Study on Function Allocation Application in Human-machine System

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***Abstract* — Function allocation is an important part of the human-machine systems discipline. The function allocation screening worksheet (FASW) was researched and applied in the human-machine system. In the FASW, Functions were determined by the analysis of system function flowcharts. Human and machine capabilities based the Fitts list were gotten, and weight of capabilities was calculated through the subjective survey. The result of functions allocation was determined by comparison between evaluation scores for human and machine capabilities. Taking functions in landing phase of aircraft for example, the application of functions allocation was researched by the FASW. The results of function allocation are verified the validity of the FASW. The study of function allocation application could provide the reference for the early design stage of human-machine system.**

Keywords - Function Allocation; Human-machine System; Human and Machine Capabilities; Automation Level

I. INTRODUCTION

In the human-machine system, functions allocation is taken rational distribution to human and machine according to respective strengths and limitations. In the process of function allocation, many factors typically need to be considered, including the abilities of human, the level of automation, design period, costs and others. The results of human-machine functions allocation greatly influence on the system structure and hardware and software technology, directly affect the man-machine interface design of the system. And the allocation results also affect the human to perform a task, relating to the human how to operate to make the whole system efficient, stable and safe [1]. The function allocation of human-machine system has gradually become a problem cannot be ignored. Automation of system can reduce workload and operation of human. However, excessive automation may cause human-dependent enhancement and skills decline. High-level automation would lead system development cost too high. Low-level automation cannot meet system requirements. Therefore, the reasonable function allocation is a core activity of the human-machine system discipline [2].

The function allocation methods of the man-machine are mostly based on a single standard, and the simple prototypes and algorithm. Or the methods are seldom combined with practical engineer application demands. Aimed at these problems, application of function allocation screening worksheet was studied. In the paper, based on detailed analysis of the system function, the capabilities of human and machine, performing the various functions of the system, were objectively assessed. The functions in landing phase of aircraft were allocated by function allocation screening worksheet. And the automation level of the functions was analyzed. The results were verified to reliable by pilots subjective survey. Function allocation screening worksheet is proved to be a quantitative and effective evaluation method of man-machine function allocation.

II. STATE OF THE ART

The concept of function allocation-"the allocation of functions or tasks between the humans and machines in a system" [3]. A variety of functions allocation methods are formed, combining different application background. Paul Fitts (1951) marked the outset of function allocation research with an 11-statements list, including respective advantages of man and machine characteristics [4]. Since then allocation decisions are based on the Fitts list (or HABA-MABA lists-"humans are better at, machines are better at") [5, 6]. Functions or tasks are assigned either human or machine by the abilities, also considering temporal effects, individual differences, safety, economic utility, the evolution of technology, etc. [7, 8]. Otherwise, the level of automaton is researched, considering functions allocation between human and automation [9~12]. Levels of automation have been explored as binary function allocations. This approach allows comparing levels of automation in a standardized manner and potential costs and benefits are considered as a function of automation. Level of automation is divided into ten consecutive rank in the process of tasks allocation [9, 15]. And the impact of automation reliability on human performance has been studied [13~16]. However, evidence of the anticipated benefits with automation is limited [17, 18]. And automation changes the nature of human work, often in ways unanticipated by designers [2, 19, 20].

The remainder of this paper is organized as follows: Section 3 describes the methodology of the function allocation screening worksheet and the application of the method. Section 4 presents the analysis and discussion of the result of the method application. Section 5 summarizes the conclusions.

III. METHODOLOGY

In the process of human-machine system design, function allocation should be carefully considered at the earliest design stages of system [21, 22]. The function allocation screening worksheet (FASW) based on Fitts list is adopted in the early stage. The evalution value of human-machine capabilities by FASW can be used not only in the early design, but in improvement of system by the modifying evaluation criteria. The concrete application steps of this method are given as following.

3.1 The function allocation screening worksheet

When using the method of function allocation screening worksheet, the first step is to establish function allocation screening worksheet. The function allocation screening worksheet established shall be the same as the example, shown in Table 1. Function allocation screening worksheets are constructed by listing each of the several functions to be allocated on the left side of the worksheet. Two sets of evaluation criteria are listed across the top of the sheet. The first set pertains to human capabilities; the second set pertains to machine capabilities. Each capability of human-machine is determined through the experts (such as designers and pilots) investigation based on the Fistts list [4].

TABLE I FUNCTION ALLOCATION SCREENING WORKSHEET

Function	The capability of human(1)	The capability of human (2)	…	The capability of machine (1)	The capability of machine (2)	…	Total score		Result of allocation			
							human	Machine	human	Machine	Both	Automation level
Sub-function1												
Sub-function2												
…												

The overall process of human-machine function allocation is shown in Figure 1.

3.2 Weight of human and machine capabilities

Weight of human and machine capabilities is the key core of function allocation screening worksheet. With the function allocation screening worksheet, the capability needs to be taken tradeoff evaluation, obtaining the importance order of capability. Weight of the capability is the importance or the position in all capabilities, and expresses the relationship between the capabilities. The reasonable weight of capabilities is the key to the quantitative evaluation of human-machine function allocation. In the paper, the weight was determined by the relative important degree of the human and machine capabilities. The method of G_1 was adopted [23].

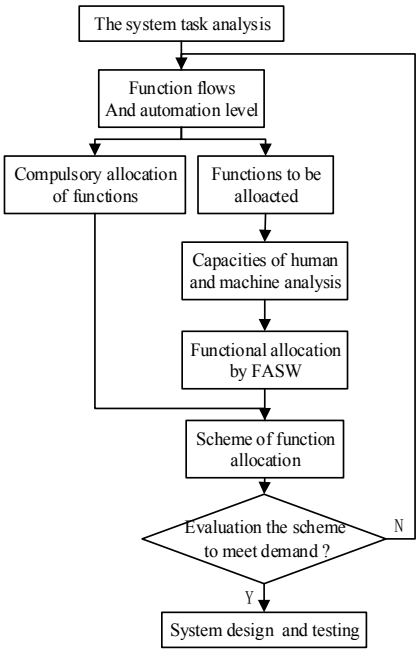

Figure 1. The overall process of human-machine function allocation

The weight of capabilities of human and machine was calculated by the method of G_1. If the degree of relative importance of capability c_i is greater than the c_j, denoted by $c_i \succ c_j$.

If capabilities c_1, c_2, …, c_n have relation

$$c_1^* \succ c_2^* \succ ... \succ c_n^* \tag{1}$$

, then the order relation is established between capabilities c_1, c_2, …, c_n according to "$\succ$". c_i^* expresses the i-th capability of $\{c_i\}$ according to the order relation ($i = 1, 2, ..., n$).

Let the ratio of the degree of importance of c_{k-1} and c_k is w_{k-1} / w_k

$$w_{k-1} / w_k = r_k,\ k = n, n-1, n-2, ..., 3, 2 \tag{2}$$

The reference value of r_k is shown in the table 2 [23].

TABLE II THE REFERENCE VALUE OF r_k

r_k	Description
1.0	Index u_{k-1} and Index u_k equal importance
1.2	Index u_{k-1} is slightly more important than index u_k
1.4	Index u_{k-1} is obviously more important than index u_k
1.6	Index u_{k-1} is strongly more important than index u_k
1.8	Index u_{k-1} is extremely more important than index u_k

Based on the value of r_k , the weight w_i of the u_i is calculated by using formula (2) and (3). The weight of $\{c_1, c_2, ..., c_n\}$ is also calculated.

$$w_n = (1 + \sum^{n} \prod^{n} r_i)^{-1} \tag{3}$$

$$w_{k-1} = r_k w_k, k = n, n-1, n-2, ..., 3, 2 \tag{4}$$

3.3 The results of functions allocation

The actual evaluation is made by totaling each of the weighted for the human versus machine allocation. The allocation result is determined by the human score(S_H) and machine score(S_M). The results of the allocation are tabulated in the far right-hand columns as either "human", "both", or "machine". Based the situation awareness model proposed by Endsley [24], the function is divided to perception, decision making and execution. The level of automation is showed in table 3. The appropriate level of automation was determined by the total score of human and machine. Finally, the various evaluation schemes of human-machine function allocation were proposed.

TABLE III THE LEVEL OF AUTOMATION

	Level	Description
Perception	5	The system automatically get the information, without telling the human
	4	The system automatically get the information, and if necessary to provide the human
	3	The human is prompted to view important information display by the system
	2	The important information is provided to the human
	1	The human own view the flight information
Decision making	5	The system automatically makes decision, without the human
	4	The system provide the results to the human, and provide process and reason when the human need
	3	The human and system commonly make decision
	2	The human own makes decisions. And the advice is provided by the system when human need
	1	The human own makes decisions. The system does not interfere
Execution	5	The system automatically executes, without the human
	4	The system only provides the implementation process and results when the human needs
	3	The system provides for human selection procedure, and the system may intervene
	2	The human and the system perform operations, which is triggered by the human
	1	The Humans executes all operation procedure , the system does not participate

The evaluation value of human and machine capabilities through pilots survey is

$$V_H = \begin{bmatrix} V_{H_{11}} & V_{H_{12}} & \cdots & V_{H_{17}} \\ V_{H_{21}} & V_{H_{22}} & \cdots & V_{H_{27}} \\ \cdots & \cdots & \cdots & \cdots \\ V_{H_{i1}} & V_{H_{i2}} & \cdots & V_{H_{i7}} \end{bmatrix}$$

$$V_M = \begin{bmatrix} V_{M_{11}} & V_{M_{12}} & \cdots & V_{M_{17}} \\ V_{M_{21}} & V_{M_{22}} & \cdots & V_{M_{27}} \\ \cdots & \cdots & \cdots & \cdots \\ V_{M_{i1}} & V_{M_{i2}} & \cdots & V_{M_{i7}} \end{bmatrix} \tag{5}$$

i represents the number of functions, i=1,2,…,n.

The score of human capabilities S_H of FASW is calculated.

$$S_H = V_H w_H^T \tag{6}$$

The score of machine capabilities S_M of FASW is calculated.

$$S_M = V_M w_M^T \tag{7}$$

IV. RESULT ANALYSIS AND DISCUSSION

In this section, to illustrate the application of function allocation screening worksheet in the man-machine system, the paper analyzed allocation of function in the process of landing. And the function of landing was taken as an example.

The principles of the function allocation are considered to follow. The limit of human and machine ability is determined. And functions must be automated, which must be mandatorily controlled by the people. The other functions are allocated by function allocation screening worksheet. According to the pilot ability, automation level, reliability, and research cycle, the basic principles of the allocation were determined:

(1)The essential function, affecting the flight safe, should be allocation to both human and machine. The human control backup was provided, in addition to the automation system.

(2)The workload of human was considered in the process of function allocation. Human was ensured to have enough time, suitable ability and guarantee condition to complete the function in the system.

4.1Function allocation screening worksheet (FASW) of the landing

For establishing the FASW, two works may be taken. One is to ensure the functions in the FASW by analyzing the task of the landing. The other is to select suitable capacities of human-machine needed in the process of the landing.

Function flowchart are generally used to function analysis. When establishing the function flowcharts of the system, the descent is one of the first-level functions of system. To analyze the process of the descent, the second-level functions of the descent were the fourth turn, decline, landing, and so on. In the function flowcharts, the number means the relationship of the functions and the position (see Fig. 2 and Fig. 3).

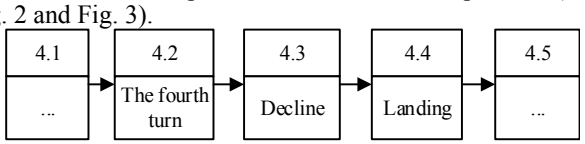

Figure 2. The function flowchart of the descent

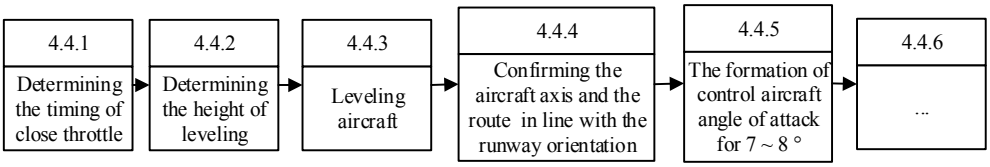

Figure 3. The function flowchart of landing

By analyzing the capacities of the human-machine maybe using in the system based on Fitts list, the capacities of human are as follow:

- Detecting signal in noise and vibrating environment (H_1);
- Sensitivity to an extremely wide variety of stimuli (H_2);
- Ability to perform fine manipulations, especially where misalignment appear unexpected (H_3);
- Performing from experience (H_4);
- Inferring the process of the task by the ability to reason inductively (H_5);
- Handling unexpected occurrences or low-probability events (H_6);
- Carrying out the task in advance during the process (H_7).

The capabilities of the machine are as follow:

- Responding very quickly to control signals (M_1);
- Storing and recalling large amounts of information in short time-periods (M_2);
- Performing complex, repetitive, or very precise operations (M_3);
- Not feel fatigue by working long hours (M_4);
- Ability to repeat operations very rapidly over a long period (M_5);
- Doing many different things at one time (M_6);
- Exerting large amounts of force smoothly and precisely (M_7).

In the investigation, 20 experts, including pilots and designers of airplane, were selected in the investigation. The duty of the pilots is commander.

First, weight of capabilities was surveyed. Based on the system functional requirements, the subjects ordered all the capabilities according to the importance. The judgment of importance was determined by comparing the adjacent capabilities in the new order, including equal importance, slightly more important, obviously more important, strongly more important and extremely more important. And then, on the basis of the importance of the evaluation capabilities, the scale (1~5, 1 represents unimportant. 5 represents the most important) was selected to fill in the FASW. After completion of the investigation, the twenty questionnaires are valid.

4.2 The calculation of capabilities weight

The weight of capabilities of human and machine was calculated by the method of G_1 .

The order relation and the value r_k of the human capabilities is shown in the table 4.

The order relation and the value r_k of the machine capabilities is shown in the table 5.

TABLE IV THE ORDER RELATION AND THE VALUE r_k OF HUMAN CAPABILITIES

	Order relation	The ratio of the importance					
		r_2	r_3	r_4	r_5	r_6	r_7
1	$O_6 \succ O_3 \succ O_7 \succ O_5 \succ O_2 \succ O_4 \succ O_1$	1.8	1.2	1.0	1.0	1.2	1.4
2	$O_6 \succ O_2 \succ O_7 \succ O_5 \succ O_3 \succ O_1 \succ O_4$	1.6	1.0	1.4	1.0	1.6	1.0
…	…	…	…	…	…	…	…
19	$O_2 \succ O_6 \succ O_3 \succ O_5 \succ O_4 \succ O_7 \succ O_4$	1.0	1.0	1.4	1.4	1.4	1.0
20	$O_6 \succ O_2 \succ O_3 \succ O_7 \succ O_5 \succ O_1 \succ O_4$	1.0	1.2	1.2	1.2	1.4	1.4

TABLE V THE ORDER RELATION AND THE VALUE r_k OF MACHINE CAPABILITIES

	Order relation	The ratio of the importance					
		r_2	r_3	r_4	r_5	r_6	r_7
1	$O_3 \succ O_1 \succ O_2 \succ O_6 \succ O_7 \succ O_4 \succ O_5$	1.8	1.2	1.0	1.0	1.2	1.4
2	$O_1 \succ O_7 \succ O_4 \succ O_2 \succ O_3 \succ O_5 \succ O_6$	1.6	1.0	1.4	1.0	1.6	1.0
…	…	…	…	…	…	…	…
19	$O_1 \succ O_6 \succ O_2 \succ O_3 \succ O_4 \succ O_5 \succ O_7$	1.0	1.0	1.4	1.4	1.4	1.0
20	$O_1 \succ O_3 \succ O_2 \succ O_4 \succ O_6 \succ O_7 \succ O_5$	1.0	1.2	1.2	1.2	1.4	1.4

The weight of the human's capabilities as follows:

$$w_H = \{w_{H1}, w_{H2}, w_{H3}, w_{H4}, w_{H5}, w_{H6}, w_{H7}\} = \{0.158, 0.180, 0.158, 0.155, 0.136, 0.117, 0.096\}.$$

The weight of the machine's capabilities as follows:

$$w_M = \{w_{M1}, w_{M2}, w_{M3}, w_{M4}, w_{M5}, w_{M6}, w_{M7}\} = \{0.165, 0.167, 0.167, 0.148, 0.135, 0.118, 0.100\}.$$

4.3 The result analysis of function allocation

The result of allocation was estimated by the sums. The results of the allocation are assigned either "human", "both", or "machine". Based on the design cost, technology level and efficiency requirements of system, the result of "both" is determined when the ratio of S_H and S_M of function is greater than 80%. When the ratio is less than 80%, result of function allocation is determined by the higher score. Considering safety risk and cost, the appropriate level of automation was determined by comparing the human-machine capabilities score. The scheme of the functions allocation was proposed. In the paper, the result of the functions allocation in landing is listed in table 6.

TABLE VI THE RESULT OF THE FUNCTIONS ALLOCATION IN LANDING

Function	HC	MC	Result	Level of automation
Determining the time of reducing throttle	3.57	2.78	human	Decision making (level 1)
Determining the altitude of level	3.13	2.31	human	Decision making (level 1)
Confirming the aircraft axis and the route in line with the runway orientation	3.55	3.12	both	Decision making (level 2)
The formation of control aircraft angle of attack for 7 ~ 8 °	3.11	2.40	human	Execution (level 1)
…	…	…	…	…

According to the human-machine capabilities score, sometimes, different automation level of function is determined. The results should be evaluated by the efficiency-cost ratio [25]. The formula for the ratio of the system efficiency (E) and life cycle costs (LCC):

$$R = \frac{E}{LCC} \tag{8}$$

The LCC includes research costs, design costs, initial equipping costs, operational costs and support costs. Scores of LCC and E are evaluated by the experts. The ratio R of the results is calculated by using formula (8). If $R_i > R_j$, the i scheme of function allocation is better than the j scheme. The i scheme is chosen as the result of the human-machine system function allocation.

In the paper, the scheme result of functions allocation of landing by the FASW needs to be analyzed and verified. The scheme was verified by subjective evaluation of 12 pilots on active duty. And the scheme was compared with the actual allocation of the cockpit. The result of evaluation shows that the function allocation screening worksheet is valid.

V. CONCLUSION

In the paper, the FASW was applied to function allocation in the human-machine system. By the method of G_1 , the weight of human and machine capabilities was calculated. The human and machine capabilities of function were evaluated through pilots survey. The result of function allocation was obtained according to the scores of human and machine capabilities of functions. The application result shows that the method of FASW is effective in the process of function allocation of human-machine system. Suggestions of function allocation are proposed in the early design stage of system by using the FASW. The method could assist the

designer to improve the design efficiency and save cost of design.

Further research of the method is required. Because the FASW is a subjective methodology, the individual difference is considered to reduce in the process of investigation. The method is still needed to research in the process of dynamic function allocation.

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