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Analysis of the Optimization Strategy Based on the Cooperation of Drones and Intelligent Robots for the Inspection of Substations

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Abstract: *With the continuous development of the power system, the operation environment and scale of the power grid substation are more complex. It will become an inevitable trend for automated detection methods to replace manual detection methods because of their intelligence and security. However, at present, the use of intelligent robot inspection substation technology is not very mature, there are visual blindness, long inspection cycle, poor inspection effect, and other problems. By the development trend of the substation, this paper proposes a high altitude, low altitude, and ground inspection strategy of a substation based on the cooperation of UAV and intelligent robots. This strategy uses the grid method to construct the two-dimensional planning of the substation and then optimizes the inspection path of UAV and intelligent robots based on the improved ant colony algorithm. The UAV and the intelligent robot cooperate to realize the real-time inspection of the substation, forming a three-dimensional inspection system of "low-mid-high", "dynamic + static". The simulation results show that the inspection strategy using UAVs and intelligent robots is safer and can effectively reduce inspection time.*

Keywords: *substation, cooperative inspection, path planning, ant colony algorithm*

1. Introduction

With the rapid development of power system, intelligent substation has gradually become the mainstream. Ensuring the stable operation and daily safety of the substation is the key goal of the power system. However, the layout of equipment in substations is compact and complex, and the traditional inspection work is done manually, which requires a high level of staff, and when there are abnormalities in the substation, it is easy to cause casualties and economic losses, bringing adverse effects to the safe and stable operation of the power grid. Based on this, we can improve the security, intelligence, and automation of substation patrol inspection, which is an important trend in the future.

At present, many researchers at home and abroad have made outstanding achievements in the detection methods and detection optimization strategies of intelligent substations. Wang Binhai of Shandong Luneng Intelligent Technology proposed a comprehensive indoor and outdoor equipment inspection robot technology for the low efficiency and small coverage of substation inspection [1]. To optimize the inspection path and reduce the inspection time of the substation, Yuan Jiaquan of Nanjing University of the technology proposed a path planning method for the semi-structured environment of the substation [2]. SmartGuard system to optimize the equipment inspection scheme of substation inspection intelligent robots [3]; Li Junhai of the Chinese Academy of Sciences used BeiDou high-precision positioning to build an inspection system for UAVs in the narrow space of substations [4]; Hu Jinlei of Guangdong Power Grid Company proposed a UAV edge computing framework design and resource scheduling method for UAV inspection image analysis requiring computing and storage resources [5].

In summary, relying on a single intelligent robot or UAV for substation inspection can improve the shortcomings of manual inspection methods, but it cannot achieve an all-around and dead-end inspection of substations and has many defects. This paper proposes a substation inspection strategy based on the combination of UAV and intelligent robot. This method not only enables inspection of overhead locations and ground locations but also enables the sharing of vision between UAVs and intelligent robots, which is more conducive to path planning and shortening the inspection cycle. Firstly, the two-dimensional plane simulation map of the substation is constructed by combining UAV scanning and the raster method. Then, the ant colony algorithm is used to realize the optimal path planning of UAV and intelligent robots.

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This paper improves the ant colony algorithm and optimizes it from the expected function. The simulation results show that the improved ant colony algorithm can effectively improve the effect of path planning.

2. Model construction of inspection strategy approach

2.1 Substation inspection demand analysis

Intelligent inspection of substations requires ensuring that the intelligent robot can successfully reach the end of inspection requirements; At the same time, the path selected in the path planning of the intelligent robot is the shortest, and the intelligent robot can avoid obstacles perfectly in the working process. This analysis of substation inspection requirements is particularly important.

This paper refers to the 220kV substation, which is equipped with three three-phase transformers, and the voltage levels on each side are 220kV, 110kV, and 10kV respectively. 220kV is the incoming end with four circuits and double busbar wiring; 110kV has eight circuits and double busbar wiring; 10kV has ten circuits and single busbar wiring.

For inspection of intelligent robots and drones, the main functions include:

(1) Detection functions: detection of thermal defects in primary equipment using an infrared camera, which includes infrared temperature measurement of the body and joints of current-causing and voltage-causing equipment; external inspection of equipment using an in-line visible camera instrument; identification of abnormal sounds in equipment using audio；

(2) Navigation functions: enables normal driving on planned routes, adjusts the attitude of the vehicle, and is reasonably well designed for turning, including differential steering and turning in place；

(3) Substation patrol analysis and alarm: to realize the intelligent analysis of the equipment, the intelligent robot can automatically generate the substation inspection report at the end of the comprehensive inspection.

Video transmission access: the UAV needs video transmission to achieve the scanning the 2D map of the substation, the robot identifies obstacles and achieves optimal path planning through vision.

In a typical 220kV substation, the main inspections are divided into the following areas.:

(1) 220kV equipment area includes circuit breakers, disconnectors, voltage, and current transformers, lightning arresters, outlet connectors, and other substation equipment；

(2) Circuit breakers, disconnect switches, voltage and current transformers, SF6 pressure gauges, lightning arresters, earth cutter status, contacts, etc. in the 110kV equipment area；

(3) Special fire-fighting systems, relays, oil temperature gauges, oil level gauges, etc. for the main transformer equipment area.

According to the type of inspection task, it can be divided into main transformer equipment inspection, station-wide lightning arrester inspection, station-wide isolation switch inspection, station-wide infrared temperature measurement inspection, station-wide oil level inspection, and also includes 110kV equipment area inspection and 220kV equipment area inspection.

2.2 Substation 2D floor plan model construction

In this paper, the grid method is used to construct the two-dimensional plan of the substation, and the environment of the intelligent robot is described as several simple grid areas, in which the obstacles and the intelligent robot are described by the grid, as shown in ‘Fig1’. The grid can directly reflect the location coordinates of the obstacles in the substation environment. From this, a path planning model can be constructed to find an optimal path in the raster map. The advantage of grid map modeling is that the two-dimensional map is easy to build and express, which can determine the location and obstacle location more efficiently and accurately, and it is easier to realize path planning.

In the raster method, two colored rasters are used to replace the distribution of spatial physical objects in the substation and are digitized with the numbers 0 and 1. Based on the above description, the grid with obstacles can be represented as black, the corresponding value is 1, white represents the position without obstacles, the corresponding value is 0, and the green represents the settable start and end positions. This results in a binarisation of the environmental location thing where the intelligent robot

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and the U AV are located based on the raster method, with unique coordinates existing for each area.

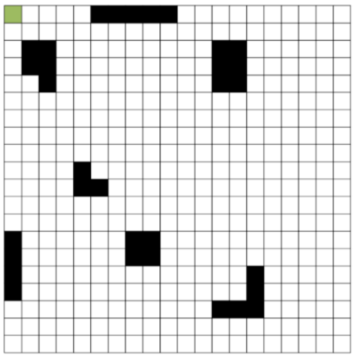

Figure 1: The raster method

2.3 Principle analysis of the ant colony algorithm

In nature, because ants do not have a vision, they guide their movements by secreting pheromones. Based on this natural factor, ants choose paths based on pheromone concentration. Ants on shorter paths have more round trips and higher pheromone secretion concentration, so ant colony realizes optimal path planning. Based on the biological principle of ant colony foraging Professor Dorigo M proposed the ant colony algorithm, which is widely used in path planning problems, and its structure flow chart is shown in 'Fig2'.

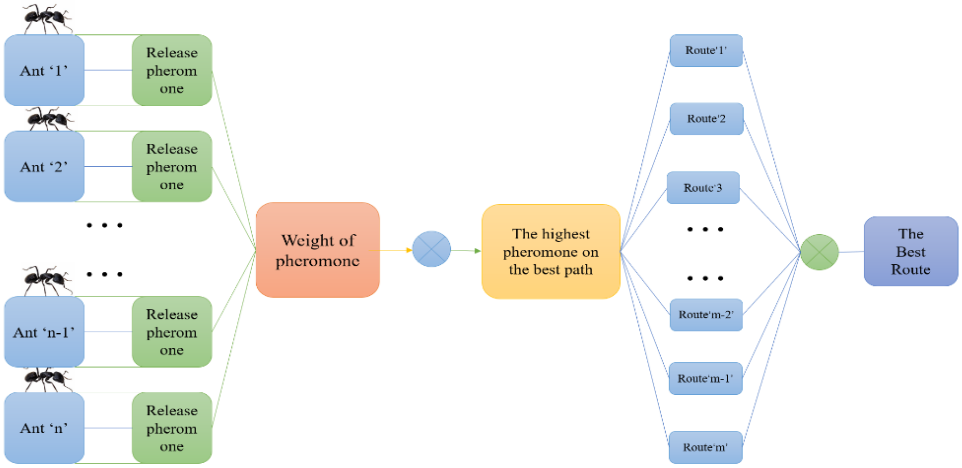

Figure 2: Block diagram of the ant colony algorithm

Based on the pheromone released by the ant colony, the mathematical model of the ant colony algorithm is established, in which the state transition function is used to represent the probability value of the path. The model assumes that the probability of ant k moving from position i to position j at a given moment t is represented by the state transfer function $P_{ij}^{k}(t)$:

where when (i,j) $\in$ $allowd_k$ as shown in equation(1):

$$P_{ij}^{k}(t)=\frac{\left[\tau_{ij}(t)\right]^{\alpha}\left[\eta_{ij}(t)\right]^{\beta}}{\sum_{s\in allowd_k}\left[\tau_{is}(t)\right]^{\alpha}\left[\eta_{is}(t)\right]^{\beta}} \tag{1}$$

When (i,j) $\in$ other, as shown in equation(2):

$$P_{ij}^{k}(t)=0 \tag{2}$$

Where: (1) τ_{ij} (t) denotes the pheromone concentration on (i,j) at moment t ; (2) $allowd_k$ is the point

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that ant k can choose next among the points not visited at moment t; (3) α indicates the information heuristic factor, that is, the weight factor of pheromone concentration; (4) β denotes the expectation heuristic factor, which represents the weighting factor of visibility; (5) η_{ij} denotes the degree of expectation to move from position i to position j the degree of expectation, as shown in equation(3):

$$\eta_{ij} = \frac{1}{d_{ij}} \tag{3}$$

Where d_{ij} is the distance from position i to position j, inversely proportional to η_{ij}.

It is important to specify that a larger value of α indicates that the path is more likely to be chosen; a larger value of β indicates that the ants are more likely to choose proximity. In the updating process of the ant colony algorithm, pheromone and residual information are updated in the actual modeling to prevent flooding residual information and heuristic information. The update method is shown in equations (4) and (5):

$$\tau_{ij}(t+n) = (1-\rho)\vartriangle\tau_{ij}(t) + \vartriangle\tau_{ij}^{k}(t) \tag{4}$$

$$\vartriangle\tau_{ij}(t) = \sum_{k=1}^{m} \vartriangle\tau_{ij}^{k}(t) \tag{5}$$

Where: (1) (1-ρ) denotes the pheromone residual factor and $\rho \in (0,1)$ is maintained pheromone concentration; (2) $\vartriangle\tau_{ij}(t)$ denotes the pheromone concentration released by ant k moving from position i to position j; (3) $\vartriangle\tau_{ij}(t)$ denotes the sum of the pheromone concentrations released by the ant colony moving from position i to position j.

The flow of the improved ant colony algorithm is shown in 'Fig3'.

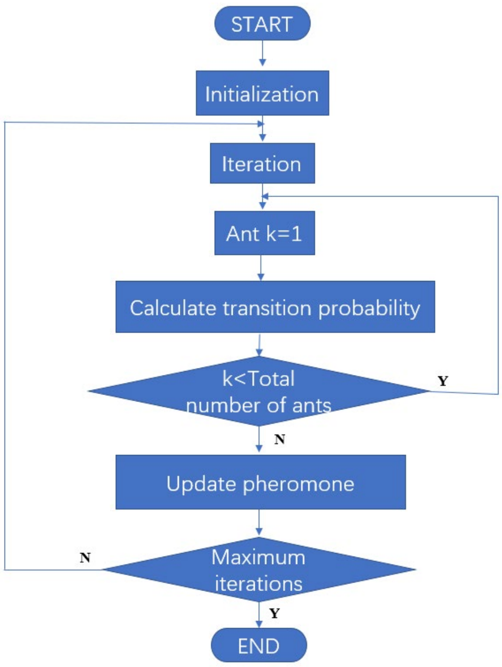

Figure 3: Flow chart of the ant colony algorithm

3. Analysis of inspection strategy optimization

3.1 Scene planning

This paper is based on a 220kV/110kV/10kV multi-voltage level intelligent substation, whose electrical main wiring diagram is shown in 'Fig.4'. The substation includes electrical equipment of three

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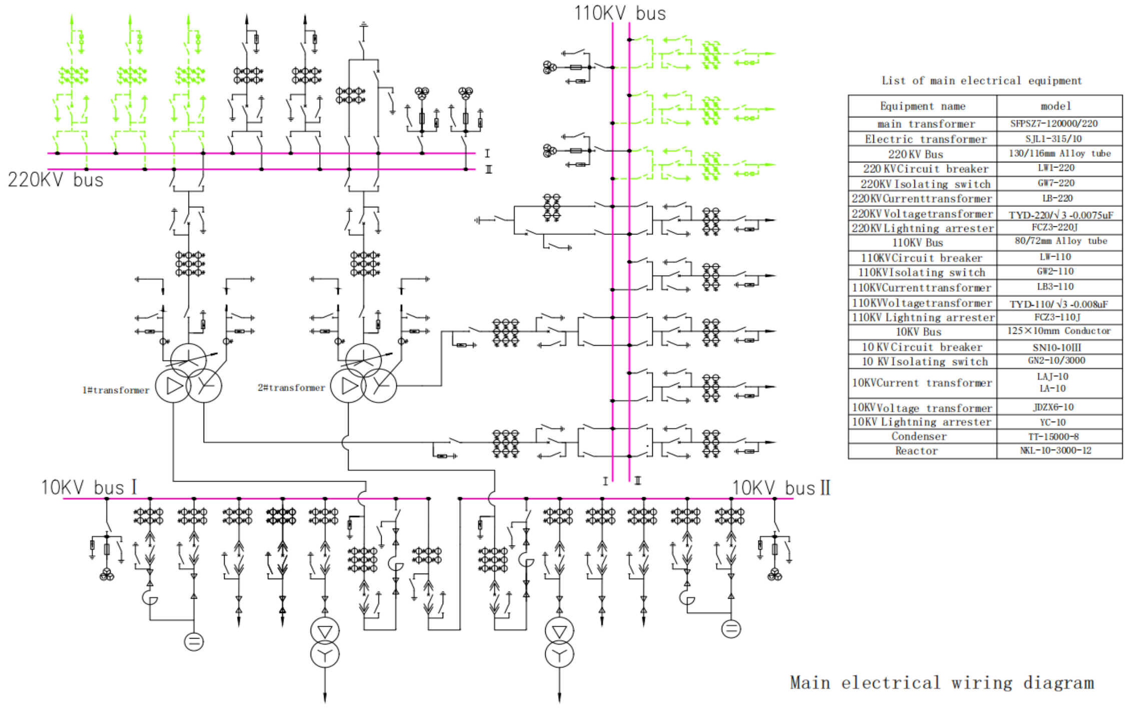
voltage levels: 220kV, 110kV, and 10kV. It mainly includes main transformers, circuit breakers, disconnect switches, current transformers, voltage transformers, lightning arresters, bus bars, and equipment such as regulators and reactors.



Equipment name	model
main transformer	SFPSZ7-120000/220
Electric transformer	SJL1-315/10
220 KV Bus	130/116mm Alloy tube
220 KVCircuit breaker	LW1-220
220KV Isolating switch	GW7-220
220KVCurrenttransformer	LB-220
220KV Voltagetransformer	TYD-220/√3 -0.0075uF
220KV Lightning arrester	FCZ3-220J
110KV Bus	80/72mm Alloy tube
110KVCircuit breaker	LW-110
110KVIsolating switch	GW2-110
110KVCurrenttransformer	LB3-110
110KVVoltagetransformer	TYD-110/√3 -0.008uF
110KV Lightning arrester	FCZ3-110J
10KV Bus	125×10mm Conductor
10 KVCircuit breaker	SN10-10III
10 KVIsolating switch	GN2-10/3000
10KVCurrent transformer	LAJ-10 LA-10
10KVVoltage transformer	JDZX6-10
10KV Lightning arrester	YC-10
Condenser	TT-15000-8
Reactor	NKL-10-3000-12

Figure 4: 220kV substation main wiring diagram

3.2 Analysis of inspection strategies with drones and intelligent robots

This paper presents a substation inspection strategy based on the cooperation of UAV and intelligent robots. Firstly, based on the high-altitude two-dimensional scanning of UAV, the grid method is used to establish the two-dimensional plane of the substation, and on this basis, the ant colony algorithm is used to realize the path planning of UAV and intelligent robots. The path planning of the ant colony algorithm can realize the dynamic path planning from the starting point to the detection target point.

The simulation is based on the MATLABR2020a computing platform with the following parameters: α=1; β=7; ρ=0.3. The initial number of ants is m=50 and the number of iterations is 100. The final simulation results show that the inspection strategy using the cooperation of the UAV and the intelligent robot has a better effect on safety, timeliness, and all-around and full-time monitoring.

(1) Security

At the equipment inspection level, intelligent robots are responsible for ground substation equipment inspection, and UAVs are responsible for high-level inspection of lightning rods, structural supports, and other equipment, which can effectively improve the safety of inspection. The point-to-point path planning is applied to the cooperative path planning scheme of UAV and intelligent robots to realize the optimal path under a single objective path.

As shown in ‘Fig.5’, from the above simulation results, we can see that the path planning effect of the ant colony algorithm is very prominent. As the number of iterations increases, the length of path planning tends to converge. For the traditional joint inspection method of UAV and intelligent robots, it is more difficult to inspect high equipment such as a lightning rod. Using the strategy of cooperation between UAV and intelligent robots, we can realize the full coverage of substation inspection equipment, make up for the blind area that cannot be observed in ground inspection, and reduce the work intensity and risk of operation and maintenance personnel.

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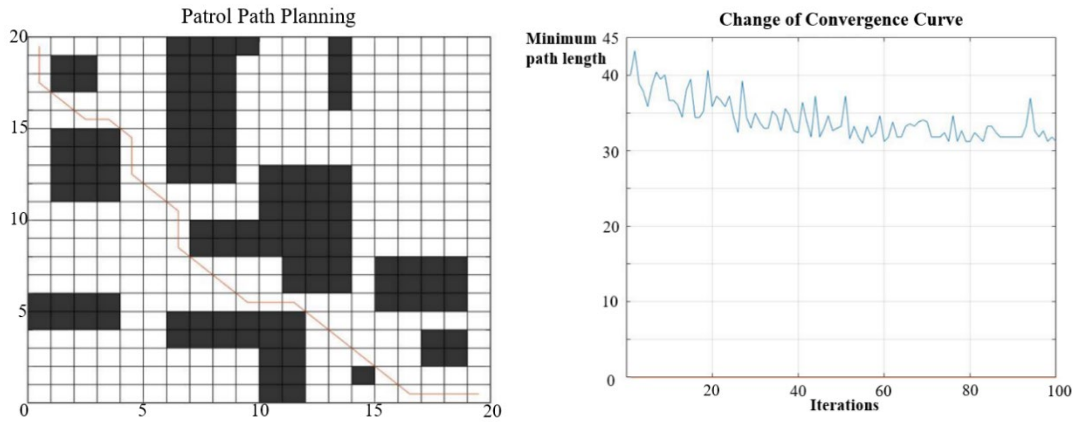

Figure 5: Simulation diagram of path planning and iterative convergence

(2) Timeliness

This paper discusses the improvement effect of the ant colony algorithm based on selection probability and updating pheromone, as shown in "Fig.6". The simulation results show that the traditional ant colony algorithm has a long path and poor convergence.

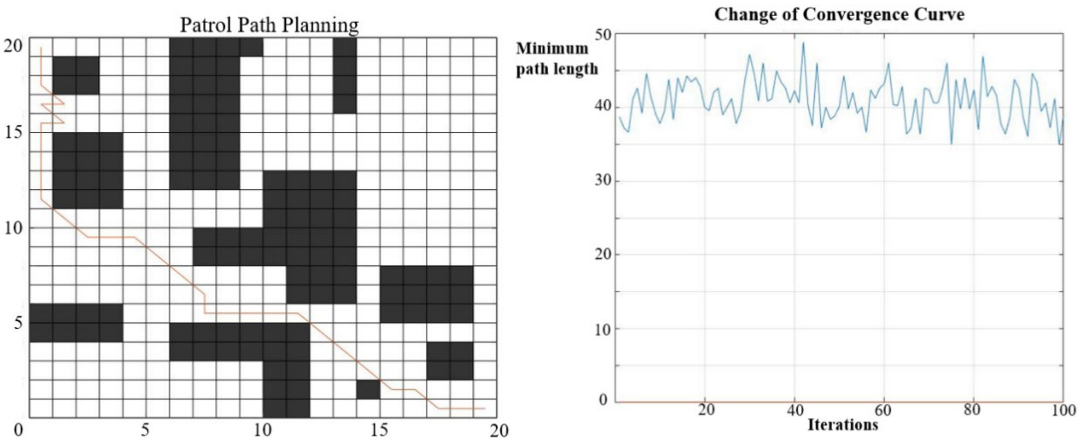

Figure 6: Basic ant colony algorithm path planning and iterative convergence diagram

From ‘Table.1’ compared with the traditional ant colony algorithm and the improved ant colony algorithm, the improved ant colony algorithm has significant improvements in turning nodes and the optimal path length under the condition that the environment and other relevant requirements are consistent. The improved ant colony algorithm reduces the number of turning nodes by 16.9% and the length of the optimal path by 28.6%.

Table 1: Comparison table of improvements to the ant colony algorithm

Algorithm and Comparison	Path Length	Turning Node
Traditional ant colony algorithm	38.97	14
Improved ant colony algorithm	32.38	10
Comparison results	16.9% reduction	28.6% reduction

It can be concluded that inspection path planning based on the cooperation of drones and intelligent robots can reduce the inspection time to a large extent. At the same time, cooperation with UAVs can significantly reduce the inspection time compared to the inspection method that only relies on intelligent robots.

(3) "Low-Medium-High" all-round and "Dynamic+Static" all-time inspection

Drones and intelligent robots can be used in conjunction with the substation inspection strategy to achieve a "low-middle-high" all-around inspection system. The intelligent robot inspects the operation of the inspection equipment located on the ground, the drone inspects the inspection equipment in the middle and high positions such as lightning rods and structural supports, and at the same time overlooks the entire substation at a height of about 80 meters to achieve a full scan and dynamic inspection of the substation at high altitude, using the raster method to establish a planar two- dimensional map of the

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substation.

Based on the improved ant colony path planning algorithm, UAV and the intelligent robot can cooperate with patrol inspection to realize point-to-point "dynamic + static" full-time detection. When there is no inspection command, the UAV and robot will patrol at a fixed point of inspection; when an inspection command is issued, the improved ant colony algorithm is used for path planning of the inspection target point, thus realizing a "dynamic + static" full-time inspection.

4. Conclusion

The substation is the core hub of the power grid. A reasonable and effective substation inspection strategy is very important for the safe operation of electrical equipment. Considering the safety risk and timeliness of intelligent robots, this paper proposes a coordination inspection strategy between UAV and intelligent robots. Through simulation and verification analysis, the strategy has good security, timeliness, and the advantages of all-around and full-time monitoring. The specific conclusions are as follows:

(1) The strategy can achieve full coverage of substation inspection devices, and the cooperation of UAVs and intelligent robots can greatly avoid blind inspection areas and reduce the operational risks of inspection personnel, greatly improving the safety of substation inspection；

(2) The strategy is based on an improved ant colony algorithm, which can achieve 16.9% path optimization and 28.6% reduction in turning nodes while benefiting from the good timeliness of the UAV and inspection robot working simultaneously；

(3) The strategy can achieve "low – medium-high" all-around and "dynamic + static" all-time inspection, the entire substation inspection is highly hierarchical.

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