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Research on Quality Improvement and Safety Measures of Highway Pavement Construction by Unmanned Aircraft Swarm Operation Based on Optimal Control Theory

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ABSTRACT

Aiming at the traditional pavement construction, there are problems such as poor construction conditions, limited quality inspection methods, backward control mode and incomplete management means. In this environment, the project in this paper (Gansu Road and Bridge Anlin Pavement Second Standard Project) uses multi-objective particle swarm optimization algorithm to establish a multi-objective machine group optimization configuration model based on quality constraints under the schedule - cost, and the first time to quote asphalt pavement to carry out the intelligent construction of unmanned machine group in Gansu Province. Analyze the intelligent unmanned machine group composed of auto-pilot paving technology and roller auto-pilot technology. Design the optimal configuration model of highway construction machine group, and use multi-objective particle swarm algorithm to design the cooperative operation of unmanned machine group. Combined with the optimal configuration of highway construction fleet problem itself, the standard particle swarm algorithm and fleet configuration model are also modified and improved. Simulate the highway pavement construction process, emphasizing the preparation of construction personnel, machinery, and management platform. The parameters of particle swarm algorithm are designed to solve the optimal construction machine fleet optimization configuration under quality constraints of duration-cost. The machine utilization and duration of scheme 2 are 15.23% and 10.96%, respectively. With the priority of duration, scheme 2 is selected as the machine fleet configuration scheme. Option 4 has the lowest machinery cost of 9.41%. With the priority to ensure the maximum profit, option 4 can be chosen as the machine swarm configuration scheme.

Keywords: multi-objective particle swarm; cooperative operation of machine fleet; optimal configuration of machine fleet; duration – cost

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1. Introduction

In recent years, China's highways have been continuously upgraded and upgraded, highway management has been moving towards informationization and intelligence, and all kinds of new highway maintenance technologies, new techniques, new materials, and new equipments have been gradually applied and popularized.In the era of 5G, the intelligent, unmanned, and standardized mechanical construction has become a trend of the industry [1-3]. Domestic and foreign academics and the industry have carried out a lot of research work in highway intelligent paving, compaction and quality monitoring, which significantly improves the digitalization of highway construction, and highway engineering construction further develops in the direction of unmanned [4-5]. Theoretically, unmanned construction technology can automatically optimize the construction parameters by combining different external conditions after big data analysis, so as to achieve more accurate and higher quality asphalt pavement construction [6-7].

One of the major difficulties in pavement construction is the harsh environmental conditions that make labor costly, operator shortage, and management inconvenient [8-9]. The unmanned intelligent machine group operation can reduce the manual work in the harsh environment and also improve the work efficiency to achieve 24h uninterrupted construction. This technology can dataize, online and visualize the construction process, and display the construction process data and pavement compaction through graphical color scale diagram, which is convenient for managers to control the quality of the construction process in real time [10-12].

The operation parameters of the unmanned paving machine group, such as oil volume, water temperature, obstacles, faults and other information, can also be monitored and managed through the platform, and the construction process data and construction quality report are clear at a glance, providing data services for construction process data monitoring and construction quality traceability The technology can achieve no pressure leakage, no pressure, and no overspeed, which effectively avoids the problems of leakage, overpressure, undervoltage, and overspeed that often occur in the process of human operation [13-15].

And unmanned clusters combined with Beidou high-precision positioning, in the strategy of roller clusters and pavers set up a safe distance between the roller followed by pavers outside the safe distance, echelons and echelons of the set safe distance between the echelons of the vehicles will not enter the other areas, while the entire system is equipped with a 3-level braking control strategy to ensure that the equipment in the process of the construction of the absolute safety [16-18]. It also reduces the construction cost manifested as saving people, materials and time.

The application of intelligent technology in highway engineering construction helps to reduce the pressure of personnel construction, but also can improve the quality of highway engineering construction, helping to improve the overall interests of the construction unit. Literature [19] carries out evaluation tests to reveal the good performance of intelligent unmanned maintenance technology in asphalt pavement maintenance, which provides a reference for highway operation and maintenance automation. Literature [20] based on the unmanned construction situation investigation learned that unmanned construction machine paving accuracy error within 2CM, and to avoid the phenomenon of no rolling, while reducing the construction cost and improve the construction quality and efficiency. Literature [21] analyzes the current situation of road construction technology development and emerging technology integration path and development direction, that semi-automation and technology integration helps highway construction cost prediction and efficiency and quality of all aspects of the improvement. Literature [22] combined high-precision satellite positioning and intelligent sensing theory technology to design an unmanned roller to solve the problems of highway construction leakage, underpressure, overpressure, low construction efficiency and strong vibration. Literature [23] conceived a roller path generation strategy based on the automatic generation of unmanned aircraft, and introduced computer vision technology to simplify the process, which effectively promotes the development of intelligence and automation of road construction. Literature [24] designed an innovative gain-adaptive Kalman filter (IG-AKF) algorithm to enhance the precise positioning of unmanned vibratory rollers, and verified the feasibility of the proposed method through simulation experiments.

Based on the reality of highway pavement construction problems, this paper proposes the introduction of intelligent unmanned machine group technology, and for the first time in Gansu Province to the asphalt surface layer. Analyze the composition of intelligent unmanned machine group, including automatic driving paving technology and roller automatic driving technology. Analyze the process of optimizing the configuration of highway construction fleet, and put forward the requirements for optimizing the configuration of construction fleet implementation. Using multi-objective particle swarm algorithm, propose the optimal configuration model solution of construction machine group based on particle swarm optimization algorithm. Simulate the highway pavement construction process, respectively, construction preparation and construction program description, proposed asphalt pavement testing and inspection. Combined with the real situation of the project, the multi-objective machine group optimization configuration model solution under the quality constraint is carried out. Propose the complexity of asphalt pavement construction, analyze the influence of asphalt mixture transfer truck on asphalt pavement temperature, and analyze the importance of transfer truck on asphalt pavement construction.

2. Intelligent unmanned swarm pressurization construction technology

2.1. Realistic needs of highway pavement construction

For the traditional pavement construction exists in the poor construction conditions, quality inspection method limitations, backward control mode, management tools are not comprehensive and other problems. In this environment, Gansu Road and Bridge Anlin pavement project actively responded to the call of the state, in Gansu Province for the first time to quote the asphalt surface layer unmanned flock of intelligent construction, for the province of pavement engineering high quality construction has accumulated valuable practical experience.

2.2. Intelligent unmanned aircraft fleet

The system includes paver auto-pilot paving technology, roller auto-pilot compaction technology, machine group cooperative control construction technology, digital platform and other technologies, and organically integrates advanced intelligent technologies such as artificial intelligence, 3D leveling, intelligent compaction, cloud platform, big data and road machine products.

2.2.1. Automated paving technology. Paver automatic driving paving technology: real-time dynamic differential positioning, automatic driving algorithm, full electro-hydraulic controller and paving management system are utilized to realize automatic control of paver driving and paving operation.

1) Self-developed automatic driving algorithm combined with RTK high-precision positioning technology, real-time planning path, speed, etc. to realize automatic driving.

2) The upper computer system, infrared temperature monitoring system, paving data acquisition system, communication bridge and paving status monitor form the paving management system. Through the temperature sensor and rotational speed sensor installed on the paver, all the real-time parameters (paving temperature, square volume, fuel consumption, vibration frequency, paving speed, real-time position and movement track) currently in the construction state are collected and recorded, and transmitted to the control console for data summarization and analysis through wireless communication. Through the electronic LED display installed on the paver, combined with the remote control technology, it can provide remote prompts and remote interventions for abnormal paving

parameters (low material temperature, abnormal leveling) and take downtime measures when necessary.

3) Remote control technology realizes remote monitoring of the real-time construction scene of the paver through radio technology, wireless network bridge and high-definition camera, and realizes remote control of various actions of the paver from the console through wireless remote control technology [25].

4) 3D digital leveling technology is embodied in the following aspects. Firstly, the pavement design data are imported into the 3D leveling controller, and the real-time centimeter-level 3D point position information of the paver screed is acquired in real time and the corresponding elevation design information is calculated through the GNSS receiver using the RTK (carrier phase differencing) technology. Secondly, based on the domain laser transmitter and laser receiver, the laser signal received from the 3D point position is converted into an electrical signal. The difference between the measured elevation and the designed elevation is calculated based on the amount and change of the electrical signal, and the leveling electromagnetic proportional hydraulic reversing valve is controlled to realize millimeter-level leveling accuracy. Finally, through the background data processing, it realizes pile-less paving, reduces the paving error caused by human intervention, and realizes the construction requirements of frequently changing slopes and curves.

2.2.2. Autopilot technology for rollers. Development of driverless operation system: Utilizing RTK high-precision positioning, automatic driving algorithm, full electro-hydraulic controller and compaction management system to realize automatic driving and automatic compaction of road roller.

1) Self-developed automatic driving algorithm combined with RTK high-precision positioning technology, real-time planning path, speed, etc. to realize automatic driving.

2) Intelligent compaction management system: integrated system of compaction sensors, processing units and display devices.

3) Developing the wireless communication system of the machine group, establishing high-speed wireless communication between the control center and the machine group equipment, as well as between the machine group equipment.

4) Establishing a safe scheduling mechanism for the machine group. Assign tasks and construction path dynamic planning to all rollers through the platform. Control the safety distance between road rollers to prevent collision.

5) Millimeter-wave radar, ultrasonic sensing system composed of safety obstacle avoidance system to realize the roller automatic obstacle avoidance, risk avoidance, detection of people or objects around the safety range of the roller autonomous braking, to be moved away from the people or objects and autonomous start.

6) Automatic watering operation, driverless roller automatic watering function optimization.

2.3. Construction machine fleet optimization model

Optimal configuration of road construction machine group refers to the configuration of economically reasonable, technologically advanced and safe and reliable use of the optimal mechanical operation group according to the specific conditions of engineering construction, in order to give full play to the comprehensive efficiency of the machine group, and to achieve the optimal allocation of engineering resources, work efficiency and quality of work.

2.3.1. Optimized fleet allocation process. Road engineering mechanization construction machine group optimization configuration contains three aspects.

1) According to the specific project, operation task and construction progress for the selection of machinery type, the initial selection of machine group optimization configuration scheme.

2) Allocation and optimization of machinery dosage according to the amount of engineering work, i.e., reasonable selection of machine group, optimization of selection and selection of implementation conditions.

3) Determine the method of optimal configuration of the machine group, and at the same time, carry out global and dynamic optimization of the whole construction process, and determine the organization and management measures to make the machine group play the maximum efficiency.

As a result, the process of optimizing the configuration of the machine group can be divided into three stages: reasonable selection of the machine group, optimization of the machine group and implementation of the combination of the machine group.

The first stage of rational selection of the fleet is to determine the type and specification parameters of the fleet structure and constituent machinery. Determine the types and specifications of the constituent machinery and a reasonable fleet structure.

The second stage is to determine the optimum fleet combination required from the feasible machinery and equipment resources.

The third stage is to determine the whole process of real-time dynamic organization and management measures to maximize the efficiency of the fleet.

The general process of optimal configuration of the machine fleet is shown in Figure 1.

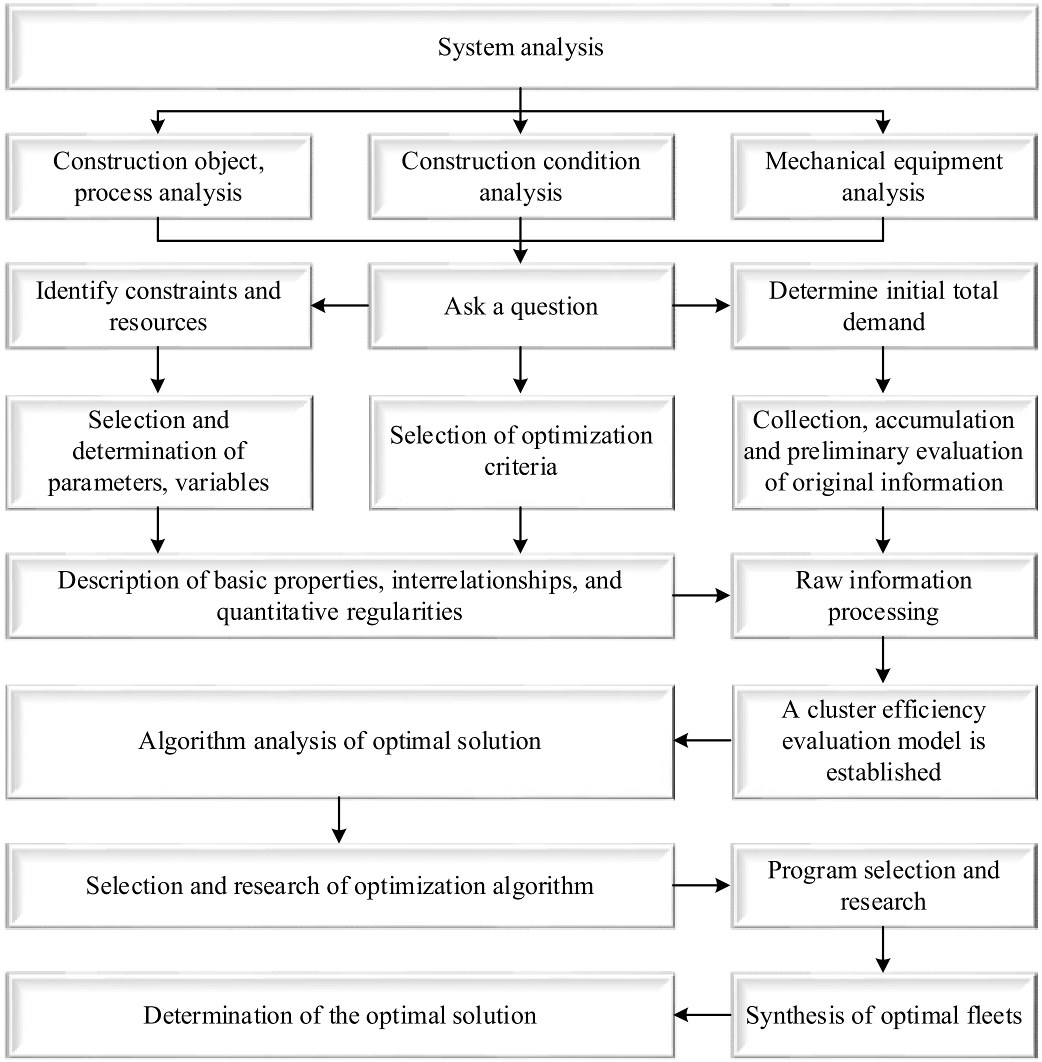

Fig. 1. The general process of optimizing the configuration of the fleet

2.3.2. Real-time optimization of construction fleet configuration. According to the asphalt concrete pavement construction technology and construction process, the asphalt concrete pavement construction system can be divided into three subsystems: mixing-transportation subsystem, transportation-paving subsystem and paving-compaction subsystem.

1) Mixing-transportation subsystem. Construction conditions, mixing equipment production capacity, mix transportation routes, transportation distance and time, paving capacity of concrete paving equipment and the amount of mix are the influencing factors of the mixing-transportation subsystem.

For the mixing-transportation subsystem, the subsystem influencing factors are regarded as variables of time, and a real-time optimal allocation model of the construction fleet of mixing-transportation subsystem is established:

$$y_1 = \begin{bmatrix} a_{11}(t) & a_{12}(t) & \cdots & a_{1n}(t) \end{bmatrix} \tag{1}$$

where y_i is the mixing-transportation subsystem objective. $a_{1j}(t)$ is the mixing-transportation subsystem influencing factors, both as a function of time.

2) Transportation-paving subsystem. The transportation-paving subsystem aims to meet the continuous paving operation of asphalt concrete pavers.

The influencing factors of the transportation-paving subsystem are mainly the production capacity of the mixing equipment, the transportation capacity of the trucks, and the paving capacity of the pavers.

For the transportation-paving subsystem, the subsystem influencing factors are regarded as variables of time, and a real-time optimal allocation model of the transportation-paving subsystem fleet is established:

$$y_2 = \begin{bmatrix} b_{21}(t) & b_{22}(t) & \cdots & b_{2n}(t) \end{bmatrix} \tag{2}$$

where y_2 is the transportation-paving subsystem objective. $b_{2j}(t)$ is the transportation-paving subsystem influencing factors, all as a function of time.

3) Paving-compaction subsystem. The paving-compaction subsystem takes the formation of good pavement quality as its goal.

The influencing factors of the paving-compaction subsystem mainly include the requirements of pavement construction process, compaction temperature, compaction capacity of compaction machinery, compaction speed, compaction method, number of compaction passes, and paving rate of the paver.

For the paving-compaction subsystem, the subsystem influencing factors are regarded as variables of time, and the real-time optimal configuration model of paving-compaction subsystem machine group is established. Namely:

$$y_3 = \begin{bmatrix} c_{31}(t) & c_{32}(t) & \cdots & c_{3n}(t) \end{bmatrix} \tag{3}$$

where y_3 is the paving-compaction subsystem objective. $b_{3j}(t)$ is the paving-compaction subsystem influencing factors, all of which are functions of time.

4) Real-time optimal configuration model of construction machine group. From the above analysis, asphalt concrete pavement construction machine group real-time optimization configuration model can be expressed as:

$$X = \begin{bmatrix} a_{11}(t) & a_{12}(t) & \cdots & a_{1n}(t) \\ b_{21}(t) & b_{22}(t) & \cdots & b_{2n}(t) \\ c_{31}(t) & c_{32}(t) & \cdots & c_{3n}(t) \end{bmatrix} \tag{4}$$

Where, X - the total construction system matrix of influencing factors, is $3 \times n$ matrix.

If the total objective matrix of the construction system is represented by Y:

$$Y = \begin{bmatrix} y_1 & y_2 & y_3 \end{bmatrix}^T \tag{5}$$

expressed as a function:

$$Y = f(X) \tag{6}$$

In the actual construction process, if the influencing factors of a subsystem change, adjustments can be made to the system configuration scheme from the following two options to optimize the configuration of the construction fleet in real time:

Ⅰ. Adjustment of construction process parameters

This program is mainly used in the construction process. Generally, it is to adjust the speed of paver and compaction machinery and change the service rate of paving subsystem and compaction subsystem.

Ⅱ, increase or decrease the number of construction equipment

This program is mainly used in the process of construction system configuration equipment. It is usually to increase or decrease the number of material transportation vehicles to achieve the balance of the whole fleet system.

2.4. Multi-objective optimization algorithm solution

2.4.1. Multi-objective particle swarm algorithm:

1) Multi-objective optimization problem description, i.e., in the usual sense of single-objective optimization problem [26-27]. It can be expressed by Eq. (7):

$$\begin{aligned} &\max \quad z = f(x) \\ &st. \quad g_i(x) \le 0, i = 1, 2, \cdots, m \end{aligned} \tag{7}$$

where $x \in R^n$ is the vector with n decision variables, $f(x)$ is the set of objective functions, $g_i(x)$ is the set of m inequality constraint functions, and the feasible solution region is usually denoted by S the feasible region in the decision space, expressed in the form of Eq. (8):

$$S = \left\{ x \in R^n \mid g_i(x) \le 0, i = 1, 2, \cdots, m, x \ge 0 \right\} \tag{8}$$

The multi-objective optimization problem is transformed into the form of Eq. (9). Given the decision vector $x = \left[x_1, x_2, \cdots, x_n \right]^T$ let it satisfy the following constraints:

$$g_i(x) \ge 0 \; i = 1, 2, \cdots, k \tag{9}$$

$$h_i(x) = 0 \; i = 1, 2, \cdots, l \tag{10}$$

Suppose it contains m optimization objective and the m objectives are in conflict with each other:

$$f(\overline{x}) = \left[f(\overline{x}), f_2(\overline{x}), \cdots, f_m(\overline{x}) \right]^T \tag{11}$$

Seek $x = [x_1', x_2', \cdots x_n']^T$ such that $f(x)$ is optimal while satisfying the constraints of the above equation.

Maximization and minimization problems can be transformed into each other, so the minimization multi-objective optimization problem will be studied here only. A multi-objective problem can be expressed in the form of Eq. (12), where the decision vector $x \in R^m$ and the objective vector $y \in R^m$:

$$\mathrm{n}y = f(x) = [f_1(x), f_2(x), \cdots, f_n(x)] \tag{12}$$

Definition 1: (Superiority and Inferiority) Suppose $u = [u_1, u_2, \cdots, u_n]$ is superior to $v = [v_1, v_2, \cdots, v_n]$, denoted as $up > v$. If some part of u is less than v i.e.: $\forall i \in \{1, 2, \cdots, n\}, u_i \le v_i \wedge \exists i \in \{1, 2, \cdots, n\}, u_i < v_i$. Conversely it is denoted as $vp < u$.

Definition 2: (Non-inferiority) Assuming that the objective vectors $u = [u_1, u_2, \cdots, u_n]$ and $v = [v_1, v_2, \cdots, v_n]$ are non-inferior to each other, non-inferiority can be termed as Pareto if u is neither better than v nor worse than v.

Definition 3: (Non-inferior optimal solution) Decision variable $x_u \in R^n$ is called a non-inferior optimal solution to a multi-objective optimization problem if and only if there is no decision variable $x_v \in R^n$ such that the corresponding objective vector. Will:

$$v = f\left[x_v \in R^n \right] = \left[v_1, v_2, \cdots, v_n \right] \tag{13}$$

Is better than $u = f\left[x_u \in R^n \right] = \left[u_1, u_2, \cdots, u_n \right]$, i.e. $vp > u$. Then this solution can be called Pareto optimal solution.

2) In order to improve the convergence performance of the algorithm effectively, the concept of inertia weights is introduced into the algorithm, and the updating formula of speed is modified. However, no change is made to the position update formula, and the modified update formulas for velocity and position are as follows:

$$v_{id}^{k+1} = \omega v_{id}^{k} + c_1 r_1 (p_{id}^{k} - x_{id}^{k}) + c_2 r_2 (p_{gd}^{k} - x_{id}^{k}) \tag{14}$$

$$x_{id}^{k+1} = x_{id}^{k} + v_{id}^{k+1} \tag{15}$$

where ω is called the inertia weight, and its magnitude determines how much is inherited to the current velocity of the particle. It can be seen that the elementary particle swarm algorithm is a special case of the standard particle swarm algorithm with inertia weight $\omega = 1$.

2.4.2. Optimized fleet allocation model solution:

1) Improvements made to the standard PSO algorithm before computing the model. In order to accelerate the convergence speed and at the same time avoid the premature convergence phenomenon in order to search the global optimal solution, the following improvements are made to the standard PSO algorithm before computing the model:

Dynamically adjusting the inertia weights can be achieved by setting time-varying weights. As the iteration proceeds, the inertia weight ω in the velocity update formula decreases linearly from a maximum value of $\omega_{\max}$ to a minimum value of $\omega_{\min}$, causing the particle to explore a larger region at the beginning. That is, the exploration ability is increased and the approximate location of the optimal solution is localized faster. As ω decreases, the particle slows down and begins a finely localized search. That is, the exploitation ability is increased, the optimal solution is found faster, and the time-varying weights better accelerate the convergence rate. The variation of ω with the number of iterations of the algorithm is given by Eq:

$$\omega_k = \omega_{\max} - \frac{\omega_{\max} - \omega_{\min}}{k_{\max}} \times k \tag{16}$$

where k is the current iteration number and $k_{\max}$ is the maximum iteration number. Usually $\omega_{\max} = 0.9, \omega_{\min} = 0.4$ is taken.

Add random deflection strength d, that is, in the particle swarm following the optimal particle at the same time, if the particle's movement speed, direction to increase the random deflection, so that the particles can be avoided to fall into the local optimal solution during the search, resulting in the phenomenon of premature convergence, so that the particle swarm search to the entire solution space. The velocity and position update formula for adding random deflection intensity is:

$$v_{id}^{k+1} = \omega_k v_{id}^{k} + c_1 r_1 (p_{id}^{k} - x_{id}^{k}) + c_2 r_2 (p_{gd}^{k} - x_{id}^{k}) + dr \tag{17}$$

$$x_{id}^{k+1} = x_{id}^{k} + v_{id}^{k+1} \tag{18}$$

where the random flexural strength d depends on the specific case and r_3 is a random number between [0,1].

2) PSO algorithm implementation of the duration-cost optimization function. The encoding of the problem solution is designed to solve how to map the feasible solution space of the problem to the search space of the particle swarm. In the MATLAB environment, the particles in the population and their velocities are encoded in real numbers. The format of particle parameter encoding is shown in Table 1, where size dim denotes the parameter dimension.

Table 1. Particle parameter coding format

$X_1, X_2, \ldots, X_{dim\ size}$	$V_1, V_2, \ldots, V_{dim\ size}$	$\mathrm{F}(X)$
The representation of the particle's location	The velocity of the particle	Fitness function

For the swarm optimization configuration model problem, the key work of coding design is to realize the one-to-one mapping between the swarm configuration schemes and the feasible solution search space of the particle swarm. That is, to transform each configuration scheme into a point in the dimsize-dimensional search space of the particle swarm. This maps each configuration scheme to a particle, and a change in the configuration scheme is equivalent to an update of the particle's position in the search space. This results in a specific mapping relationship between the swarm configuration schemes and the particles.

Process of PSO algorithm:

The flow of the particle swarm algorithm for duration-cost optimization under quality constraints for the optimal configuration problem of highway construction machine fleet is as follows:

Step1: Set the problem domain system parameters. The system parameters are: population size popsize, parameter dimension size dim, learning factors c_1 and c_2, maximum number of iterations k_{max}, maximum inertia weight ω_{max}, minimum inertia weight ω_{min}. And random number perturbation strength d.

Step 2: Initialize the position and velocity of all particles. Initialize the particle population randomly with function $randn()$ within the allowed range to produce size dimensional vector. And use function $round(x_{i,j})$ to set the particle position rounding. The pbest of each particle is set as the initial position, and the optimal value in pbest is set as pgbest.

Step 3: Calculate the adaptation value of each particle according to the adaptation function and update pbest. Calculate the adaptation value of the particle. If it satisfies the constraint and is better than pbest, pbest is replaced by the current position, otherwise pbest remains unchanged.

Step 4: Update pgbest. Select the optimal value among all individual optimal solutions pbest as the current global optimal solution pgbest of the particle population.

Step 5: Update the position and velocity of the particle.

Step 6: Judge the termination condition. If the termination condition is satisfied (find the optimal value or reach the maximum number of iterations), then terminate the iteration, and the position recorded by pgbest is the optimal solution of the problem. Otherwise, go to Step 3.

3. Highway pavement construction simulation

The pilot operation content for the K47 +300-K48 +880 section of the left width of the asphalt pavement layer, K32 +800-K54 +680 full width of the asphalt pavement layer intelligent unmanned swarm amortization construction operations, the pilot time for the period from April 6, 2023 to April 13, 2023, the pilot.

Gansu Road and Bridge Construction Group Co., Ltd. was awarded the top ten “innovative platforms” of key research platforms in the transportation industry in 2018, and Sany Heavy Industry Co., Ltd. adheres to the concept of “everything comes from innovation”, and is committed to researching and developing the world's most cutting-edge technology and the most advanced products of construction machinery. The most advanced products.

3.1. Drone swarm management

The construction management cloud platform for unmanned paver fleet consists of three centers, namely, engineering center, equipment center and application center, carrying core functions such as quality management system, equipment digital management system, customized homepage and scalable application. Before construction, the basic information of construction sites and construction equipment (equipment type, construction mileage, construction object, construction process, etc.) can be entered into the management platform, which provides the basis for the digital management of construction in the later stage.

The on-site deployment and control of the UAV swarm includes the following aspects:

1) Power supply system erection. Before the construction of the unmanned amortization machine group, the power supply system needs to be set up in advance to provide power for the platform as well as the positioning and communication of the machine group, and it is recommended to use 220V utility power or 3kw generator.

2) Establish communication network. In the construction area to establish a local communication network, can be used in two ways of communication, one is to build a bridge for communication, the other is through the radio for communication.

3) Establishment of base station. In the vicinity of the construction area, choose a relatively open area to set up the base station, and calibrate the base station and other related work.

4) Control room function debugging. Test the health of each equipment sensor (e.g. LIDAR, millimeter-wave radar, temperature sensor, etc.), and test the operation status of each equipment (e.g. spraying, walking, changing lanes, etc.).

5) Construction area cleaning. Before construction, the construction area will be cleaned up, the surface of the road section to be paved with water trucks, supplemented by manual shoveling debris, floating dust, shoveling debris does not fall on the roadbed slope side ditch and the central divider, especially by the longitudinal drainage ditch side of the strict sweeping, the soil contamination of serious localized high-pressure water jet with water trucks rinsed clean and dried, cleaned road sections without floating dust, debris and construction waste.

6) Road data generation. In the construction of unmanned paver group, the generation of road data is an extremely important part. The road information in the construction area is collected in advance and the road data required by the unmanned machine group is generated.

7) Elevation check. In order to realize better paving effect, the roadbed elevation information of the construction area can be reviewed in advance and feedback in time.

3.2. Construction Preparation

3.2.1. Construction staffing. 1 construction team leader, 1 paving operator, 2 roller operators, 2 technical service personnel, and a number of auxiliary workers.

3.2.2. Preparation of construction machinery. Unmanned paver group construction varies the mechanical equipment for different construction materials.

Asphalt construction machinery and equipment equipment table (preliminary) is shown in Table 2.

Table 2. The asphalt construction machinery equipment is equipped with a table (initial)

Device name	Specification type	Quantity	Technical condition	Where to use	Remark
Paver	Three heavy industriesSAP130C-10	1	Good	Face layer	/
Double steel wheel roller	13t STR130C-8	3	Good	Face layer	/
Rubber wheel roller	30t PR300C-8	3	Good	Face layer	1 as a spare

3.2.3. Management platform setup. The construction management cloud platform for unmanned paver fleet consists of three centers, namely, engineering center, equipment center and application center, carrying core functions such as quality management system, equipment digital management system, customized homepage and scalable application.

Before construction, the basic information of construction sites and construction equipment (equipment type, construction mileage, construction object, construction process, etc.) can be entered into the management platform, which provides the basis for the digital management of construction in the later stage.

3.3. Construction Program

3.3.1. Mixing of asphalt mixtures:

1) The mixing of asphalt mixture adopts fully automatic asphalt mixture mixing equipment.

2) Temperature control. For asphalt mixtures, there is no quality without temperature, so temperature control is crucial. The temperature of asphalt mixture production process is shown in Table 3.

Asphalt mixture before leaving the factory, by the mixing station test, quality personnel visually and vehicle by vehicle temperature testing, qualified to fill out the bill of materials and certificate of conformity before leaving the factory. After the material truck to the site, the temperature should be detected by a person car by car, after passing the test can be paved.

The construction process must control the temperature of each construction stage of the mixture from the beginning to the end. The residual moisture content of the dried aggregate shall not be more than 1%. Storage period, the temperature drop should not exceed 10 ℃, and shall not occur combined material aging, dripping and coarse and fine aggregate particles segregation phenomenon.

Ordinary asphalt mixture discharge temperature higher than 190 ℃ should be discarded, modified asphalt mixture temperature higher than 195 ℃ should be discarded, hot mix asphalt mixture must be naturally cooled, the temperature is lower than 50 ℃ before paving the upper layer or open to traffic.

Strictly control the heating temperature of asphalt and aggregate, to avoid high temperature caused by asphalt aging. A person is responsible for detecting the temperature of the discharged material at the discharge port of the mixing building, and detecting the factory temperature of the asphalt mixture at the covering platform of the mixing plant, so as to ensure that the temperature of the mixture is suitable and stable.

Control the amount of dust, not to use recycled dust, mixing machine emissions of dust using wet processing, into the ground dust pool, to be around the frequent sprinkling of water, and then use the loader with cars piled up in the location designated by the supervising engineer, dust cleanup must be supervised by the supervising engineer number of statistical review before being transported, the establishment of the recycling and waste ledger.

Table 3. The temperature of the process of the asphalt mixture

Asphalt type		SBS Modified asphalt
Asphalt label		
Asphalt heating temperature (℃)		165~175
The heating temperature of the ore		The aggregate is 10-20as high and the filler is not heated.
The asphalt mixture is normally factory temperature		175~185
Mixed storage storage temperature(℃)		The mixing material temperature in the storage process is no less than 10.
Mixed waste temperature(℃)		195
Transport to the scene temperature is no lower than(℃)		165
Lay the minimum temperature(℃)	Normal construction	160
	Low temperature construction	/
Start the lowest temperature in the mixture(℃)	Normal construction	155
	Low temperature construction	/
The temperature of the road table is not lower(℃)		100
Open traffic temperature, not higher(℃)		50

3) Mixing station quality testing content. In order to ensure the quality of asphalt mixture production, in each shift construction, the quality of asphalt mixture must be tested, the main test of the following project indicators: asphalt mixture out of the temperature, stability, flow value, density, void ratio, residual stability, extraction (asphalt dosage and gradation), the above content according to the production of the shift for testing.

3.3.2. Transportation of asphalt mixtures. In order to ensure the paving temperature of asphalt mixture, attention should be paid to the process of mixture transportation:

1) The use of large tonnage (> 20T) dump truck transportation.

2) The bottom of the carriage and the side panels of the material transportation vehicle painted with appropriate oil and water mixture for isolation, and exclude the visible free residual liquid, prohibit the use of diesel fuel as a segregation fluid.

3) When loading the vehicle shall be moved back and forth, each carload of material loading move more than 3 times, shall not be piled up in one location, divided into the front and rear of the right and left compartments as far as possible to maintain uniformity, in order to avoid segregation of the mixture.

4) each transport vehicle in the transport process must be covered with cloth insulation, rain and dust, in the longer distance and temperature below 15 ℃, cover the quilt or double felt to achieve feasible thermal insulation measures.

5) After the material truck arrives at the construction site and is qualified by inspection, it will be directed by a person to pour the material. The material truck will stop at 10-30cm in front of the paver, and the roller will push the material truck forward synchronously, and pour the material while moving forward.

3.3.3. Paving. The paving width of this project is 9.5 meters, and the paver screed splice width is 9.25 meters.

1) Paver Starting Control. Install the contact type automatic leveling device, after determining the thickness, use the hardwood mat to the loose paving thickness, the starting speed of the paver is controlled at 1m/min to be normal after paving at a speed of 2m/min in an even and continuous manner.

2) Paving process control. The paving process needs to pay attention to whether the paving line is consistent with the design requirements.

In the process of paver traveling, its speed should be with the material supply car with the material car in the feed can not hit the paver, should be in the distance from the paver 10cm ~ 30cm at the stop, by the paver to implement.

The paving temperature of asphalt mixture shall not be lower than 160℃. During the paving process, the tamper of the paver and the vibration of the screed should be opened, and the opened gear should not be less than 2/3 of the highest gear, and the compaction degree after the screed should be more than 85%.

The paver operation after the field has professional workers for local defects treatment, including segregation at the sprinkle of fine material inlays, etc. are in charge of.

The loose paving coefficient of asphalt paving needs to be communicated and coordinated with the construction unit in advance, and in the process of paving, special personnel are sent to test the paving thickness with a brazier every other section (about 100 meters) to check the loose paving thickness.

With the historical experience of the scale readings to correct the screed paving angle to the best state, and with hardwood liner to the construction of the loose paving thickness, paving start speed control at 1m/min, to be normal after 2m/min speed forward uniform continuous paving, encountered anomalies allowed to slow down the speed.

3.3.4. Crushing. The unmanned asphalt concrete compaction process is divided into three stages of initial, re-compaction and final compaction with reference to the traditional construction process.

According to the driving construction situation, the combination of rolling is determined as follows:

Initial compaction immediately after the mixture paving, the temperature is not less than 150 ℃, the use of two double drum rollers vibration 3 times (specific technology coordination before construction to determine), the line pressure should not be less than 35N/mm, speed of 4 ~ 5km / h, and shall not produce the phenomenon of push and hair cracks, the length of the crush is controlled in the 30 meters, not more than 50 meters, the initial compaction of the machine is equipped with a temperature monitoring system, displaying the current milling temperature The initial press is equipped with temperature monitoring system to display the current temperature and speed of rolling.

Re-pressing using two 30-ton heavy-duty tire rollers to knead and crush 3 times (the specific process of pre-construction coordination to determine), tire inflation pressure of not less than 0.55Mpa, speed of 3.5~5km/h, re-pressing the length of the work is generally controlled at about 50m, the maximum should not exceed 80m.

Final pressure using a double drum roller static pressure 1 times (specific process before construction coordination to determine), so that the asphalt surface without obvious wheel marks. After the final pressure, when the road surface temperature is lower than 50 ℃ allows the opening of traffic.

3.3.5. Seam treatment:

1) The joints of asphalt pavement must be tight and connected smoothly, and the leveling of the joints shall be checked with a 3m straightedge to ensure compliance with the specification requirements.

2) The longitudinal joints shall be hot jointed, and two pavers shall be paved in parallel echelon, with the distance between the two adjacent pavers about 10 meters, and the screeds shall be set at the same level. In the front part of the paved mixture, 10~20cm width is left unrolled for the time being as the back elevation reference surface, and there is an overlap of about 3~6cm of the paving layer, in the form of hot joints in the last cross joints are rolled in order to eliminate the seams.

3) construction, due to the construction of the formation of transverse seams, in the next day before the construction of the three-meter straightedge will not meet the requirements of the side of the mouth, cut with a cutting machine to remove, and clean brush adhesive layer of oil, milling, in the conditions allow, transverse milling, the conditions do not allow the case, the roller diagonal milling.

4) Flat stone, manhole and other structures and asphalt road connection, its contact surface should be clean, before construction with emulsified asphalt material coated on its contact surface, and then in the paving construction.

3.4. Asphalt pavement testing and inspection

The asphalt mixture testing criteria are shown in Table 4.

Table 4. Asphalt mixture detection standard

Project	Check frequency	Quality requirement or permissible error	Remark
Compaction (%)	The two-lane meter is measured at 200 meters	Not much in 96. Theoretical density 92-95	/
Smoothness	100 meters 10 feet	≤5mm	/
Neutral plane offset	200 meters and two points	30mm	/
Longitudinal height	Two sections of 200 meters	±20mm	/
Width	Four sections of 200 meters	±30mm	/
Cross slope	Two sections of 200 meters	±0.5%	/
Ore grading	One time	Meet the production mix	/
Asphalt content	One time	Meet the production mix	/
Marshall stability	One time	Meet the production mix	/

4. Application of engineering examples

4.1. Model solving based on multi-objective particle swarm algorithm

For the data measured on site under this working condition, it can be seen that the unmanned machine group operation mainly includes paver, double drum roller and rubber wheel roller, among which there is one paver, three double drum rollers and three rubber wheel rollers. The average arrival rate can be obtained $\lambda_1 = 1/42$, $\lambda_2 = 1/86.1$, $\lambda_3 = 1/96.6$. The average service rate $\mu_1 = 1/5.5$, $\mu_2 = 1/38.2$, $\mu_3 = 1/45.6$. The paving process, the compaction process constraints on the construction progress of the key processes, so in the subsystem given the weights of the index of machinery utilization, respectively, so that $\alpha_1 = 0.5$, $\alpha_2 = 0.3$, $\alpha_3 = 0.2$.

Set the decision variables as the number of pavers, double drum rollers, rubber wheel rollers, according to the mathematical model constructed in the previous section as well as the basic data of each construction machinery, establish the following multi-objective optimization machine group configuration model.

4.1.1. Algorithm parameterization. For the multi-objective optimization model solution, this paper uses MATLAB2020a to write the MOPSO algorithm program, and the initial parameters of the algorithm are set as shown in Table 5.

Table 5. MOPSO algorithm parameters

Parameter	Numerical value
Population scale	50
Maximum iteration number	300
Individual acceleration coefficient	$c_1 = 3$
Global acceleration coefficient	$c_2 = 3$
Inertia weight	$\omega_{\max} = 0.9, \omega_{\min} = 0.4$.
Archive size	100

4.1.2. Analysis of optimization results. Through the above table algorithm parameter settings, the Pareto frontier results are obtained for the duration-cost multi-objective optimization machine group configuration model under the constraint of machine utilization. It can be seen that the multi-objective particle swarm algorithm has a good optimization effect on the machine group configuration model, and the Pareto solution set is uniformly distributed, orderly, and has obvious convergence.

The following five optimization schemes are selected from the Pareto solution set according to the project contract duration and cost requirements, of which the design variable values of each optimization scheme are shown in Table 6. Due to the construction needs, the wet sprayer and loader are included in the design variables of the optimization scheme.

Table 6. The design variable of the optimization scheme

Optimization plan	Design variable value				
	Paver	Double steel wheel roller	Rubber wheel roller	Wet jet	loader
Existing plan	1	3	3	1	2
Solution 1	1	2	3	1	2
Solution 2	1	3	2	1	1
Solution 3	2	3	3	1	1
Solution 4	2	2	3	1	1
Solution 5	2	3	2	1	2

The optimization degree of the objective function values of machinery utilization, construction duration and machinery cost of the optimization scheme and the existing scheme is shown in Table 7.

It can be seen that the mechanical utilization, construction period and cost objective function values of the solutions from Scheme 1 to Scheme 5 are better than those of the existing scheme, and all the solutions of the five optimization schemes are not dominated by each other, indicating that the solutions obtained by the multi-objective particle swarm algorithm for the configuration model are all Pareto optimal solutions. Among them, the optimization degree of machine utilization and duration objectives of scheme 2 is the largest compared with other schemes. The machine utilization and duration of scheme 2 are 15.23% and 10.96% respectively. With the priority of construction period, option 2 can be chosen as the machine group configuration plan. Option 4 has the least machinery cost with a machinery cost of 9.41%. With the priority to ensure the maximum profit, option 4 can be selected as the machine group configuration plan.

Table 7. Optimization of all cases

Optimization plan	Target function value			Degree of optimization		
	Mechanical utilization	Time/d	Cost / 10,000 yuan	Mechanical utilization	Time/d	Cost / 10,000 yuan
Existing plan	0.821	412.5	423.37	0	0	0
Solution 1	0.917	382.1	402.16	11.69%	7.37%	5.01%
Solution 2	0.946	367.3	415.74	15.23%	10.96%	1.80%
Solution 3	0.935	374.9	406.95	13.89%	9.12%	3.88%
Solution 4	0.862	401.4	383.53	4.99%	2.69%	9.41%
Solution 5	0.899	399.0	396.12	9.50%	3.27%	6.44%

4.2. Paving tests

The purpose of this section is to test the effect of the transfer truck on temperature segregation.
1) The test method for temperature loss from the transfer vehicle to the paver is that the temperature test points are inside the storage bin of the transfer vehicle and on the outside of the paver.
2) The paving surface temperature uniformity test method is to set up 8 temperature test points in 6m paving width with 60s time interval.

4.2.1. Control of temperature segregation by transfer vehicles:

1) Temperature loss of asphalt mixture from transfer truck to paver. The test results of temperature loss from transfer truck to paver are shown in Fig. 2. From the field test results, the temperature loss of asphalt mixture reaching the outside of the paver through the material transfer truck and asphalt mixture transfer truck is about 1~14℃, and the temperature of asphalt mixture reaching the outside of the paver is about 148~154℃, which is fully able to satisfy the needs of the construction process.

Due to the low temperature during construction (the lowest temperature was only 6℃), it was already lower than or close to the construction limit temperature stipulated in the specification, and the larger temperature loss was a normal phenomenon.

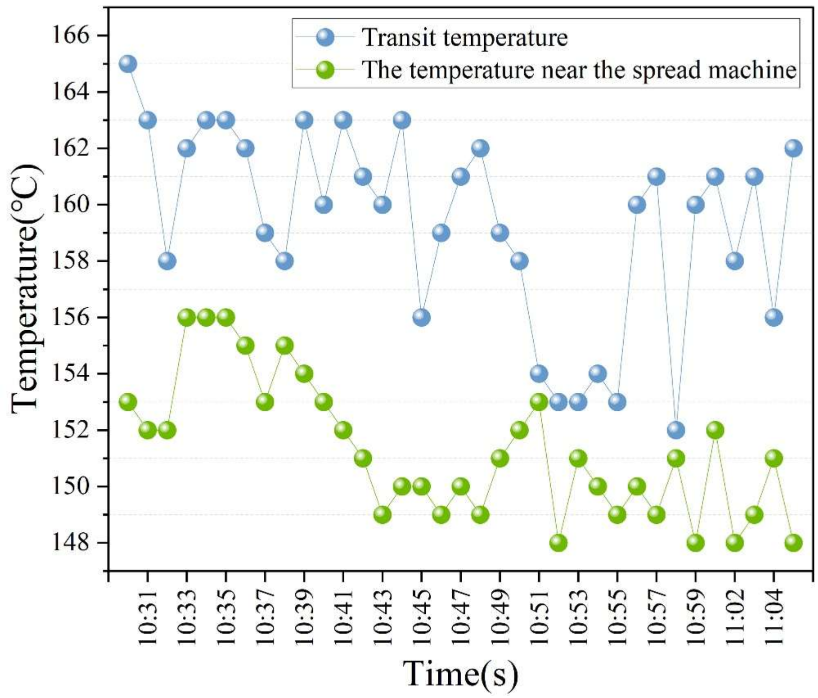

Fig. 2. The temperature loss test results of the transporter to the spread machine

2) Paving surface temperature uniformity. The infrared camera was used to capture the asphalt mixture in the truck and the temperature distribution of the pavement surface without and with the transit truck, respectively. The temperature distribution of the paved surface with the transfer truck is shown in Fig. 3, which shows the temperature distribution of the paved surface with the transfer truck at 0.5m, 1.0m, 1.5m, and 2.0m, respectively.

The temperature distribution of the paved surface is very uniform when there is a transfer vehicle, and the temperature variation is always kept at 0~11℃ in the four distances of 0.5m, 1.0m, 1.5m and 2.0m. On the one hand the temperature change over time is uniform and stable. On the other hand, the temperature along different paving widths at the same moment is also very uniform, with very small differences, basically eliminating the phenomenon of temperature segregation.

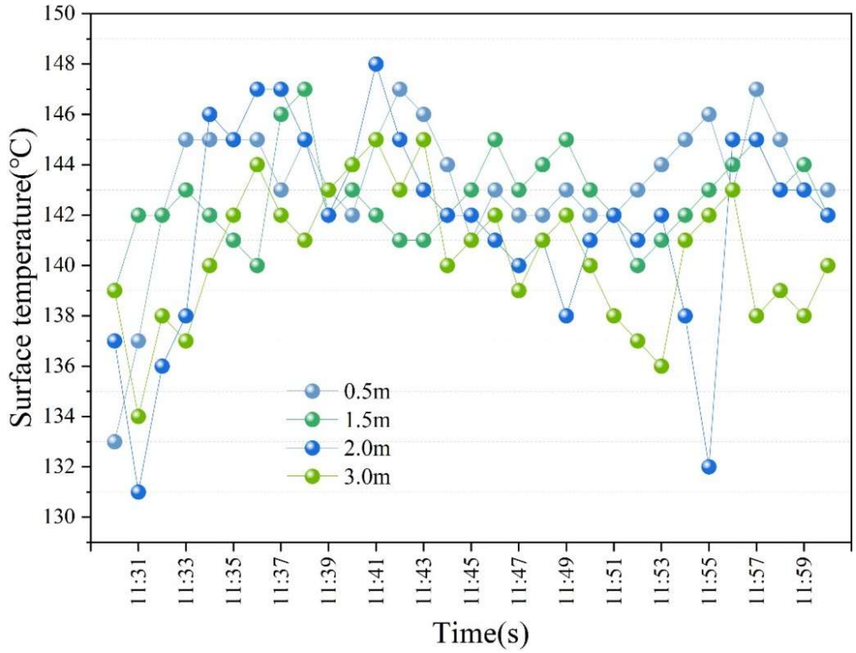

Fig. 3. The temperature of the surface on the surface of the transporter

The temperature distribution of the paved surface without the transfer truck is shown in Figure 4.

The temperature variation of the paved surface without the transfer truck is very large and uneven. The temperature variation of the paved surface with time is in the range of 0 to 22°C. On the one hand the temperature fluctuation with time is very large. The mix with very low temperatures came mainly from the bucket edges, where frequent skimming of the bucket caused periodic localized low temperature zones. The length of each low-temperature zone is about 5 to 10 meters (estimated from the paving speed). On the other hand, there are also more pronounced differences in temperature along different paving widths at the same time.

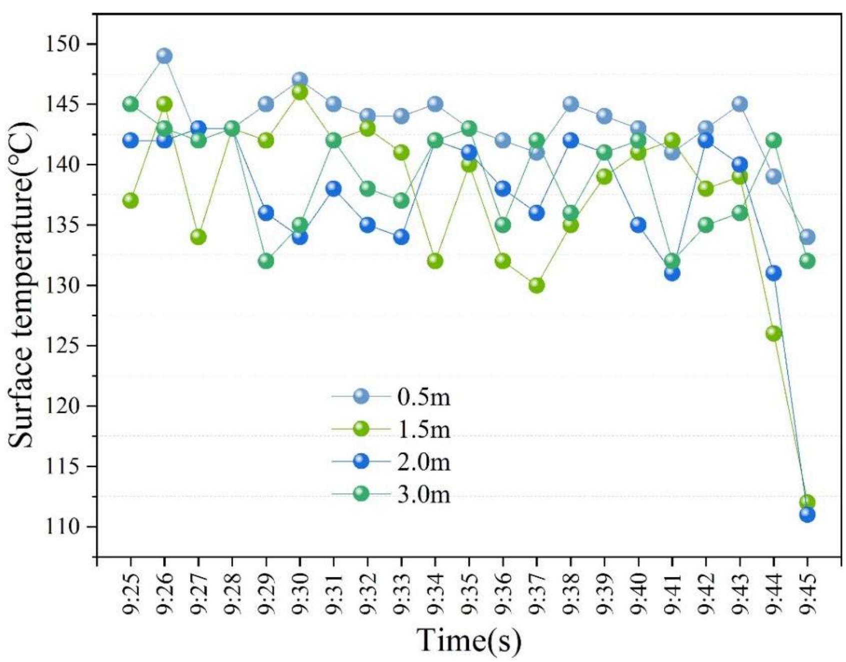

Fig. 4. The temperature distribution of the spread surface without a transporter

4.2.2. Temperature uniformity of paver feed belts. Paving feeder belt temperature distribution when there is a transfer vehicle is shown in Figure 5, when there is a transfer vehicle paving feeder belt temperature distribution is very uniform, with the time change of asphalt mixture temperature uniformity and stability, basically eliminating the temperature segregation phenomenon.

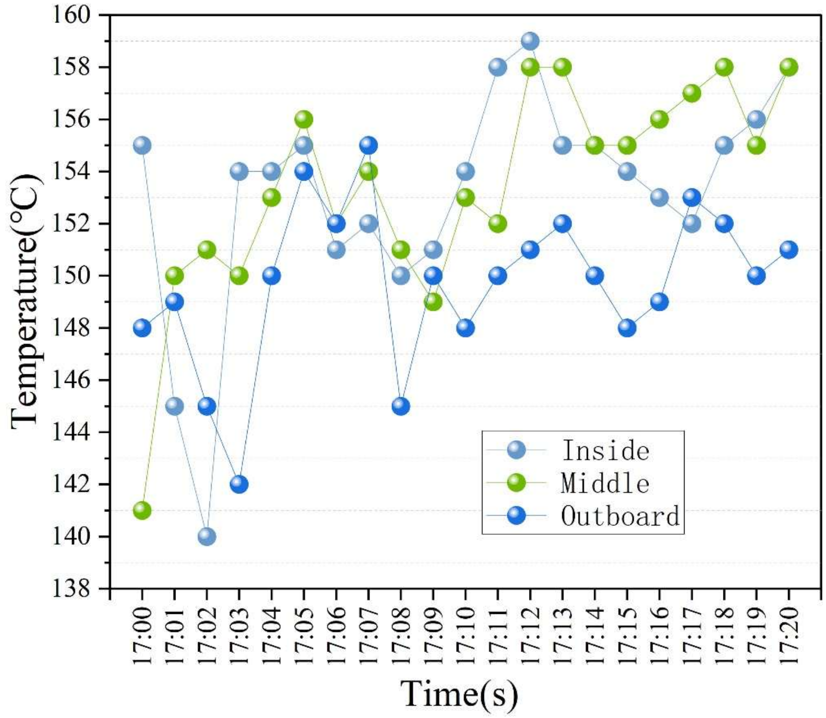

Fig. 5. The temperature distribution of the spread strip is carried out

The temperature distribution of the paving feeder belt when there is no transfer vehicle is shown in Figure 6, and the temperature difference of the paving feeder belt when there is no transfer vehicle is very large and uneven. With the time change of temperature cyclic ups and downs, the fluctuation amplitude of temperature change is very large, the temperature difference reaches about 0~28 ℃, this phenomenon is similar to the test results of the paving surface temperature.

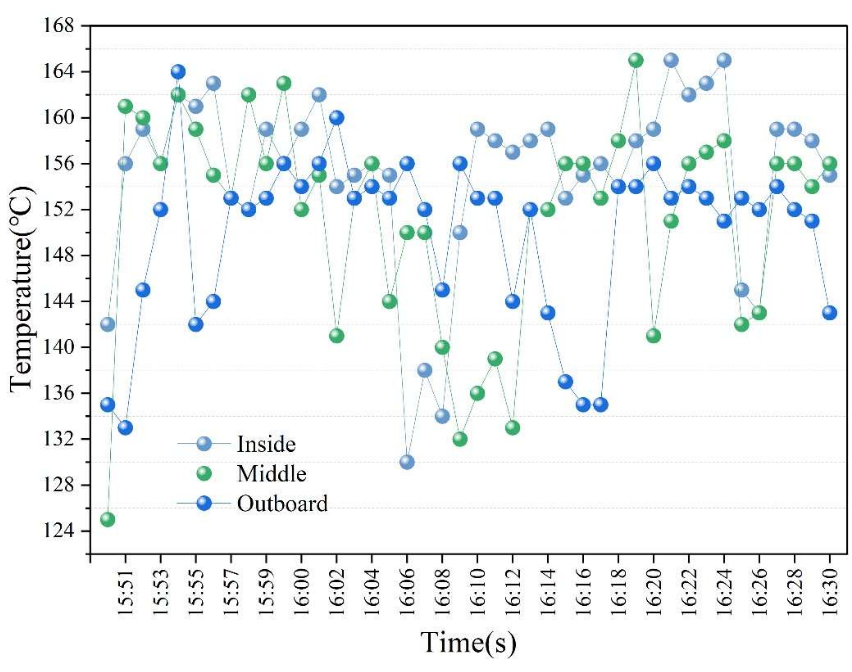

Fig. 6. The temperature distribution of the spread conveyor is not available

In summary, it can be learned:
1) Under the conventional process conditions (without using a transfer vehicle), in the loading, transportation and paving process of asphalt mixture, the asphalt mixture has the phenomenon of gradation segregation, so that the final formation of the pavement structure, the surface roughness is not the same, and the size of the internal pores and their distribution are not uniform. Along the paver on both sides of a certain width range, the coarse aggregate is relatively more, the surface is rough, the internal pores are large, and the connectivity is strong.
2) The temperature of the mixture on both sides of the paver hopper in the conventional paving process is very low, resulting in the paved asphalt mixture showing cyclic temperature ups and downs over time. The temperature of the asphalt mixture fluctuates up to 28 ℃, and the temperature of the asphalt mixture at the local low temperature is only 111 ℃. This temperature of the asphalt mixture in the case of conventional construction technology has been unable to compact. The use of asphalt mixture transfer vehicle, paving the asphalt mixture temperature changes over time its temperature distribution is very uniform, temperature segregation phenomenon has basically disappeared.
3) As the temperature of the asphalt mixture is uniform and stable, it provides convenience for the rolling work, and makes the quality of asphalt pavement more uniform and stable. It can reduce the long-term maintenance cost of asphalt pavement and prolong the service life, which has better social and economic benefits.

5. Conclusion

In this paper, in order to optimize the traditional pavement construction method, improve the construction conditions and organization and management, etc., the unmanned swarm intelligent construction plan is proposed. Using multi-objective particle swarm algorithm, joint control of automatic driving paver and roller, set particle swarm algorithm parameters, to obtain the best highway asphalt pavement construction program.
1) Simulate the highway asphalt pavement construction process, deploy and control the UAV swarm on site, and control the UAV swarm by the unmanned paver swarm construction management cloud platform. Prepare the construction personnel, construction machinery and construction platform before construction. Analyze the mixing and transportation of asphalt mixtures as well as the test and inspection standards of asphalt pavement.
2) Set the parameters of the multi-objective particle swarm algorithm, combined with the basic data of on-site construction machinery, establish a multi-objective optimization model of the construction fleet in the engineering case, and then use the multi-objective particle swarm algorithm to obtain the Pareto solution set of the fleet configuration scheme. Comparing the utilization rate of on-site machinery, duration and cost of the best configuration scheme and the original scheme, Scheme 2 is selected as the fleet configuration scheme under the priority consideration of duration. In the case of prioritizing the guarantee of maximum profit, scheme 4 can be selected as the machine group configuration scheme.
3) As this paper in Gansu Province for the first time cited in the asphalt surface layer of unmanned driver flock intelligent construction, based on the optimal construction of the flock configuration program, analyzed the transfer vehicle on the asphalt mixture temperature impact. The use of asphalt mixture transfer truck makes the temperature of asphalt mixture uniform and stable, which provides convenience for the milling work and makes the quality of asphalt pavement more uniform and stable. And it can produce better social and economic benefits.

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