Reuse of Pilot Motions for Improving Layout Design of Aircraft Cockpit

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***Abstract*—The layout design of aircraft cockpit is of great importance to the efficiency of the operation and the flight safety. In this paper, the reuse method of pilot motions for improving layout design of cockpit is proposed. The pilot motions are inertial tracked with man-in-the-loop mode and obtained on the basis of the operation procedures. The motions are represented by mapping the orientation of the pilot body segments to the virtual human model as motion cases. The case base is established, and the spatial position of the manipulation device is determined by case-based reasoning (CBR). The application instance presented indicates that the method proposed is effective and practical.**

***Index Terms*—aircraft cockpit, layout design, reuse approach, pilot motions, manipulation device**

I. Introduction

The layout design is an important part of cockpit design. Recent advances in science and technology have made the airborne systems and equipment in the cockpit more complex and numerous. There are so many manipulation devices in the cockpit that the layout design has great influence to the efficiency of the operation of pilot and the flight safety, and becomes one of the key evaluation indexes [1, 2].

The layout design problem has attracted many researchers' attention and many investigations have been conducted on this area. Bonney et al. [3] provided a computer program to layout controls and panels based on relative importance of certain design criteria. Palmiter and Elkerton [4] developed a computer-based tool which provided a quantitative analysis of the ergonomic quality of a control panel layout. Palmer et al. [5] proposed the crew centered design philosophy for the cockpit design considering the limit of the capacity of the pilot. Wang et al. [6] proposed a systematic multi-criteria method for designing panel layout. Vincent et al. [7] developed an internet virtual layout system to improve facility design and reduce hazards in the workplace. Yan et al. [8] proposed ergonomics based layout method for the modern complex control panel layout design and the pair-wise comparison decision method of analytic hierarchy process was used to determine the relative importance of devices. Wang et al. [9] established the rigid model for the pilot's upper limbs, and simulated two operation movements of the pilot using SimMechannics, and the simulation result suggested that it was necessary to analyze matters with an eye to manipulation characters.

Although many methods have been proposed for layout design, it still remains some problems during the process of layout design of the aircraft cockpit. Firstly, the engineers cannot consider the experience and technique that pilots possess on the typical types of aircraft thoroughly, and don't know the motions of the pilots when operating the manipulation devices under different flight conditions clearly. Secondly, the rationality of the layout cannot be analyzed and evaluated in time, and most of the time the pilots are invited to simulate operations after the physical prototype is established, so that the design cycle is prolonged and the expenses are increased.

In this paper, the reuse approach of pilot motions for improving layout design of cockpit is proposed in three steps based on the knowledge reuse theory [10, 11]. The pilot motions are inertial tracked with the man-in-the-loop mode, and the motions in each flight phase of the aircraft are obtained on the basis of the operation procedures under different conditions. The pilot motions are represented by mapping the orientation of the pilot body segments to the virtual human models as motion cases. The case base of pilot motions is established, and the pilot motions are reused by CBR, and then the spatial position of the manipulation device can be determined with the assistance of the reused cases.

II. Approach to Obtain the Pilot Motions

For each of the typical aircrafts, there is a flight simulator which can recreate aircraft flight and various aspects of the flight environment. It is the same as the aircraft in the cockpit, and could be used to simulate most of the flight tasks the pilot needs to execute, so the pilot motions are obtained based on the flight simulator platforms.

A. Decomposition of the Flight Task

Generally, when executing the flight task, the pilots get the information about the flight environment conditions of the aircraft by sweeping the outside of the cockpit, observing the displays, and control the aircraft on the

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basis of the operation procedures during each phase of the flight profile (shown in Fig. 1), so it is necessary to decompose the flight task to get various motions of the pilots before the motion obtained.

Based on the investigation and analysis of the aircrafts at the airport, the flight task is decomposed into five categories, denoted as $T=\{A, F, C, P, D\}$, where A is the aircraft type, F is the flight phase, C is the flight condition, P is operation procedure and D is the manipulation device.

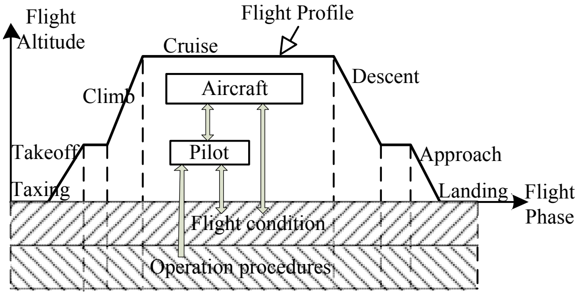

Figure 1. The interaction process of the typical flight profile

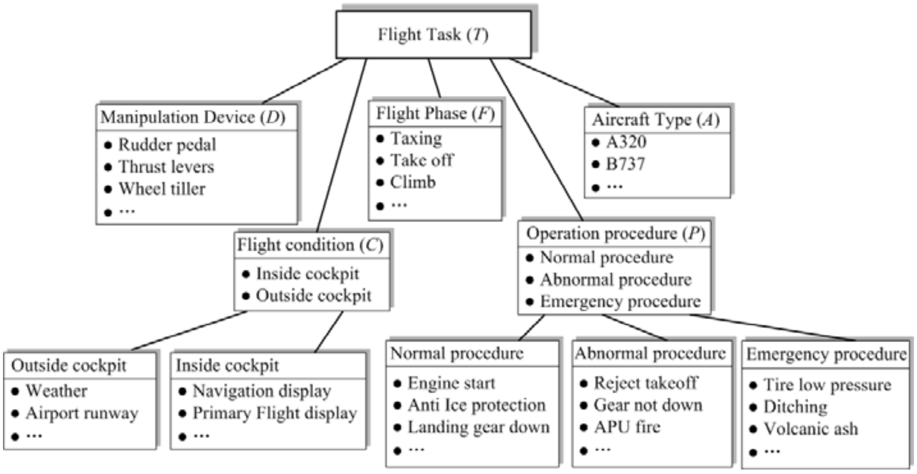

Figure 2. Decomposition of the flight task

As shown in Fig. 2, according to the flight profile of an aircraft, the flight phase may comprise seven phases, which are taxing, takeoff, climb, cruise, descent, approach, and landing. In each phase, on the basis of flight environment, the pilot will choose normal, abnormal, or emergency procedures to control the aircraft by operating the devices such as rudder pedal, thrust levers and buttons to make the aircraft as safe as possible. Take A320 aircraft for example, in the process of taxing before takeoff, the pilot can use the pedals to steer the aircraft on straight taxiways, but in sharper turns, the pilot must use the tiller. If an engine failure occurs during taxing, the resultant yaw may be significant, leading to rapid displacement from the runway centerline. For this reason, directional control will be achieved by immediately closing the thrust levers and using maximum rudder and braking. The task decomposition of taxing of A320 aircraft is shown in Table 1.

TABLE I

EXAMPLE OF TASK DECOMPOSITION

Aircraft Type (A)	Flight Phase (F)	Flight Condition (C)	Operation Procedure (P)	Manipulation Device (D)
A320	Taxing	Straight taxiways	Normal	Pedals
		Sharper turns	Abnormal	Tiller
		One engine failure	Emergency	Thrust levers
				Rudder
				Braking

B. Motion Tracking and Capture

For reusing of pilot motions, it is essential to track and capture the motions. At present, most of the motions can be recognized by the motion capture system based on the computer vision technology. However, this kind of technology needs multiple angles shooting with multiple cameras and has high requirements on the environment, including the background and the lighting [12]. Considering the spatial dimensions and environmental conditions, the approach of inertial tracking of pilot motions is proposed, which can be used under any lighting condition. As shown in Fig. 3, the inertial measurement units (IMU) are attached to pilot body segments, such as head, upper arms, forearms, hands, thighs and legs. When operating the manipulation devices, the postures of pilot can be resolved and the orientation parameters of segments of the body can be transmitted to host computer by the IMUs in real time.

Figure 3. IMUs attached to the pilot body segments

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The schematic diagram of inertial tracking is shown in Fig. 4. The IMU is mainly made up of tri-axial accelerometers and tri-axial gyroscopes. The accelerometers provide a measurement of specific force f^b in a segment fixed axis set, and the turn rate $\omega_{\mathrm{ib}}^{\mathrm{b}}$ of the segment is measured by the gyroscopes with respect to the inertial frame [13, 14]. With the initial attitude angle, the direction of the body segment could be calculated by integral operation. For the position of the body segment, after the resolution of specific force f^b, the position of the body segment could be achieved with the acceleration of gravity and the initial position of the segment, which will be defined at the very beginning of motion tracking. The calculated orientation parameters of each body segment will be transmitted in real-time to the host computer.

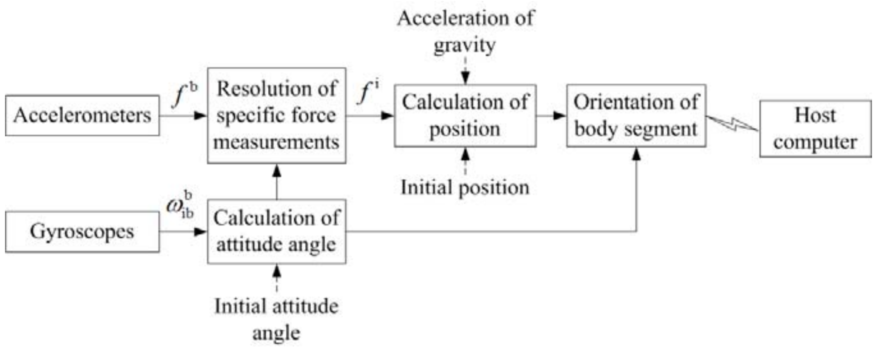

Figure 4. The schematic diagram of inertial tracking

The orientation of the body segment is express by a quaternion. It is based on the idea that a transformation from one coordinate frame to another may be effected by a single rotation around a vector $\boldsymbol{\mu}$, which defined with respect to the reference frame. The quaternion, denoted here by the symbol $\boldsymbol{q}$, is a four element vector, the elements of which are functions of this vector and the magnitude of the rotation:

$$\boldsymbol{q}=\begin{bmatrix}a\\b\\c\\d\end{bmatrix}=\begin{bmatrix}\cos(\mu/2)\\\mu_x/\mu\sin(\mu/2)\\\mu_y/\mu\sin(\mu/2)\\\mu_z/\mu\sin(\mu/2)\end{bmatrix} \tag{1}$$

where μ_x, μ_y and μ_z are the components of the angle vector $\boldsymbol{\mu}$ and μ is the magnitude of $\boldsymbol{\mu}$.

III. Representation of Pilot Motions Based on the Virtual Human Model

A. The Virtual Human Model

After the data that contains the orientation parameters is transmitted to the host computer, the motions of the pilot need to be reproduced, so that the cockpit designers can see and refer to the motions of the pilot. Here the virtual human modeling technology is used to express the pilot motions. The virtual human model is the digital expression of the geometric characteristic of human body in the virtual environment. Because of its great help to workspace design, more and more designers are using virtual human models in the computer aided design. However, the anthropometry data of pilots is different from the natural population due to the pilot selection requirements. For this reason, the virtual human model must meet the need of mapping from pilot to the virtual human model. The percentile of the virtual human model is transformed by (2).

$$P_K=\overline{X}\pm S_D K \tag{2}$$

where $\overline{X}$ is the mean value of the samples measured, S_D is the standard deviation and K is the transform coefficient.

In this paper, the anthropometry data of pilots is used as the data source, and the parameterized virtual human model is developed based on the Human Builder module of the software DELMIA, which is shown in Fig. 5. The number of degree of freedom (DOF) of each virtual human body segments should be defined at the beginning, and then the model, driven by the orientation of pilot body segments, can simulate most of natural movements.

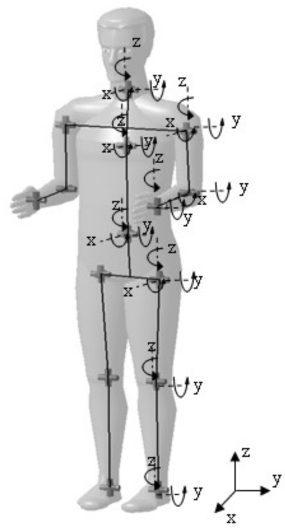

Figure 5. The virtual human model of pilot

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B. Representation of Pilot Motions

The representation of pilot motions is based on the parameters transmitted to the host computer by IMUs in Section 2-B. When using the virtual human model to represent the motions, a transformation from one coordinate frame to another is needed for the segment of the virtual human most of the time. In the virtual environment, the transformation can be carried out as three successive rotations around different axes. The three rotations are expressed mathematically as three separate direction cosine matrices:

$$\boldsymbol{R}(x,\theta_1)=\begin{bmatrix}1 & 0 & 0\\ 0 & \cos\theta_1 & \sin\theta_1\\ 0 & -\sin\theta_1 & \cos\theta_1\end{bmatrix} \tag{3}$$

which is the rotation θ_1 around x-axis, and

$$\boldsymbol{R}(y,\theta_2)=\begin{bmatrix}\cos\theta_2 & 0 & -\sin\theta_2\\ 0 & 1 & 0\\ \sin\theta_2 & 0 & \cos\theta_2\end{bmatrix} \tag{4}$$

which is the rotation θ_2 around y-axis, and

$$\boldsymbol{R}(z,\theta_3)=\begin{bmatrix}\cos\theta_3 & \sin\theta_3 & 0\\ -\sin\theta_3 & \cos\theta_3 & 0\\ 0 & 0 & 1\end{bmatrix} \tag{5}$$

which is the rotation θ_3 around z-axis.

The quaternion elements in Section 2.2 may be expressed directly in terms of direction cosines with the following equations:

$$\begin{cases} a=\cos\frac{\theta_1}{2}\cos\frac{\theta_2}{2}\cos\frac{\theta_3}{2}+\sin\frac{\theta_1}{2}\sin\frac{\theta_2}{2}\sin\frac{\theta_3}{2}\\ b=\sin\frac{\theta_1}{2}\cos\frac{\theta_2}{2}\cos\frac{\theta_3}{2}-\cos\frac{\theta_1}{2}\sin\frac{\theta_2}{2}\sin\frac{\theta_3}{2}\\ c=\cos\frac{\theta_1}{2}\sin\frac{\theta_2}{2}\cos\frac{\theta_3}{2}+\sin\frac{\theta_1}{2}\cos\frac{\theta_2}{2}\sin\frac{\theta_3}{2}\\ d=\cos\frac{\theta_1}{2}\cos\frac{\theta_2}{2}\sin\frac{\theta_3}{2}+\sin\frac{\theta_1}{2}\sin\frac{\theta_2}{2}\cos\frac{\theta_3}{2}\end{cases} \tag{6}$$

The transformation may be expressed as the product of these three separate transformations:

$$\begin{aligned} {}^{A}_{B}\boldsymbol{R} &= \begin{bmatrix}\cos\theta_3 & \sin\theta_3 & 0\\ -\sin\theta_3 & \cos\theta_3 & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}\cos\theta_2 & 0 & -\sin\theta_2\\ 0 & 1 & 0\\ \sin\theta_2 & 0 & \cos\theta_2\end{bmatrix}\begin{bmatrix}1 & 0 & 0\\ 0 & \cos\theta_1 & \sin\theta_1\\ 0 & -\sin\theta_1 & \cos\theta_1\end{bmatrix}\\ &= \begin{bmatrix}\cos\theta_2\cos\theta_3 & -\cos\theta_1\sin\theta_3+\sin\theta_1\sin\theta_2\cos\theta_3 & \sin\theta_1\sin\theta_3+\cos\theta_1\sin\theta_2\cos\theta_3\\ \cos\theta_2\sin\theta_3 & \cos\theta_1\cos\theta_3+\sin\theta_1\sin\theta_2\sin\theta_3 & -\sin\theta_1\cos\theta_3+\cos\theta_1\sin\theta_2\sin\theta_3\\ -\sin\theta_2 & \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\end{bmatrix}\\ &= \begin{bmatrix}a^2+b^2-c^2-d^2 & 2(bc-ad) & 2(bd+ac)\\ 2(bc+ad) & a^2-b^2+c^2-d^2 & 2(cd-ab)\\ 2(bd-ac) & 2(cd+ab) & a^2-b^2-c^2+d^2\end{bmatrix}\end{aligned} \tag{7}$$

With the geometrical transformation approach proposed above and the orientation parameters of the body segments, in the virtual environment, the virtual human model can be driven to represent most of the motions that the pilot conducted when operating the manipulation device to execute the flight task in the aircraft cockpit.

IV. Reuse of Pilot Motions

A. The Case base of Pilot Motions

The case base mainly comprises the relation of flight tasks and relation of the virtual human segments. The relation of flight tasks has been discussed in Section 2-A. For the relation of the virtual human segments, each of the segments can be described by motion element, denoted $\Psi_{ME}^{(i)}$. It is related to DOF. For a segment with 3 DOF, the motion could be expressed as $\Omega_s=\left(\Psi_{ME}^{(1)},\Psi_{ME}^{(2)},\Psi_{ME}^{(3)}\right)$, and for a segment with 2 DOF, it is $\Omega_s=\left(\Psi_{ME}^{(1)},\Psi_{ME}^{(2)}\right)$. For instance, when the arm is stretched out, the forearm needs two motion elements $\left(\Psi_{ME}^{(1)},\Psi_{ME}^{(2)}\right)$ to express, where $\Psi_{ME}^{(1)}$ is pronation, and $\Psi_{ME}^{(2)}$ is extension. Hence, the relational model of pilot motions can be developed with relation schema and relation instance. A relation schema specifies the domain of each field in the relation instance, and it can be formally expressed as $R(\mathrm{g}_1:d_1,\cdots,g_i:d_i,\cdots,g_n:d_n)$, and for each $g_i\,(1\le i\le n)$, Dom_i is the set of values associated with the domain d_i. And an instance of R, which satisfies the domain constraints in the schema, is a set of tuples with n fields:

$$\{<g_1:d_1,\cdots,g_n:d_n>|\,d_1\in Dom_1,\cdots,d_n\in Dom_n\} \tag{8}$$

The relational model of pilot motions is shown in Fig. 6. It contains both the relations of flight tasks that the pilot executes on different flight simulators and the virtual human models. With the relation model of pilot motions, the case base is established, so that when the pilot is operating on the flight simulator according to the flight task, the IMUs would transmit the orientation parameters of the body segments to host computer and the motion case would be stored to the case base. The experience and technique that pilots possess are integrated into the cases.

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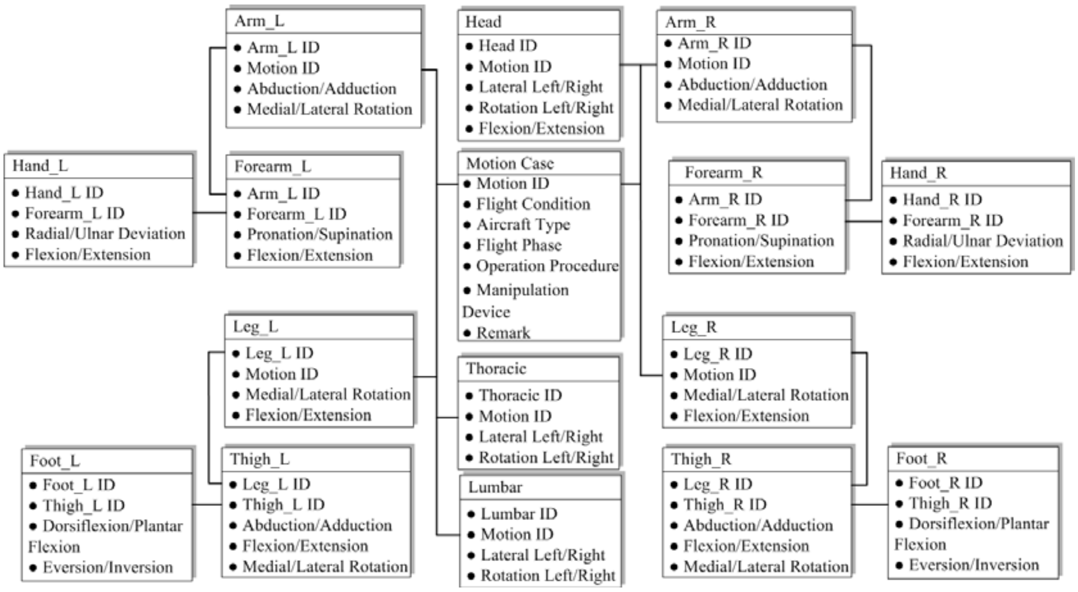

Figure 6. The relational model of pilot motions

B. Motion Case based Reasoning

When reusing the pilot motions for layout design of cockpit, CBR approach is used. CBR is efficient for providing the motion cases in the case base that satisfy the layout design. The approach applied to develop the pilot motion reuse system is described as follows:

Requirements definition. Requirements definition is to understand what kind of cockpit to be designed, such as the resource allocation for pilots, the changes expected to the current operating environment. In other words, the consumer's needs to the cockpit should be found out.

Design objects description. According to the information gathered in the requirements analysis step, the design sequence and the function of the device, each of the devices to be arranged can be described as a multiple attribute set $F=\{c_1,\cdots,c_i,\cdots,c_n\}$, where c_i is the *i*th attribute, *n* is the number of attributes. And there is a weight matrix $W=[\omega_1\cdots\omega_i\cdots\omega_n]$, where ω_i is the *i*th attribute correspondingly. The weight for each attribute is determined using the analytic hierarchy process (AHP) approach [15].

Case retrieval. For the attribute set of the device and related tuples of the cases in the base, case retrieval, which is a SQL-like query, is to find the motion cases that meet the attached conditions and are possible for reusing. The cases possible for reusing can be expressed as a matrix in (9)

$$\boldsymbol{E}(k,n)=\begin{bmatrix} c_{11} & \cdots & c_{1j} & \cdots & c_{1n} \\ \vdots & & \vdots & & \\ c_{i1} & \cdots & c_{ij} & \cdots & c_{in} \\ \vdots & & \vdots & & \vdots \\ c_{k1} & \cdots & c_{kj} & \cdots & c_{kn} \end{bmatrix} \tag{9}$$

where c_{ij} is the *j*th attribute of the *i*th case, *k* is the number of cases which are possible for reusing.

Similarity analysis. The similarity is used for further analysis to the motion cases found in Step 3. The similarity between the case *i* and the condition of the object designing is determined by (10).

$$SIM(X,Y)=\frac{\sum_{i=1}^{n}\omega_i\times sim(x_i,y_i)}{\sum_{i=1}^{n}\omega_i} \tag{10}$$

where *n* is the number of attributes in a case, ω_i is the weight of attribute *i*, and $sim(x_i,y_i)$ is the similarity between two values of the same attribute. With the similarity analysis results, that whether or not the cases satisfy the requirements is determined.

Case revise. If the cases do not satisfy the requirements, it is needed to revise the motions of pilot in the base by changing the value of motion element of the segments. Pilots or experts can be consulted for the change, and the changed cases may be stored to the base for further reuse.

Case invoking. For the cases that satisfy the requirements, they are invoked to the virtual environment, and the virtual human model expresses the motion of pilot naturally then. With the assistance of the model, the operation workspace of pilot and the spatial position of the device are determined; the constraints between the device arranging and other equipment will be established; the interference can be detected and the visibility can be evaluated.

The flowchart of reusing pilot motions for improving layout design of aircraft cockpit is shown in Fig. 7.

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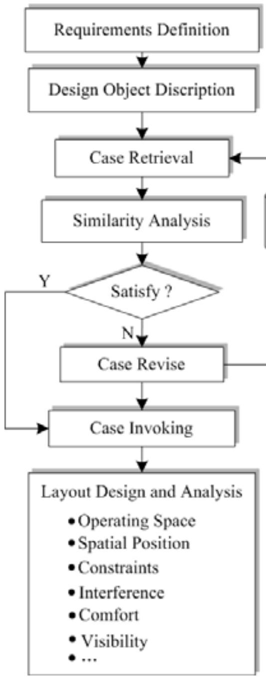

Figure 7. The flowchart of motion reuse

V. THE CASE STUDY

The thrust levers in the cockpit of a certain type civil aircraft in design are used as the study object. The pilot motion cases in the base are reused for improving the layout design of the thrust levers, the position of thrust levers on the pedestal is provided and the field of pilot's vision when operating the thrust levers is analyzed.

From the requirements defined, it is known that it is a medium-range civil transport aircraft, and has two engines mounted under the wings. The cockpit of the aircraft should accommodate two pilots and an observer. As main interface among the flight management guidance computer (FMGC), the full authority digital engine control system (FADEC) and the flight crew, the thrust levers to be arranged on the pedestal should be operated by both of the pilots to achieve the following functions in times of need: 1) manually select engine thrust; 2) arm and activate auto thrust (A/THR); 3) engage reverse thrust; 4) engage the takeoff and go around modes. The work detents of the thrust levers are shown in Fig. 8.

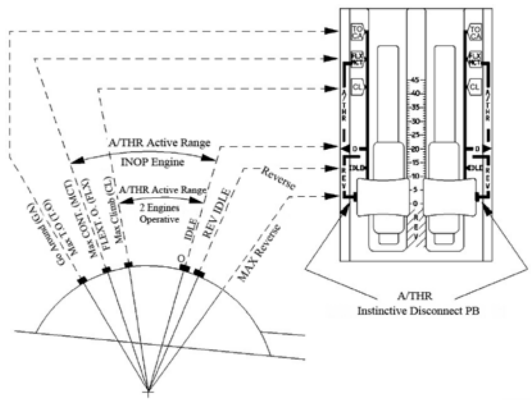

Figure 8. The work detents of the thrust levers

With the requirements of the thrust levers analyzed and the description of the device, the motion cases retrieved from the base are shown in Fig. 9 and Fig. 10.

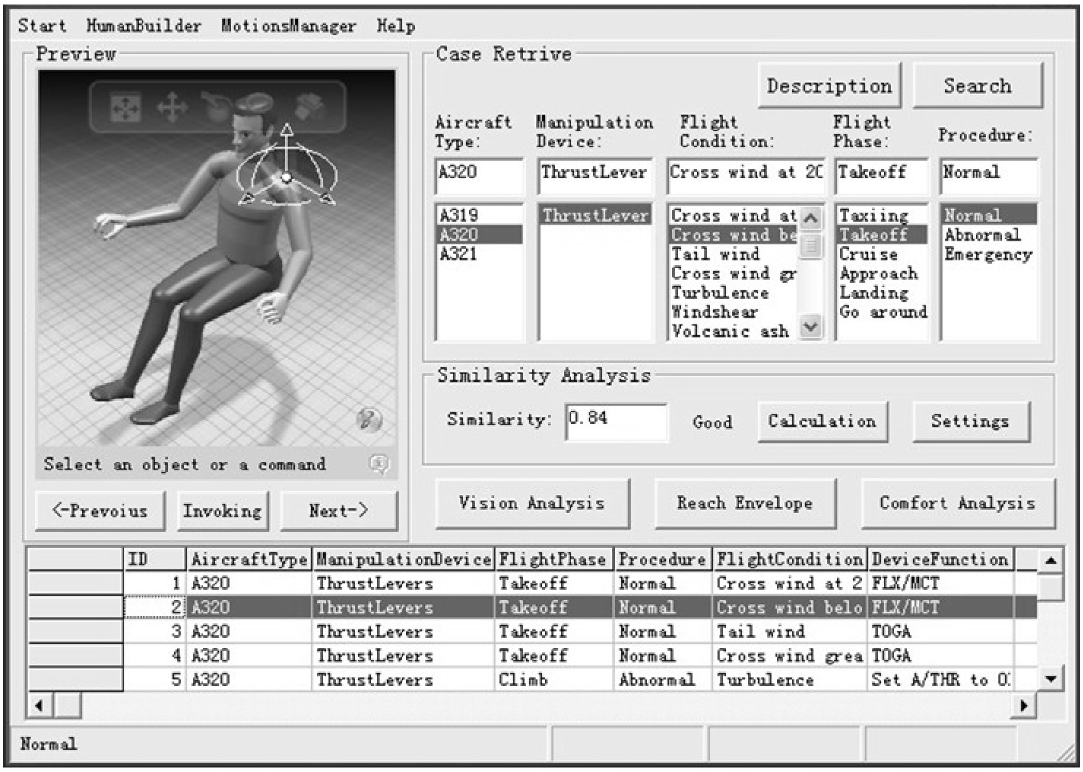

Figure 9. The main interface of case base

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Figure 10. Pilot motion cases retrieved

When the pilot motion cases have been invoked to the virtual environment, the workspace of the pilot under different conditions is analyzed using the virtual human model. The boundary of the motions could be determined with the help of the motion cases. Fig. 11 is the simulation results that shows the workspace when the virtual human model is operating the thrust levers, which provides the boundary constraint of spatial position of the thrust levers and the optimal region.

In terms of the simulation results, the thrust levers are arranged by analyzing the constraint and interference between the multipurpose control and display unit (MCDU) and the thrust levers. Fig. 12 shows the final position of thrust levers on the pedestal. The field of pilot's vision is analyzed, which indicates that the arrangement of the thrust levers meets the operation need of the pilot during the operation. The analysis results of the visibility of the pilot are shown in Fig. 13.

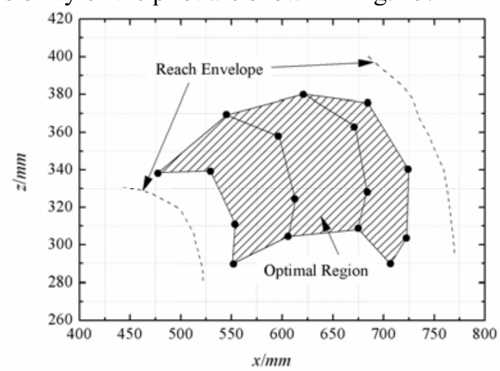

Figure 11. The distribution of work positions

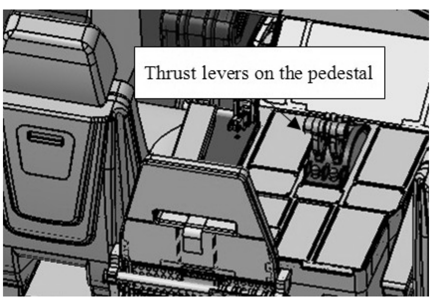

Figure 12. The position of thrust levers on the pedestal

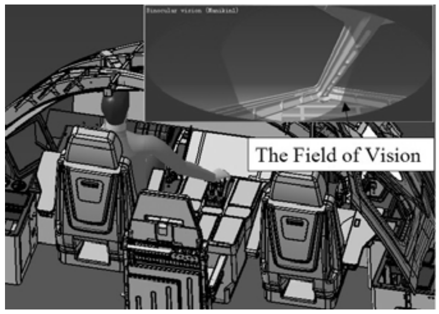

Figure 13. The field of the pilot's vision

VI. CONCLUSIONS

The pilot motions are inertial tracked with man-in-the-loop mode and the motions in each flight phase of the aircraft are obtained on the basis of the operation procedures under different conditions.

The virtual human model of pilot is developed, and the transformation between coordinate frames for the segment of the virtual human is provided. Furthermore, the pilot motions are represented by mapping the orientation of the pilot body segments to the virtual human models as motion cases.

The case base of pilot motions is established, and the reuse approach of the pilot motions is proposed based on case-based reasoning (CBR), so that the spatial position of the manipulation device can be determined with the assistance of the reused cases. The application instance presented in this work indicates that the approach proposed is effective and practical.

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