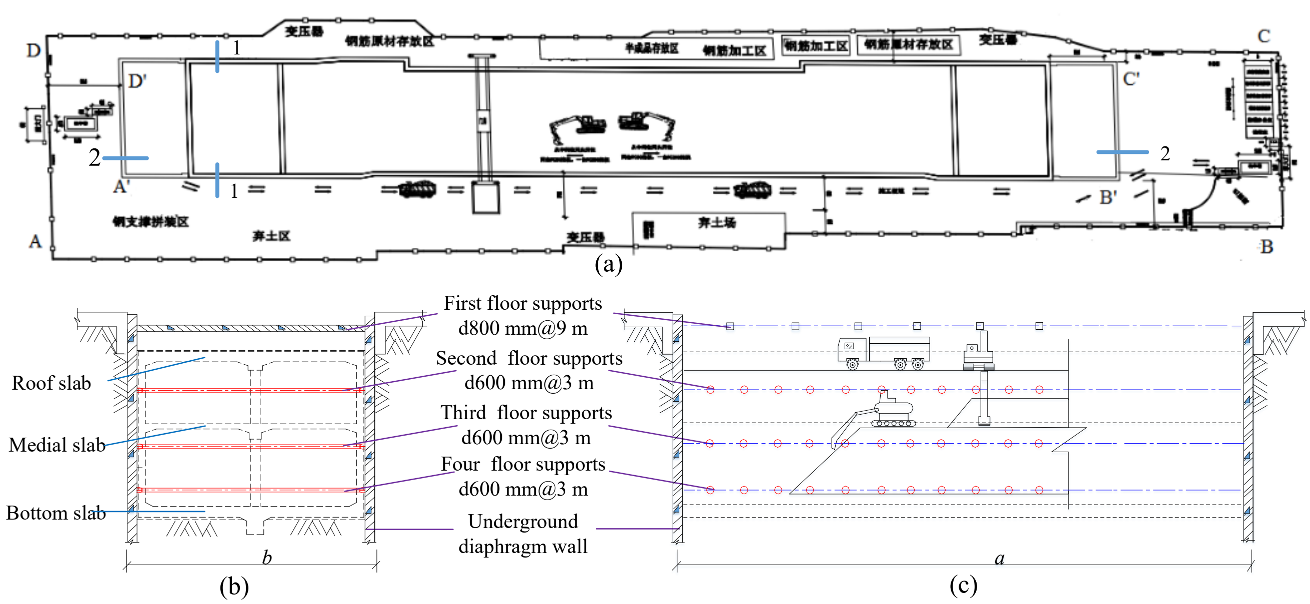

Fig. 7. (a) Sketch of the metro station construction site, (b) 1-1 section view, (c) 2-2 section view

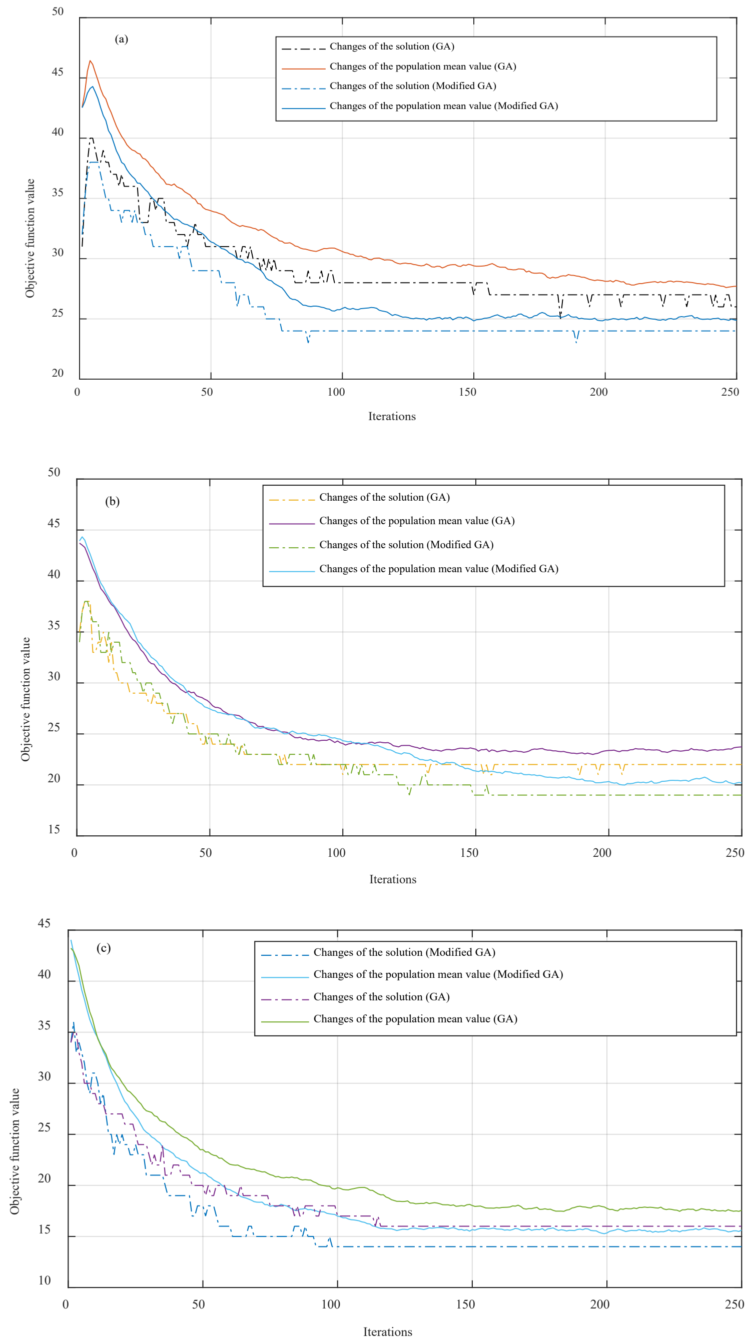

Fig. 8 Output based on the modified and standard GAs for (a) bottom slab, (b) medial slab, and (c) roof slab constructions

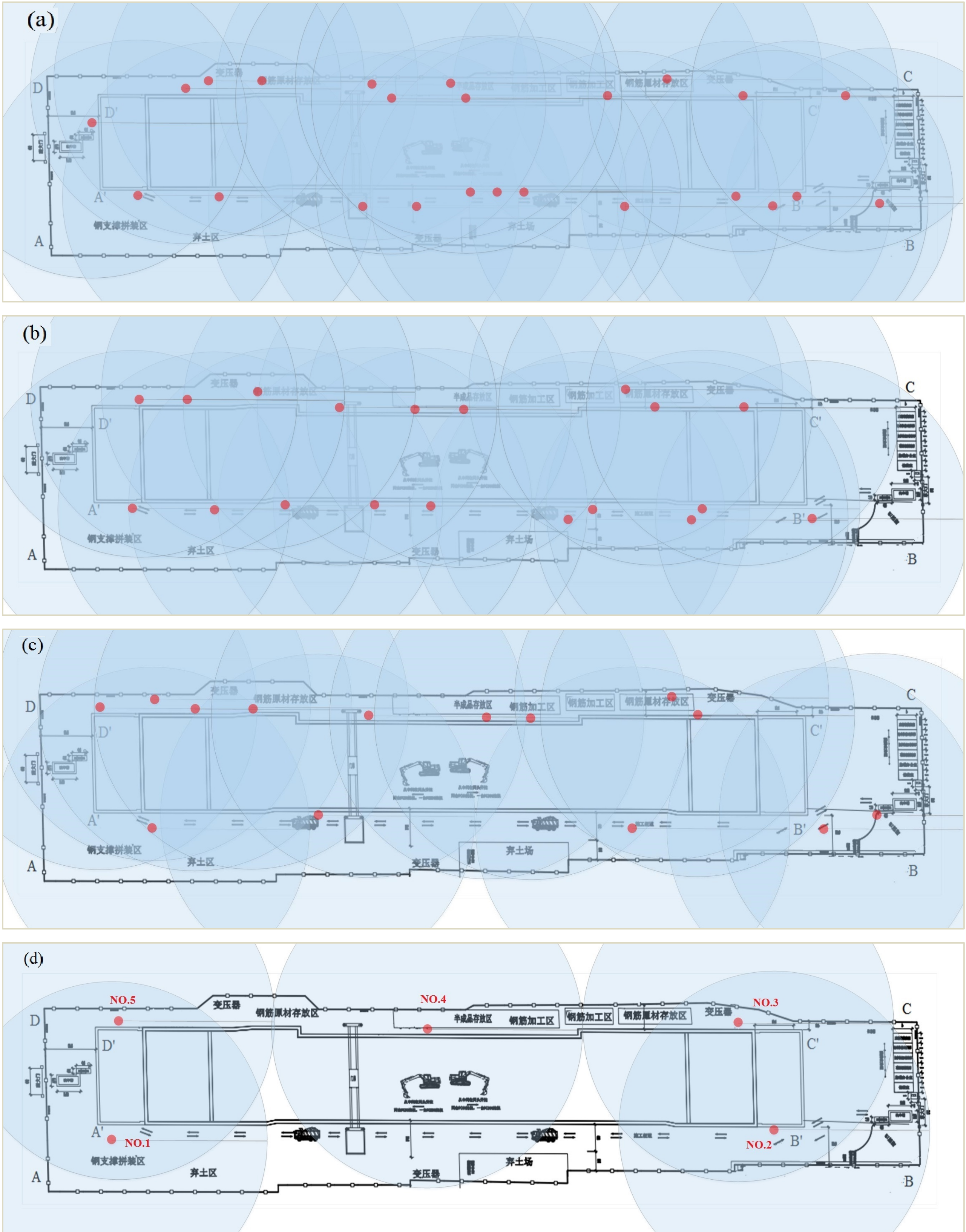

Fig. 9 Coverage of optimal camera placement plan for (a) bottom slab, (b) medial slab, and (c) roof slab constructions; (d) placement plan of original cameras

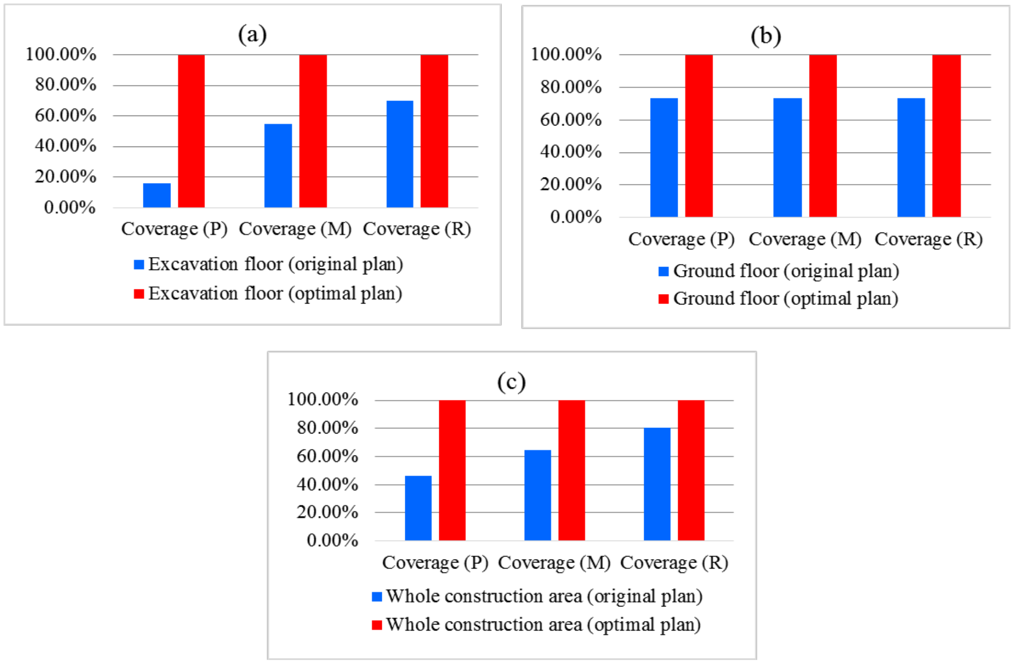

Fig. 10. Comparison of the coverage between original and optimized plans (a) coverage for excavation floor, (b) coverage for ground floor, and (c) coverage for whole construction area

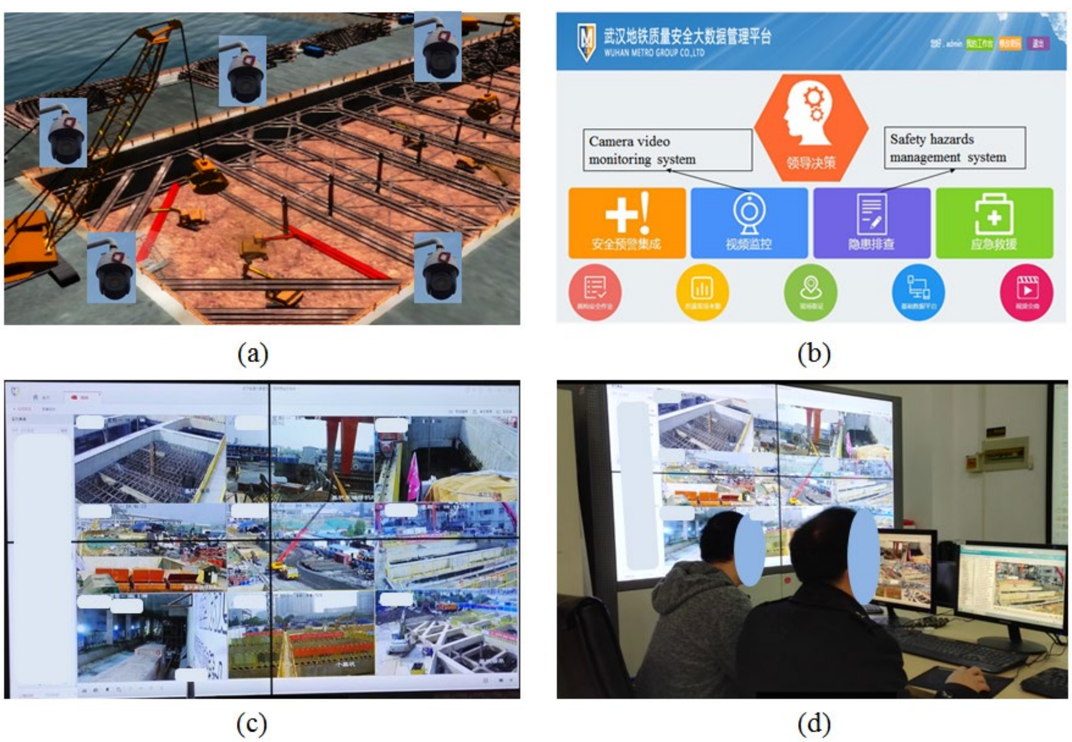

Fig. 11 Application of the proposed approach for camera placement optimization on metro station sites: (a) model of cameras on metro station sites; (b) interface of the web-based Quality and Safety management system for Wuhan Metro; (c) and (d) system use by engineers.

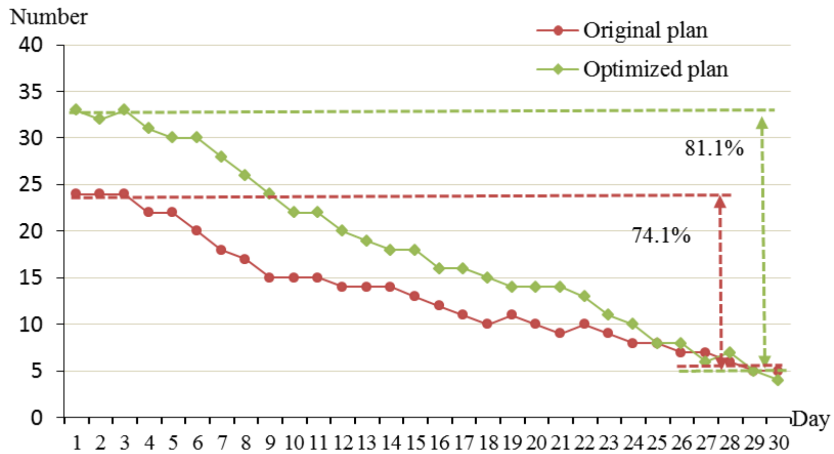

Fig.12. Performance of the change of safety hazards detection based on original plan and optimized plan