A Space Station Dynamic Mission Planning Based on Multi-objective Constraint Values

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Abstract. A dynamic mission planning method based on multi-objective constraint values is designed for the situation in case of emergent mission happens to space station in orbit. A space station dynamic mission planning model is described based on the ontology model, and the comprehensive evaluation function of the space station dynamic mission planning is proposed by weighing the factors such as the mission stability of the space station , the mission impact on astronauts, the mission planning ratio, and the mission resource utilization. The dynamic mission time backtracking iteration method is adopted to solve the conflict of each constraint in dynamic mission planning by repeated mission search and mission reconstruction. Base on this, Mission Number Maximization Strategy, Consumption Most Economical Strategy and Astronaut Impact Minimization Strategy are proposed. The proposed approach is evaluated in a test case with twenty-three missions and two astronauts. The simulation results show that the proposed replanning method based on multi-objective constraint values can meet different dynamic mission planning requirements of a space station.

Keywords: Mission planning, multi-objective constraint values, space station.

1. Introduction

As a largest and most complex project in space, space station needs to execute many kinds of operational missions, such as science experiments, crew rotation, maintenance[1]. The life cycle of space station normally lasts more than 10 years from building, assembling, operating to eventual decommission. In such a long time, how to balance the astronauts' work and life , ensure the normal operation of the station equipment, carry out all kinds of payload experiments orderly, is the problem that the space station mission planning needs to solve [2][3].

The missions, which space station operation need to plan, include the space station operation and maintenance missions, the crew training and rotation missions, payload experiment missions, cargo supply missions and so on [4-6].

Mission planning is a key technique for the long-term operation of a space station. Currently, many researches on space station mission planning mainly focus on the International Space Station (ISS) operation requirements [7].

The ISS has been orbiting over the years, the main countries taking part in the operation of the ISS have developed a variety of mission planning systems, including the United States Johnson space center's space station mission planning system [8], the Marshall space flight center's station load mission planning system [9], Japan's executive-level mission planning system [10] and European Space Agency (ESA)'s strategic-tactical planning support tool [11]. The literature of the systems mentioned above mainly introduces the functional architecture of the software system, and there are few studies on specific models and methods of the space station mission planning. China's space station is scheduled to be launched in 2020, which will support more than three astronauts, and various missions will be carried out in orbit [12-14]. At the same time, there are more and more studies on the in-orbit space station mission system, including the typical space station mission planning system [15][16], the space station long-term operation mission planning and modeling [17][18], the short-term mission planning analysis [19], and research on parallel mission planning[20].

In the space station mission planning studies above, only the maximization of mission number has been used as the single target for the mission planning, and there is no research related to the mission planning about astronauts, resource utilization and other multi- objective constraints.

Compared with the mission planning about other spacecraft, the dynamic mission planning of a space station has more complicated constraints: it not only needs to consider the safety of astronauts, but also needs to balance the platform mission, scientific research and other missions, and also needs to meet the resource constraints of energy, information transmission bandwidth and thermal dissipation. Therefore it is necessary to find a mission replanning method based on multi-objective constraint values. This paper first introduces the mission planning model, including mission model and resource model. Then, based on the method of time backtracking iteration, a dynamic mission planning strategy with multi-objective constraint values is proposed. Finally, a typical simulation case is used to verify the result.

2. Model Description

Normally, space station executes a list of planned missions in sequence. In case of equipment failure, operational error and external environment impact, it is necessary to replan the space station mission list in order to resume the operation within an acceptable response time. A space station dynamic mission planning is to take the original mission list as the initial condition, and apply the dynamic mission planning strategy to replan the mission list, meanwhile, meet the resource and other constraints. The schematic diagram of a space station dynamic mission planning is shown in the figure below.

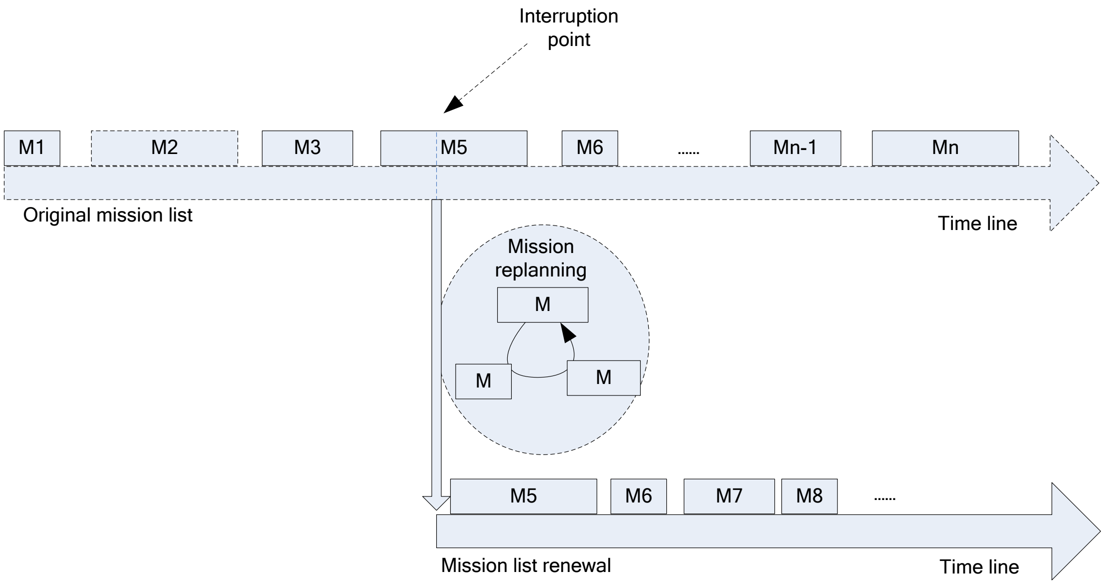

Fig. 1 Schematic diagram of spatial replanning problem

2.1 Mission Model

Literature[2] describes the concept of overall mission planning of a space station by using ontology model, and subdivides the mission into two levels: mission and activity. In order to simplify the analysis, this paper does not describe the activities in the space station mission, but uses the ontology model to define the mission.

A space station mission model is described as follows:

$$M = (d, n, t_{st}, t_{ed}, \theta_m, R) \quad (1)$$

Where, M is the mission set, d is the mission number, n is mission name, $t_{st}$is the earliest start time of the mission; $t_{ed}$is the last completion time of the mission; $\theta_m$is the mission type, including Important Mission, Daily Maintenance Mission, Payload Experiment Mission and Astronaut Training Mission; R is the set of mission resources.

The resource conceptual model is described as follows:

$$R = (j, R_{max}, R_{jm}, t_j, T_{jm}) \quad (2)$$

Where, R is the set of resource occupied by activities, j is resource number, R_{max} is rated capacity of resources; R_{jm} is resource consumption per unit time; t_j is beginning time of resource consumption; $T_{jm}$is duration of resource consumption.

2.2 Planning Model

1) Variables

The main variables of dynamic mission planning are the starting time of the replanning missions. The set of variables is described as follows:

$$X = (t_{r1}, t_{r2}, \dots, t_{rn}) \tag{3}$$

X is the set of variables at start time of replanning mission; t_{ri} is the start time of mission i replanning, which is within the range of the earliest and last start time of mission i; n is the total amount of replanning missions.

The resource consumption variables per unit time include energy, information transmission bandwidth, thermal dissipation consumption, propellant consumption, etc. For recoverable resources, the total resource consumption per unit time should be less than the rated total resource, as shown below:

$$\sum_{i=1}^{n_t}(P_{mi}) \le P_{max} \tag{4}$$

$$\sum_{i=1}^{n_t}(B_{mi}) \le B_{max} \tag{5}$$

$$\sum_{i=1}^{n_t}(Q_{mi}) \le Q_{max} \tag{6}$$

Where, n_t is the total number of missions consuming resources at time t; P_{mi}、B_{mi}、Q_{mi} are the amount of energy, information transmission bandwidth and thermal dissipation resources consumed by mission i at time t; P_{max}、B_{max}、Q_{max} are the total amount of rated energy, information transmission bandwidth and thermal dissipation resources per unit time.

Propellant resource consumption G_{mi} is unrecoverable resource consumption, and its total consumption should not exceed the total amount of propellant resourcesG_{max}, as shown below:

$$\sum_{i=1} G_{mi} \le G_{max} \tag{7}$$

2) Evaluation function

Evaluation of station dynamic mission replanning should include impact of mission plan, mission completion ratio, resource utilization, and mission planning operation time. Astronaut impacts should also be taken into account in mission replanning. Therefore, this paper proposes four evaluation factors including mission stability, the mission impact on astronauts, mission planning ratio and resource utilization.

a) mission stability

The mission stability presents the offset quantity of the replanning mission and the original mission, which is defined as follows:

$$f = \sum_{i=1}^{n-n_c}\left(\theta_{mi} \times (t_{ri} - t_{oi})\right) \tag{8}$$

Where, f is the mission stability factor; θ_{mi} is the importance factor of the mission; t_{ri} is the start time of the replanning of mission i; t_{oi} is the original start time of mission i; n is the total amount of missions; $n_c$is total amount of cancel missions.

b) mission impact on astronauts

The mission impact on astronauts is to evaluate the deviation between replanned missions and the original missions:

$$\omega = \sum_{i=1}^{n_a-n_{ca}}\left(\theta_{mai} \times (t_{rai} - t_{oai})\right) \tag{9}$$

Where, ω is astronaut impact factor; $n_a$is the total number of astronaut missions; n_{ca} is the total amount of missions cancelled by astronauts; θ_{mai} is the important level coefficient of single astronaut's mission; t_{rai} is the execution start time after replanning of mission i; t_{oai} is the original execution start time of mission i.

c) mission planning ratio

The mission planning ratio refers to the ratio between the number of re-planned missions and the number of original missions, expressed as follows:

$$\lambda = \frac{n_f}{n} \tag{10}$$

Where, n_f is the amount of replanned missions which have completed, and n is the total amount of original missions.

d) resource utilization

The resource utilization rate represents the resource consumption of the replanned mission, which is defined as follows:

$$u = \frac{1}{q}\sum_{j=1}^{q}\left(\sum_{i=1}^{n_f}\left(R_{jmi} \times T_{jmi}\right) + R_{jb} \times T\right)/\left(R_j \times T\right) \tag{11}$$

Where, u is the resource utilization rate; q is the amount of resource types; n_f is the amount of missions completed; n is the total number of missions; R_j is Resource j consumption per unit time; R_{jmi} is mission i 's consumption of resource j per unit time; T_{jmi} is the time for mission i 's consumption of resource j; R_{jb} is the basic consumption of resource j; T is the mission planning period.

v is evaluation function for the consumption of unrecoverable resource, which is defined as follows:

$$v = \frac{R_c}{R_T} \tag{12}$$

Where, R_c is the resource consumption amount for single mission, and R_T is the total resource consumption amount.

e) comprehensive mission evaluation function

The following general evaluation functions are obtained from the above four mission evaluation functions.

$$C = \frac{1}{f} \times a + \frac{1}{\omega} \times b + \lambda \times c + (u - v) \times d \tag{13}$$

In the formula, a, b, c and d respectively represent the weighted factors of each function, and $a + b + c + d = 1$.

3. Methods

3.1 Time Backtracking Iteration Method

When an emergent mission happens to a space station, the current mission is suspended, and the original mission list that has not been executed is put into the dynamic mission planning model as input. The space station dynamic mission planning strategy works out the replanned mission list by steps as follows: arranges the initial planning mission list on the timeline; searches resource conflict points on it; uses the basic method of time backtracking iteration to match the mission's requiring time and resources; output the replanned missions list. The schematic diagram of dynamic mission planning based on resource conflict is as follows.

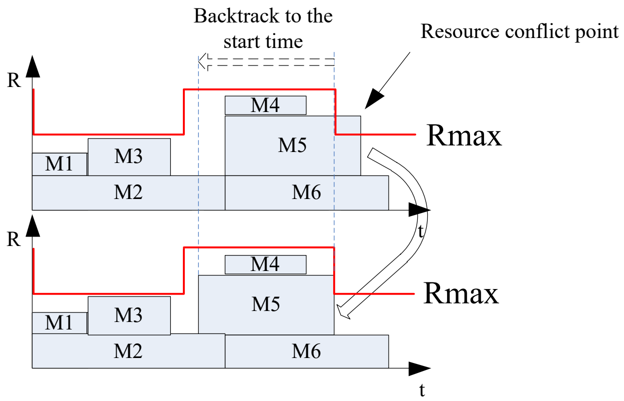

Fig. 2 Time backtracking iteration method schematic diagram

3.2 Planning Strategy Based on Resource Allocation

The existing research on spacecraft mission planning is mission stability oriented. Compared with the mission planning of satellites and spacecraft, the dynamic mission planning of a space station has the following characteristics: a) astronauts work and live on the space station, which means that the safety and health of the astronauts should be taken into consideration; b) a space station has more types of missions and more complex mission constraints. Therefore, the dynamic mission planning strategy of a space station should have varied strategy modes according to different application scenarios.

To meet the varied requirements of dynamic mission planning of a space station, this paper presents three planning strategies: maximizing the number of planned missions, making the most economical use of resources, and making the minimum impact of astronauts.

1) Mission Number Maximization(MNM) Strategy, that is, plan the maximum number of missions arranged on the timeline, and treat astronaut related tasks as ordinary tasks, without considering the economy of task resource consumption.

2) Consumption Most Economical(CME) Strategy, that is, plan with the lowest mission cost, prioritize the use of recoverable resources.(Example: utilize CMG (Control Moment Gyro) in preference to jet propulsion control in attitude adjustment).

3) Astronaut Impact Minimization(AIM) *strategy*, that is, take the rest and training tasks of the astronauts as the highest priority for time curing, then arrange other missions.

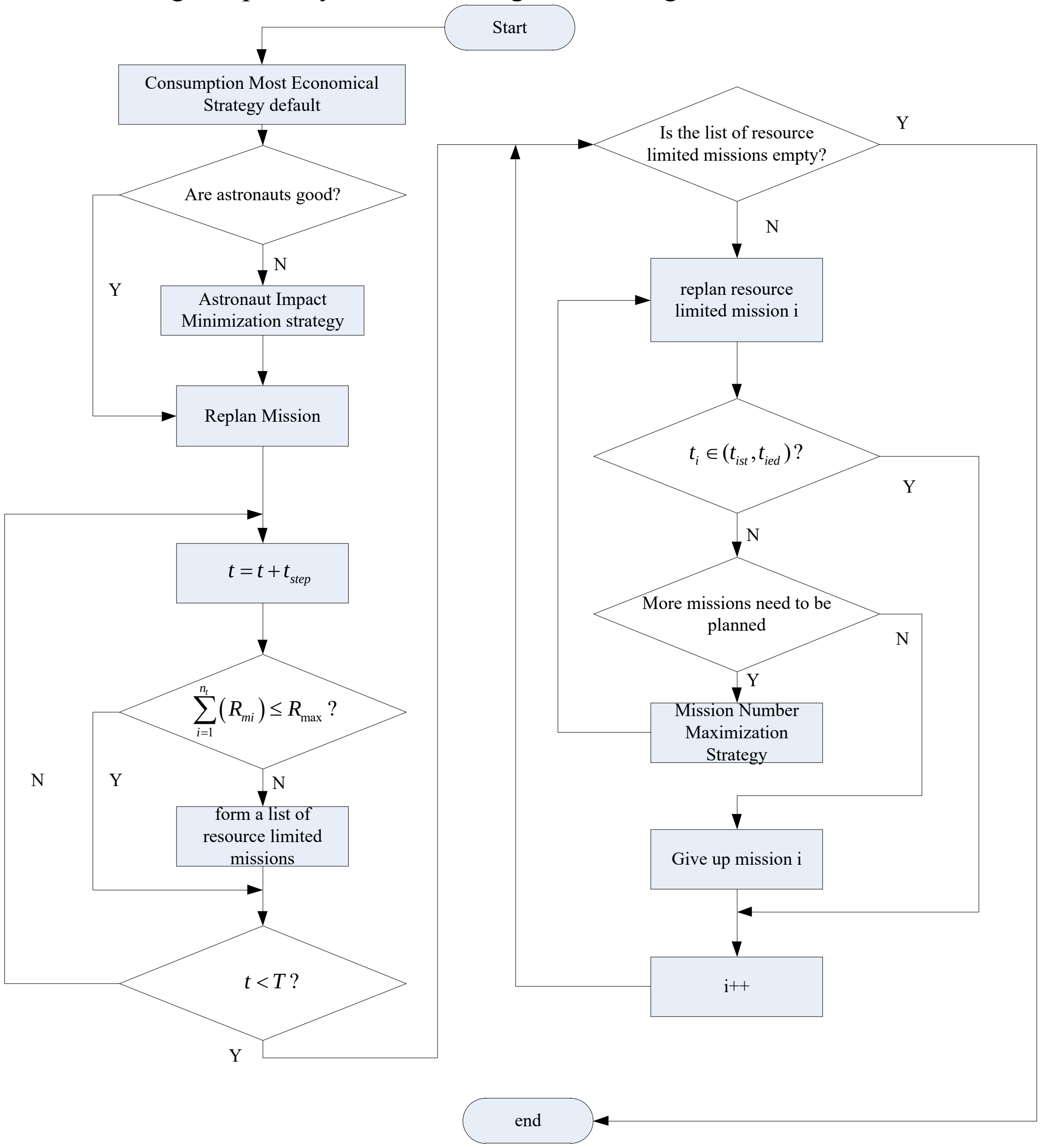

Fig. 3 Dynamic mission planning process

Three strategies are integrated into one process, and different strategies are selected according to the requirements of different scenarios. The process is as follows:

Step1: CME Strategy is selected as the default mode.

Step2: Judge whether the mode should be switched to AIM Strategy base on astronaut's health status and working hours.

Step3: replan missions according to priority.

Step4: search the missions with resource conflict in the entire mission planning period and form a list of them.

Step5: The missions with resource conflict are sorted according to priority, and then replanned into the period with the most resource redundancy.

Step6: Judge whether the mode should be switched into MNM strategy, if there are unplanned missions, whose θ_{mi} (Mission importance factor) exceed the preset limitation.

Step7: Give up the missions which are still unable to meet the constraints after replanning.

Step8: Output the updated mission list until all mission replanning are finished.

4. Simulation Results

In order to verify the effectiveness of the algorithms for three strategies proposed in this paper, the same example is used to test. The results of the three strategies were evaluated and compared through mission stability, astronaut impact, mission planning ratio and resource utilization.

4.1 Example Configuration

In order to facilitate the analysis, the mission planning duration was compressed and 24-hour planning time was set for verification.

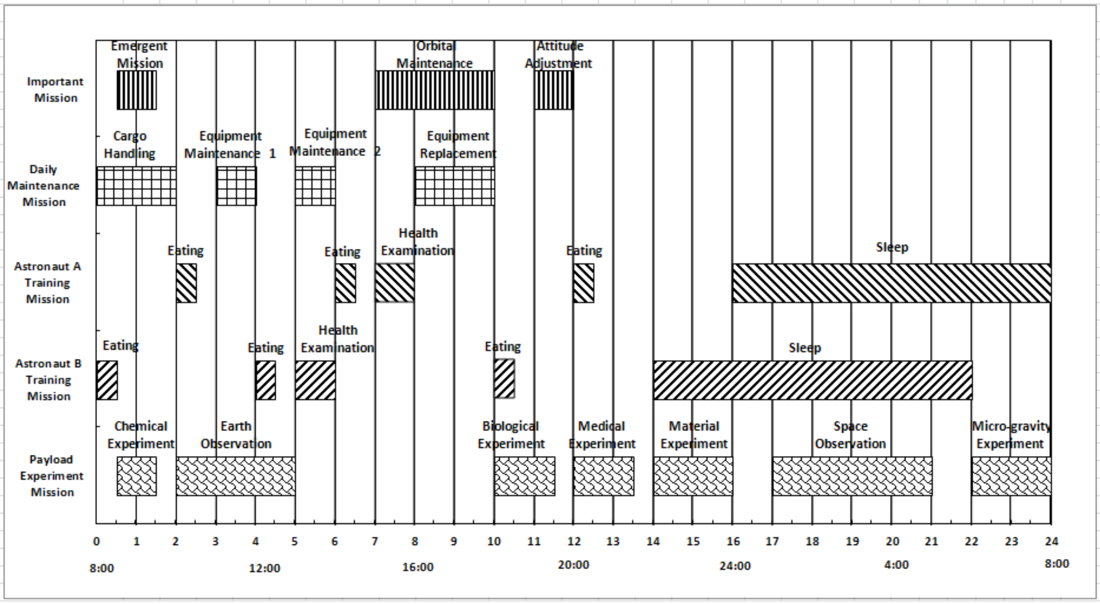

Fig. 4 Original mission diagram

The example includes 24 missions, categorized into 4 types, which are Important Mission, Daily Maintenance Mission, Astronaut Training Mission, and Payload Experiment Mission. Among the missions, orbital maintenance mission and attitude adjustment mission are designed in two modes, one is resource saving mode and the other is time saving mode, which is used for simulation strategy selection. Every mission consumes resource, including energy, information transmission bandwidth, thermal dissipation and astronaut workload, which are limited by the rated resource limitation of space station. The assumption is that there are two astronauts working and living in the space station. The static rated mission power is 8000W, the information transmission bandwidth is 1Gbps, and the static rated thermal dissipation is 7000W. The emergent mission was set to happen at 8:30.

4.2 Analysis of Replanning Results

According to the three dynamic mission planning strategies proposed in this paper, the emergent mission was prioritized and the conflicting mission Chemical Experiment was suspended. According to each strategy, the missions are replanned, and the dynamic replanning function is realized. Simulation results of mission replanning are shown in the following table.

Table 1 Mission replanning results

Simulation Method	Strategy	Mission Amount		
		replanned	cancelled	delayed
1	AIM +CME	22	1	5
2	CME	23	0	8
3	AIM+MNM	23	0	6

1) analysis of planning results

As can be seen from the mission planning results, simulation method 1 ensures that the replanning has the smallest impact on astronauts, the most economical use of resources, and the largest amount of mission changes. Simulation method 2 ensures the most economical use of resources without considering astronaut's priority, and the amount of mission changes is relatively small. Simulation method 3 is the strategy to maximize the amount of missions. Although it consumes more resources, the amount of task changes is the least.

2) comparative analysis of results of different strategy

The impact planning missions of the three different planning algorithms are evaluated through mission stability, astronaut impact, mission planning ratio and resource utilization as Fig. 5.

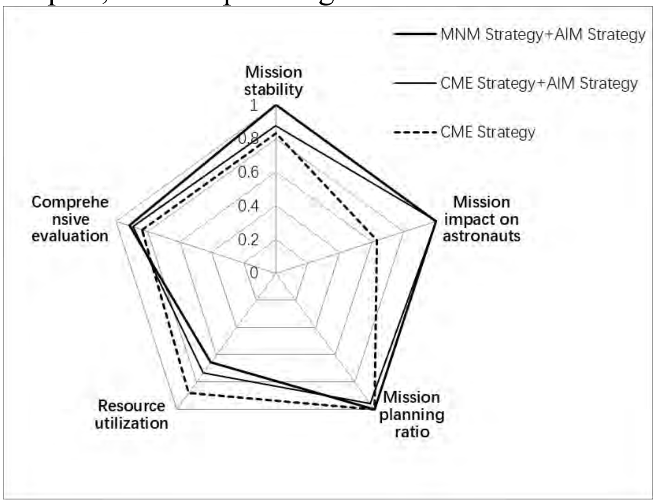

Fig. 5 Comprehensive comparison chart of different strategies

As can be seen from the figure above, the three algorithms have different features. According to the result of comprehensive mission evaluation function（the weighted factors of each function are the same, MNM Strategy + AIM strategy is optimal.

5. Conclusion

This paper presents and describes the station dynamic mission model based on the ontology model, and designs the evaluation function of dynamic mission planning. The mission planning algorithm is comprehensively evaluated from the aspects of mission stability, astronaut impact, mission planning proportion and resource utilization. The resource conflict problem of a space station mission planning is solved by the basic method of time backtracking iteration, and three replanning strategies are designed to cope with different application scenarios, which are MNM Strategy, CME Strategy, AIM Strategy. Simulation result shows that the time backtracking iteration method adopted in this paper can effectively reduce the impact of direct cancelled mission caused by resource conflict in space station. The three dynamic mission planning strategies with specific features can be applied in varied scenarios and agilely switched to meet different requirements. Base on the research in this paper, the strategies can be further optimized and developed to support the application in future.

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