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RESEARCH ARTICLE

An Optimization Method for Satellite Data Structure Design Based on Improved Ant Colony Algorithm

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ABSTRACT The telemetry data structure is the embodiment of satellite telemetry format, the rationality and correctness of which determine the satellite telemetry capacity as well as transmission capability. Conventional satellite telemetry data structure designs excessively depend on manual experience, easily leading to problems such as waste of satellite resources, low telemetry transmission efficiency and unintuitive ground decoding. In this paper, a novel method was proposed to optimize the design of satellite telemetry data structure, based on rasterized modeling to visualize the design constraints, and an improved ant colony algorithm with grey relational analysis to optimize the telemetry data structure. The method is not only effective in preventing the deficiencies of conventional approaches, but also beneficial to the rational allocation of telemetry resources. The feasibility was verified by the telemetry data of a satellite with DFH-4 platform, and the results showed favorable convergence, along with valid improvement of the design process efficiency and application effect.

INDEX TERMS Ant colony algorithm, optimization design, satellite data structure, satellite telemetry.

I. INTRODUCTION

As an important part of an overall satellite design, telemetry format design mainly includes satellite tracking, telemetry, and command (TT&C) demand analysis and resource allocation, satellite telemetry format definition, TT&C information flow planning and telemetry data structure design. Among them, the result of telemetry data structure design is the embodiment of satellite telemetry format, which not only needs to meet the telemetry demand, but also the correctness and reasonableness determines the utilization rate of satellite telemetric capacity and the transmission capability of telemetry signal. Meanwhile, the quality of telemetry data structure design will directly affect the validity of satellite in-orbit status monitoring, and the timeliness of failure plan implementation as well.

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The design of satellite data structure is essentially a problem of satellite data resource optimization and allocation. Under the two constraints of limited satellite data capacity and certain requirements for satellite data update rate, it is necessary to reasonably allocate capacity resources and optimize the satellite data structure in order to finally obtain the optimal results [1]. To address the problem of optimal allocation of satellite resources, there have been various studies based on intelligence algorithms. Chen et al. [2] developed a two-stage heuristic method with high quality solutions in a reasonable amount of computation time based on priority and conflict-avoidance to improve the scheduling mechanism of satellites with limited observing ability. He et al. [3] proposed a hierarchical scheduling algorithm based on ant colony algorithm by dividing imaging processes of optical satellites into three steps to avoid the waste of computational resources. Liu et al. [4] proposed a novel satellite scheduling framework based on the divide and conquer principle, under which an ant colony optimization algorithm was adopted for distributing observation tasks to different satellite orbits, and an adaptive simulated annealing algorithm was employed to solve the satellite observation problem involved in each orbit. Meng et al. [5] adopted accumulated historical data to solve strong correlation problems of deep neural network (DNN), and thus improved the efficiency of multi-satellite TT&C resources utilization and automation. Yan et al. [6] provided an automatic method of classification and extraction for pulse code modulation (PCM) system-based satellites based on the feature structure. Selvakumar et al. [7] provided a novel approach for load-balancing based on the enhanced ant colony optimization by distributing the load evenly among all servers in the cloud to maximize the utilization of resources to optimize resource allocation and ensure the quality of service. Song et al. [8] proposed an efficient algorithm that combines improved genetic algorithm and local search method for rapidly improving the quality of the planning scheme and the subsequent small-scale optimization as well to solve satellite range scheduling problems. Wang et al. [9] adopted advanced K-means algorithm (AKG) and breadth-first-search-based spanning tree algorithm (BFST) to achieve ECS resource division and ISL construction, and thus realized satellite dynamic resource scheduling. He et al. [10] proposed an improved ant colony algorithm based on construction of initial solution set and extra pheromone deposition to overcome disadvantages of slow initial search speed and weak local search ability, suitable for scheduling satellite communication system resources of multi-beam dense networking. In addition, a number of task planning and machine learning algorithms are also worthwhile. Phung et al. [11] presented spherical vector-based particle swarm optimization (SPSO) algorithm to deal with the problem of path planning for unmanned aerial vehicles (UAVs) in complex environments subjected to multi-threat. Chu et al. [12] introduced improved nonlinear dynamic inertia weights (INDIW) into the particle swarm optimization (PSO) algorithm along with velocity adaptive adjustment and chaotic initialization to improve the convergence speed and fitness function value as well. Haghighi et al. [13] introduced individual revisit time cell value into a new efficient modified A-star algorithm to generate faster and more efficient trajectories in complex multi-agent scenarios. Pan et al. [14] proposed a deep learning trained by genetic algorithm (DL-GA) to improve the efficiency of path planning for data collection. Pehlivanoglu et al. [15] introduced Voronoi vertices as additional waypoints into GA for accelerating convergence process. Cao et al. [16] proposed a novel deep learning based random subspace method (RSM) known as Neural Random Subspace (NRS) to achieve faster inference speed and higher accuracy with only incremental cost. Lacotte et al. [17] presented a novel randomized optimization method for high-dimensional convex problems based on restrictions of variables to random subspaces, enabling significant speed ups in a wide variety of machine learning and optimization problems.

Although promising outcomes have been achieved, yet most of the above achievements are not oriented to the optimization of satellite telemetry data structure, that is, the existing characteristics of research objects are mostly regarded as the reference for the primary improvement of the algorithm, which leads to the lack of applicability to the improvement of the resource allocation algorithm for satellite telemetry data structure. With the development of space technology in recent years, the number of satellites has been growing, and the difficulty of satellite design has been increasing. Conventional telemetry data structure design methods which rely on manual design have gradually exposed the problems such as poor generality, incomplete consideration of the satellite data imbalance, incomplete solution of the local convergence, etc. At the same time, the repetitive design workload is high, which easily leads to fatigue and thus increases the risk of design errors [18], [19].

In this paper, from the general perspective of satellite telemetry format design, an in-depth analysis of the telemetry data imbalance problem was carried out, and an improved ant colony algorithm-based satellite telemetry data structure optimization design method was proposed, which effectively solved the above problems.

The specific work and conclusions of this paper are as follows.

1) The design principle of satellite telemetry data structure was analyzed, the data structure design requirements and constraints were modeled, a raster model architecture based on expert knowledge was constructed, and the evaluation principles for the effect of satellite telemetry data structure design were formulated.
2) A grey relational analysis was adopted to analyze the satellite telemetry data correlation, and taking China's DFH-4 satellite platform as an example, seven relational characteristics were selected as metrics for telemetry parameter correlation analysis, followed by the verification with simulated data, and the results met the requirements.
3) Based on the above simulation data, the conventional ant colony algorithm was utilized to carry out the design of satellite telemetry data structure, and the results showed that the traditional algorithm converged quickly and had a small computational effort, but was prone to problems such as confusion in the correlation of sorted elements.
4) An improved ant colony algorithm combined with grey relational analysis was proposed, and a satellite telemetry data structure design process was developed based on the algorithm, followed by the experimental verification with simulation data, and the results satisfied the evaluation principles of design effect and practical needs, proving that the proposed method can improve the utilization of satellite data structure resources, enhance the standardization of telemetry data structure design process, improve the design efficiency and

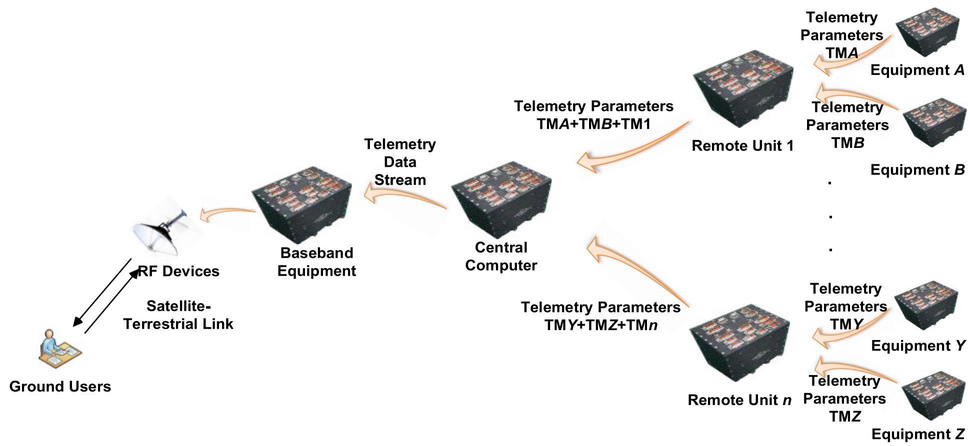

FIGURE 1. Diagram of satellite telemetry data transmission flow.

quality, reduce the iterative workload, and provide a reference basis for the efficiency improvement of telemetry data structure design of satellites or satellite constellations.

II. DESIGN PRINCIPLE OF SATELLITE TELEMETRY DATA STRUCTURE

As shown in Fig. 1, the current mainstream of satellite telemetry data structure is a data management architecture dominated by a central computer, which is also the data structure type mainly adopted by DFH-4 satellite platform. After collecting sensor data through Transistor-Transistor Logic (TTL), RS422 and other serial ports, the central computer schedules the telemetry data and frames them according to the designed logic to form telemetry data streams, and finally transmits the streams to ground users through transmitters (or transponders).

The outcome of the procedure above, after scheduling of telemetry data by the central computer, is referred to as the satellite telemetry data structure. Conventionally, two methods are mainly adopted for the scheduling process: the manual arrangement method and the standard greedy algorithm embedded in primitive digital telemetry data structure design tools. The manual arrangement method is mainly based on device numbers and telemetry parameter numbers on corresponding devices for straightforward sorting. The advantage of the approach is simplicity, which could be time efficient especially when only limited quantity of telemetry parameters needs to be scheduled, but when the quantity increases significantly, the approach is inefficient and error-prone; furthermore, the sequence of telemetry parameters is relatively disorganized within the scheduling result, thus unfavorable to searching for telemetry parameters with high correlations. Whereas the primitive digital telemetry data structure design tools have adopted the idea of standard greedy algorithm considering the associated relationship between devices, and base on which the telemetry parameters are scheduled. The approach delegates the scheduling task to computers, which lowers the error potential of manual arrangement, in addition, the scheduling procedure of telemetry data based on relationship of devices could enhance the search efficiency in general. However, because only the associated relationship between devices has been simply accounted for, the correlation attributes between the internal or external telemetry parameters of the devices have not been comprehensively considered, that is, the relational analysis between telemetry parameters has not been implemented, leading to insufficient correlation-based scheduling, which tends to cause disruption in the telemetry data structure to a certain extent.

The proposed approach of designing satellite telemetry data structure based on improved ant colony algorithm is not only effective in preventing the deficiencies of the conventional methods, but also beneficial to the rational allocation of telemetry resources. The overall experimental procedure of the proposed approach was designed in four steps, as shown in Fig. 2.

1) *Rasterized modeling of the satellite telemetry data structure*. Different attributes were assigned to data units in combination with relevant design constraints, thereby preparing the telemetry parameters of different properties to be scheduled into certain data units with corresponding attributes.
2) *Calculating the correlation of telemetry parameters with grey relational analysis*. The attributes of telemetry parameters were collated, and among which 7 correlational metrics (including telemetry parameter data length, sampling period of telemetry parameter, etc.) were selected; meanwhile, the reference telemetry parameter was identified, and correlations between associated telemetry parameters and the reference were calculated based on grey relational analysis. The calculation result of the correlations would be regarded as an important argument for the subsequent optimization procedure.

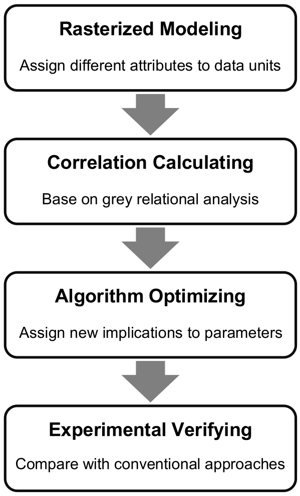

FIGURE 2. Experimental procedure of optimized design approach.

3) *Optimizing the ant colony algorithm*. Combined with the results of the previous steps and based on the essential ideology of conventional algorithm, new implications were assigned to the basic parameters in the algorithm to achieve the optimization. In particular, the correlation was adopted as the pheromone concentration, meanwhile the distance between parameters under rasterized model was employed as the basis for the derivation of heuristic term; in addition, the flow of the improved ant colony algorithm for the purpose of optimizing the satellite telemetry data structure design was finally proposed.
4) *Verifying experimental results*. The test objects were selected for the design of satellite telemetry data structure by the proposed approach, and the results were compared with the manual arrangement method and the standard greedy algorithm, to evaluate the optimization performance in terms of process efficiency, convergence effect, and application effect.

III. MODELING OF SATELLITE TELEMETRY DATA STRUCTURE BASED ON RASTER METHOD

Firstly, the satellite telemetry data structure was modeled based on the raster method. The raster method is a way to equivalently model the data cells of telemetry parameters in the central computer framing process by using a series of raster of the same size. This method visualizes the structure of data layers in a data link based on expert knowledge, so that the data structure is visually represented while retaining the authenticity and validity as well.

The structural model of satellite telemetry data is shown in Fig. 3. A data structure with the satellite central computer as the data processing and framing center was m rows $\times$ n columns of data units, collectively referred to as a format, where m indicated the number of frames of the format, while n indicated the length of the format, also called the path, and each data unit transmitted 8-bit data. The bit value of

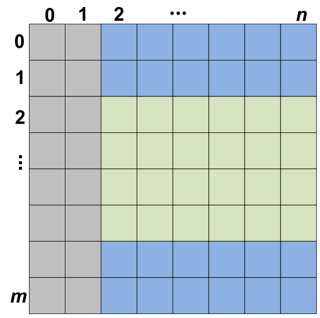

FIGURE 3. Satellite telemetry data structure based on rasterized modeling.

$m \times n \times 8$ was fixed, which characterized the maximum theoretical value of telemetry information allowed to be transmitted in one complete format of satellite data stream. Within the same format, telemetry information was transmitted according to the order of frame code from smallest to largest, and within the same frame, the information was transmitted according to the order of path code from smallest to largest. If the amount of telemetry information was larger than the maximum theoretical value allowed to be transmitted, or there was special demand for certain important telemetry data, it was necessary to perform format multiplexing on some data units in the data structure, so that the multiplexing area transmitted different telemetry information in different formats. Format multiplexing extends the amount of satellite telemetry information transmission, but reduces the information refresh frequency [20].

In the data structure, the data unit contained three attributes: ■ represented the frame header or identification bit with significance, which was generated by the central computer when framing the data and usually occupied a fixed position in the data structure, mostly in the front position of each data frame or data area; ■ indicated the data units related to the hardware contacts of certain acquisition devices, which were usually assigned a fixed area by the central computer at the design stage to transmit some hardware telemetry parameters characterizing the status of the devices; ■ represented a fixed area designated by the central computer for transmitting software telemetry parameters related to satellite status or mission execution, which usually involved a large variety and number of parameters, resulting in a high difficulty and workload in the design.

Based on the experience of satellite design and engineering practice, the following four principles were adopted to evaluate the effectiveness of satellite telemetry data structure design.

1) Under the premise of meeting the design requirements and complete transmission of telemetry information, all data units in the data structure should be utilized reasonably and efficiently, and format multiplexing should be applied as minimal as possible to ensure the refresh frequency of telemetry information.

2) In order to ensure priority transmission of key telemetry information, in the same format, the key information should be placed in the top numbered frames when possible, whereas in the same frame, the information should be placed in the top numbered path as possible.
3) Telemetry information with high relevance, such as telemetry data belonging to the same device or representing the same type of information, should be designated according to the principle of proximity to ensure that the refresh time of such information is consistent when decoding on the ground, which is conducive to the analysis of satellite status or problem identification under satellite failure.
4) Telemetry parameters with special correlation need special designs, *e.g.*, telemetry parameter A is taken as the calibration source of telemetry parameter B, which means B needs to adopt the value of A in the process of ground decoding, so it is necessary to arrange A before B in the data structure design to ensure that the decoding of B could adopt the latest value of A to guarantee the accuracy.

In the satellite telemetry data structure, the telemetry data stream transmission rate is generally 1000kbps or 1024kbps, so the high quality design outcomes, in the case of data format without multiplexing, can accomplish the transmission of an integrity format in telemetry data stream once in a few seconds, which features fast transmission rate and intuitive data structure, thus can well meet the needs of high-speed transmission of on-board telemetry data stream and convenient data decoding for ground users [21]. And in case of satellite failure, the better data structure helps to quickly locate the problem telemetry, thereby providing strong support for troubleshooting [22].

However, due to the limited capacity of the integrity format of satellite telemetry data stream, when the amount of telemetry information is large, in order to make the data stream transmission more efficient and ground data decoding more convenient, the design process of the satellite telemetry data structure needs to fully consider the capacity of telemetry transmission, the reasonableness of telemetry information scheduling, the correlation between telemetry information, the correspondence between data units and hardware contact tables, the transmission system and device versatility, as well as the telemetry sampling and refresh periods, in order to seek an optimal design result that takes into account both the utilization of telemetry capacity and the overall design efficiency.

IV. CORRELATION CALCULATION OF SATELLITE TELEMETRY DATA BASED ON GREY RELATIONAL ANALYSIS

Taking a telecommunication satellite with DFH-4 platform as an example, there are over 6000 satellite telemetry parameters, which contain about 1500 hardware telemetry parameters and over 4500 software telemetry parameters. The manual design of data structure for satellite telemetry parameters can follow the design principles, but the design optimizations are often not well considered. The study mainly focused on telemetry parameters of a satellite transmitted by PCM data structure, such parameters primarily included the state values indicating the status of devices, temperature values indicating the status of temperature measurement points, and digital values indicating the switch status of devices, which were mainly collected by sensors and then transmitted through serial ports and finally converged to the satellite central computer for group framing; moreover, there could be nesting relationships between the parameters in the decoding process.

The grey relational analysis [23], [24] is a method that allows to evaluate the correlation level between metrics of research subjects under small sample conditions. It is applied to determine the extent to which the subjects affect one another. A measure of how certain metrics change in association with time or different subjects is called correlation. If the level of simultaneous changes between the metrics is high, the correlation of the subjects is referred to as high; conversely, it is low. Therefore, the grey relational analysis provides a quantitative approach to measure internal relations between research subjects based on the similarities or differences in the trends between metrics. For the property of satellite telemetry parameters, and based on the grey relational analysis, the constraint metrics related to the correlation between telemetry parameters could be screened, then their correlation could be calculated, and the result of the correlation could be regarded as an important reference for the schedule of telemetry parameters and an essential rationale for subsequent algorithm improvement as well.

The following is the example analysis. Seven telemetry parameters (A_0, A_1, A_2, A_3, B_1, B_2, C_1) were selected, assuming that each telemetry parameter was the output from different circuit interfaces, where A_0- A_3 belonged to device A (device *No.*1), B_1, B_2 belonged to device B (device *No.*2), C_1 belonged to device C (device *No.*3), and the above telemetry parameters were collected by the same electrical connector X_1 of the same collection device. The relationship of telemetries for each device was shown in Fig. 4, which briefly demonstrated relative positions of devices A, B and C. Meanwhile, Fig. 4 showed the positions of the seven telemetry parameters (indicated by black dots) and the electrical connectors to which they belonged, the distances between parameters and the reference telemetry A_0 (indicated by blue lines), and the acquisition point positions of parameters on electrical connector X_1 (indicated by red dots). A_0 was selected as the reference telemetry parameter, while the correlations between A_0 and the other six telemetry parameters were calculated by the grey relational analysis, and the calculation process is shown in Fig.5.

A. ANALYSIS AND PRE-PROCESSING OF ORIGINAL DATA

Analysis metrics include: telemetry parameter data length, sampling period of telemetry parameter, calibration

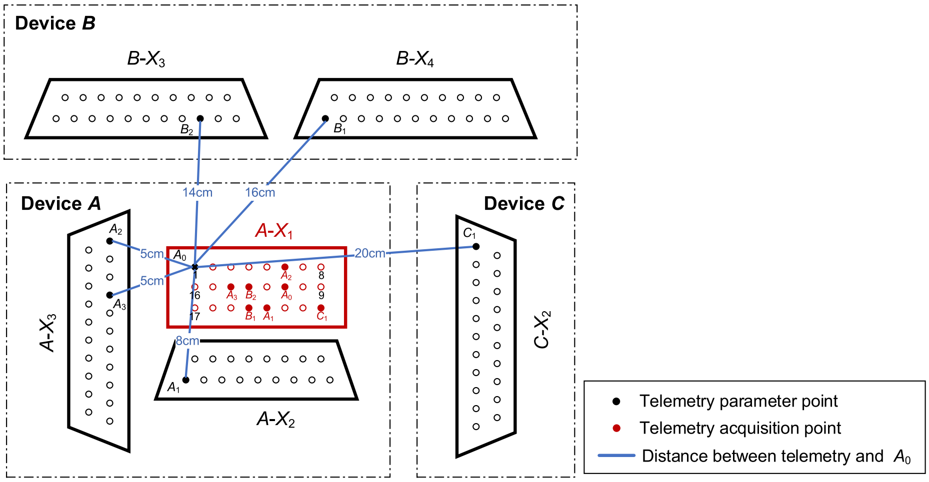

FIGURE 4. Relationship diagram of telemetry parameters.

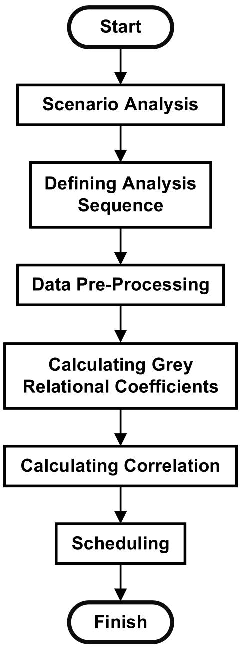

FIGURE 5. Flow chart of grey relational analysis.

voltage after telemetry parameter sampling, linear distance from output interface of other telemetry circuits to A_0 interface, contact *No.* of electrical connector of acquisition device, device *No.* to which telemetry parameter belongs and *No.* of the electrical connector. After processing the raw data, the details are shown in Table. 1.

B. DETERMINE REFERENCE SEQUENCE

Taking the data of A_0 as the reference base sequence, it yielded

$$\{x_0\} = \{8, 8, 5, 0, 11, 1, 1\}. \tag{1}$$

C. FIND DIFFERENCE SEQUENCES AND MAX & MIN VALUES

The difference sequences between the other parameters and A_0 were calculated as follows,

$$|x_0(k) - x_i(k)|, \tag{2}$$

and the results are shown in Table. 2.

The max & min values were calculated separately by

$$\min_{i=1}^{n} \min_{k=1}^{m} |x_0(k) - x_i(k)| = \min(0, 0, 0, 0, 1, 0) = 0, \tag{3}$$

and

$$\max_{i=1}^{n} \max_{k=1}^{m} |x_0(k) - x_i(k)| = \max(10, 5, 5, 16, 14, 20) = 20. \tag{4}$$

D. CALCULATE CORRELATION COEFFICIENT

Based on the following formula (5), as shown at the bottom of the next page.

where coefficient ρ, referred to as resolution factor, is an indicator that controls the degree of differentiation between metrics, taking values from 0 to 1. The smaller the coefficient, the greater the differentiation of the correlations between the metrics, and vice versa. Therefore, it determines the weight of the maximum value of a metric during the calculation of correlations. Since the selected metrics are all closely related to the correlations between telemetry parameters, the weights of the maximum values of the metrics are basically the same, thus according to the former experience, the coefficient ρ takes the value of 0.5 is more appropriate. As a result, the correlation coefficient $\zeta_1(1)$ was found to be

$$\zeta_1(1) = \frac{0 + 0.5 \times 20}{0 + 0.5 \times 20} = 1. \tag{6}$$

Similarly, all values of $\zeta_i(k)$ $(i = 1 \sim 6, k = 1 \sim 7)$ could be obtained, and the results are shown in Table. 3.

TABLE 1. Telemetry parameter corr elation metrics.

Telemetry parameter	Data length (bit)	Sampling period (s)	Calibration voltage (V)	Linear distance to A_0 interface (cm)	Contact *No.* of electrical connector	Device *No.*	Electrical connector *No.*
$\boldsymbol{A_0}$	**8**	**8**	**5**	**0**	**11**	**1**	**1**
A_1	8	8	3	8	21	1	2
A_2	8	8	5	5	6	1	3
A_3	6	4	2	5	14	1	3
B_1	8	8	4	16	20	2	4
B_2	1	4	0	14	13	2	3
C_1	8	8	5	20	24	3	2

TABLE 2. Difference sequences between other parameters and A_0.

$\boldsymbol{A_0}$	**8**	**8**	**5**	**0**	**11**	**1**	**1**
A_1	0	0	2	8	10	0	1
A_2	0	0	0	5	5	0	2
A_3	2	4	3	5	3	0	2
B_1	0	0	1	16	9	1	3
B_2	7	4	5	14	2	1	2
C_1	0	0	0	20	13	2	1

TABLE 3. Correlation coefficient of parameters.

$\boldsymbol{A_1}$	1	1	0.833	0.556	0.5	1	0.909
$\boldsymbol{A_2}$	1	1	1	0.667	0.667	1	0.833
$\boldsymbol{A_3}$	0.833	0.714	0.769	0.667	0.769	1	0.833
$\boldsymbol{B_1}$	1	1	0.909	0.385	0.526	0.909	0.769
$\boldsymbol{B_2}$	0.588	0.714	0.667	0.417	0.833	0.909	0.833
$\boldsymbol{C_1}$	1	1	1	0.333	0.435	0.833	0.909

E. RELEVANCE CALCULATION

Based on the correlation formula,

$$r_{0i} = \frac{1}{m}\sum\nolimits_{k=1}^{m} \zeta_i(k), \tag{7}$$

the correlations between A_0 and other telemetry parameters were obtained as: $r_{A1} = 0.828$, $r_{A2} = 0.881$, $r_{A3} = 0.798$, $r_{B1} = 0.785$, $r_{B2} = 0.709$, and $r_{C1} = 0.787$, respectively.

F. RELEVANCE RANKING

Assuming that the weights of each index were not regarded, the correlations of the six telemetry parameters with A_0 were A_2, A_1, A_3, C_1, B_1, and B_2 in order from better to worse.

V. IMPROVEMENT OF ANT COLONY ALGORITHM FOR OPTIMAL DESIGN OF SATELLITE TELEMETRY DATA STRUCTURE

A. CONVENTIONAL ANT COLONY ALGORITHM

The ant colony algorithm is a bionic algorithm that simulates the behavior of an ant colony to transmit path information with its peers through pheromones [25]. The ant in action decides the next target location based on the concentration of pheromones on the path between locations, and the colony eventually finds the solution with the highest pheromone concentration through multiple iterations. Ant colony algorithms have been successfully applied to such problems as VLSI wiring [26], 2D packing and multiple travelling salesman [27]. Taking multiple travelling salesman problem as an example, the flow chart of the ant colony algorithm is shown in Fig. 6, and details of each specific step are as follows:

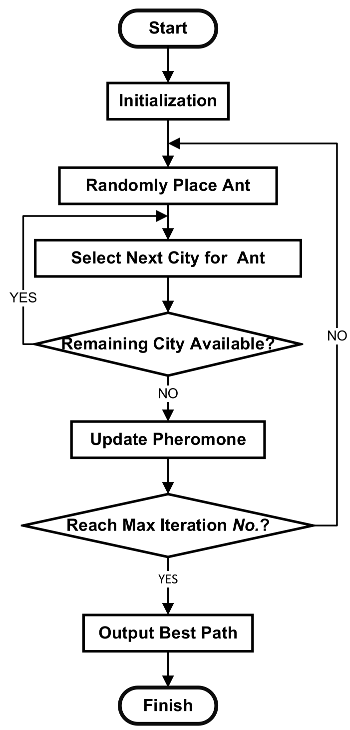

FIGURE 6. Flow chart of conventional ant colony algorithm.

Step 1: Initialize the parameters, including the colony ab initio size, pheromone, heuristic term, volatility coefficient, maximum of iterations, etc., while loading the relevant data into the program and performing basic processing, such as converting the coordinate positions of the cities into the corresponding matrix.

$$\zeta_i(k) = \frac{min_i min_k |x_0(k) - x_i(k)| + \rho \times max_i max_k |x_0(k) - x_i(k)|}{|x_0(k) - x_i(k)| + \rho \times max_i max_k |x_0(k) - x_i(k)|} \tag{5}$$

Step 2: Randomly place the ant at different departure point and calculate the next city to be visited for each ant until all ants visit all cities.

Step 3: Calculate the length of the path traveled by each ant, record the optimal solution in the current iteration, and update the pheromone concentration on each city-connected path.

Step 4: Determine whether the maximum number of iterations reached, if not, then return to step 2, otherwise terminate the program.

Step 5: Output the result.

The optimal design of satellite telemetry data structure is different from the VLSI wiring and 2D packing problems, in which the connection relationships between telemetries are varied with the selection of columns or rows; it is also different from the multiple travelling salesman problem, in which not only the capacity limitation exists but also the constraint relationship between the research objects; it is similar to a 2D vehicle routing problem with conflicts and capacity constraints, which belongs to a non-deterministic problem with polynomial complexity.

If the idea of conventional ant colony algorithm was simply transferred to the problem mentioned in Section *IV*, by adopting a 3 × 3 data structure with an 8 bits data length of each data, the sorting result of the optimized telemetry data structure considering the premise of minimizing the waste of data structure resources is shown in Fig. 7.

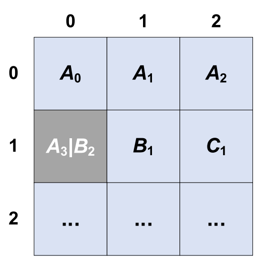

FIGURE 7. Sorting result by conventional ant colony algorithm.

The grey part indicated that the data length of the cell was less than 8 bits. According to Table. 1, the length of A_3 was 6 bits and the length of B_2 was 1 bit, although the cell (1,0) appeared to be 1 bit empty, but in the current situation, the result did not lead to excessive resource waste, and if with no consideration of other factors, it seemed to be the optimal solution. However, the order of correlation between telemetry parameters and reference A_0 was confusing, which tended to cause non-intuitive ground data decoding, and thus obviously was not a global optimal solution. In summary, when utilizing the conventional ant colony algorithm to solve the problem of satellite telemetry data structure design, although the algorithm converges quickly and the computational effort is low, problems such as confusion of sorted element correlations are prone to occur, which lead to a non- convergent design.

B. IMPROVEMENT OF ANT COLONY ALGORITHM

The basic idea of ant colony algorithm was retained, on the premise that the correlation of telemetry parameters was adopted as the pheromone concentration, meanwhile the distance between parameters after rasterization was considered as the basis for the derivation of heuristic term, so as to enhance the convergence speed and path finding ability as well. Parameters involved in the improved algorithm and the corresponding implications are shown in Table. 4.

TABLE 4. Parameters and corresponding implications of proposed algorithm.

Parameters	Implications
$p_{ij}(t)$	Probability of telemetry parameter j in equipment i being selected at generation t
$\tau_{ij}(t)$	Pheromone concentration of telemetry parameter j in equipment i at generation t
η_{ij}	Heuristic term of telemetry parameter j in equipment i
SET_tele	Set of alternative telemetry parameters meeting constraints
α	Pheromone factor
β	Heuristic term factor
$D_{ij,x}$	Prediction distance on x direction from alternative telemetry parameter to the reference telemetry
$D_{ij,y}$	Prediction distance on y direction from the alternative telemetry parameter to the reference telemetry
tele_end	The last telemetry parameter of the last equipment
ρ	Volatility coefficient of pheromone concentration
Γ_α	Set of telemetry parameters traveled by ant α in generation t
$\Delta\tau_\alpha$	Increase value of pheromone concentration
Q_{it}	Sum of correlations of alternative telemetry parameters on equipment i at generation t
$L_k(\alpha)$	Total distance traveled by ant α
s	Population size
$\tau_{\max}$	Upper limit of pheromone concentration
$\tau_{\min}$	Lower limit of pheromone concentration

Based on the convergence speed and path finding capability of the improved ant colony algorithm, the problem of optimal design of satellite telemetry data structure was studied.

1) THE SELECTION STRATEGY OF TELEMETRY PARAMETER SCHEDULING

During the probability calculation for the same generation, the probability of selecting a specific parameter to be placed in certain data unit of the satellite data structure among all alternative parameters that met the constraints by means of the improved ant colony algorithm was determined by (8),

$$p_{ij}(t) = \begin{cases} \dfrac{\left[\tau_{ij}(t)\right]^{\alpha}\left(\eta_{ij}\right)^{\beta}}{\sum_{\psi\in \mathrm{SET\_tele}}\left[\tau_{\psi}(t)\right]^{\alpha}(\eta_{\psi})^{\beta}} & \psi \in \mathrm{SET\_tele}, \\ 0, \quad \psi \notin \mathrm{SET\_tele}, \end{cases} \tag{8}$$

where pheromone concentration $\tau_{\mathrm{ij}}(t)$ was referred to the correlation of the telemetry parameter j on the device i in generation t, and heuristic term η_{ij} was related to the reciprocal of the distance from the parameter to the reference, with pheromone factor α and heuristic term factor β indicating the significance of pheromone concentration and heuristic term on the selection of telemetry parameters, respectively. Note that the distance here refers to the relative distance between the two parameters placed in a raster after rasterized modeling of the satellite data structure. Therefore, the heuristic term η_{ij} was calculated via (9),

$$\eta_{ij} = \begin{cases} \dfrac{1}{\sqrt{\left(D_{ij,x}\right)^2 + \left(D_{ij,y}\right)^2}}, & ij \neq \text{tele\_end} \\ 1, & ij = \text{tele\_end}, \end{cases} \tag{9}$$

when the last parameter was scheduled, the correlation between it and the reference was the lowest, meanwhile the distance between the two was the farthest, so the heuristic term of such telemetry was taken as 1.

Although the correlation-based telemetry parameter selection method avoids the path search from falling into local optimum to a certain extent, yet it reduces the algorithm convergence speed. To solve the problem, the selection of telemetry parameters was carried out by means of roulette-wheel selection [28]. Roulette-wheel is an approach that features relatively fast convergence while avoiding falling into local optimum, incorporating the idea of greedy algorithm for the purpose of goal selection. The stochastic number *random* ∈ (0, 1) was introduced, and it was stipulated that when *random* was greater than the set threshold, the probability of a telemetry parameter being selected was determined by (8), otherwise such parameter would be directly skipped. A smaller threshold could be set at the beginning of the algorithm iteration, while a larger threshold was set at the later part of the iteration, to ensure that as the number of scheduled objects decreased, the algorithm could maintain a fast convergence and still avoid falling into a local optimum.

2) PHEROMONE CONCENTRATION UPDATE STRATEGY

After the selection probability of current generation was completed calculating, the pheromone concentration of the parameters would be updated. The choice made by the ant of next generation was based on the pheromones left by the ant of the previous generation, hence the pheromone concentration was updated as per (10).

$$\begin{cases} \tau_{ij}\left(t+1\right) = \left(1-\rho\right)\tau_{ij}\left(t\right) + \Delta\tau_{\alpha}, & ij \in \Gamma_{\alpha} \\ \Delta\tau_{\alpha} = \dfrac{Q_{it}}{L_k(\alpha)}, & \alpha = 1, 2, \ldots, s. \end{cases} \tag{10}$$

The problem of scheduling telemetry parameters requires the algorithm to be equipped with strong global search capability at the early stage and sound local search capability at the later stage, but the conventional ant colony algorithm sets the pheromone concentration as a constant value, which cannot satisfy the above requirements [29]. Therefore, the correlation between telemetry parameters was considered as the pheromone concentration, and the sum of correlations from alternative telemetries on each equipment was adopted as reference, on the basis of which the update strategy of pheromone concentration was developed. As shown in (10), Q_{it} was introduced as the sum of correlations of alternative telemetry parameters on equipment i at generation t, which gradually grew as the iterations increased, thus ensuring that the pheromone concentration was small at the early stage to avoid falling into a local optimum, while the value increased at a later stage to improve the local search capability.

In addition, the pheromone concentration was limited to a certain range as in (11), to prevent the algorithm from falling into a local optimum due to a massive accumulation of pheromones from the equipment on which the alternative telemetry was located.

$$\tau_{ij}(t) = \max\left\{\tau_{\min}, \min\left\{\tau_{ij}(t), \tau_{\max}\right\}\right\}. \tag{11}$$

3) IMPROVED ANT COLONY ALGORITHM FLOW

To address the problem of satellite telemetry data structure design, the ant colony algorithm was improved based on the demand of ground data decoding and priority consideration of important design principles such as efficient utilization of resources and telemetry nesting relationships (*i.e.*, when a telemetry parameter of one device is taken as a reference for other parameters of different devices, the relationship between these two parameters is called telemetry nesting), combined with the grey relational analysis. Firstly, the correlation between each telemetry parameter and the reference parameter was calculated (*i.e.*, reference telemetry parameters provides a baseline for the calculation of telemetry parameters of the device it belongs to or of other devices), based on which the device with high average value of correlation was selected for priority scheduling, thus achieving the best overall effect of devices scheduling; then the correlation of telemetry parameters on each device was calculated, and the parameters within the device were scheduled according to the decreasing order of correlation, thus achieving the best local effect; finally, the telemetry parameters with data length less than 8 bits were scheduled collectively according to the decreasing order of correlation to optimize the resource coordination. In engineering practice, constraints such as telemetry nesting should be comprehensively considered. The improved algorithm flow is shown in Fig. 8.

The specific implementation is as follows.

1) All telemetry parameters were defined as a set {TM}, each parameter being an element of the set.
2) Within {TM}, elements with data length of 8 bits were defined as the subset $\{TM_0\}$, where all reference telemetry parameters were defined as $\{TM_{0-0}\}$, while the remaining parameters were defined as $\{TM_{0-1}\}$; elements with data length less than 8 bits were defined as the subset $\{TM_1\}$.
3) The importance of parameters through satellite design requirements and experience of designers was defined, and a key telemetry parameter was selected as the overall reference; then the correlation between all elements in the $\{TM_{0-0}\}$ and the key parameter were calculated, and ranked according to the correlation value, where the element with the highest correlation was defined as TM_{0-0-0}.

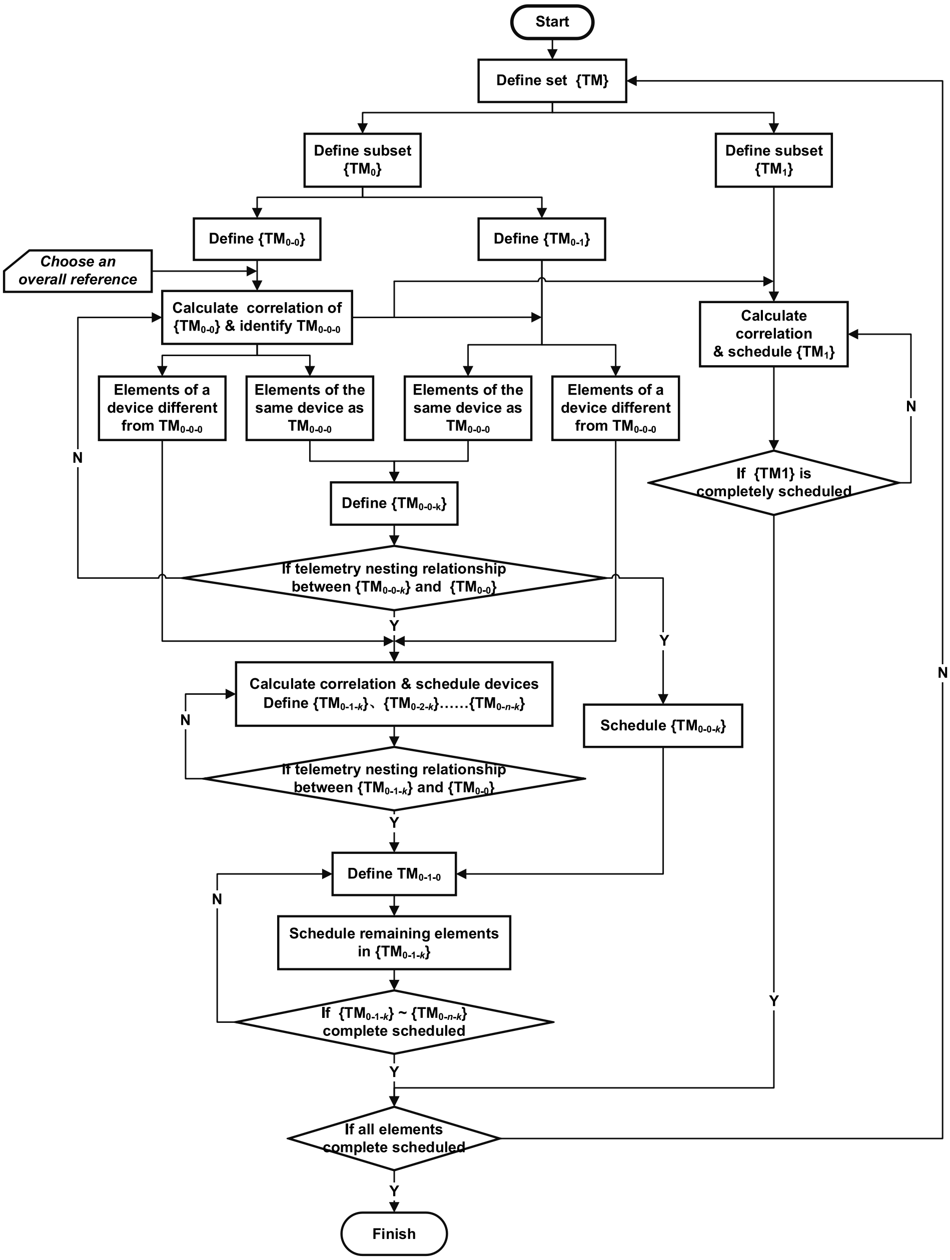

FIGURE 8. Flow chart of improved ant colony algorithm.

4) The elements in $\{TM_0\}$ that belonged to the same device with TM_{0-0-0} were defined as $\{TM_{0-0-k}\}$.
5) Whether there existed telemetry nesting relationship between elements in $\{TM_{0-0-k}\}$ and other reference parameters in $\{TM_{0-0}\}$ except TM_{0-0-0}, if not, went to step 6); if so, the element in $\{TM_{0-0}\}$ with the second highest correlation to the above key parameter was selected and defined as TM_{0-0-0}, and steps 4) and 5) were repeated until a TM_{0-0-0} satisfying the requirements was selected (based on design experience, there must exist a TM_{0-0-0} meeting the conditions in general after enumeration of all elements in $\{TM_{0-0}\}$).
6) The correlations of the remaining elements in $\{TM_0\}$ with TM_{0-0-0} were calculated, and the average of all telemetry parameter correlations on one device was weighted to obtain the correlation of such device with TM_{0-0-0}, then all devices were ranked in decreasing order of correlation, with the set of telemetry parameters on each device defined as $\{TM_{0-1-k}\}$, $\{TM_{0-2-k}\}$ …… $\{TM_{0-n-k}\}$.
7) All elements in $\{TM_{0-0-k}\}$ were scheduled, preferentially TM_{0-0-0}, then those elements originally belonging to $\{TM_{0-0}\}$ in decreasing order of correlation with TM_{0-0-0}, and thereafter the remaining

elements in decreasing order of correlation with TM_{0-0-0}.

8) Whether any element in $\{TM_{0-1-k}\}$ suffered from telemetry nesting relationship with the elements in $\{TM_{0-0}\}$ except those contained in $\{TM_{0-0-k}\}$, if not, entered step 9); if so, the next set $\{TM_{0-2-k}\}$ was chosen for verification until one set is selected as $\{TM_{0-1-k}\}$ that met expectations. According to design experience, in general, only a few devices with acquisition function suffered from telemetry nesting, if all sets were not satisfied, it allowed to redefine the sets and ranked them according to the practical necessity after step 6);
9) All the elements in $\{TM_{0-1-k}\}$ were scheduled, and the element in the set that originally belonged to $\{TM_{0-0}\}$ with the highest correlation to TM_{0-0-0} was defined preferentially as TM_{0-1-0}, then the other elements in $\{TM_{0-1-k}\}$ that belonged to $\{TM_{0-0}\}$ were scheduled in decreasing order of correlation to TM_{0-0-0}; meanwhile, the correlation to TM_{0-1-0} for the remaining elements were calculated and scheduled in decreasing order of correlation.
10) The correlations of all elements in $\{TM_1\}$ to TM_{0-0-0} were calculated and scheduled in decreasing order of correlation.
11) Whether elements in all sets were scheduled, if so, end of work; if not, entered step 12).
12) The reasons for incomplete scheduling and propose solutions were checked: If it was due to an element omission, the set it belonged to was determined and rescheduled according to the certain step of the process; if due to the total data length of the elements was longer than the length of the current format capacity, format multiplexing should be adopted as follows: Based on the principle that 1 data cell accommodated 8 bits of data length, the minimum number of data cells j (which was an integer) to be allocated by unscheduled telemetry data was calculated, and number of j data cells were taken as the format multiplexing area starting from the end of the scheduled telemetry data cells in the back-to-forth order, and then the remaining elements were scheduled in the data cells of the format multiplexing area as per step 6) to 9).

The improved ant colony algorithm combining raster method, grey relational analysis and roulette-wheel selection is capable of utilizing all units in the data structure reasonably and efficiently, and reducing the format multiplexing as much as possible to ensure the high refresh frequency of most telemetry information; moreover, priority transmission of most key telemetry information within the same format or frame has been achieved; meanwhile, the telemetry information with high correlation was scheduled according to the proximity to ensure that the refresh time of such telemetry data is consistent when decoding on the ground, which is conducive to analyzing the satellite state or problem identification under satellite fault state; in addition, scheduling requirements of parameters with special correlation such as telemetry nesting have been catered.

C. TARGET TELEMETRY LOCALIZATION

Target telemetry localization is a task to retrieve and locate the target telemetry based on the demand of ground data analysis and the result of satellite telemetry data structure design. When a certain telemetry of the satellite appears abnormal, it is necessary to define it as a target telemetry and locate it accurately within the minimum period, which can help to quickly locate the root cause, formulate solutions, dispose of the abnormal situation, and ensure the safe and stable operation of the satellite. The conventional target telemetry localization method mainly depends on manual or simple telemetry analysis tools, and locates the target telemetry step by step through the retrieval route of ''subsystem - device - module - target telemetry''. In such method, it requires high experience of the retrieval personnel, otherwise it is difficult to locate the target telemetry quickly among thousands of telemetries and the error rate is high; in addition, the step-by-step method features a long retrieval chain and time-consuming process, which is not suitable for problem location and disposal in emergency situations.

The proposed method gives telemetry data a new characteristic - ''correlation'', which could be applied to locate the target telemetry quickly and accurately. At the same time, based on the correlation information, the few telemetries with high correlation to the target telemetry could be quickly sorted out to narrow the problem search. Target telemetry localization is not a part of satellite telemetry data structure design, but the localization accuracy and efficiency are usually employed to judge the effectiveness of telemetry data structure design.

VI. EXPERIMENTAL VERIFICATION AND RESULT ANALYSIS

The DFH-4 satellite platform features a high degree of maturity and a strong inheritance of the telemetry data structure. In this paper, telemetry data of a certain commercial satellite of such platform were selected for test and verification.

A. SELECTION OF TEST OBJECTS & IDENTIFICATION OF REFERENCE TELEMETRY

60 telemetry parameters from 6 devices (*No. A* to *F*) were collected as test objects. Such parameters primarily included the state, temperature, and digital values, which were mainly collected by sensors, then transmitted through serial ports and finally grouped for framing. Each device contained 10 parameters, and their numbers within the device were 0 to 9 respectively, where parameter A_0 was the reference telemetry of the device.

B. CORRELATION CALCULATION & TELEMETRY DATA STRUCTURE DESIGN

Moreover, 7 metrics of each parameter, such as telemetry parameter data length, sampling period of telemetry

TABLE 5. Correlation of test objects relative to reference telemetry parameter.

No.	Test object	Relevance	No.	Test object	Relevance	No.	Test object	Relevance
1	A_0	-	21	C_0	0.795	41	E_0	0.625
2	A_1	0.959	22	C_1	0.785	42	E_1	0.670
3	A_2	0.857	23	C_2	0.905	43	E_2	0.618
4	A_3	0.939	24	C_3	0.882	44	E_3	0.552
5	A_4	0.797	25	C_4	0.842	45	E_4	0.589
6	A_5	0.844	26	C_5	0.872	46	E_5	0.585
7	A_6	0.890	27	C_6	0.891	47	E_6	0.496
8	A_7	0.871	28	C_7	0.849	48	E_7	0.603
9	A_8	0.815	29	C_8	0.809	49	E_8	0.512
10	A_9	0.802	30	C_9	0.820	50	E_9	0.512
11	B_0	0.842	31	D_0	0.493	51	F_0	0.353
12	B_1	0.836	32	D_1	0.458	52	F_1	0.349
13	B_2	0.744	33	D_2	0.476	53	F_2	0.422
14	B_3	0.714	34	D_3	0.522	54	F_3	0.458
15	B_4	0.730	35	D_4	0.427	55	F_4	0.496
16	B_5	0.760	36	D_5	0.440	56	F_5	0.476
17	B_6	0.698	37	D_6	0.492	57	F_6	0.484
18	B_7	0.684	38	D_7	0.484	58	F_7	0.504
19	B_8	0.645	39	D_8	0.440	59	F_8	0.440
20	B_9	0.677	40	D_9	0.424	60	F_9	0.425

A_0	A_1	A_3	A_6	A_7	A_2	A_5	A_8	A_9	A_4
C_0	C_2	C_5	C_6	C_3	C_7	C_4	C_8	C_1	C_9
B_0	B_1	B_4	B_5	B_7	B_6	B_2	B_9	B_3	B_8
E_0	E_1	E_2	E_5	E_4	E_8	E_6	E_7	E_3	E_9
D_0	D_3	D_1	D_7	D_2	D_6	D_5	D_8	D_4	D_9
F_0	F_4	F_3	F_5	F_1	F_7	F_6	F_8	F_2	F_9

FIGURE 9. Results of satellite telemetry data structure design.

parameter, calibration voltage after telemetry parameter sampling, linear distance from output interface of other telemetry circuits to reference telemetry circuit interface, contact *No.* of electrical connector of acquisition device, device *No.* to which telemetry parameter belongs and *No.* of its electrical connector, were selected as the relational analysis metrics, by adopting the proposed algorithm.

Device *A* was selected as the reference device, with telemetry A_0 as the reference parameter, and correlations were calculated for the remaining test objects, yielding the results in Table. 5. According to the results, the correlations between device *B* to *F* and device *A* were: *C*, *B*, *E*, *D* and *F* in descending order. Based on the sorting, the first parameter of each device was selected as the reference telemetry of the device, and correlations were calculated for the rest of the test objects, with the following results in Table. 6. On the basis of the above calculation results, assuming that the data structure was an area of 6 rows and 10 columns, the 60 telemetry parameters were scheduled in accordance with the proposed algorithm flow indicated in Fig. 8, and the outcome is shown in Fig. 9.

C. EVALUATION OF TELEMETRY DATA STRUCTURE DESIGN RESULTS

Relative to the reference telemetry A_0, the correlations of the remaining telemetry decreased with the growth of distance. The convergence effect of the correlation was quantitative evaluated by linear regression metrics as root-mean-square error (RMSE), mean absolute error (MAE), and coefficient of determination (R^2). As illustrated in Fig. 10, RMSE is 0.0681, MAE is 0.0551, and R^2 is 0.853, which lead to a favorable overall telemetry convergence effect.

TABLE 6. Correlation of test objects within device relative to reference telemetry.

No.	Test object	Relevance	No.	Test object	Relevance	No.	Test object	Relevance
1	A_0	-	21	C_0	-	41	E_0	-
2	A_1	0.959	22	C_1	0.841	42	E_1	0.955
3	A_2	0.857	23	C_2	0.923	43	E_2	0.933
4	A_3	0.939	24	C_3	0.901	44	E_3	0.783
5	A_4	0.797	25	C_4	0.858	45	E_4	0.873
6	A_5	0.844	26	C_5	0.911	46	E_5	0.899
7	A_6	0.890	27	C_6	0.908	47	E_6	0.841
8	A_7	0.871	28	C_7	0.869	48	E_7	0.805
9	A_8	0.815	29	C_8	0.841	49	E_8	0.842
10	A_9	0.802	30	C_9	0.785	50	E_9	0.776
11	B_0	-	31	D_0	-	51	F_0	-
12	B_1	0.944	32	D_1	0.929	52	F_1	0.870
13	B_2	0.818	33	D_2	0.915	53	F_2	0.785
14	B_3	0.794	34	D_3	0.952	54	F_3	0.945
15	B_4	0.874	35	D_4	0.798	55	F_4	0.959
16	B_5	0.869	36	D_5	0.862	56	F_5	0.924
17	B_6	0.834	37	D_6	0.889	57	F_6	0.834
18	B_7	0.860	38	D_7	0.919	58	F_7	0.850
19	B_8	0.780	39	D_8	0.821	59	F_8	0.798
20	B_9	0.811	40	D_9	0.793	60	F_9	0.780

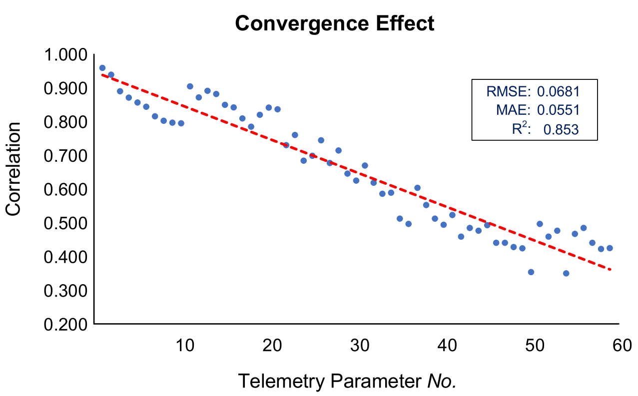

FIGURE 10. Convergence effect of proposed method.

In addition, the manual arrangement method and the standard greedy algorithm [30] of the conventional design process were also used to design the test data, respectively. The manual arrangement method is mainly based on the simple sorting of devices and telemetry data, whereas the idea of standard greedy algorithm used in initial digital telemetry data structure design tool is simply considered the correlation between devices and then scheduled. The design results of the above two methods are shown in Fig. 11(a) and 11(b), and convergence effects of both approaches are shown in Fig. 12(a) and 12(b), respectively.

Evaluation of satellite telemetry data structure design is generally determined by whether the design process is efficient, the design results are convergent, and the design applications are effective. In this paper, the overall design time consumption was selected to evaluate the design process efficiency, the RMSE, MAE and R^2 of correlation were selected to evaluate the design convergence effect, and the accuracy and time consumption of target telemetry localization were selected to evaluate the design application effect.

Comparison results between the two traditional approaches and the proposed method are shown in Table. 7 and Fig. 13. In terms of design process efficiency, the overall design time of the proposed method is 1.3 hours, which improved 59.4% relative to the manual arrangement and 43.5% relative to the standard greedy algorithm; in terms of design convergence effect, the proposed method has the smallest RMSE and MAE, meanwhile the R^2 of which is also most close to 1, showing the best convergence with respect to the correlation of reference telemetry; in terms of design application effect, the localization accuracy of the proposed method is 98.3%, which is 90% and 80% better than the manual arrangement and the standard greedy algorithm, respectively; besides, the target localization time of the method is 2s, which is 81.8% and 60% better than the other two approaches. The proposed method achieved the most effective results, and the feasibility and effectiveness were verified.

FIGURE 11. Results of satellite telemetry data structure design based on two traditional methods.

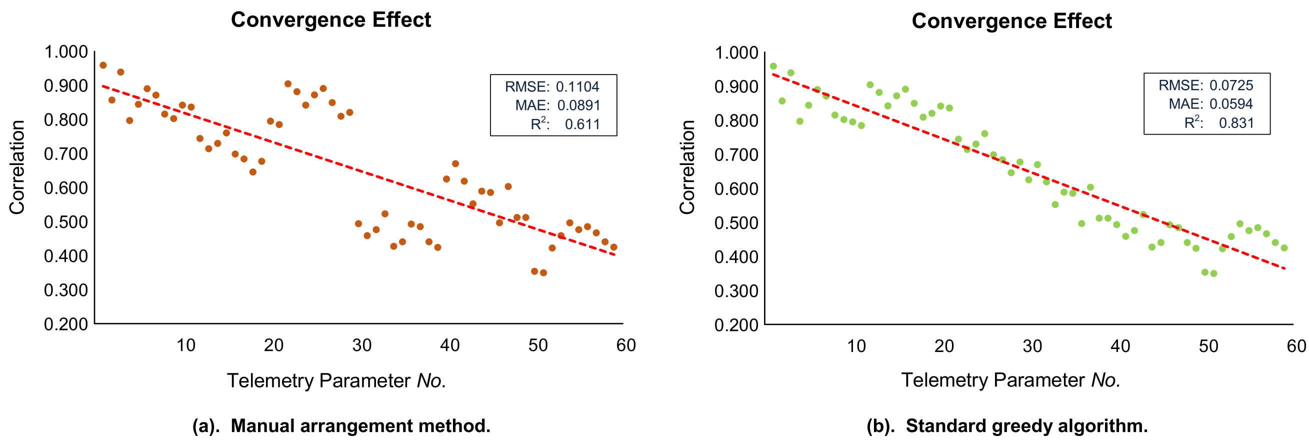

FIGURE 12. Convergence effect of two traditional methods.

TABLE 7. Comparison results of three methods.

	Process Efficiency	Convergence Effect			Application Effect	
	Time Cost	RMSE	MAE	R^2	Localization Accuracy	Localization Time Cost
Manual Arrangement	3.2 h	0.1104	0.0891	0.611	83.3%	11 s
Greedy Algorithm	2.3 h	0.0725	0.0594	0.831	91.7%	5 s
Proposed Method	**1.3 h**	**0.0681**	**0.0551**	**0.853**	**98.3%**	**2 s**

D. ANALYSIS OF EXPERIMENTAL RESULTS

The optimization method of satellite telemetry data structure design based on improved ant colony algorithm proposed in this paper features the following advantages over conventional methods.

1) In terms of design process, the factors considered by the method are comprehensive, ensuring the efficiency and reliability of the design process and validity of the results.
2) In terms of design approach, the method leverages machine logic execution with thorough consideration of design factors by means of algorithms such as statistics, which is more dependable than the empirical guarantee of designers.

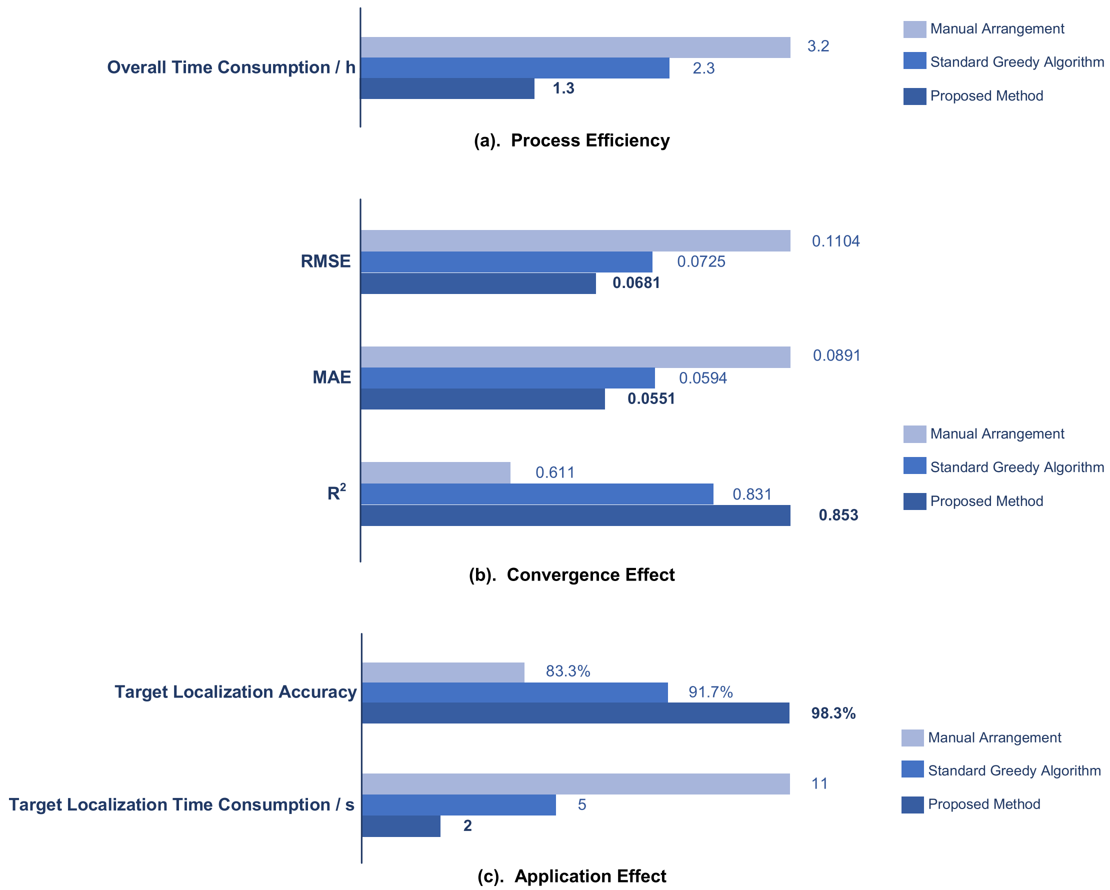

FIGURE 13. Comparison results of three methods.

3) In terms of design results, the proposed method is capable of balancing telemetry transmission capacity and overall design efficiency to achieve a reasonable and effective data structure, thus ensuring convenient decoding of ground data.
4) In terms of design application, the method endows telemetry data with new characteristics, simplifies the target telemetry retrieval path, and improves target telemetry localization accuracy and efficiency.

The proposed design method in the subsequent research will further combine with the engineering reality, optimize the design factors and accurately define the constraints, while deepen the integration with the experience of designers, so as to ensure that the design results fit the practical engineering application requirements.

VII. CONCLUSION

The rationality of satellite telemetry data structure design is an important factor for ground data decoding and satellite health status monitoring. With the gradual improvement of satellite capability, the increase of load ratio also indicates that the number of parameters contained in the telemetry data structure is increasing, thus how to design the data structure more efficiently and rationally is a common problem faced by satellite TT&C system design.

In this paper, a novel satellite data structure design method based on improved ant colony algorithm was proposed to address the problems such as inefficient utilization of data structure resources, illogical arrangement of telemetry parameters, excessive reliance on personal experience of designers, and incomplete synthesis of key principles in manual design, combining the figurative characteristics of rasterized modeling and the merits of grey relational analysis. Through the analysis and verification of sample data simulation, it is proved that the proposed approach significantly improves the data structure resource allocation, which is consistent with the design evaluation principles and applicable to the satellite telemetry data structure design. The idea of data structure optimization of the proposed method also offers implications for similar problems in other application fields, *e.g.*, for information transmission within a satellite constellation, the critical information that can be placed in an important position through structure optimization to facilitate access by additional satellites; or when the satellite constellation transmits information to ground users, the demands of different users can be converted into various correlation information to satisfy diverse needs so as to achieve customized information transmission as required.

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