2015 Chinese Control Conference

Proceedings of the 34th CCC

第三十四届中国控制会议论文集

Technical Committee on Control Theory

中　文

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IEEE Catalog Number: CFP1540A-USB

ISBN: 978-988-15638-9-7

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July 28-30, 2015, Hangzhou, China

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ISBN: 978-988-15638-9-7

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Proceedings of the 34th Chinese Control Conference
July 28-30, 2015, Hangzhou, China

The Design and Analysis of Hierarchical Decision-making for Manned/Unmanned Cooperative Engagement

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Abstract: This paper mainly discusses Manned/Unmanned Cooperative Engagement. We propose a framework of hierarchical decision-making system considering the requirements of the manned/unmanned integrated system. Then we expound the process of decision-making as well as the key techniques within two aspects, the pilots and the unmanned combat aerial vehicle. Three cases have been designed and simulated to demonstrate the effectiveness of the system in executing appointed missions similar to these cases.

Key Words: Cooperative engagement, UCAV, hierarchical decision-making, maneuver chain

1 Introduction

Recently, Cooperative Engagement （CE） has been a hot research topic[1] all around the world especially in developed countries. Manned/Unmanned Cooperative Engagement （MUCE） is a typical case of the CE. It not only makes the best of the subjective evaluation from pilot and his actual aerial combat experience, but also utilizes the advantages of the Unmanned Combat Aerial Vehicle（UCAV）[3] such as the high maneuverability, low risk and expense and strong survivability. Nowadays, MUCE needs the control and guidance of the mission ground control center or airborne warning and control system, in which case precious time may be spent over the transmission process. In this paper, we propose a new control approach in which pilots in the manned aircraft operate the UCAV directly to gain competitive advantages in aerial combat.

To control the UCAV there are two common strategies. One is based on quantitative analysis which searches for the optimal solution given the mathematical model. Examples include matrix countermeasure and differential game. The other strategy is qualitative evaluation based on existing experience. Example include expert system and neural network. Combining the two different strategies potentially leads to better performance, so hierarchical thought is widely applied in UCAV decision-making. Aerial combat decision-making is normally divided into three levels strategy, tactics and maneuver. In this paper, we simplify the model in these three hierarchical levels into quantitative and qualitative decision-making levels. The former is accomplished by the pilots in the manned aircraft and the latter is implemented by the UCAV through maneuver-based control[4].

Then in chapter 2 we will mainly analyze the authority allocation, chapter 3 will mainly discuss the hierarchical decision-making system, chapter 4 will describe the decision-making process and key technology both in manned aircraft and UCAV, chapter 5 will illustrate the effectiveness through simulating of three missions using the system proposed this paper and chapter 6 will give a conclusion and some deficiencies to be improved.

2 Analysis of Authority Allocation

Central to this task is authority allocation between the UCAV and pilots[5]. Deciding the relative level of manual and autonomous operation is critical to maximizing mission effectiveness and poses one of the greatest developmental hurdles. Considering the overall MUCE hierarchical decision-making system, three basic requirements has been raised as follows：

1） Make the best of subjective estimating ability and actual aerial combat experience, while not causes much operational burden for pilots[6].
2） The control system of the UCAV can't be beyond the existing technological capability[7].
3） Pilots can operate the UCAV directly in case of emergency.

Firstly, in the hierarchical decision-making of the MUCE, pilots in the manned aircraft mainly accomplish qualitative decision-making. Here, qualitative decision-making refers to selecting and sending appropriate emission commands to the UCAV. UCAV employed in the actual aerial combat is to fulfil the specific mission, especially those high risk indeed that manned aircrafts can't finish easily such as reconnoitering, searching, intelligence gathering and close attacking. So we can summarize these missions to a mission library. Thus, what the pilots need to do in the hierarchical decision-making is to choose the appropriate mission from the existing mission library according to the situation assessment[8]and aerial combat experience.

Secondly, in the hierarchical decision-making of the MUCE, UCAV mainly accomplishes quantitative decision-making. Each mission of UCAV can be divided into several phases and each phase can be regarded as a certain maneuver. That is to say, a specific mission can be represented as a maneuver chain. This maneuver-based control has received much attention[9] and made some achievements among the decision-making of UCAV[10]. But majority of the current results are based on seven frequently-used maneuvers proposed by NASA[6], that is maximum acceleration, maximum deceleration, variables unchanged, maximum overload pulling up, maximum overload diving, maximum overload turning left and maximum overload turning right. The control inputs of the UCAV should be changed in every control period and all control variables are working at ultimate state, which leads to heavy computation as well as hard to be applied.

Obviously, NASA's seven maneuvers strategy can't satisfy above requirements of maneuver chains and a new maneuver library should be established containing. In the new maneuver library, each maneuver has several different parameters to describe the degree of the maneuvers. Besides, the control inputs of UCAV only change between two maneuvers as conversion precondition is satisfied, which is much slower than the traditional one. Thus, what the UCAV need to do automatically is to choose the appropriate maneuver, set corresponding parameters accurately and switch between two maneuvers at right time.

Lastly, pilots must operate the UCAV absolutely in case of emergency, in other words, pilots' control authority is always higher than autonomous control.

3 Hierarchical Decision-making System

Based on the above analysis, the framework of hierarchical decision-making system is shown as Fig. 1. The hierarchical decision-making system[11] consists of four separate parts, namely pilots' decision-making parts, UCAV's decision-making parts, information interaction parts and command transmission parts. Status information contains the information of manned aircraft, UCAV and target aircraft.

The function of information interaction part is to send the information collected by manned aircraft to UCAV. Both input and output of information interaction model are the status of manned aircraft, UCAV and target aircraft. The status information consists of 12 state variables, which contains all six degree of freedom information.

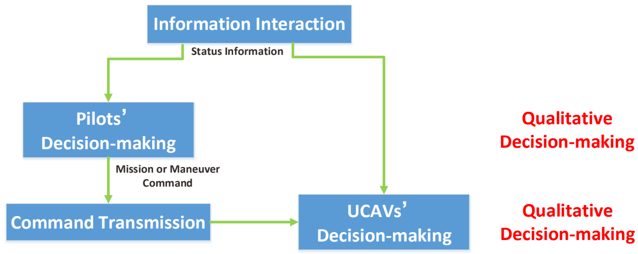

Fig. 1: Framework of Integrated System

The function of command transmission model is to send the mission or maneuver command generated by pilots. In normal condition, the output of decision-making by pilots is the mission command and in emergency, pilots can operate UCAV directly.

The task of pilots' decision-making part is to complete qualitative decision-making. The input of it is the status of the three aircraft and the output is pilots' choice among the mission library. The structure of the pilots' decision-making is showed as Fig. 2.

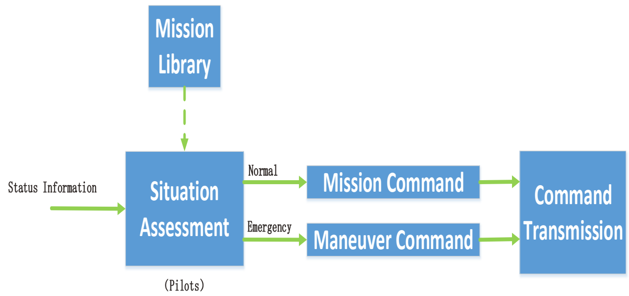

Fig. 2: Structure of Decision-making by Pilots

The task of UCAVs' decision-making is to execute a maneuver chain after receiving command from pilots. The process of it mainly contains choosing optimal maneuver chain, switching between maneuvers and set accurate maneuver parameters. Then the maneuver controller will generate the commands of angle of attack, sideslip and roll as well as throttle as control variables of UCAV. The structure of UCAVs' decision-making is showed as Fig. 3.

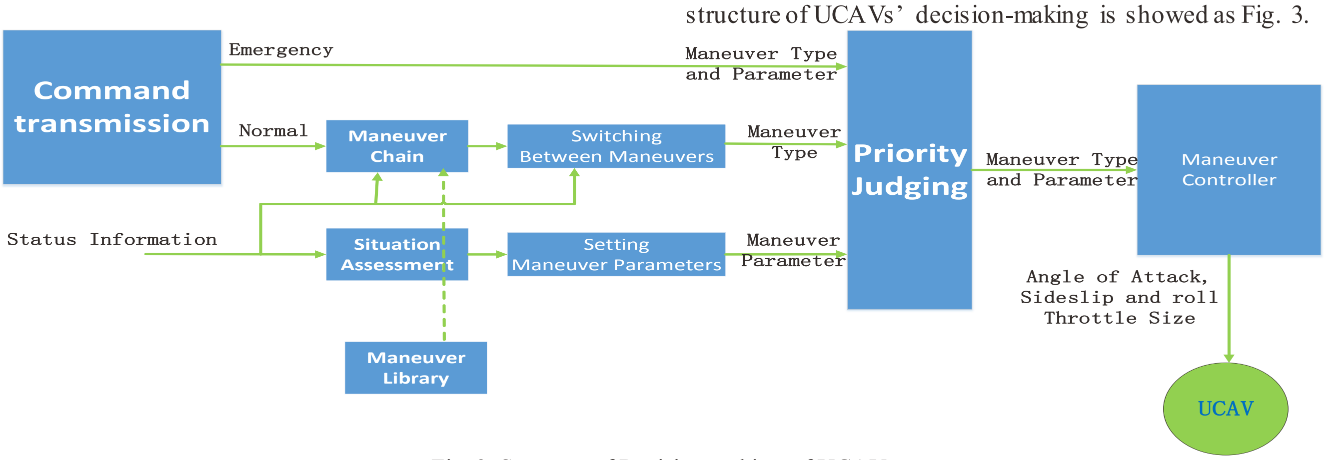

Fig. 3: Structure of Decision-making of UCAV

4 Process of Decision-making and Key techniques

We can briefly describe the process of hierarchical decision-making in MUCE mentioned above as follow. First pilots assess the situation present and make qualitative decision based on the status and their rich experience. The tasks here are to generate the mission or maneuver command and handle the manned aircraft to the position desired at the same time. Afterwards, UCAV chooses an optimal maneuver chain and executes it through switching between maneuvers and setting maneuver parameters under the premise of knowing the situation present. Of course, that is only the normal condition. In emergency pilots must operate the UCAV directly. At last, in both condition, the maneuver controller generates the commands of attack angle, sideslip angle, roll angle and throttle from maneuver type and parameters and then utilizes them to control the UCAV automatically. Next we will discuss the decision-making by pilots and UCAV in detail.

4.1 Qualitative Decision-making by Pilots

The same as the requirements describing, operational burden must be taken into account when utilizing subjective evaluation ability and actual experience in pilots' qualitative decision-making of MUCE. Before the decision is made, pilots must assess the situation present comprehensively based on the status of three aircraft. Normally, assessment factors herein mainly contain angle, distance, approaching velocity, energy, etc. According to corresponding reference[12], the results of the situation assessment naturally can be sorted into three conditions, advantage, disadvantage and neutrality. Then pilots choose an optimal mission from the mission library for UCAV according to the results of situation assessment.

Key techniques lie in the algorithm of situation assessment and the establishing of mission library.

4.2 Quantitative Decision-making of UCAV

UCAV is the main force among aerial combat and the process of quantitative decision-making is implemented automatically. After receiving the mission command from pilots, UCAV chooses an optimal maneuver chain, switches and set maneuver parameters according to status information. Then commands of attack, sideslip and roll angle as well as throttle size are generated in related maneuver controller to handle the UCAV for executing missions.

Key techniques we emphasize here mainly contain establishing of maneuver library, setting of maneuver parameters and switching between maneuvers.

4.3 Key Techniques

4.3.1 Situation Assessment

There are many different methods on situation assessment[12]. As pilots can contribute to estimating and making decision, we only discuss angle, distance and energy factors this paper to get the result of situation assessment. Following is the brief analysis of angle, distance and energy separately and synthetically.

- Angle Factor

The aspect angle and entering angle are discussed here. The former denoted φ is the angle between the direction of sight and UCAV's velocity and the latter denoted q is the angle between the direction of sight and target's velocity. In order to determine the symbol of φ and q, we define φ and q are as positive value when the velocity direction is on the left of sight direction. Thus the range of φ and q is [-180°, +180°]. The plane can be divided into advantage, disadvantage and neutral condition according to the value of φ and q theoretically as Fig. 4.

The smaller the value of |φ| and |q| is, the advantage of UCAV is more obvious. In other words, it's much closer for UCAV to execute stern attack. Considering the influence of angle similar to cosine distribution, this paper the function of angle is defined as follow.

$$Y_{angle} = \frac{1}{2}(1 + \cos\frac{|\varphi| + |q|}{2}) \qquad (1)$$

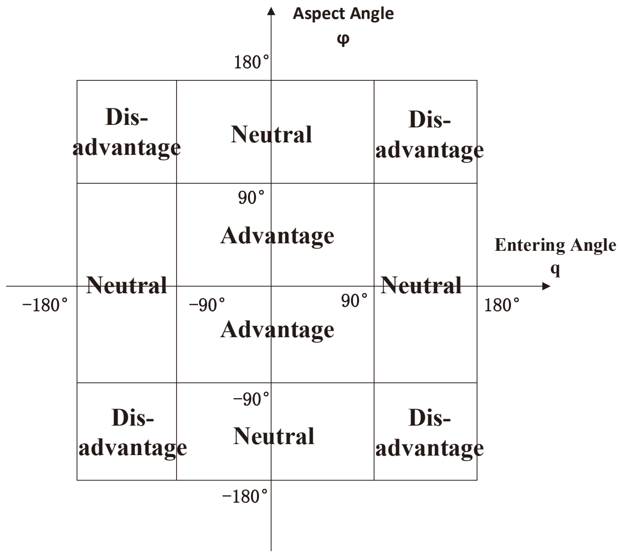

Fig. 4: Situational partition

- Distance Factor

When the distance between UCAV and target aircraft is relatively far, the effect caused by angle will reduce significantly and the condition will turn into more neutral. So we must revise the angle function with distance as follow：

$$Y_g = \frac{1}{2} + (Y_{angle} - 0.5)\max(0, \frac{10R_0 - |R|}{9R_0}) \qquad (2)$$

Therein, R_0 is the boundary of close-range and beyond-visual-range aerial combat and R is the actual distance between UCAV and target. Equation 2 takes both angle and distance into account and is called function of geography.

- Energy Factor

Customarily, we use energy height denoted H_E to describe the kinetic and potential energy of aircrafts.

$$H_E = H + \frac{V^2}{2g} \qquad (3)$$

The energy height represents the mechanical energy of aircraft without the impact of quality. Generally speaking, one will have more advantage when possessing higher energy. The energy ratio of UCAV and target is used to define the energy function as follow：

$$k = \frac{H_{E,UAV}}{H_{E,Target}} \qquad (4)$$

$$Y_E = \begin{cases} 1, & k \geq 2 \\ 0.5 + \frac{1}{3}(k - \frac{1}{k}), & 0.5 < k < 2 \\ 0, & k \leq 0.5 \end{cases} \qquad (5)$$

Equation 5 shows that one will occupy absolute advantage when its energy is twice as the other's at least and the value of energy function is 1. When the ratio is between 0.5 and 2, a simple fitting is adopted using three points (0.5, 0), (1, 0.5), (2, 1).

The values of advantage function above all vary from 0 to 1 and 0.5 refers to neutral. The larger the value is, the advantage of UCAV is much more obvious. Finally, considering the three factors discussed above, we use a comprehensive advantage function to execute the situation assessment as follow:

$$Y = \omega_g Y_g + \omega_E Y_E \tag{6}$$

Therein, ω is the weight of geography and energy while the sum of the weight is 1. Similarly, 0.5 refers neutral and UCAV will occupy advantage if the value is larger than 0.5.

4.3.2 Establishing of Mission Library

Several missions[13] like air-superiority, ground-attack, reconnoiter, searching, transportation and electronic warfare can be executed by MUCE. We conclude these missions into two classifications named combatant missions and non-combatant missions. Mission library established up to now is showed as Table 1.

Table 1: Mission library

Classification		Name	Describing
Combatant missions	Advantage	Attack	Follow the target and attack directly
		Intercept	Intercept target when occupying absolute advantage
	Neutral	Sneak	Execute silence attack when undetected
	Disadvantage	Avoiding	Escape quickly through high maneuver
		Back striking	Go around to execute antitracking
Non-combatant mission		Reconnoiter	Reconnoiter the specific area
		Searching	Searching the specific area

4.3.3 Establishing of Maneuver Library

Principle of adapting mission requirements must be kept to when designing the maneuver library. In actual aerial combat, each maneuver has its own distinct tactical significance while it's not difficult for executing. It's important to point out that several parameters have been defined for each maneuver so that even one maneuver can realize different trajectories. For example, the symbol of turning angular velocity represents turning left or right and the symbol of flight-path slope angle represents climbing or diving. According to related references, maneuver library is showed as Table 2. It's important to point out that there is still some space to improve the library.

Table2: Maneuver library

No.	Name	Parameter 1	Parameter 2	Parameter 3	Significance
1	Line	Course angle	Slope angle	Acceleration	Changing of position and velocity
2	Turning	Turning angular velocity	Slope angle	Acceleration	Changing of heading
3	Barrel roll	Intensity			Dodging
4	Flip	Vertical overload	Slope angle of flip plane		Dodging
5	Course	Waypoint 1	Waypoint 2	Distance	Tracking the course
6	Formation	Azimuth angle	Distance	Height difference	Formation with manned aircraft
7	Pursuit	Tracking angle	Velocity		Tracking target
8	Approach	Tracking angle	Distance threshold	Velocity	Approaching target
9	Circling	Central point	Radius	Velocity	Waiting
10	Coverage	Central point	Area size		Searching

4.3.4 Setting of Maneuver Parameters

In the maneuver library, every parameter has its own actual physical meaning. We only state several parameters used in our simulation. For the course maneuver, parameter distance means the parallel space from the course. For the formation maneuver, the position of UCAV is determined through the three parameters. Parameter tracking angle is used to distinguish pure pursuit, lead-angle pursuit and lag-angle pursuit. This paper we choose pure tracking in our simulation. For the circling maneuver, as level circling with a constant speed is assumed, the angular velocity can be easily calculated according to equation: $\omega = V / r$.

4.3.5 Designing of Maneuver Chain

A maneuver chain consists of several maneuvers from maneuver library of UCAV and each mission corresponds to a maneuver now, perhaps multiple chains will be designed with the further research of UCAV. For a maneuver chain, it's equally important to design the sequence as well as switching conditions. Next we will take three missions from mission library as example to explain how to execute a maneuver chain and switch between maneuvers.

First in the searching mission, circling, course and coverage maneuvers are included. UCAV executes circling maneuver waiting for commands from pilots. Then UCAV utilizes course maneuver to reach optimal entry point and set adequate waypoints to finish the mission. Here we only discuss rectangle region and design a 'Z' path to search in the area. Different entry points will be simulated later.

Table3: Maneuver chain of searching

Mission	Maneuver	Describing	Switch conditions
Searching	Circling	Waiting	——————
	Course	Reaching entry point	Receiving commands

	Coverage	Searching	Distance from waypoints

Second in the sneak mission, formation, approach, course and pursuit maneuvers are included. The formation maneuver determines the position of UCAV and then UCAV try to approach the target in the condition of undetected. Last UCAV flies following the target and attacks it.

Table4：Maneuver chain of sneak

Mission	Maneuver	Describing	Switching conditions
Sneak	Formation	Waiting	——————
	Approach	Approaching	Receiving commands
	Course	Keeping distance and approaching	Less than threshold value of approaching
	Pursuit	Pure pursuit	Passing by the target

Last in the back striking mission, formation, flip and pursuit maneuvers are included. Similarly, formation is used for waiting commands. As target is following the UCAV, UCAV needs to execute flip to avoid the attack of target. And then if condition allows, UCAV will strike back.

Table5：Maneuver chain of back striking

Mission	Maneuver	Describing	Switching conditions
Striking back	Formation	Waiting	——————
	Flip	Dodging	Receiving commands
	Pursuit	Striking back	Falling behind the target

5 Simulation

The three missions and chains discussed above will be simulated in this chapter.

First in the searching mission of UCAV, we design two areas at different position to test and verify that UCAV has the ability to choose the optimal entry point. The trajectories of UCAV are given as Fig 5 and 6. From the figures we find out that the path of circling and coverage maneuvers can fulfil the requirements excellently.

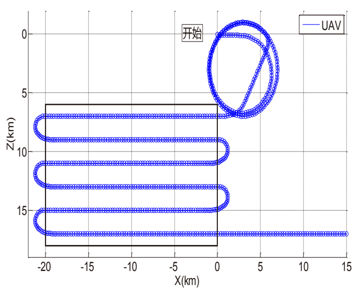

Fig. 5: Trajectory of coverage mission 1

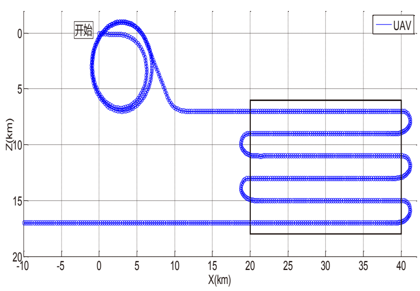

Fig. 6: Trajectory of coverage mission 2

Next two combatant missions named sneak and back striking within neutral and disadvantage conditions are simulated. In sneak mission, UCAV and target fly face-to-face at initial time and the value of assessment function are all near to 0.5. In back striking missions, UCAV is exposed in front of target and UCAV is in danger. Trajectories of UCAV and target are showed in Fig 7 and 8.

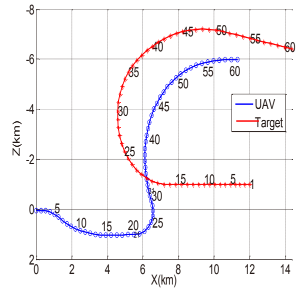

Fig. 7: Trajectory of sneak mission

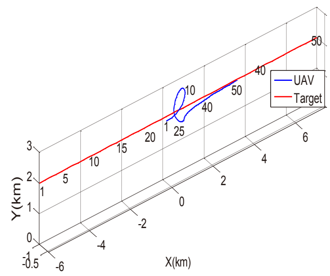

Fig. 8: Trajectory of back striking mission

From Fig 7 and 8 we can see that UCAV executes the specific maneuver chain. In Fig 7, approaching maneuver is executed in the first 10 seconds and the next 15 seconds is course maneuver, last is the pursuit maneuver. In Fig 8, flip and pursuit maneuvers are nearly switched at 25s.

Besides, the value of situation assessment functions is showed in Fig 9 and 10. From the figures, we can find out that UCAV losses some energy but get the angle advantage in return. The red line shows that UCAV occupies much more advantages at last.

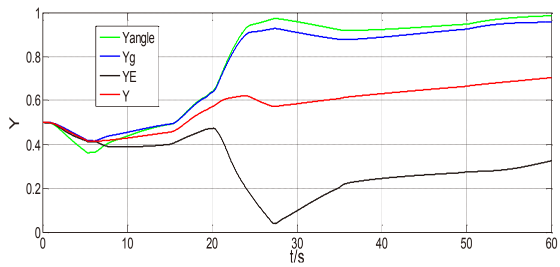

Fig. 9: Situation assessment of sneak mission

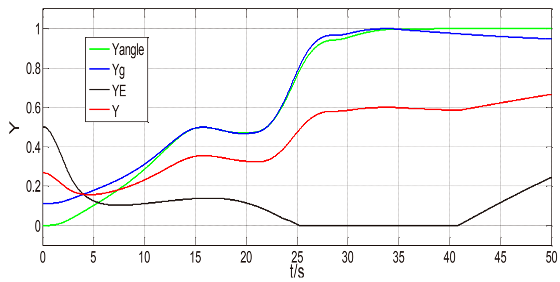

Fig. 10: Situation assessment of back striking mission

6 Conclusion

In this paper, we propose that the manned/unmanned integrated system is effective in executing appointed missions. Results of simulations show what pilots need to do is choosing an optimal mission and the rest is done by UCAV automatically. Flight trajectories of the UCAV demonstrate that UCAV can execute maneuver sequences as designed previously.

According to the variation of situation function value, UCAV can occupy some advantages no matter in neutral or disadvantageous conditions. That is to say, missions designed in this paper can be performed well by the hierarchical decision-making system.

Indeed, there are still some deficiencies existing in the method. The mission and maneuver libraries need to be supplemented and improved. Thus, the maneuver chains might be redesigned as well. Finally, the situation assessment functions should be improved over the precision and practicality.

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