International Journal of Engineering Education Vol. 32, No. 5(A), pp. 2083–2097, 2016
Printed in Great Britain
0949-149X/91 $3.00+0.00
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Marine Engineering Virtual Training and Evaluation System: A Learning Tool for Marine Engineers*

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To improve the application value and range of the traditional marine engine room simulator, a marine engineering virtual training and evaluation system is developed in this paper. Through comparing with the similar applications in the market, advantages of the one developed in this paper are showed. In addition, automatic evaluation function based on fuzzy evaluation method is developed and integrated in the training system, which is able to realize the fixed evaluation items regulated in the seafarers examination outline and the user-defined situation evaluation items by using XML to establish the evaluation question base. To improve the automatic evaluation accuracy, "Least Square Method" is used to fit the fuzzy membership function. At last, to verify the practicability and application value of the learning tool developed in this paper, 60 juniors majored in marine engineering, 10 experienced chief engineers are selected to carry out an experiment. By analyzing the experiment result, it is found that the virtual training system is accepted as a learning tool by the participants and the evaluation score generated by the automatic evaluation module is reasonable and real.

Keywords: engineering education; marine engineers; visual simulation; virtual training; automatic evaluation

1. Introduction

With the development of computer science and technology, the computer-aided education software has achieved satisfactory results in various kinds of the engineering education fields by virtue of its advantages including low cost, high efficiency and safety [1, 2]. In the field of marine engineering education, MERS (Marine Engine Room Simulator), designed as a simulative operation platform, is similar with the real marine engineering system and similar feedbacks can be got by operating the simulative equipment, so for the trainees a lot of working experience can be got within a short time by training with the MERS. In addition, certain training items, which are impossible or forbidden in the real ship, can be carried out and training limiting factors in the real ship such as working condition, navigation area and environmental condition can be overcome by utilizing MERS. Based on the above-mentioned advantages, MERS is widely used in the field of the marine engineering education [3, 4].

At present, the mainstream MERS manufactures and research institutes mainly include Norway's Kongsberg Maritime, England's Transas, Poland's UNITEST and China's Wuhan University of Technology and Dalian Maritime University. To consider the "Neptune" full-mission MERS developed by Kongsberg Maritime as the representative, it is mainly composed of the 2-D simulation software and the physical simulation consoles [5], and most of the training items can be carried out by using MERS. Although the traditional MERS has achieved satisfactory results in the field of marine engineering education, it still has several disadvantages when compared with the real ship and the important one of them is the poor sense of reality. Due to the poor sense of reality, the trainees have no chance to cognize the actual structure and composition of the MER (Marine Engine Room), therefore the application value of the traditional MERS is restricted. To solve this disadvantage, the relevant MERS manufactures and research institutes all have tried to introduce the visual simulation technology into the traditional MERS, which can make the trainees carry out the training in the virtual MER [6, 7]. The introduction of the visual simulation technology makes up the disadvantages of the traditional MERS and improves its application value and range. However, after experiencing and analyzing the existing MERVSS (Marine Engine Room Visual Simulation System), it should still be optimized in several aspects, such as the sense of reality, human-machine interaction content and mode, and auxiliary functions.

In addition, the development purpose of MERS should be not only to cultivate the professional ability of the trainees, but also to evaluate the professional ability. The latest STCW (International Convention Standards of Training, Certification and Watchkeeping for Seafarers) amendment passed by the diplomatic conference held in Manila in 2010 enhanced the related rules of training and certification for the marine engineers by utilizing the MERS and highlighted the role of MERS in the training and evaluation of the marine engineers. At present, the evaluation of the professional ability for

* Accepted 26 June 2016.

the marine engineers is mostly carried out in manual method and it is difficult to form unified evaluation method and standard during the evaluation process. In addition, the evaluation result is determined by the subjective judgment of the coaches largely, which makes it difficult to ensure fair. To solve the above-mentioned problem, relevant scholars and research institutes all have tried to apply the automatic evaluation function to MERS [8–11].

By fully absorbing the advantages and analyzing the disadvantages of the existing relevant MERS and MERVSS, a marine engineering virtual training and evaluation system is developed in this paper.

2. Structure design of marine engineering virtual training and evaluation system

The marine engineering system belongs to a typical large-scale system that is composed of multi-subsystems such as the main propulsion system, fresh water cooling system and fuel supply system. To implement the virtual training and evaluation function, it is necessary to establish objective and accurate math model for the marine engineering system, virtual MER scene with high sense of reality, friendly and convenient human-machine interaction mechanism, and objective automatic evaluation module. As shown in Fig. 1 is the structure of the marine engineering virtual training and evaluation system developed in this paper, which is mainly composed of four parts: math model module of marine engineering system, automatic evaluation module, trainee client module and coach client module. The math model module is in charge of the real-time simulation and calculation of the math model, which is the foundation of the whole system. The automatic evaluation module is in charge of the analysis, inference and judgment of the accuracy, correctness and timeliness for the trainees' practical operation process. The coach client module is in charge of editing the evaluation questions and controlling the running state of the whole system. The trainee client module allows the trainees to operation the marine engineering system in the virtual MER scene.

According to Fig. 1, the real-time simulation data calculated by the math model module of marine engineering system is transferred to the trainee client to update the running state of virtual MER scene, meanwhile, the operation information generated in the trainee client will be transferred back to artificially interpose the math model to make it run from a new state. In the Fig. 1, the SDC (System Data Class) defines the marine engineering simulation data. In view of the great number of simulation data, the simulation data is defined in the form of "Data type + Global identification + Actual physical meaning", the definition format of which makes the tracking and recording process of the evaluation data by the automatic evaluation module more convenient.

3. Marine engineering virtual training and evaluation scene

In recent years, many MERS manufacturers and research institutes all have tried to introduce visual simulation technology into the traditional MERS and corresponding MERVSS is established. Several successful applications can be found in the market, such as the LER3D, MED3D, PSV3D MERS developed by UNITEST [12], the K-Sim MERS by Kongsberg Maritime [13], the ERS 5000 MERS by Transas [14], MAK11 MERS by Maritime Institute Willem Barentsz, Terschelling, and the DMS (Dalian Maritime University Simulation) MERS by the research team where the authors belong to. DMS-AHTS-3D is selected to show the

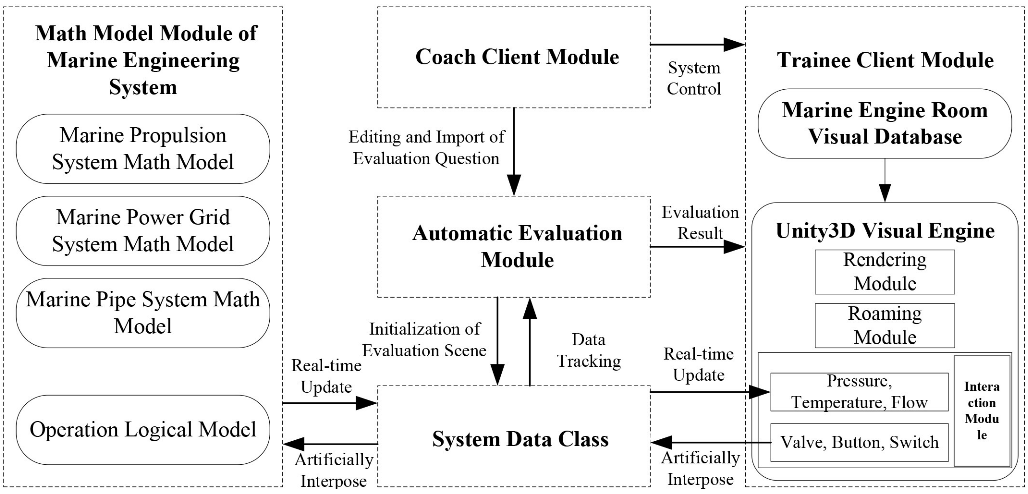

Fig. 1. Structure of the marine engineering virtual training and evaluation system.

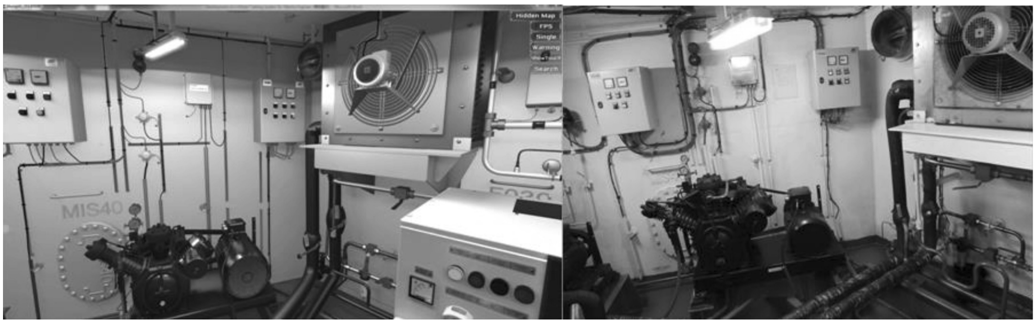

Fig. 2. Comparison diagram between the DMS-AHTS-3D scene and the real scene.

advantages by comparing with the mainstream similar MERVSS.

3.1 Comparison of sense of reality

An important goal of visual simulation technology is to provide the users a virtual scene that is highly in accordance with the real one, so it is necessary to establish a virtual MER scene with high levels of detail and sense of reality. Fig. 2 is the comparison diagram between the real scene and the virtual scene presented by DMS-AHTS-3D. Fig. 3 are the final effects of the virtual MER scene respectively presented by UNITEST, Transas, Kongsberg Maritime and Maritime Institute Willem Barentsz, Terschelling. Through comparison, it can be found that the sense of reality of DMS-AHTS-3D and K-Sim are obviously better than the others are. K-Sim uses hand-drawn maps to express the texture of material and the sense of rust and smudginess, which enhances the sense of reality greatly, but the virtual scene is only composed of certain important equipment, such as the main diesel engine, diesel generator and purifier. As the whole MER scene is not established, the application value of K-Sim is limited and it can be only used for the training of certain equipment. For DMS-AHTS-3D, the whole MER scene is established in strict with the photos, videos, engine room arrangement plan, equipment instructions and the system schematic diagram of the parent ship. Although the workload of modeling and rendering during the development process is rather heavy, the high sense of reality can enhance the immersion of the users and attracts the interests of the trainees. On the other hand, establishing virtual MER scene with high sense of reality can avoid misleading the trainees caused by the mistakes and imperfection of the virtual scene.

3.2 Comparison of the human-machine interaction content and mode

The development purpose of MERVSS should be not only the simple virtual roaming, but also to realize the operation and management of the virtual marine engineering system and further evaluate the professional ability of the trainees. Table 1 shows the comparison of the human-machine interaction content and mode of the above-mentioned MERVSS.

The human-machine interaction content and mode performance of the five MERVSS is compared from three aspects including roaming method, integrity of interactivity and whether multi-person collaborative training mode is supported. Among them, LER3D, MAK11 and DMS-AHTS-3D support first-person manual and automatic roaming, and the others only support observation mode in fixed visual angle, which makes the panoramic roaming in the virtual MER scene impossible and limits its application value. In addition, DMS-AHTS-3D also supports auxiliary roaming functions including interactivity visual angle, zoom-in and zoom-out, which makes the trainees observe the virtual scene clearly and operate the interaction entities conveniently. In the

(a) LER3D (b) K-Sim (c) ERS 5000 (d) MAK11

Fig. 3. Similar MERVSS applications in the market.

Table 1. Comparison of the human-machine interaction content and mode

Application	Roaming Method	Integrity of Interactivity	Whether multi-person collaborative training mode is supported
K-sim	Fixed Visual Angle	Incomplete	No
LER3D	Free Visual Angle	General	No
ERS 5000	Fixed Visual Angle	General	No
MAK11	Free Visual Angle	Complete	No
DMS-AHTS-3D	Free Visual Angle	Complete	Yes

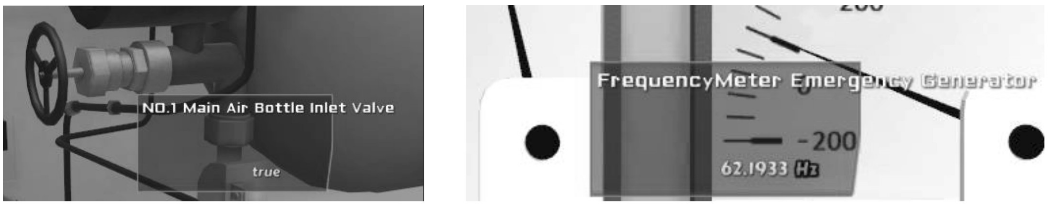

Fig. 4. Name and state information display.

aspect of the integrity of interactivity, as the whole virtual MER scene is not established by K-Sim, so the interaction content of the marine engineering system is not integrated. Although the virtual MER scene established by LER3D and ERS 5000 is more integrated than K-Sim, the amount of interaction content is still relatively small, which limits the training effect. MAK11 supports the integrated and systematic interaction of the marine engineering system and it can be used jointly with the "Neptune" MERS developed by the Kongsberg Maritime. In addition, several special interaction contents, such as draining of the water tank and measuring the depth of bilge well can be carried out in MAK11, but the relative rough virtual MER scene restricts the promotion of the whole quality of MAK11. Compared with the above-mentioned similar applications, DMS-AHTS-3D supports the integrated full-mission training, which covers the most of the operation content of the marine engineering system.

3.3 Auxiliary functions

Through experiencing K-Sim, LER3D, ERS and MAK11, it is found that the main function of them are only the virtual roaming and operation of the marine engineering system and necessary auxiliary functions are missing, which makes it different and inconvenient for the fresh trainees to handle the training software. Compared with the similar applications, DMS-AHTS-3D is integrated with several practical auxiliary functions as follows:

Name and state information display: As shown in Fig. 4, the name and real-time state information of various kinds of interaction entities, such as valve, meter and indicating lamp can be displayed when the mouse picks them successfully. In virtue of this function, the trainees can easily recognize the usage and state of a certain interaction entity, which will make it easier for the trainees to master the DMS-AHTS-3D.

Document repository of the marine engineering system: The trainees can motivate the Document Repository to browse the corresponding technical document to assist the training process and learn about the knowledge about marine engineering system.

3-D virtual map: Fig.5 is the 3-D Virtual Map of the marine engine room. The red spot in the virtual map shows the specific location of the trainee in the virtual scene.

Equipment search and scene navigation: As the MER belongs to a typical kind of large-scale scene, the trainees usually need to frequently switch among different equipment and scene for completing a certain practical operation task. To save the training and evaluation time, equipment search and

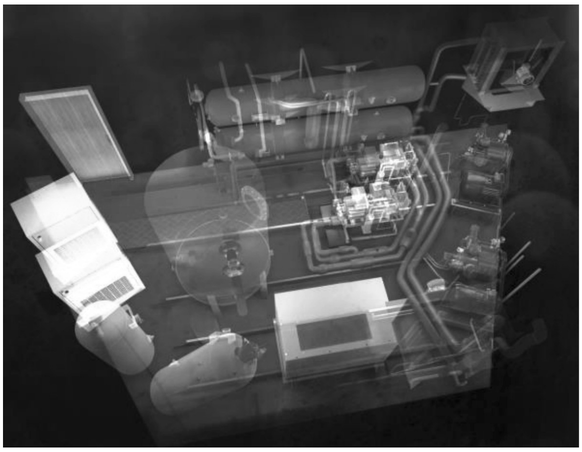

Fig. 5. 3-D virtual map of MER.

Fig. 6. Equipment search and scene navigation.

scene navigation function as the Fig.6 shows is added to make the switching process more convenient and efficient.

According to the above comparison and analysis, it can be found that the virtual MER scene created by DMS-AHTS-3D is integrated and real enough, the human-machine interaction content is abundant and the auxiliary function is convenient and practical. On this basis, automatic evaluation function is developed and integrated in DMS-AHTS-3D.

More details about DMS-AHTS-3D can be seen by browsing website "http://v.youku.com/v_show/id_XMTU3OTg0Mjc5Mg==.html".

4. Design of automatic evaluation module

4.1 Definition and introduction of the automatic evaluation function

The automatic evaluation function can be regarded as a quantized evaluation mechanism of the validity, accuracy and timeliness for the trainees' certain operation procedure such as handling various kinds of MER circumstances pattern, process of fault analysis and diagnosis, and management of the staff and equipment [15].

The procedure of automatic evaluation process designed in this paper can be simply concluded as follows: The experts or coaches are in charge of the designing and editing of the evaluation questions and knowledge base. Once the trainee loads a certain evaluation question, the automatic evaluation module will initialize the state of the marine engineering system. During the evaluating process, the operation actions and corresponding state parameters of the marine engineering system are tracked, recorded and analyzed by the automatic evaluation module at the same time. Finally, the evaluation result is given in the form of transcript with scoring details.

4.2 Disassembling of the marine engineering evaluation program

As the content and complexity of each evaluation program is not the same, to balance the different complexity the whole evaluation program is disassembled into a series of independent and meaningful units, such as the starting of air compressor, separating of fuel oil and synchronizing operation. The disassembling is very helpful for designing the evaluation question and carrying out the evaluation process.

4.3 Structure and description of the evaluation question

To carry out the automatic evaluation function conveniently and fast, the structure and description of each evaluation question should has universal standard.

Although the content and complexity of each evaluation question is not the same, they can be divided into "State Parameter" and "Operation Action". The "State Parameter" such as the pres-

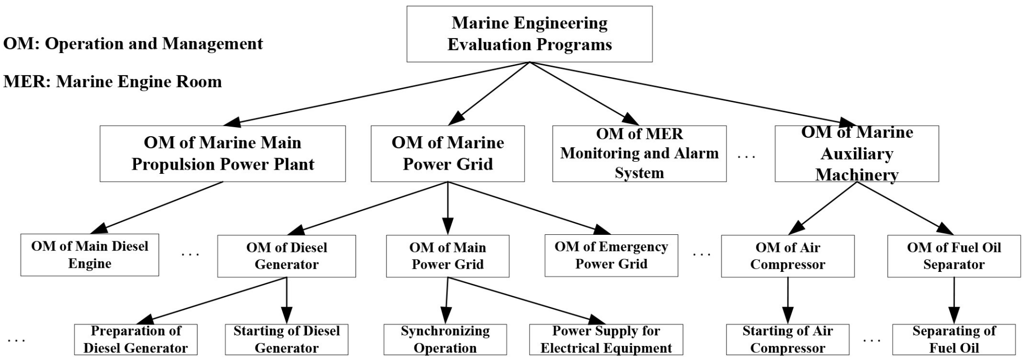

Fig. 7. Disassembling of the marine engineering evaluation program.

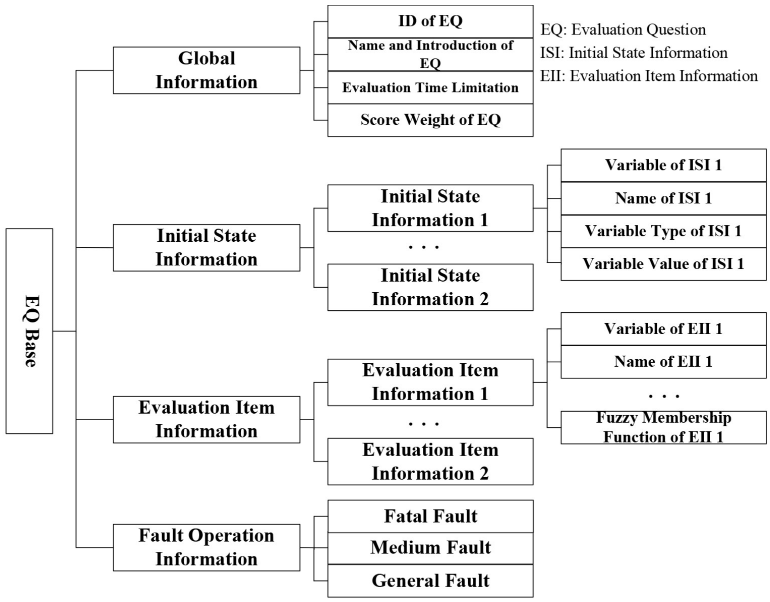

Fig. 8. Hierarchical structure of the evaluation question

sure, temperature, revolution speed represents the running state of the marine engineering system. The "Operation Action" represents the operation of interaction entities, such as the button, feeder switch and speed governor. In certain situation, the "Operation Action" should be completed in right order and timing. Although the "State Parameter" and "Operation Action" have different meanings, they are all described in the form of variable and stored in the SDC, therefore the automatic evaluation process can be simply regarded as the tracking, recording and analyzing of these variables.

To reduce the dependency for the third-party platform, the evaluation question base is established by using XML (Extensible Markup Language). The hierarchical structure of the evaluation question is described in the form of "Tree" and each layer of "Tree" describes a certain kind of evaluation information. The upper layer information can be seen as the entirety of the lower layer information and the lower layer information can be seen as the branch of the upper layer information. Fig. 8 is the XML hierarchical structure of the evaluation question, which is mainly composed of four parts: Global information, Initial state information, Evaluation item information and Fault operation information. The meaning of each part is as follows:

Global information: The "Global information" mainly describes the ID, name, score weight, evaluation content, and evaluation time limitation for a certain evaluation question.

Initial state information: To shorten the evaluation time and improve the evaluation efficiency, each evaluation question should be designed and carried out based on a certain initial state of marine engineering system. For example, for the evaluation question "Manual Synchronizing Operation", the initial state is that two DG (Diesel Generator) are running, one is linked with the power grid and the other is not. In this way, the trainees could only focus on the manual synchronizing operation and the preparation and starting process of DG can be omitted, which saves the evaluation time greatly. So the initial information node is added to the hierarchical structure of the evaluation question. The initial information is composed of the variable ID, name, type and initial value.

Evaluation item information: The composition of the evaluation item information for each evaluation question is as shown in Table 2. The evaluation item information describes the specific evaluation requirements of each evaluation question, which is the important gist for carrying out the automatic evaluation process. The meaning of each item in Table 2 is as follows:

(1) Evaluation item variable: It describes the variable of the evaluation item, which has the unique data identification in the SDC.
(2) Name of the evaluation item variable: It describes the actual physical meaning of the evaluation item variable.
(3) Data type of the evaluation item variable: It describes the data type of the evaluation item variable, such as the Integer, Float and Boolean.
(4) Type of the evaluation item: It is used to judge the evaluation item belongs to "State Parameter" or "Operation Action".

Table 2. Evaluation item information of the evaluation question

Evaluation Item Variable	Name of Evaluation Item Variable	Data Type of Evaluation Item Variable	Type of Evaluation Item	Type of Fuzzy Membership Function	Parameters of Fuzzy Membership Function	Operation Condition	Operation Sequence	Score
IV_1	VN_1	VT_1	IT_1	FT_1	FP_1	OP_1	OL_1	SW_1
IV_2	VN_2	VT_2	IT_2	FT_2	FP_2	OP_2	OL_2	SW_2
...	...	...	...	...	...	...	...	...
IV_n	VN_n	VT_n	IT_n	FT_n	FP_n	OP_n	OL_n	SW_n

(5) Type of the fuzzy membership function: It describes the type of fuzzy membership function adopted for the corresponding evaluation item, such as the single-point membership function and the trapezoid membership function.
(6) Parameters of the fuzzy membership function: It is used to determine the specific form of the adopted fuzzy membership function.
(7) Operation condition: The operation condition of the "Operation Action" is described in the form of set. The set is Null when a certain "Operation Action" does not have the requirement of operation condition.
(8) Operation sequence: For the "Operation Action" that has the requirement of operation sequence, numbers such as 1,2 and 3 are used to express the priority of operation sequence and "Null" is used for expressing the "Operation Action" that does not have the requirement of operation sequence.
(9) Score: It describes the score of the corresponding evaluation item.

Fault operation information: The fault operation information is used to judge if fault operation happens during the evaluation process. If certain alarm signals are detected such as high-temperature alarm and low-pressure alarm, it can be identified that fault operation happens during the evaluation process. In this paper, three kinds of fault operation information are defined, which are respectively the fatal, medium and general fault, and score deduction coefficient differs from each kind.

To ensure the authority of the evaluation question, it is defined and edited by the industry specialists or the coaches. As the evaluation question base is established by using XML, the editing and modification of the evaluation question become convenient and rapid, meanwhile, both the vested evaluation program in the evaluation outline for seafarers and the self-defined scene evaluation program can be carried out in the automatic evaluation module. The design mode further meets the competency evaluation requirement for the "Marine Engine Room Resource Management" regulated in the new convention (STCW 78/10 Convention).

5. Definition of the fuzzy membership function

5.1 Fuzzy membership function for "operation action"

For the evaluation item belonged to "Operation Action", the data type of which is usually Boolean and the operation result is either true or false, so single-point membership function is adopted for evaluating the "Operation Action".

A is defined as a fuzzy set in the discourse domain U, which only contains one single element x, and fuzzy membership function $\mu_A(x)$ represents the membership degree of x relative to set A [16].

$$\mu_A(x) = \begin{cases} 0 & x = x_i \\ 1 & others \end{cases} \tag{1}$$

5.2 Fuzzy membership function for "state parameter"

For the evaluation item belonged to "State Parameter", the normal and possible running interval of which is usually a certain continuity interval and it is obviously unreasonable to give out zero or full marks by simply judging if the "State Parameter" x belongs to interval [a,b]. It is because that optimal running interval [c,d] belonged to interval [a,b] usually exists for the "Running Parameter". $x \in [c, d]$ represents that the "State Parameter" x is in the optimal running range. $x \in [a, b]$ but $x \notin [c, d]$ represents that the "State Parameter" x is in the normal running range but not in the optimal running range; $x \notin [a, b]$ represents that the "State Parameter" x is completely not in the normal running range. So according to the running feature of the "State Parameter", it is evaluated by using fuzzy membership function in the automatic evaluation module.

A is defined as a fuzzy set in the discourse domain U and fuzzy membership function $\mu_A(x)$ represents the membership degree of x relative to set A [16].

$$\mu_A(x) = \begin{cases} 0 & x\ doesn't\ belongs\ to\ A \\ (0,1) & x\ belongs\ to\ A\ partly \\ 1 & x\ belongs\ to\ A \end{cases} \tag{2}$$

In the automatic evaluation module, the frequently used fuzzy membership functions include the trapezoid membership function as the Equation (3) shows, lower semi-trapezoid membership function as the Equation (4) shows and the upper semi-trapezoid membership function as the Equation (5) shows.

$$\mu_B(x) = \begin{cases} 0 & 0 \le x \le a \\ \frac{x-a}{b-a} & a < x < b \\ 1 & b \le x \le c \\ \frac{d-x}{d-c} & c < x < d \\ 0 & x \ge d \end{cases} \quad (3)$$

$$\mu_C(x) = \begin{cases} 1 & x \le a \\ \frac{b-x}{b-a} & a < x < b \\ 0 & x > b \end{cases} \quad (4)$$

$$\mu_D(x) = \begin{cases} 0 & x \le a \\ \frac{b-x}{b-a} & a < x < b \\ 1 & x \ge b \end{cases} \quad (5)$$

The trapezoid membership function is suitable for the "State Parameter" that has a continuity optimal running interval $[c, d]$, which becomes a point when c equals to d. The lower semi-trapezoid and upper semi-trapezoid membership functions are suitable for the "State Running" that is better when the running value of the "State Parameter" gets smaller or larger. The functional image of the above-mentioned three kinds of fuzzy membership function and the single-point fuzzy membership function are as shown in Fig. 9.

The parameters to determine the specific form of the fuzzy membership function are given by the industry specialists or the coaches. As the above-mentioned fuzzy membership functions have the feature of convenient-setting, easy form and fast-calculation, so they are widely adopted in the automatic evaluation module. However, the evaluation results are demanded more precise for several "State Parameters", so the numerical fitting method "Least Square Method" is used to generate the corresponding fuzzy membership function.

5.3 Numerical fitting of fuzzy membership function

To make the evaluation results of certain "State Parameter" precise and realistic, "Least Square Method" is used to generate the corresponding fuzzy membership function [17]. The "Least Square Method" is a kind of mathematical optimization technique, which tries to find the optimal functional matching of data by minimizing the quadratic sum of the deviation.

When a large sum of data is obtained by experiments, the deviation between the observed value and the functional value of the fitting function $\varphi(x)$ in the data point (x_i, y_i), namely, $\delta_i = \varphi(x_i) - y_i$ $(i = 1, 2, \cdots, m)$ cannot be ensured to be zero strictly. To make the fitted curve reflect the variation trend of the given data points and restrict the deviation size at the most extent, the quadratic sum of the deviation as the Equation (6) shows is demanded to be minimum and this method is called "Least Square Method". More details about the numerical fitting process of fuzzy membership function by using "Least Square Method" can be referred to Appendix A.

$$\sum_{i=1}^{m} \left|\delta_i^2\right| = \sum_{i=1}^{m} (\varphi(x_i) - y_i)^2 \quad (6)$$

6. Analysis of automatic evaluation process and calculation of the evaluation score

The evaluation content for the trainees in the automatic evaluation module is mainly composed of five parts: evaluation of the "State Parameter", "Operation Action", "Operation Sequence", "Operation Timing" and "Fault Operation". The final evaluation score is generated by the automatic evaluation module based on the above five evaluation parts.

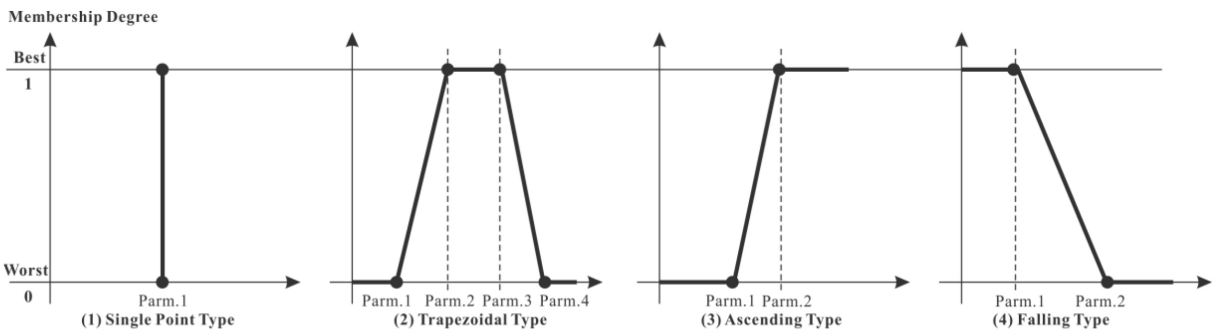

Fig. 9. Functional image of four kinds of fuzzy membership function.

6.1 Analysis of automatic evaluation process

Evaluation of "State Parameter" and "Operation Action": The fuzzy membership functions defined in Section 5.2 and 5.3 are used to evaluate the "State Parameter", and then scoring coefficient is got according to the membership degree of "State Parameter" relative to optimal running interval. The single-point membership function defined in Section 5.1 is used to evaluate the "Operation Action".

Evaluation of "Operation Sequence": In common situations, the operation of marine engineering system should follow a series of standard operation procedure, which is the basic guarantee for the normal running of marine engineering system. Therefore, the evaluation of "Operation Sequence" is taken into consideration during the automatic evaluation process.

It is assumed that the standard operation procedure of a certain evaluation question is $A \to B \to C \to \cdots \to X$. To implement the evaluation of "Operation Sequence", each operation sequence is numbered according to its operation priority and then the standard operation procedure can be expressed as $\frac{A}{1} \to \frac{B}{2} \to \frac{C}{3} \to \cdots \to \frac{X}{n}$. The n natural numbers are identified as standard sequence when they are arranged from small to large.

$p_1p_2\cdots p_n$ is a certain arrangement of n natural numbers. The inversed number of the element $p_i(i = 1, 2, \cdots, n)$ is t_i if there are t_i elements, which are ahead of p_i and larger than p_i, and then the sum of inversed numbers of all the elements is as Equation (7) shows.

$$t = t_1 + t_2 + \cdots t_n = \sum_{i=1}^{n} t_i \tag{7}$$

where t is the inversed number of the arrangement $p_1p_2\cdots p_n$. The inversed number can be used to reflect the confusion degree of the actual operation sequence and it gets more confused when the inversed number gets larger, especially the actual operation sequence is most confused when the inversed number t reaches the maximum $t_{\max}$. In Equation (8), u is used to expressed the confusion degree of the actual operation sequence.

$$u = \frac{t}{t_{\max}} \tag{8}$$

Evaluation of "Operation Timing": For certain "Operation Action", it must be completed in proper timing, that is to say, the "Operation Action" has the requirement of operation conditions, for example, the pressure of the hydraulic oil in the reservoir should reach 200 *bar* at least before pressing the hydraulic starting spring to start the emergency generator. Therefore, the evaluation of "Operation Timing" is taken into consideration during the automatic evaluation process.

To evaluate "Operation Timing", the automatic evaluation module will record the operation moment t and calculate the deviation between the actual running value V_i of the corresponding operation condition c_i in the operation condition set C and the standard running value V_{mi} at the moment t as the Equation (9) shows.

$$ES_i = \frac{|V_{mi} - V_i|}{V_{mi}} \tag{9}$$

where ES_i is the deviation degree and it is identified that "Operation Timing" is worse when ES_i is greater. If the operation condition belongs to "Operation Action", it can be evaluated according to the evaluation of "Operation Sequence".

6.2 Calculation of the evaluation score

Calculation of the total score: Hundred-mark system is adopted in the automatic evaluation module. It is assumed that there are totally n evaluation questions and the total score S_{total} is calculated as Equation (10) shows.

$$S_{total} = \sum_{i=1}^{n} w_i S_i \ (i = 1, 2, \cdots, n) \tag{10}$$

where S_i is the score of the *n-th* evaluation question based on the hundred-mark mechanism, w_i is the corresponding score weight coefficient. The score weight coefficient is given by the industry specialists or coaches, meanwhile, it also can be determined based on AHP (Analytic Hierarchy Process). The weight coefficient should meet the condition as Equation (11) shows.

$$\sum_{i=1}^{n} w_i = 1 \tag{11}$$

Calculation of the score for each evaluation question: Based on the analysis of automatic evaluation process, the score for each evaluation question is calculated as Equation (12) shows.

$$S_i = \left(\sum_{i=1}^{n} sc_i \cdot FS_i + (1-\mu) \cdot FS_\mu + \sum_{j=1}^{m} (1 - \frac{|V_mj - V_j|}{V_{mj}}) \cdot FS_j \right) \cdot (1 - kf_1 - kf_2 - \cdots - kf_n) \tag{12}$$

where $sc_i \in [0, 1]$ is the scoring coefficient of "State Parameter" and "Operation Action", which is calculated according to the corresponding fuzzy membership function; kf_n is the deduction coefficient for "Fault Operation"; FS_i, FS_μ and FS_j are respectively the pre-set scores given by the industry specialists or coaches, which should meet the Equation (13).

$$\sum_{i=1}^{n} FS_i + FS_\mu + \sum_{j=1}^{m} FS_j = 100 \qquad (13)$$

6.3 Example of the automatic evaluation function

The evaluation question "Emergency Generator Starting and Operation" is selected as an example to verify the feasibility of automatic evaluation function developed in this paper. The trainees should complete operations as follows:

(1) Open the fuel inlet valve of emergency generator.
(2) Switch the power switch of local control box from "Off" to "On".
(3) Switch the control position of emergency generator form "Remote" to "Local".
(4) Ensure that the liquid level of lubrication-oil sump tank is between 40% and 70%.
(5) Stable the speed of emergency generator between 1750 *r/min* and 1800 *r/min*.
(6) Ensure that the temperature of emergency generator fresh water expansion tank is between 50 $^\circ C$ and 60 $^\circ C$.
(7) Ensure the liquid level of emergency generator fresh water expansion tank is between 40% and 70%.

Figure 10 shows the evaluation-setting interface and score report. As the liquid level of lubricating-oil sump tank is too high, the speed of emergency generator does not stable between 1750 *r/min* and 1800 *r/min* and the temperature of fresh water expansion tank is too low, certain scores are deducted and the final score is 66.3. The score report shows the operation comparison result of key evaluation items, which can make the evaluation result convinced by the trainees.

7. Learning aspects discussion

The DMS MERS research team where the authors belong to have successfully developed a series of marine engineering virtual training and evaluation systems for multi-type vessels including VLCC (Very Large Crude Carrier), Container, AHTS (Anchor Handling Tug Supply) vessel, teaching-training vessel and maritime police law-enforcement vessel, which can satisfy different training and evaluation requirements. At present, they have been applied to the teaching and examination task of the undergraduates and postgraduates majored in marine engineering in Dalian Maritime University and several other navigation-training institutions at home and abroad. The relevant information can be seen by browsing website http://blog.163.com/zhjundong@126/album/#m=1&aid=201756522&p=1.

7.1 Main educational achievements

The main educational achievements of DMS-AHTS-3D developed in this paper are as follows:

(1) Training and evaluation in the 3-D virtual scene has the advantages of stronger interactivity,

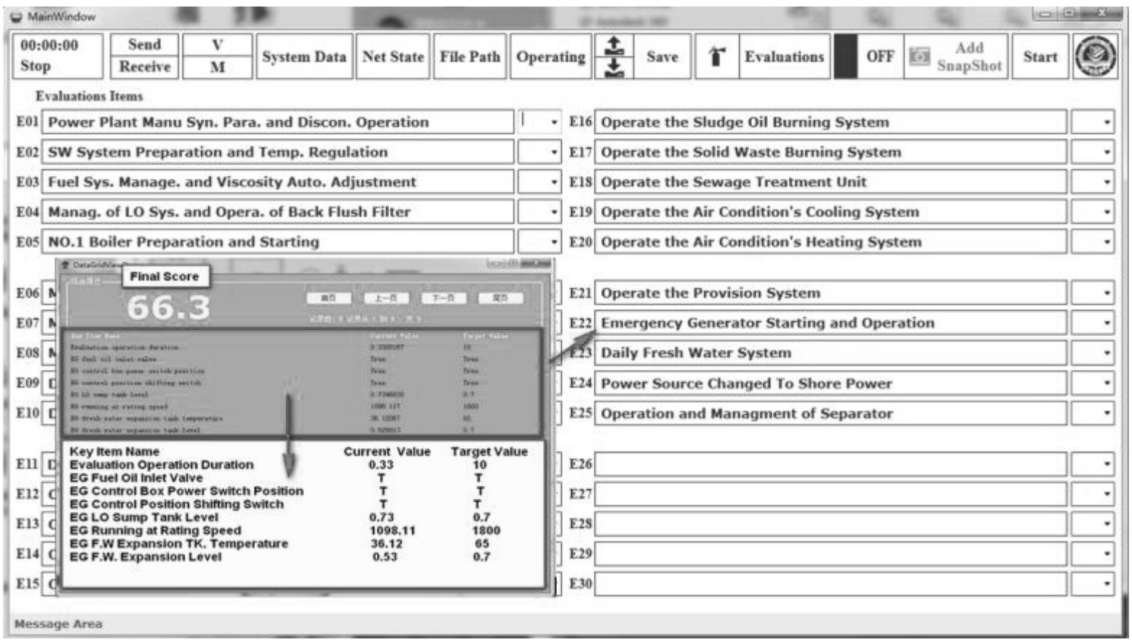

Fig. 10. Evaluation-setting interface and score report.

intuition and safety compared with the traditional MERS. The trainees can intuitively observe the actual structure and composition of the marine engine room and learn the working principle of the marine engineering system, meanwhile, as the virtual training and evaluation scene is very closed to the real one, so the training and evaluation effect is promoted greatly.

(2) The automatic evaluation function developed in this paper solves the problem that unitive evaluation method and standard is difficult to form for the traditional evaluation method and the evaluation result is influenced by the coach's subjective judgment largely, meanwhile, it can also quantify the evaluation process and ensure the evaluation result fair and just.

(3) Two kinds of evaluation mode is realized: Fixed evaluation programs in the examination outline for the seafarers and the user-defined evaluation programs, which enriches the evaluation content and lays the foundation for the comprehensive evaluation of the trainee's working ability.

(4) As the training and evaluation is completely carried out in the form of 3-D virtual simulation, which makes the large-scale training and evaluation possible and eases drastically the working load of the coaches, meanwhile, the potential safety hazard during the training and evaluation process is avoided effectively and the corresponding cost is saved largely.

7.2 Feedback of the students and industry specialists

To verify the practicability and application value of the marine engineering virtual training and evaluation system developed in this paper, an experiment is designed and carried out to get the feedback of the students and industry specialists. Totally 60 juniors majored in marine engineering from Dalian Maritime University and 10 experienced chief engineers from Shipping Department, China Oilfield Services are selected as the participants.

Based on the questionnaire methods for usability assessment proposed by J. Kirakowski [18] and the heuristic evaluation of virtual reality applications proposed by A. Sutcliffe [19], the experiment analyzes the practicability and application value mainly from two aspects: the virtual training function and the automatic evaluation function. The specific experiment content and feedback is as follows:

(1) Feedback of the virtual training function

The trainees' experience and industry specialists' experience [The scale used was 1(poor) to 5(good)] on the practicability of the virtual training function are got by carrying out experiment. The experiment results are shown in Table 3 [20]. According to the experiment results, the reality of the virtual MER scene can meet the expectations of industry professionals and the virtual training system is accepted by the trainees and industry professionals as a learning tool. However, in the aspect of "Easy to Handle", the trainees give more feedback scores than the professionals, it shows that it is relatively difficult for the old industry professionals to handle the virtual training and evaluation system than the young trainees. With the rapid development of virtual reality technology, it is believed that VR will be applied in the field of marine engineering education widely. As the core element of the engineering education, the coaches and the industry specialists are required to keep pace with the times and master various kinds of the advanced engineering education software and technology for improving the quality of teaching.

(2) Assessments of the Automatic Evaluation Function

Distribution of the evaluation score: First, the participants are divided into two groups, one is 60 juniors majored in marine engineering and the other is 10 experienced chief engineers. Then four evaluation questions are selected and carried out by all the participants of the two groups. At last, the distribution of evaluation score for each group is counted respectively. The distribution of evaluation score for 60 juniors and 10 chief engineers is respectively shown in Fig. 11 and Fig. 12 (Fig. 11 and Fig. 12 can

Table 3. Feedback of the virtual training function

Comparison Between VR Methodology and Traditional Methodology	**[1–5]**
The Trainee's Experience	4.3
1. Easy to handle	
2. Helps to consolidate the learning of the topic	4
3. Motivate the learning interests	4
The Professional's Experience	3
1. Easy to Handle	
2. Improves the level of attention of trainees	4
3. Improves the level of understanding of trainees	3
4. Restore the MER scene truly and delicately	4
5. The running state and response of the marine engineering system is consistent with the real one	3.5
6. The action behavior of the interaction entity is consistent with the real one	3.8

Table 4. Comparison of Automatic and Manual Evaluation Score

Evaluation Question	Evaluation Mechanism	1	2	3	4	5	6	7	8	9	10
Manual Synchronizing	Automatic Evaluation	81.7	84.5	97.7	89	82.3	81.7	85.7	74.3	71.7	86.9
	Manual Evaluation	85	81	95	90	80	80	85	70	75	85
Starting of Air Compressor	Automatic Evaluation	87.5	79.5	94.8	74.6	89.1	88.3	77.4	85.5	90.7	80.2
	Manual Evaluation	90	85	95	70	90	85	75	80	95	75
Separating Operation of Fuel Oil	Automatic Evaluation	96.3	79.2	86.2	85.6	75.6	91.1	81.5	84.9	74.9	89.8
	Manual Evaluation	85	80	90	90	80	90	85	90	75	90
Emergency Operation of Steering Gear	Automatic Evaluation	80.3	85.1	79.7	93.5	74.2	90.1	87.4	88.5	86.7	79.1
	Manual Evaluation	80	85	80	95	80	90	90	90	85	80
Preparation of Diesel Engine	Automatic Evaluation	91.9	86.5	88.1	95.3	75.7	89.6	78.7	68.7	86.6	73.6
	Manual Evaluation	90	85	85	95	80	95	80	75	95	75

be seen in Appendix B). By analyzing the distribution of evaluation score, it is found that the evaluation score of the trainees obeys the normal distribution and the score is mainly distributed in 70–80 and 80–90, and the evaluation score of the chief engineers is mainly distributed in 80-90. The evaluation score distribution of participants in different levels shows that the evaluation score given by the automatic evaluation module conforms with the general score rule.

Validity of the automatic evaluation score: To verify the validity of evaluation score given by the automatic evaluation module, 10 juniors and 5 evaluation questions are randomly selected and each participant is required to complete the selected evaluation questions. After completing all the evaluation questions by each participant, each evaluation process is scored by 10 chief engineers and the average of 10 scores is taken as the manual evaluation score, and then compare the manual evaluation score with the evaluation score given by the automatic evaluation module. It can be found that the automatic evaluation score keeps consistent with the manual evaluation score from the comparison data as the Table 4 shows, so the validity of the automatic evaluation score is verified.

8. Conclusion

This paper presents a marine engineering virtual training and evaluation system. Compared with the similar products on the markets, the system developed in this paper has advantages on the sense of reality, human-machine interaction content and mode, and auxiliary functions. By analyzing the feedback result of the trainees and professionals, the system is accepted as a learning tool by participants and it is believed that it will boost the development of visual simulation technology in the field of navigation engineering education and expands the application range of the MERS. The automatic evaluation module developed in this paper saves the problem that the evaluation result of the practical operation ability for the marine engineers generated in manual method is determined by the subjective judgment of the coaches to a great extent, which is difficult to ensure fair. By applying the automatic evaluation function, unified evaluation method and standard is formed during the evaluation process, and it is found that the evaluation result is fair and reasonable by analyzing the experiment result.

The marine engineering virtual training and evaluation system developed in this paper has been successfully applied in several navigation colleges at home and abroad and undertakes the teaching, training and evaluation task for the postgraduates, undergraduates and social marine engineers. According to the subsequent application demands, dynamic loading and LOD technique will be studied to realize the seamless roaming of the virtual marine engine room, marine engine room emergency scene such as fire disaster, flooding water and anti-pirate will be simulated and WEB-version will be also developed to extend the application range and better substitute the traditional MERS.

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Appendix A

(1) Acquisition of the Discrete Fitting Data Points

It is assumed that the parameter that is described by a certain fuzzy language variable v is a continuous changing physical quantity u, and m adjacent intervals $[a_i, a_{i+1}](i = 0, 1, \cdots, m-1)$ are obtained by fuzzy statistics method. Let the midpoint element $x_i = (a_i + a_{i+1})/2$ of each adjacent interval represent the interval and the corresponding membership $\mu(x_i)$ of the midpoint element represent the membership of the interval, and then m discrete fitting data points are obtained in the two-dimensional space.

(2) Fitting Data Processing

To reduce the truncation error and the restriction of data storage accuracy and promote the accuracy of numerical fitting result, the fitting data is pre-processed as the following steps:

Step 1: Arrange the physical quantity u in the set of fitting data in the increasing order.

Step 2: Find the median of the original fitting data after arranging in the increasing order and convert the median into the range of 10^o order of magnitudes, and then the converting coefficient t is got, meanwhile, the membership value of the median remains unchanged.

Step 3: Convert all the physical data u in the set of the fitting data according to $x = ut$, meanwhile, the membership value of all the fitting data remain unchanged.

(3) Numerical Fitting Process

It is assumed that f is the given discrete function of m discrete data points in the interval $[a, b]$ and the discrete observed data is $(x_i, f(x_i))(i = 0, 1, \cdots, m)$. Φ is defined as a linear space:

$$\Phi = span\{\varphi(x), \varphi_1(x), \cdots, \varphi_n(x)\} \tag{1}$$

where $\varphi(x), \varphi_1(x), \cdots, \varphi_n(x)$ are the linearly independence groups in the interval $[a, b]$.

It is assumed that the arbitrary fitting function $s(x) \in \Phi$ and $\Phi = \{1, x, x^2, \cdots, x^n\}$ in this paper, and then the structural form of the arbitrary fitting function $s(x)$ is as follows:

$$s(x) = a_0 + a_1 x + \cdots + a^n x^n = \sum_{j=0}^{n} a_j x^j \tag{2}$$

According to the principle of "Least Square Method", the numerical fitting process of the m discrete data points can be converted into the seeking minimum process of the multivariate function as the Equation (3) shows.

$$F(a_1, a_2, ..., a_n) = \sum_{i=1}^{m} (f(x_i) - s(x_i))^2, n \leq m - 1 \tag{3}$$

According to the necessary condition of seeking minimum, Equation (4) can be got:

$$\frac{\partial F}{\partial a_k} = \frac{\partial \left[\sum_{i=1}^{m} (f(x_i) - s(x_i))^2 \right]}{\partial a_k} = 2 \sum_{i=1}^{m} (f(x_i) - \sum_{j=0}^{n} a_j x_i^j)(-x_i^k) = 0, k = 0, 1, .., n. \tag{4}$$

The unique solution $a_j^* (j = 0, 1, ..., n)$ of the Equation (4) can make the multivariate function $F(a_1, a_2, ..., a_n)$ achieve the minimum and that is the least square solution for the numerical fitting of the fuzzy membership function, and then the Equation (5) is got by simplifying the Equation (4).

$$\sum_{j=1}^{n} (\sum_{i=1}^{m} x_i^{k+j}) a_j = \sum_{i=1}^{m} f(x_i) x_i^k, k = 0, 1, ..., n \tag{5}$$

And then the Equation (5) can be expressed in the form of matrix multiplication $A \cdot b = c$:

$$\begin{bmatrix} m & \sum_{i=1}^{m} x_i & \cdots & \sum_{i=1}^{m} x_i^n \\ \sum_{i=1}^{m} x_i & \sum_{i=1}^{m} x_i^2 & \cdots & \sum_{i=1}^{m} x_i^{n+1} \\ \vdots & \vdots & \ddots & \vdots \\ \sum_{i=1}^{m} x_i^n & \sum_{i=1}^{m} x_i^{n+1} & \cdots & \sum_{i=1}^{m} x_i^{2n} \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ a_n \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{m} f(x_i) & \sum_{i=1}^{m} f(x_i) x_i & \cdots & \sum_{i=1}^{m} f(x_i) x_i^n \end{bmatrix}^T \tag{6}$$

where A is the n+1 order matrix in the left, $b = (a_0, a_1, \cdots, a_n)^T$

$$c = \begin{bmatrix} \sum_{i=1}^{m} f(x_i) & \sum_{i=1}^{m} f(x_i) x_i & \cdots & \sum_{i=1}^{m} f(x_i) x_i^n \end{bmatrix}^T.$$

And then substitute the known discrete data points into the Equation (6), the coefficient matrix A and vector c can be got. As the coefficient matrix A belongs to nonsingular matrix, so the vector b can be calculated according to $b = A^{-1} \cdot c$ and then the least square solution for the numerical fitting of the fuzzy membership function can be got as Equation (7) follows:

$$s^*(x) = a_0^* + a_1^* x + \cdots + a_n^* x^n = \sum_{j=0}^{n} a_j^* x^j \tag{7}$$

Appendix B

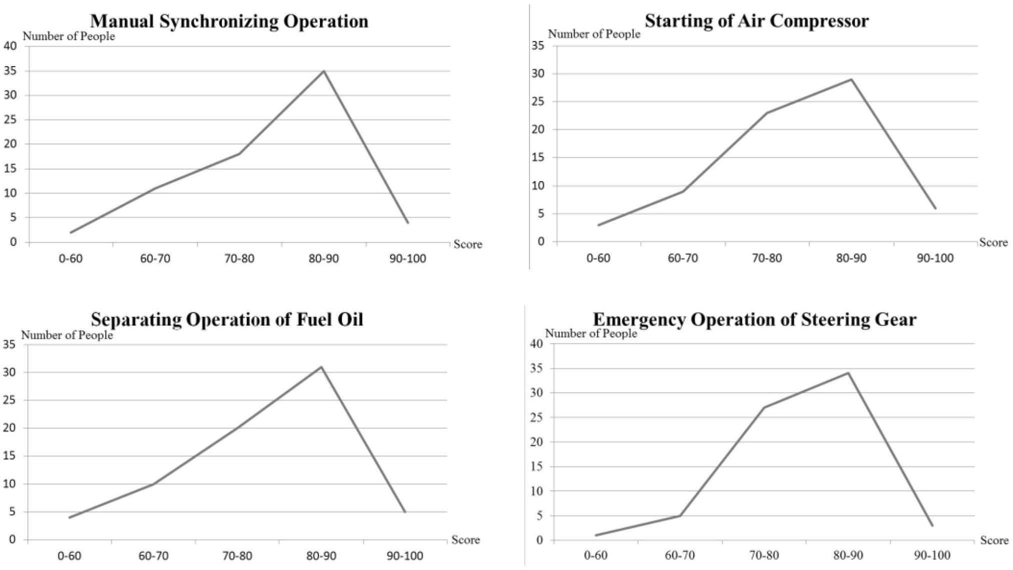

Fig. 11. Distribution of evaluation score for the 60 juniors.

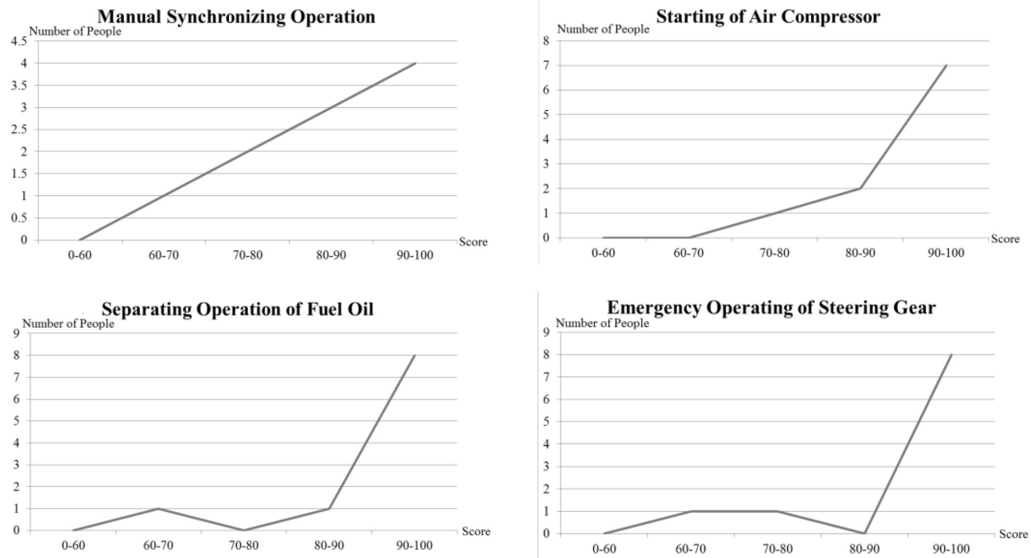

Fig. 12. Distribution of Evaluation Score for the 10 Chief Engineers.

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