A Virtual Reality-Based Experiment Environment for Engine Assembly Line Workplace Planning and Ergonomics Evaluation

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Abstract. In this paper, an integrated virtual assembly simulation experiment environment of interactive workplace planning, assembly process simulation and ergonomics evaluation is built and it provides a new ways and means for interactive and visualized workplace design and process planning. A simple and effective method of measuring the movement manipulating data of operator is presented and can provide data source for ergonomics evaluation of the operator. In order to obtain these data in VE, movement data of the operator in real environment is transformed into VE and is related with virtual objects by the corresponding relation between VH and real hand (RH). Based on these data, the operator's fatigue index and energy consumption can be calculated. The conformability and fatigue of users for repetitive assembly operations are quantitatively evaluated to reduce the health problems of operators because of unreasonable layout and repetitive work.

Keywords: Virtual reality; Workplace planning; Virtual assembly; Data acquisition and processing; Ergonomics evaluation.

1 Introduction

To obtain optimizational assembly process and workplace layout, traditional workplace planning relies on the judgment and experience of industrial engineers and the repeated testing and improvement using physical model. At present, the method of automobile engine plant is to stop the production line specifically for the trial assembly. If a problem discovered in the course of the trial assembly. The problem is returned and improved the products assembly design in CAD or revised the assembly process and workplace planning information. This repeatedly suspended for trial assembly is not only a waste of resources but also affects the production progress.

To reduce/replace the trial assembly times of certification process design and workplace planning rationality, this paper proposes a solution: Workplace panning and assembly simulation virtual experiment environment (WPASVEE) is built using virtual reality (VR) technology. In WPASVEE, operators interactively implement workplace planning and assembly simulation by virtual hand (VH) using data gloves, position tracking device (Flock of Birds, FOB) and stereo glasses. Movement data of

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the operator can be real-time collected in the process of assembly. The quantitative indexes and evaluation methods of suitable for WPASVEE are built and a unified map relation of human motion data from WPASVEE to real environment is established. The conformability and fatigue of users for repetitive assembly operations are quantitatively evaluated to reduce the health problems of operators because of unreasonable layout and repetitive work.

2 Related Works

Applying computer-aided ergonomics to new product design improves the efficiency of product design and used [1]. The method has a potential to improve assembly productivity and ergonomics and offer a better understanding among product designers and production engineers in product development processes [2].

Chryssolouris [3] develops a virtual assembly work cell. Taking high-speed boat propeller as an example qualitatively evaluates human-process-related factors in the virtual assembly work cell. In the process of assembly, the qualitative evaluation of human-process-related factors such as the perception of the working environment, the interface with the work cell layout, the reachability of mounting locations, and the handlability of production component and tools, and the qualitative evaluation of human-process characteristics related to critical performance issues, such as the lifting capacity, the energy expenditure and the manual task cycle time, are implemented. However, the virtual assembly work cell doesn't support yet an exact representation of reality or specialized process characteristics.

Jayaram [4] introduces quantitative ergonomic analysis tools in real time for occupational ergonomic studies. The "Virtual Assembly Design Environment" (VADE) is used as VE. Human model is modeled using commercial ergonomics tool and is integrated into the VADE. Operators control the human model using interactive devices and implement assembly operation simulation. Finally, ergonomic issues are quantitatively analyzed in JACK according to operation-process data.

Rajan [5] develops an integrated VR-based environment JIGPRO for the analysis of assembly product and jig designs. CAD models of assembly product, jig and virtual hand are imported into the JIGPRO for assembly process simulation and accessibility analysis to ensure well capability of assembly and ergonomic for tools and fixtures designs.

A.Sundin [6] describes a case study of bus development and manufacturing process and presents a work process for analysis of time and ergonomic aspects in early design phases. The study focuses on a work process to visualize manual assembly and work postures for workers.

3 The Frame Structure of WPASVEE

The frame construction of WPASVEE is shown in Fig.1. The inputs of the WPASVEE are CAD assembly models and assembly process and workplace table that are obtained according to production standard and assembly sequence. They are transformed into the WPASVEE by secondary development interface.

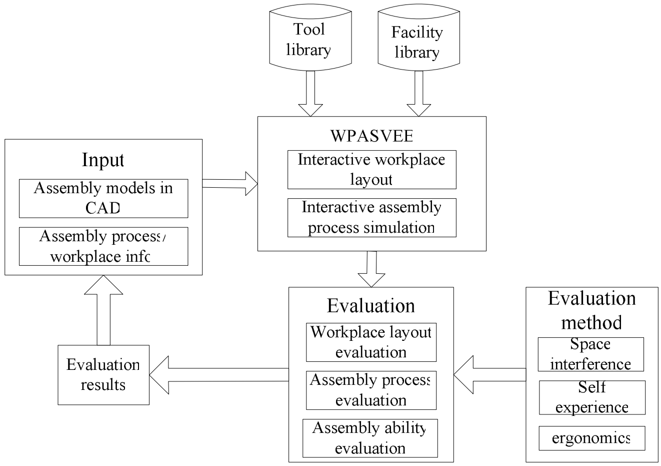

Fig. 1. The frame structure of virtual experimental environment

User can interactively layout workplace facilities and simulate assembly tasks according to the whole space of the workplace, facilities chosen and experiential knowledge using VR devices in the WPASVEE. In order to judge the reasonableness of the workplace design, on one hand, the workplace design is evaluated according to operator's the subjective experience; the other, it is quantitative evaluated by calculating LI and energy consumption according to the establishment of evaluating index, calculation equation and the operator movement data collected in the process of assembly. Finally, to improve design, the evaluation results will be returned to the CAD product design and assembly process/ workplace design. Ergonomic problems can be evaluated and found in early design phases. Assembly process and workplace layout are verified and evaluated before real production using VR technologies, thereby shortening the development cycle of new products, reducing costs and enhancing the competitiveness of their products.

4 The Key Technologies in the Virtual Experiment Environment

4.1 The Evaluation Methods Ergonomics-Based

The evaluation and analysis methods ergonomics-based are built in virtual experiment environment. The movement of data operator is recorded in the process of interactive operation. Fatigue index and energy expenditure of the operator are calculated and analyze based on these data.

NIOSH lifting equation [7-9] is to analyze fatigue grade for manual operation. The purpose of the method is to avoid or reduce the occurrence of lifting related low back pain(LBP), reduce other musculoskeletal disorders associated with lifting. The equation meets three criteria: biomechanical, physiological and psychophysical limitation. It provides with evaluating the lifting capacity of workers and meets acceptable lifting capacity of 75% of females (99% males). The outputs of the equation are Recommended Weight Limit (RWL) and Lifting Index (LI), where, LI is the ratio of the load lifted to the RWL.

For ergonomic risk assessment certain calculations determining workload are necessary. Energy consumption can be calculated applying mathematical methods. Energy consumption usually is transformed into metabolic energy expressed in vats (W), kcal/h or kcal/min. Further, energy consumption is equated to corresponding work severity categories [10].

Variables involved in the process of calculation are described in Table.1.

Table 1. The ergonomic models used in the WPASVEE

NIOSH equation	Energy consumption equation
$RWL = LC \cdot HM \cdot VM \cdot DM \cdot AM \cdot FM \cdot CM$ Where RWL: recommended weight limit(kg) LC: load constant=23kg HM: horizontal multiplier VM: vertical multiplier DM: distance multiplier AM: asymmetric multiplier FM: frequency multiplier CM: coupling multiplier LI=L/RWL Where LI: lifting index L: load weight(kg)	$A = \left(F \cdot H_n + \frac{F \cdot L}{9} + \frac{F \cdot H_O}{2} \right) \cdot K \cdot n$ Where A: amount of work(J) F: force applied(N) Hn: distance, in which the object is lifted(m) Ho: distance, in which the object is lowered(m) L: distance the object is moved horizontally(m) K: coefficient(biomechanical criterion)characterizing moving individual sections of the body and equal to 6 n: number of equal technological cycles in the given or shift

For NIOSH equation, LI<1.0 will protect most workers, LI>1.0 exists potential hazard to most workers and LI>3.0 nearly all workers are at increased risk.

For energy consumption, Institute of Health of Chinese Academy of Medical Sciences [11] studies the relation between working time and energy consumption for representative 262 kinds occupation in china. The conclusion is the limitation value of energy consumption should be from 1400 to 1600kcal in a working day (8 hour) and can't exceed 2000kcal.

4.2 Operator Movement Data Acquisition

The VH isn't completely corresponding with RH from the overall perspective because it is controlled by increment of tracker in WPASVEE. Moreover, the operator can't fully immersed in VE because he is replaced by VH and no virtual human in VE. It is very difficulty to obtain parameters needed of the above quantitative evaluation criteria and methods from the process of VA. Therefore, movement data obtained must be transformed into WPASVEE and associated with the operation objects together by the corresponding relation between the VH and the RH.

Two FOBs, which the corresponding coordinates are the CB and CH respectively, is fixed on the operator's left hand (right hand in the same way) and vertebra surface as shown in Fig. 2. Co coordinates of the human operator.

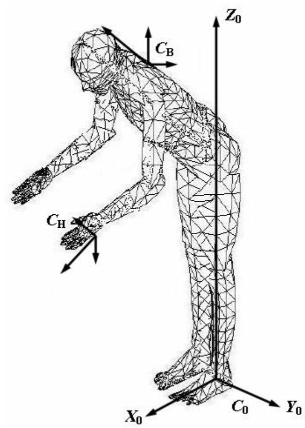

Fig. 2. Fixture location of FOB

The measurement steps include:

(1) Data samples. In a workplace, for each operation object (directly manipulated by hand) corresponds to a set of data; the each group data collected include starting and ending points in two parts, respectively.

(2) Data calibration. Before the operation began, the pose of the operator is calibrated firstly: the waist of the operator should be straight; position and orientation matrix M_{B0} of the FOB on the waist is recorded when FOB is activated.

(3) Data collection. In the process of VA, position and orientation matrix M_B of the FOB on the waist and M_{VH} of the FOB on the hand are recorded when operation object is first grasped. The coordinate origin of the object grasped is $P_0(x, y, z)$ under the world coordinate system and the quality of the object is L_{avg}. The position and orientation matrix M_B' of the FOB on the waist and M_{VH}' of the FOB on the hand are recorded when the object is released, the coordinate origin of the object released is $P_1(x, y, z)$. Existing data are replaced by current data at each releasing the object until assembly tasks are over.

(4) Determining fixed transformation. The position and orientation matrix M_{H-FOB} is a fixed transformation of FOB on data gloves relative to VH.

4.3 Operator Movement Data Processing

The known quantities include arbitrary point p_0 and normal vector n_0 of the workshop ground in WPASVEE, the operator's height h and the ratio coefficient μ between waist joint and h in the process of solving.

Data processing process is divided into the following six steps :

(1) Solve the position and orientation matrix M_{B-V} of the FOB on the operator’s back in WPASVEE when the VH is corresponding with the RH and when VH counterparts. The method includes:

Step1 : Solve the position and orientation matrix M_{VH-FOB} of FOB on the RH relative the VH in WPASVEE:

$$M_{VH-FOB} = M_{H-FOB} \times M_{VH} \tag{1}$$

Step2 : Solve the position and orientation matrix M_{H-V} of the RH in WPASVEE:

$$M_{H-V} = (M_{H-FOB})^{-1} \times M_{H} \tag{2}$$

Step3 : Solve the fixed transformation matrix M_{VH-H} between the RH in WPASVEE and the VH:

$$M_{VH-H} = M_{V-H} \times M_{VH}^{-1} \tag{3}$$

Step4 : Solve the position and orientation matrix M_{B-V} of FOB on the operator’s back in WPASVEE:

$$M_{B-V} = (M_{VH-H})^{-1} \times M_{B} \tag{4}$$

(2) Build the coordinate system C_0 of the operator in WPASVEE:

The Z axis is upward vector and perpendicular to the ground through the center O1 point of the lumbar; X axis is an intersection line between sagittal plane of the operator and the ground; and Y axis is defined according the right rules, as C0 illustrated in Fig. 3. The calculation method shown in Fig. 3: A is origin point of M_{B0}, B is origin point of M_B, A' and B' are projective points form the point A and B to the ground, O_1 is central point of waist joint of the operator, and CD parallels to $A'B'$ through the point O_1.

Known quantity: The coordinate value of the point A and B are (x_A, y_A, z_A) and (x_B, y_B, z_B), respectively.

The solving steps are:

Step1 : Calculate the coordinate value of A' and B' by the point and normal vector of the ground and coordinate of the point A and B, then the direction of X axis of C_0 should be $\overrightarrow{A'B'}$.

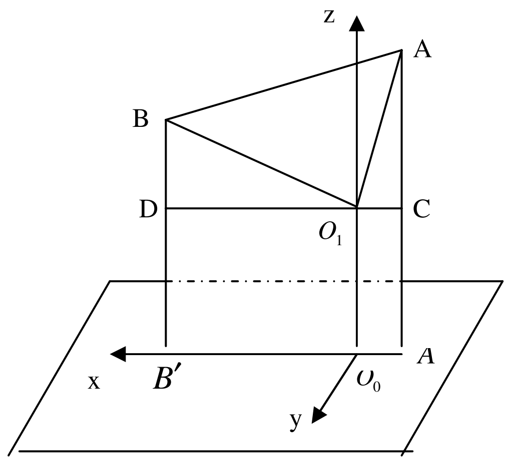

Fig. 3. Coordinate system in virtual environment

Step2：The length of O_0A' is calculated by the equation:

$$\left(|BB'|-h\cdot\mu\right)^2+\left(|A'B'|-|O_0A'|\right)^2=\left(|AB'|-h\cdot\mu\right)^2+|O_0A'|^2 \qquad (5)$$

Step3：The coordinate of O_0 is calculated according to the length of O_0A' and the coordinate of A' and B';

Step4：Build the CS C_0 whose z axis is normal vector of the ground, x axis is $\overrightarrow{A'B'}$, y axis meets the right rules and origin point is O_0.

(3) Solve the horizontal position H (distance of hands from midpoint between ankles) and vertical position V (the starting height of the hands from the ground).

Step1：Build the coordinate system C_0 of the operator in WPASVEE according to the methods and principles above.

Step2：Solve the matrix M_{B-V}' and M_{VH}' by transformation M_{B-V} and M_{VH} to CS C_0;

Step3：Obtain the origin point $P(x, y, z)$ of the position and orientation M_{VH}';

Step4：Then, obtain the horizontal position $H = x$ and vertical position $V = z$ of the RH.

(4) Solve the rotation angle A of the operator in the process of operating a object.

Step1：Solve the matrix M_{B0}' by transformation M_{B0} to CS C_0;

Step2：Calculate the increment matrix ΔM_{B-C} from M_{B0}' to M_{B-V}';

Step3：Calculate the angle A of ΔM_{B-C} around z axis of CS C_0.

(5) Calculate the vertical distance D

Step1 : For each set data obtained, its start point $P_0(x_0, y_0, z_0)$ and end point $P_1(x_1, y_1, z_1)$ of $M_{VH}{}'$ are calculated using the above method, respectively.

Step2: Calculate the vertical distance D of RH from start point to end point, $D' = z_1 - z_0$, $D = |D'|$

(6) Calculated the horizontal distance L and the lifting height H_m or the lowering distance H_n

Step 1 : $h = P_{1z} - P_{0z}$,if $h \geq 0$, then, $H_n = 0$ and if $h < 0$, then $H_m = 0$ and $H_n = |h|$;

Step2 : Calculate the projective points $P_0'(x, y, z)$ and $P_1'(x, y, z)$ by projecting $P_0(x, y, z)$ and $P_1(x, y, z)$ to the ground of the plant floor ;

Step3 : Calculate L : $L = \left| P_0' P_1' \right|$ 。

These relevant data are obtained by the above measurement and processing methods. The fatigue index and energy consumption will be calculated by incorporated these data into the NIOSH equation and energy equation in Table 1.

5 Example

In order to verify above theories and methods, an example of the workplace planning of engine crankshaft in assembly line is given. The virtual scene of workplace layout and assembly operation is described in Fig. 4. In the workplace, first, crankshaft is assembled to cylinder body by crane; second, five bear caps are assembled to cylinder body to fix the crankshaft; then ten bolts is inserted into ten tap holes on five bear caps; finally, the ten tap holes are tightened by tool to fix the crankshaft on the cylinder body.

Fig. 4. Data measurement of operator in VA

In the process of assembly operation, three FOBs are fixed on both hands and back of the operator. Before the operation began, the operator should calibrate his pose firstly. The position and orientation matrix of each FOB are recorded when the object is grasped and released by VH. When these data are collected, the data needed for planning and evaluation workplace is obtained according to above methods. The results are shown in Fig. 5 for the operator in the crankshaft assembly workplace.

Based on the above data and the calculation methods in Table 1, the fatigue index of operator is $CLI = 0.474$, and energy expenditure is 2128J through calculating in the workplace of crankshaft assembly,. In order to the correctness of and evaluation models and data measurement and treatment methods are verified by commercial software JACK.

In JACK (Fig.6), set parameters include operating frequency of Labor experienced cycles and rest interval. These parameters should be set up in line with the WPASVEE. The results is calculated, LI equivalent to the value of 0.465; 525kcal task is in a cycle energy consumption. WPASVEE with the experimental data is very close to that from an engineering point of view, the outcome is feasible.

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Task# Description Avg. Load Max. Load O.H. O.V. D.H. D.V. Dist O.A. D.A.
100 安装轴瓦1 0.037 0.4 25.912 71.507 29.746 96.621 25.114 1 1
200 安装轴瓦2 0.037 0.5 29.746 73.621 37.963 99.163 25.542 1 1
300 安装轴瓦3 0.037 0.5 30.963 94.163 34.638 68.625 25.538 1 1
400 安装轴瓦4 0.037 0.5 30.010 91.490 26.210 65.621 25.869 1 1
500 安装轴瓦5 0.037 0.5 25.058 90.623 26.313 63.677 26.946 1 1
600 轴承盖1 0.507 1 26.056 71.624 51.249 101.391 29.767 1 1
700 轴承盖2 0.507 1 26.062 71.623 49.289 105.142 33.519 1 1
800 轴承盖3 0.507 1 26.054 71.624 59.097 104.775 33.151 8.973 8.9
900 轴承盖4 0.507 1 26.059 71.623 54.990 105.361 33.738 1 1
1000 轴承盖5 0.507 1 26.064 71.623 55.692 106.317 34.694 8.976 8.6
1100 螺栓1 0.047 1 26.064 71.623 54.476 108.492 36.869 8.962 9
1200 螺栓2 0.047 1 43.433 79.617 51.523 104.924 25.307 1 1
1300 螺栓3 0.047 1 47.924 82.199 55.798 107.220 25.021 1 1
1400 螺栓4 0.047 1 47.923 82.200 53.639 107.966 25.766 1 1
1500 螺栓5 0.047 1 47.922 82.200 52.532 109.716 27.516 1 1
1600 螺栓6 0.047 1 57.083 82.711 50.370 110.499 27.788 1.840 2
1700 螺栓7 0.047 1 57.084 82.711 55.224 109.422 26.711 1.840 1
1800 螺栓8 0.047 1 59.518 81.653 51.199 112.732 31.079 1 1
1900 螺栓9 0.047 1 57.055 83.724 52.487 114.337 30.613 42 42.694
2000 螺栓10 0.047 1 57.055 83.724 51.664 111.701 27.977 0.921 9.724
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Fig. 5. The data result file of operator in crankshaft assembly workplace

Fig. 6. The assembly tasks simulation in JACK

6 Summary

Traditional assembly line planning and ergonomics evaluation is implemented through the collection plentiful movement data of operator. The method is time-consuming and expensive. A large amount of data is needed for solving new similar problems such as evaluation the conformability and efficiency of the operator; and then the results are verified and further improved in the physical environment.

An integrated virtual experiment environment is built for interactive workplace planning, assembly simulation and evaluation. The environment provided a new way and mean for interactive and visual workplace design and process planning.

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