

## Hierarchical Model and Evaluation Method for Autonomy Levels of Unmanned Platforms

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**Abstract:** In order to evaluate the autonomy levels of Unmanned Platforms, A new hierarchical model for autonomy levels of unmanned platforms and a new evaluation method are provided. Firstly, human interface, situational awareness, environmental adaptation and decision-making of an unmanned platform are determined as four indicators applied to evaluate the autonomy levels. Secondly, evaluation method is used to quantify the four indicators. Finally, the average of the four indicators is the value on behalf of the autonomy level. The new model has been applied to judge the autonomy level of Global Hawk USA, Red FlagHQ3 UGV and Spartan Scout USV. The results show that the four indicators are comprehensive and visualized, and the evaluation method is simple.

**Key words:** Autonomy level, evaluation method, hierarchical indicators, unmanned platform

### INTRODUCTION

With the development of computer and communication technologies, the complexity and automation degree of unmanned platforms is increasing day by day. The highly dynamic, uncertainty and the complexity of mission and flight conditions of application environment reveal that the autonomy level has become a new challenge faced by unmanned platforms (Yang and Zhang, 2009). At present, many countries have struggled for years to research the autonomy levels of unmanned platforms. However, the restrictions of the technical level and some other conditions prove that it is impossible for unmanned platforms to achieve the full autonomy without the person's supervision. Therefore, it is imperative to establish a hierarchical model for autonomy levels of unmanned platform. The correct assessment of the autonomy level will make unmanned platforms complete the task efficiently and timely, and in the process of accomplishing the task, the cost is the lowest and the reliability is the highest.

Los Alamos uses mobility, acquisition, and protection to measure the autonomy level of unmanned platforms, but the metrics do not address operational characteristics of unmanned platforms and not show the difference among different autonomy levels (Clough, 2002); Charles Stark Draper utilizes mobility control, task planning and situational awareness to describe the autonomy level of unmanned platforms (Cleary *et al.*, 2000), however, task planning isn't a prerequisite to the autonomy, it is just the reaction to complicated situations. Situational awareness is only based on the number and information fusion of sensors, which does not reflect whether the unmanned platforms have understood what's going around the environment or not. The ALFUS identifies that the

autonomy levels for unmanned platforms must be characterized through the following three perspectives: the missions that the UMS is required to perform or is capable of performing, in the kinds of environments, and with the levels of human interaction (Huang *et al.*, 2003a,b). They devise a three-axis representation for the concept (Huang *et al.*, 2005a,b). Each axis is elaborated with a set of metrics. But this method is not directly measure the autonomy levels of unmanned platforms, only by determining the relationship between external and unmanned platform to measure the autonomy, is not reliable. For instance, an unmanned platform is remotely controlled for a very complex mission in a very difficult environment, but we can't warrant that its autonomy level is high enough (Huang *et al.*, 2004a,b). Metrics for each axis and the weight distribution are also ill-founded. As a result, this paper presents a new hierarchical model and evaluation method for autonomy levels of unmanned platforms.

### METHODOLOGY

**Hierarchical model:** The hierarchical model consists of two components: indicator model and level model. The Indicator model is elaborated with a set of indicators determining the autonomy level of unmanned platforms. The level model is the short description of each autonomy level.

#### Indicator model:

**The indicator model includes four kinds of hierarchical indicators:** human interface, situational awareness, environmental adaptation and decision-making.

**Human interface includes four sub-indicators as following:**

**Operator control time:** in the process of performing mission, the longer the operator controls the platform, the lower the platform's autonomy level is. Accordingly, the points on behalf of operator control time are much lower. Full points are 100. For example, when performing a mission, half of the time is controlled by operators, then this sub-indicator can get 50 points. If the operators don't need to participate in the process all the time, then this sub-indicator can get 100 points. The points are determined by people and not calculated by mathematical formula. Therefore, the points are subjective:

- **Operator control number:** the more number of platforms an operator controls, the higher the platform's autonomy level is, and this sub-indicator will get higher points.
- **Operator skill level:** the operators' skill level indirectly reflects the autonomy level for unmanned platforms. The division criteria for skill level are the operators' qualifications in this paper.
- **Operator workload:** this workload mainly refers to the focused intensity of an operator during the controlling time.

Situational awareness includes four sub-indicators as following:

- **Attack type:** the type of attacker mainly includes aerial (UAV), ground (UGV), underwater (UUV), surface (USV), etc. The more types an unmanned platform identifiers, the higher points the sub-indicator gets.
- **Attack frequency:** it mainly relates to the number of perceiving and getting away from attackers in a fixed period of time.
- **Attack risk index:** it relates to the ability of perceiving dangerous degree of the attacker.
- **Reaction time:** it relates to the time of perceiving danger of unmanned platforms. The shorter the reaction time is, the higher points the unmanned platform gets.

Environmental adaptation includes three sub-indicators as following:

- **Environment type:** the more types an unmanned platform can adapt to, the higher points the sub-indicator gets.
- **Adaptation time:** it relates to the time of adapting to different natural environments. The shorter the adaptation time is, the higher points the unmanned platform gets.

- **Adaptation scope:** it relates to the scope of natural environment perceived by an unmanned platform.

Human interface includes five sub-indicators as following:

- **Attack type:** this sub-indicator is mainly used to evaluate the ability of real-time diagnosing the health of unmanned platforms, especially in the process of performing missions.
- **Fault self-repair:** it relates to the ability of unmanned platform solving faults when the faults occur.
- **Path planning:** it relates to the ability of dynamic path planning and re-planning of the unmanned platform when unexpected states occur in the process of performing missions (Chen, 2007).
- **Task planning:** it relates to the ability of dynamic task planning and re-planning of the unmanned platform when unexpected states occur in the process of performing tasks.
- **Cooperation:** when a variety of unmanned platforms collaborate to complete the common task, there are many unexpected states in perception, performance, communication, etc. Therefore, how to realize the high-level autonomy collaboration among the unmanned platforms and complete the task assigned as well efficiently is quite important.

**Level model:** The general development trend of unmanned platforms is remote control-semi-autonomously fully autonomous (Gao *et al.*, 2007). So the level model is divided into three levels according to the development trend, namely, remote control, semi-autonomy and full autonomy. Each level is described a range of scores. The full scores are 100 points.

Remote control presents that unmanned platforms only operate according to a predetermined program. The software can only deliver the perception data to the operator for processing and not identify and understand the situation of the environment. The unmanned platform doesn't have access to decision-making. The perception tools and computing tools in hardware are primary and only perform the most basic functions and no weapons carrying capacity.

Semi-autonomy demands that unmanned platforms can realize autonomy in some functions. The software can distinguish between static and dynamic environment, identify weather conditions, understand operate environment, summarize the current status of the flight and the environment, perceive the current health status and have the basic weapons carrying capacity. The predetermined program can be changed partly to meet the current unexpected conditions; Hardware perception tools

and computing tool have also reached the medium level and can support to run more advanced autonomous software.

Full autonomy demands that unmanned platforms can realize autonomy in all of the functions. The software can not only distinguish between the external and internal environment, but also realize resources reorganization and the real-time planning of paths and tasks in order to make the current state of an unmanned platform achieve optimal. The hardware can support the complexity, high-level autonomous program.

**Evaluation method:** The evaluation method is used to quantify the four indicators of an unmanned platform, and gets the value on behalf of the autonomy level. Fuzzy comprehensive evaluation is the main core in the evaluation method. There are four kinds of indicators, so this paper just takes the quantitative process of uman interface indicator for example.

**Factor set U:**

The factor set of sub-indicators of human interface as follows:

$$U_1 = (\text{Operator control time, Operator control number, Operator skill level, Operator workload}) = (u_{11}, u_{12}, u_{13}, u_{14})$$

**Evaluation set V:**

$$V = (\text{remote control, semi-autonomy, full autonomy}) = (v_1, v_2, v_3)$$

In this study, the levels of autonomy are separately remote control, semi-autonomy, full autonomy. The highest scores of remote control are 20 points. The highest scores of semi-autonomy are 60 points. The highest scores of full autonomy are 100 points. Each level score is written in vector  $Q = (20, 60, 100)$ .

**Weight vector W:** This study uses the Analytic Hierarchy Process (AHP) to calculate the weight of each sub-indicator of uman interface

**Construct judgment matrix A:** Because the sub-indicators of uman interface have been given different points, the pairwise comparison method is used to establish the judgment matrix  $A_1$  of uman interface according to the different points.

$$A_1 = \begin{bmatrix} 1 & a_{12} & a_{13} & a_{14} \\ 1/a_{12} & 1 & a_{23} & a_{24} \\ 1/a_{13} & 1/a_{24} & 1 & a_{34} \\ 1/a_{14} & 1/a_{24} & 1/a_{34} & 1 \end{bmatrix} \tag{1}$$

$a_{ij}$  is the relative importance of the  $i$  indicator compared with the  $j$  indicator. The value of  $a_{ij}$  is generally a positive integer 1-9 (called scale) or their inverse.

If there is an unmanned platform, the scores of “operator control time  $u_{11}$ ” are subjective given 50 points; the scores of “operator control number  $u_{12}$ ” are 25 points; the scores of “operator skill level  $u_{13}$ ” are 35 points; the scores of “operator workload  $u_{14}$ ” are 45 points. According to the value rules of  $a_{ij}$ ,  $u_{11}$  compared with  $u_{12}$  is obviously important, then  $a_{12} = 5$ ;  $u_{11}$  compared with  $u_{13}$  is slightly important, then  $a_{13} = 3$ ;  $u_{11}$  compared with  $u_{14}$  is not slightly important enough, then  $a_{14} = 2$ .

**Calculate the weight W:** The steps of calculating the weight as follows:

- Normalizing the column of the judgment matrix

$$A_{ij} = \left( \frac{\alpha_{ij}}{\sum_{i=1}^n \alpha_{ij}} \right)$$

- Summing the elements of each row of  $A_{ij}$ :

$$W = \left( \frac{\sum_{j=1}^n \frac{a_{1j}}{\sum_{i=1}^n a_{ij}}, \sum_{j=1}^n \frac{a_{2j}}{\sum_{i=1}^n a_{ij}}, \dots, \sum_{j=1}^n \frac{a_{nj}}{\sum_{i=1}^n a_{ij}}}{\sum_{j=1}^n \sum_{i=1}^n \frac{a_{ij}}{\sum_{i=1}^n a_{ij}}} \right)^T \tag{2}$$

After the normalization of  $w$ , the weight vector can be got that.

$$W = (w_1, w_2, w_3, \dots, w_n) \tag{3}$$

The weight can change with the scores of each sub-indicator of “human interface”.

**Membership matrix R:** The results that each indicator in the factor set  $U_1 = (u_1, u_2, \dots, u_n)$  is measured by each element in the evaluation set  $V = (v_1, v_2, v_3)$  constitute the membership matrix  $R$ .

$$R = \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{22} & \dots & r_{2n} \\ \dots & \dots & \dots & \dots \\ r_{m1} & r_{m2} & \dots & r_{mn} \end{bmatrix} \tag{4}$$

$r_{ij}$  is the result that the  $j$  indicator measured by the  $i$  element.

Each indicator is given a subjective score. Therefore, in the paper, membership functions are constructed to calculate the membership that the indicator belongs to every autonomy level according to the subjective scores ( $0 \leq x \leq 100$ ). The different scores result that the indicator’s membership will also be different.

The membership function that  $x$  belonging to remote control:

$$C_1(x) = \begin{cases} \frac{80-x}{80}, & 0 \leq x < 80 \\ 0, & x \geq 80 \end{cases} \quad (5)$$

The membership function that  $x$  belonging to semi-autonomy:

$$C_2(x) = \begin{cases} 0, & 0 \leq x < 10, x \geq 90 \\ \frac{x-10}{40}, & 10 \leq x < 50 \\ \frac{90-x}{40}, & 50 \leq x < 90 \end{cases} \quad (6)$$

The membership function that  $x$  belonging to full autonomy:

$$C_3(x) = \begin{cases} 0, & 0 \leq x < 20 \\ \frac{x-20}{80}, & x \geq 20 \end{cases} \quad (7)$$

For example, the sub-indicators of human interface have been given the score subjectively. The scores of “operator control time  $u_{11}$ ” are given 50 points, then:

$$r_{11} = C_1(x) = C_1(50) = 0.375 \quad (8)$$

It shows that when “operator control time  $u_{11}$ ” is given 50 points, the membership that the sub-indicator belongs to remote control is 0.375:

$$r_{12} = C_2(x) = C_2(50) = 1 \quad (9)$$

It shows that when “operator control time  $u_{11}$ ” is given 50 points, the membership that the sub-indicator belongs to remote control is 1:

$$r_{13} = C_3(x) = C_3(50) = 0.375 \quad (10)$$

It shows that when “operator control time  $u_{11}$ ” is given 50 points, the membership that the sub-indicator belongs to remote control is 0.375.

As a result, the membership vector of “operator control time  $u_{11}$ ” is:

$$r_1 = (r_{11}, r_{12}, r_{13}) = (0.375, 1, 0.375) \quad (11)$$

**Fuzzy decision B:** Using the membership matrix  $R_1$  and weight vector  $W_1$  that have calculated to make 1-level fuzzy transformation to get the decision set  $B_1$  (Luo *et al.*, 2010) that the membership vector of human interface belonging to evaluation set  $V$ :

$$B = W \cdot R = (b_1, b_2, b_3) \quad (12)$$

Table 1: Score of each indicator of global hawk

Hierarchical indicators	Scores ( $0 \leq x \leq 100$ )
Operator control time $u_{11}$	50
Operator control number $u_{12}$	25
Operator skill level $u_{13}$	35
Operator workload $u_{14}$	45

The final scores of human interface are:

$$S_1 = B \cdot Q = (b_1, b_2, b_3) \cdot (20, 60, 100) \quad (13)$$

Similarly, the final scores of situational awareness  $S_2$ , environmental adaptation  $S_3$  and decision-making  $S_4$  can be got.

### EXAMPLE OPERATION

The new model has been applied to judge the autonomy level of Global Hawk USA, Red FlagHQ3 and Spartan Scout USV. Take the calculating process of Global Hawk USA for example. Table 1 is the subjective score of each indicator of Global Hawk.

According to the above quantitative process of human interface indicator and the score of each indicator of Global Hawk, the final quantitative scores of the four indicators of Global Hawk can be got.

The final score on behalf of autonomy levels of Global Hawk is the average score of human interface situational awareness environmental adaptation and decision-making

The scores of the four indicators of Global Hawk as follows:

- The score of human interface indicator is 32.85
- the score of situational awareness indicator is 57.22
- the score of environmental adaptation indicator is 47.15
- the score of decision-making indicator is 40.15
- The final score on behalf of autonomy level of Global Hawk is 40.15

In the United States UAV road map, the autonomy level of Global Hawk is 2 to 3 (Unmanned Aircraft System Roadmap, 2005-2030). This autonomy level reveals that Global Hawk has achieved adapting to failure and flight conditions. But the (Autonomy Control Level) ACL doesn't provide that unmanned platforms how to achieve the autonomy level and how to quantify the fuzzy indicators. The new model can just solve the defects of ACL. As a result, the new model is more convenient in practice.

Similarly, the scores of the four indicators of Red FlagHQ3 UGV as follows:

- The score of human interface indicator is 85.32
- The score of situational awareness indicator is 67.23
- The score of environmental adaptation indicator is 50.17

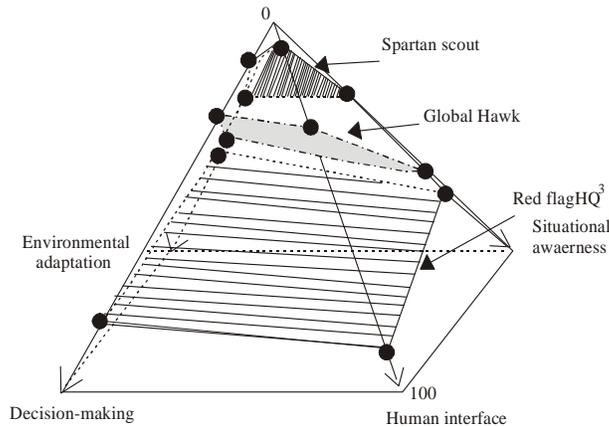


Fig. 1: The autonomy level pyramid chart

Table 2: Level model for unmanned platforms

Autonomy level	Autonomy score
Remote control	[0,20)
Semi-autonomy	[20,60]
Full autonomy	(60,100]

- The score of decision-making indicator is 78.44
- The final score on behalf of autonomy level of Red FlagHQ3 UGV is 70.29

The scores of the four indicators of Spartan Scout USV as follows:

- The score of uman interface indicator is 5.12
- The score of situational awareness indicator is 20.44
- The score of environmental adaptation indicator is 27.58
- The score of decision-making indicator is 9.20
- The final score on behalf of autonomy level of Spartan Scout USV is 15.56

According to the Table 2, the autonomy level of Global Hawk is semi-autonomy; the autonomy level of Red FlagHQ3 UGV is full autonomy; the autonomy level of Spartan Scout USV is remote control.

In order to know the four indicators how to play an impact on the autonomy level of unmanned platforms, the quantitative scores of the four indicators have been marked in the pyramid chart. It is shown in Fig. 1. The top of the pyramid is 0 score, and the bottom of the pyramid is 100 scores. The first shaded layer is the four indicators score of Spartan Scout USV. The second shaded layer is the score of Global Hawk USA. The third shaded layer is the score of Red FlagHQ3 UGV.

### CONCLUSION

A new hierarchical model for autonomy levels of unmanned platforms and evaluation method are constructed in the study. The indicator model in the

hierarchical model not only has the direct indicator, like as “decision-making”, but also has indirect indicator, like as “human interface”. The new mode is not simply using sensors and other devices to identify the environmental conditions, but understand the current environment. External factors can't play a large impact on the evaluation of autonomy level. The fuzzy comprehensive evaluation and AHP are applied to quantify the four indicators and get the scores on behalf of the four indicators. The average of the four quantified scores is the final scores on behalf of the autonomy level. According to the level model, the autonomy level of an unmanned platform can be decided. The new model and method are mainly applied to evaluate the single unmanned platform and not suitable for unmanned platform group. The autonomy level model is not very complicated, and the user can change it according to the practical application. The score of each indicator is decided by the people, and it is subjective and not fixed score.

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