Aircraft Design for Maintainability

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Maintainability of aircraft can be enhanced during design by attending to the capacities and limitations of the people who are expected to maintain the aircraft. One tool for examining the interaction of maintenance personnel and aircraft structure or equipment is a computer-generated human model. Human models can be merged with computer-aided-design (CAD) electronic drawings of aircraft structure to simulate segments of maintenance tasks. Predictions of maintainers' performance can then be based on the simulations. The process of creating simulations and extracting information from them requires the definition of a maintenance task and maintainer population, identification of critical task segments, preparation of a structure file and merging the human model, and interpreting the resulting simulation. Whereas rules and constraints help to guide selection, sizing, and merging of a human model, inference based on knowledge of human performance is important for extraction of information from a simulation.

Introduction

INCREASING attention in aerospace to the cost of aircraft maintenance is driving innovations in purposeful design for maintainability. One innovation is the merging of computer-drawn anthropomorphic models (human models) with computer-aided-design (CAD) models of vehicles. Essentially, human models are sets of anthropometric and biomechanical data transformed into human form entities compatible with the geometric environment of CAD. This paper is intended to acquaint engineers in design, maintainability, and human factors with the process of design for maintainability with computer simulation of maintenance and to indicate a few of the many literature sources that contain information for the human modeling specialist. Although simulation of many performance factors such as anthropomorphics (size and shape of persons), biodynamics, strength, vision, and apparel is possible, this paper emphasizes static simulation of anthropomorphic factors with inference to human movement. Reference to persons in the masculine refers to both men and women, except in specific, obvious references to male or female members of populations.

The application of anthropometric data to engineering is an established discipline.[1] In aerospace, highly accurate manikins of plastic or wood, and more recently electronic human models, have been used to consider human needs early in the design stage or to evaluate designs. This practice has mainly involved operations (e.g., cockpit) questions.[2] Use of human models in design for maintainability is fairly recent, and opportunities to perform this modeling in CAD carry important advantages not previously available with physical manikins. Among the advantages are automated drawing of figures in postures with accurate joint centers, rapid assessment of performance of different human populations, rotatable three-dimensional images, and a reduction of dependence on physical mock-ups for maintainability tests.

In conceptual design, when maintainability requirements are global, application of general human engineering principles is often adequate, but in preliminary and detail design, specific questions may arise about demands for unusual postures, tool use clearances, and related matters that are not answered by general principles. Thus, maintenance simulation is more common after conceptual design. It should be noted that although relatively simple examples of design for maintainability are discussed in this paper, use of simulation should be carefully considered and possibly reserved for more difficult problems if the process is expensive for a company.

The following sections present the elements of maintenance simulation for preliminary and detail design in a process-oriented format. Process is stressed in this paper in order to suggest how anthropometric data can enter into maintainability concerns in a CAD environment and to direct the reader's attention to necessary interactions among engineers in planning for maintenance.

Defining the Task to be Simulated and the Maintainer Population

Definition at this level should reveal the maintenance objective and approach. This knowledge makes the selection of critical task segments possible and provides insight into alternative maintenance approaches. Information about the task that should be gathered includes the objective; support equipment, tools, and special preparations needed; and location on the aircraft and constraints that the location presents. Definitions of common maintenance tasks, such as "inspect," "install," and "operate," that are helpful in stating the task objective are contained in MIL-STD-1388-2A, DOD Requirements for a Logistic support Analysis Record.[3] A guide to describing the support equipment, tools, access, etc., for common maintenance tasks such as removal and replacement is available in Appendices A and B of AD-1410, Aeronautical Data, Design for Maintainer Program Requirements.[4] Examples of the categories of information specified for removal and replacement tasks in the appendices are listed in Table 1. Information of this sort can also be obtained from a task analysis, if one is available. If the task to be simulated is not

Table 1 Removal and replacement task information specified in AD-1410

Weight of component
Component envelope (dimensions)
Mounting provisions and connections
Location installation
Number of personnel
Removal and installation procedures
Visual and physical access
Lifting/carrying requirements
Safety considerations

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Table 2 Selected anthropometric dimensions in pounds and inches for 95th percentile males

	USAF 1965 Nonflying (Crew Chief)	MIL-STD-1472C Ground troops	NHES, 1962 Civilian
Weight	194.0	201.9	214.0
Stature	73.2	73.1	72.6
Functional reach	34.0	35.8	34.8[a]
Hip breadth, sitting	15.8	15.1	16.0
Chest depth	10.1	10.5	10.9[a]

[a]Values from the derivation method of McConville.[8]

described in writing at a level exemplified in AD-1410, the human modeling specialist should at least know the task at this level.

If a company's human modeling capabilities are sophisticated, users can select from a menu of populations. A population in this context refers to the group of people from whom anthropometric data are obtained. Choosing a population that represents the people who will maintain an aircraft is not straightforward because few data from this group are available, although data underlying the Air Force model called Crew Chief may be one exception to this deficiency. Crew Chief is based on the human model called COMBIMAN[5] and is intended to represent Air Force maintainers.

Despite the importance of Crew Chief, modeling with this program may be unfeasible in some design situations. Therefore, different models based on military data, even though these data are not necessarily drawn from maintainers, might be used to model maintainers. For models of civilian maintainers, who probably tend to be heavier and more varied in body dimensions than their military counterparts, a model based on data from civilians is preferable. Limited data from civilian surveys[6] and from small samples of industrial workers[7] are available. Derivations of civilian dimensions from military data[8] have produced values more appropriate for civilian populations, but, unfortunately, few of these dimensions are currently available.

The importance of selection of populations is illustrated in Table 2, which presents dimensions for selected measurements from several anthropometric data bases: 1) a 1965 survey of U. S. Air Force enlistees (upon which Crew Chief is based), 2) MIL-STD-1472C, Human Engineering Design Criteria for Military Systems, Equipment, and Facilities,[9] and 3) the 1962 National Health Examination Survey (NHES).[2] For example, chest-depth values indicate that designing for access for large men under Crew Chief guidance results in too little space for large civilian men.

Simulation of a particular percentile—for example the 95th—usually refers to generating a human model with body dimensions that are greater than those of 95% of the population. Other model generation methods produce more realistic models by setting selection criteria according to one or two percentile requirements (such as stature and arm length) then randomly picking remaining dimensions within limits that are found in the population of interest. Some questions of reach and manipulation require simulation of the 5th and 95th percentile maintainers; when clearance is the concern, simulating the 95th percentile will often suffice.[7]

If maintainers must wear arctic apparel or other encumbering gear, clearance needs will be greater. Design requirements may dictate that apparel be considered.

Identifying Critical Maintenance Task Segments

Usually, before the maintenance task is well understood and its steps written out, some portion is perceived as a very difficult one for maintainers and generates an implied question and the initial interest in simulation. Regardless of the human model software used, the modeling specialist should obtain agreement among involved persons on the form of the question and assure himself that it is indeed a significant one. A question might be "bumped" by a related matter that appears after study to be more critical. For example, space to manipulate tools is a frequent issue, but access to the area of tool use may not be possible, and therefore access becomes a more important question. Examples of questions include the following. Can the maintainer reach (name of component) from (name of location)? Can the maintainer perform (name of task) and remain clear of (name of hazard)?

Critical segments are those aspects of a task (usually some aspect of a single step in a maintenance task) that are expected to "test" the question that initially prompts a simulation. Generally, this step is akin to describing a "nominal work space body position"[1] that serves as a station to perform limb movements or as a difficult point within a progression of whole body movements. Much like human engineering test programs,[10] this process requires insight, visualization, and some imagination regarding numerous possibilities of human fit and function, such as how a maintainer might maneuver himself into position or how he might support a load.

An important principle in describing body positions is that joints should not exceed their ranges of motion.[11,12] Maximum joint angles vary across populations, age divisions, types of apparel, and size of the subject, so knowledge of these effects is vital for the human modeling specialist. NASA human engineering standards recommend that 5th percentile joint angle limits (smaller angles) be used when design must allow personnel to position themselves to operate or maintain equipment and that 95th percentile limits (larger angles) be used when design must accommodate a full range of movement.[13] For a task segment requiring the maintainer to hold his body position for one or more minutes, joint angles for body positions should be selected to minimize joint loads.[1,14]

The body position selected in this step may conform to one of many in a "library" of postures. The advantage to such collections of postures is that close approximations to reasonable postures for many maintenance tasks can be quickly envisioned. With one method developed recently by Kroemer, postures are created by joining drawings of body portions coded for joint angles. The method results in combinations called "penguins" because black and white coloring is used to distinguish the body portion of interest from reference portions.[15]

The segment should be stated in writing with terms that imply its kinematics so that anthropometric or other human engineering conclusions drawn from the simulation can be appropriately referred to the task segment. For example, the phrase "lie prone, hold grease gun against lub fitting with right hand, press handle of grease gun with left hand" implies kinematics whereas the phrase "lubricate bearing" does not. Other examples of critical segments in correct terms are "stand on ladder, support module with left hand" and "crawl through access hole."

A static simulation may reveal several aspects of the maintainer's task that are relevant to design, and a dynamic simulation would almost certainly reveal multiple aspects. When a

Table 3 Verbs and verb phrases to specify aspects of maintenance task segments

Stand	Crawl	Hold
Sit	Crawl through	Squeeze
Lie prone	Position (the body)	Twist
Lie supine	Maneuver	Rotate
Lie on side	Balance	Push
Squat	Lean	Pull
Kneel on one knee	Stoop	Lift
Kneel on two knees	Reach	Support
Move	Touch	Carry
Step	Press	Pick up
Walk	Grip	Set down
Climb	Grasp	Look

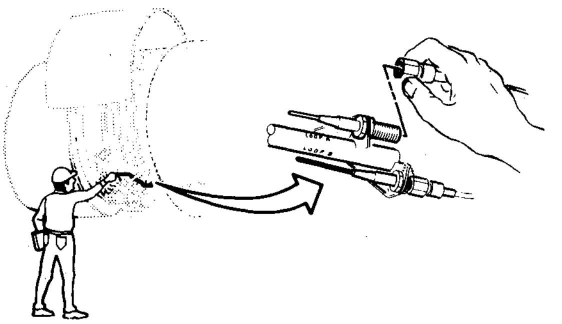

Fig. 1 Critical task segment developed from maintenance task step.

simulation is created to disclose more than one aspect of a task with relevance to design, more than one verb implying kinematics must be used to specify the segment. Words and phrases that imply kinematics are given in Table 3.

On rare occasions, written maintenance procedures will have evolved concurrently with a suspicion that maintainers will not be able to do the task. In such a case, the critical segment may be a transformation of one of the written steps into kinematic language. For military programs, the task description might be available in the form of a Logistics Support Analysis Record; for civilian applications, the maintenance task description might be available. For example, Fig. 1 illustrates a step in a DC-10 fire detection system cable continuity test.[16] The written maintenance step and its transformation into kinematic terms are shown below the drawing.

After a critical task segment has been specified, it should be described in joint configuration terms that focus attention on key aspects of the simulation. Key movements of the body that are to be visualized with the aid of the simulation should also be stated. Virtually all motion types of importance to maintenance (with the exception of dexterous hand and finger movements) can be described with terms for mobility measurement found in Roebuck et al.[1] The joint movement terminology in Roebuck et al. was developed for engineering purposes and avoids the difficulties and confusions of classical movement descriptions. For example, in standard terminology, abduction refers to movement of a limb away from the body centerline, but abduction of the shoulder past 90 deg will move the limb toward the body centerline. The Roebuck system describes movements according to plane, direction, and type to resolve such inconsistencies. The following are mobility terms used in this paper shown with their conventional versions in parentheses: 1) upper leg saginvection—sagevection (hip extension—flexion); 2) lower leg saginvection—sagevection (knee flexion—extension and hyperextension); 3) leg frontevection—frontinvection (hip abduction—adduction); and 4) thorax (chest) transerotation—transinrotation (trunk rotation—right, left).

Crucial static aspects of a simulation, such as holding a posture or applying force, can be described with terms for static conditions found in Hertzberg.[14]

Figure 2 presents a drawing that simulates the critical segment of a task. The maintainer's objective is to remove an integrated flight control module (IFCM) from the rear spar of a military transport aircraft's vertical stabilizer.

The maintainer is shown lying on his right side on one of the ribs (support equipment would protect the rib) with his right foot near the rear spar. In this plan view, the module and linkage appear to be at the same level as the maintainer, but they are actually situated in an inter-rib bay above the maintainer. In order to disengage couplings, remove fasteners, and pull the module away from the spar, the maintainer must maneuver himself into an upright position in lightening holes (the smaller of the two large openings in the ribs) near the spar. Thus the question is "Can a large maintainer maneuver himself into the rib holes near the rear spar?" Table 4 gives statements of the task, question, critical task segment, and description of key aspects in joint configuration terms relevant to this task.

Merging Files

The CAD file representing structure or equipment with which the maintainer is to interact must meet several requirements. It must be in three dimensions, be accurate, and not consume so much memory that merging of human model files is prevented. It may be necessary for a human modeling specialist who is also skilled in CAD to add the third dimension to certain files and to coordinate among various designers to

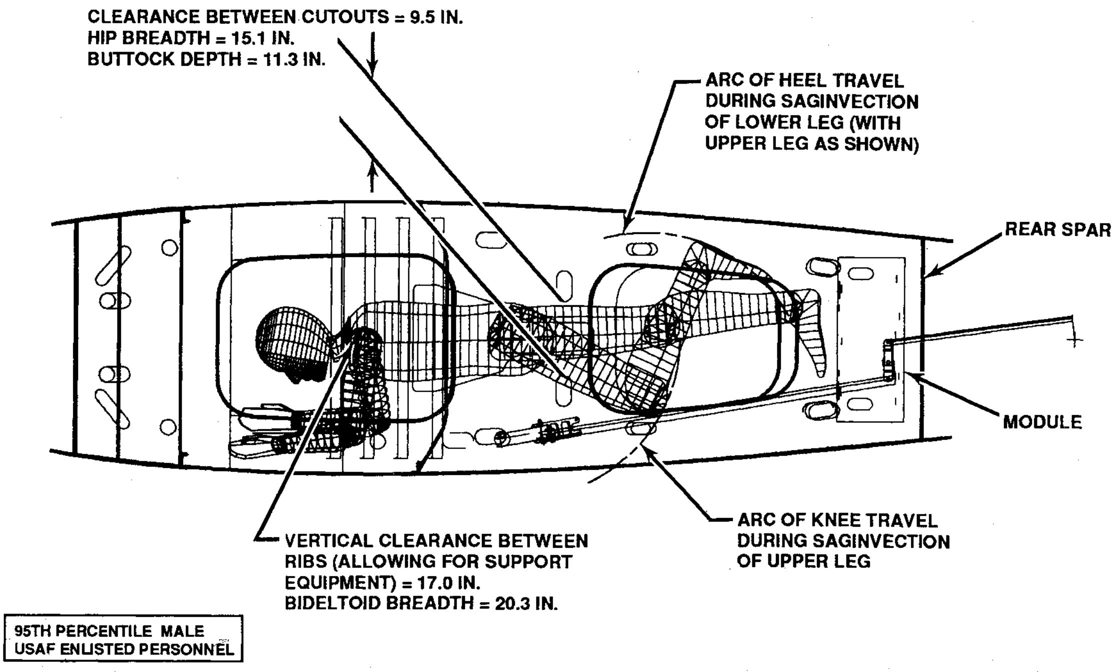

Fig. 2 Simulation of maintainer lying on side between ribs of vertical stabilizer.

insure the accuracy of files that will be merged to support human modeling.

Although the figures in this paper present wireframe drawings, surfaced drawings are preferable because they enable better collision detection and visualization. However, regardless of the construction of drawings, the modeling specialist may need to delete some details from structure files, such as lines of rivets if they are not relevant to the simulation, in order to reserve memory space for merging the human model.

The efficiency of a human model becomes apparent when it is merged with a drawing of structure to create a three-dimensional representation of structure/human interface. Placement of the human form is guided by the question that prompted simulation and requires consideration of support surfaces, available space for the human form, direction of gravity, and the nature of the critical segment being modeled. In practical terms, the model user selects coordinates that locate a human model reference point in the drawing of structure, and then complex CAD routines draw a human form in the previously selected body position.

The resulting structure/maintainer merged image can be rotated to detect collision between the two entities and, if any is found, joint angles can be adjusted until clearance is obtained or the severity of collision is reduced. Ideally, human model software contains the capability to detect these obstructions and to rotate joints around their centers within accurate ranges of motion.

Interpreting a Maintenance Simulation

To interpret a simulation, the specialist must extract useful information, visualize the task segment using the simulation as an aid, infer by extending available information to the conditions of the task segment, and apply judgment based on inferences.

Extraction of useful information means to obtain data such as loads, moments, joint angles, clearance dimensions, and collisions using the geometric capabilities of the host computer system and to conduct analyses of human performance factors. Although anthropomorphics and inferred motion are the emphases of this paper, factors such as strength and vision may be analyzed with human model software if these routines are available and valid. Analytic routines are useful but may leave some questions unanswered because the complexities of human performance are beyond the capability of such techniques.

Visualization is the human ability to create internal visual images and to find meaning in complex visual scenes. It is a common and valid method for the engineer to make sense out of vast amounts of data.[17] In maintenance simulation, the human modeling specialist must regard the data—presented as a human form entity—as a representation of a maintainer with a goal. Simulation of critical task segments usually means that a goal is expressed as the potential for various types and directions of movements, so the task of the modeling specialist is to visualize how the maintainer would move his limbs or exert force to carry out the task segment.

Inference and judgment follow from the visualization of a maintainer's interaction with the physical environment. Inference can apply to anthropomorphic and other conditions, and some of these may have the potential to limit the accomplishment of the task segment. Candidates include demands for reach, clearance, and strength[14,18,19]; space needed for manipulation of tools[20]; restrictive effects of apparel[7,14]; demands for visibility[21,22]; conditions that reduce sense of balance and position[23]; demands for fine control of movements[24]; and others. The modeling specialist applies judgment when he estimates the likelihood of performance of key aspects of the simulated task segment and draws a conclusion about the implications of the design for human performance.

In the task shown in Fig. 2 for example, the most telling information that can be extracted from the simulation is the distance between cable runs (shown as cutouts on either side of the maintainer's hips). This clearance is 9.5 in., and so the modeling specialist can conclude that whether the maintainer is on his side or lying prone or supine, he will not be able to move his hips past the cable runs.

A slightly changed design could provide for cable run placement that is just sufficient for buttock-depth clearance (maintainer lying on his side) and a vertical distance between the ribs that is sufficient for shoulder (bideltoid) breadth. In this case, the modeling specialist would visualize how a maintainer would move his limbs as he attempted to move his whole body into the cavity created by the lightening holes near the rear spar. Key movements pertaining to the task segment include upper leg sagevection (to bring foot toward body), lower leg saginvection and sagevection (to set foot over lightening hole), leg frontevection and frontinvection (to raise hip above support surface), and hip transerotation and transinrotation (to direct legs down into lightening hole). Movements of the feet, shoulder, and upper and lower arms would also be important in the maintainer's attempts to move his body but would be less critical to this task segment than the movements described above.

For the changed design, visualization with the simulation shown in Fig. 2 enables the modeling specialist to infer that a maintainer's movements in attempting to maneuver himself into the lightening holes would not be successful. Restricted to lying on his side, the maintainer could move his legs into the lightening holes, and if he moved farther toward the rear spar before bending his knees, he would have even less space to move his legs to the necessary location. So in either the original design or the slightly changed version, the modeling specialist would conclude that a large maintainer would not be able to maneuver himself into the lightening holes. The task segment is critical to the degree that removal of the flight control module could not be accomplished by a large man at least because of this segment. The implication for design is that the module should not be located on the forward side of the rear spar if large (95th percentile male) maintainers must be accommodated. Instead, other locations for the module should be considered.

Figure 3 presents a simulation of access into a wing fuel cell for a civilian transport aircraft. In this case, all the access holes were sized for the largest man that the constraints of the wing design would allow, and access through the hole into the smallest cell by a 5th percentile civilian male was simulated. (Anthropometric dimensions from subjects dressed only in undergarments indicate that a large man could squeeze through the access leading to the smallest fuel cell, but typical clothing or protective gear would be enough to prevent passage.) For whole body access into the fuel cell, the maintainer would be prevented from moving forward by the rib at his

Table 4 Narrative statements for simulation of integrated flight control module removal

Task:	Remove upper IFCM from rear spar of vertical stabilizer.
Question:	Can a large maintainer maneuver himself into the rib holes near the rear spar?
Critical segment:	Maintainer lies on right side on stabilizer rib, feet toward rear spar, body as near as possible to spar.
Description:	Body lying on right side (assumed support equipment), thorax and head in anatomical position (normal), right upper and lower leg and foot normal, left upper leg sagevected 30 deg, left lower leg saginvected 90 deg, left foot normal, shoulders normal, upper and lower arms sagevected to avoid collision with structure.

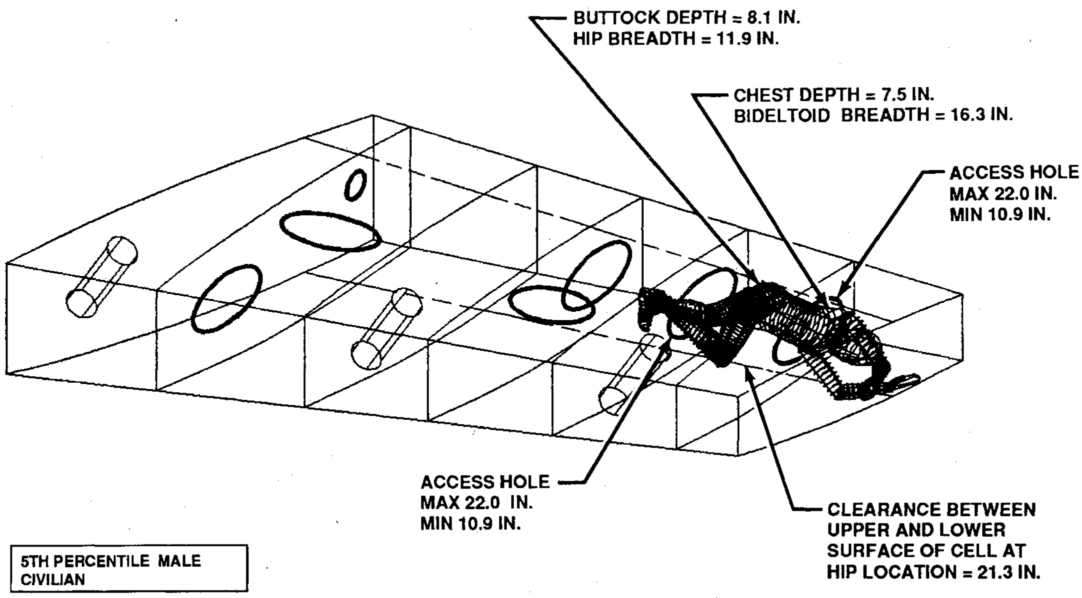

Fig. 3 Simulation of maintainer crawling through access holes in wing.

right hand, so the modeling specialist would visualize thoracic rotation and vection (twisting and bending of the trunk) as the maintainer attempted to move his hip through the access hole.

One inference from the fuel cell task segment is that due to the need for substantial thoracic rotation, the hips would also be rotated and hip breadth would then exceed the minimum dimension of the elliptical access hole. The modeling specialist would conclude that a small man could pass his shoulders and chest through the access hole, but passing the whole body through would be extremely difficult due to the narrow width of the cell. Access into the cell would be much more likely if the access concept called for an entry port through the top skin.

Finally, reporting is so important to justifying conclusions and avoiding duplication of work that it should be noted.[25] Reports should always contain sufficient detail to support conclusions and to indicate analytic methods and data sources. A report should include 1) a statement of the maintenance task under study, 2) illustrations showing key dimensions of the work site, 3) the question driving the simulation, 4) a description of the critical task segment in terms implying kinematics and in joint configuration terms, 5) descriptions of the population(s) used for the simulation, and 6) judgments or estimates of task segment performance as a function of human capacity and the relevant aircraft structure.

Conclusion

The process that has been outlined and the examples presented explain the use of maintenance simulation in aircraft design for maintainability. Overall equipment time to repair can be significantly reduced through the application of human engineering criteria,[26] and maintenance simulation is an effective method of applying criteria in early design.

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