Human: An Autocad based three dimensional anthropometric human model for workstation design

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Abstract

A three dimensional (3D) human modeling program has been developed to work in conjunction with computer aided design software, Autocad. The program allows the creation and manipulation of variable size, 3D human models and provides the flexibility of a professional CAD system. The special features of the program and its application in workstation design are described and illustrated with examples. This program operates on a personal computer and provides a low cost but effective alternative to main-frame based similar systems.

1. Introduction

An industrial workstation may consist of several physical components such as assembly area, seat, hand tools, various controls and displays, incoming and outgoing product bins, conveyors, complex machinery, electronics and electrical control panels. The design of a workstation involves laying out the necessary components within the space allocated for the workstation while maintaining the technical constraints of their finite sizes and physical and functional inter-relationships. In spite of these constraints, usually the designers have considerable latitude in making their layout decisions. It has long been established that other than the factors such as cost, productivity and reliability, ergonomics plays a

prominent role in deciding the workstation dimensions and layout decisions. In workstation design, the ergonomics consideration involves matching the physical characteristics and layout of components in relation to the anthropometric characteristics of the anticipated user population. This matching includes spatial accommodation, adequacy of posture, positioning of controls according to function, the ability to reach and see all the necessary working elements, adequacy of strength to operate the controls, ingress, egress and free mobility of the workstation users.

In designing workstation, conventional methods of evaluating human–machine compatibility involved the use of flat card board manikins along with layout drawings, or the construction of mockup workstation with evaluation by live subjects. These procedures are expensive, time consuming and are usually performed at a later stage of a design. To conceptualize and finalize the design ideas, manual drafting has been replaced currently by computer

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aided design (CAD) technology because it is more productive and accurate. Starting in the mid-seventies, several CAD based human modeling programs have emerged to aid workstation designers (Das and Sengupta, 1995). These programs contain one or more anthropometric databases. They enable users to generate three dimensional (3D) graphic images of human models on the computer video display terminal (VDT). By using these programs, the human–machine compatibility can be analyzed visually as well as objectively through various programmed outputs.

Most of these programs operate only on main frame computer systems and the installation and operating costs for such systems are often beyond the fiscal ability of many organizations (Eyada et al., 1988). Personal computers (PC) now have adequate memory and processing speed to deal with the computational needs of a full blown CAD program. Autocad (Autodesk Inc., 1988) is one of the widely known PC based engineering CAD software, which offers comparable features at an affordable price (Grobelney, 1988). Several researchers have shown the potential of Autocad in modeling human forms (Belson, 1988; Purviance and Wylde, 1989; Ulin et al., 1990). However, thus far, most of the PC based human models were in the form of flat manikins, basically in two dimensions. Mannequin is the only known PC based 3D human modeling software, which is presently available in the market. But this software lacks the flexibility of a full blown CAD system (Humancad, 1991) and workstation models are expected to be developed in a separate engineering CAD system, such as Autocad. As the design process is iterative, this involves a tedious and time consuming task of file transfers between two software packages for human-workstation compatibility analysis.

Version 13 of Autocad has been greatly upgraded to facilitate 3D solid modeling and it supports the programming languages, AutoLISP and C, for generation of user defined routines. AutoLISP language has all the necessary ingredients to effectively automate the processes of generating and manipulating 3D human models for workstation design. This paper describes a human modeling program written in AutoLISP language. Autocad, which is a general purpose engineering CAD software, can now be used more effectively for workstation design with its extended capability of human modeling. This paper describes (1) Autocad programming objectives and methods, (2) creation of variable size computer graphic manikins, (3) positioning and posture control of the manikin, and (4) ergonomic evaluative functions for workstation design. The application and effectiveness of this program are illustrated with the help of real world design applications.

2. Autocad programming objectives and methods

The Autocad has been programmed for this research to reduce time and effort required to construct and manipulate a complex 3D manikin which will otherwise be prohibitive for any effective design work. The programmed routines serve two main purposes. At the front end, they provide a logical and easy to understand user interface, in the form of command line prompts and pull down menu. Through the interface, the necessary user inputs are acquired. In the background, the routines access the geometric information from an Autocad's drawing database, perform the necessary computations, and execute a series of basic level Autocad commands to achieve the desired actions.

The program generates seven macro commands: *Import*, *Extract*, *Hmove*, *Posture*, *Reach*, *Vision* and *Analyze*, which appear under the *Human* menu. Similar to the basic level Autocad commands, the individual macro commands can be entered from the key board. Alternatively, they can be executed by pointing the cursor on the appropriate box of the *Human* menu and clicking the mouse button. For example, entering the command *Import* from the keyboard initiates the process of creation and insertion of a manikin in the current drawing field. To acquire the appropriate user input, this command produces a subsequent prompt, *Male or Female?*, ⟨ *M F* ⟩. The letters in the angled brackets show the available options in abbreviated form. To create a male manikin the user may respond by typing either, *Male* or *M*. The program is not case sensitive and accepts all combinations of the upper and lower case letters. Additionally, the program is resistant to inappropriate keyboard entries and issues warning messages when such an event occurs.
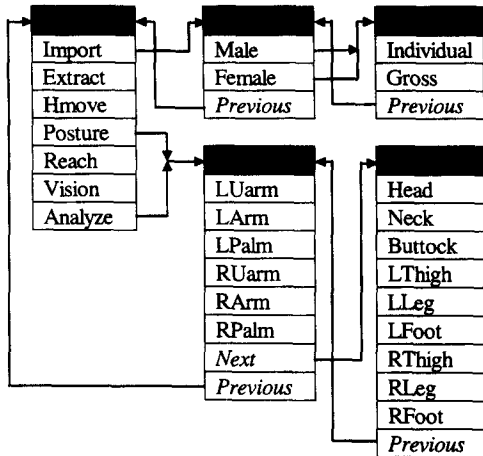
Fig. 1. The sub-menu under *Import, Posture* and *Analyze* commands of *Human* menu.

Fig. 1 shows the partial structure of *Human* menu. The menu provides a shortcut method for user inputs. For example, when the *Import* box of the *Human* menu is clicked upon (activated), the program performs the following three functions: (1) displays the *Gender* sub-menu on the screen, (2) enters the command *Import* at the command line and executes it, and (3) generates the subsequent command line prompt, *Male or Female*?, ⟨*M F*⟩. At any stage of execution of a command, the user has the option to either enter the desired response from the keyboard or to use the mouse to activate a menu box. *Previous* and *Next* options in the menu allow the user to navigate back and forth within the menu structure. Essentially, the user interface of the macro commands are designed following the similar pattern and convention of Autocad's in-built user interface to ensure faster learning for the Autocad users. The whole program is written in such a way that the user needs only to supply the minimum and essential inputs to perform any function with the human model. Any other functions which can be predetermined, have been automated. The details of the operations of the various commands will be discussed in the following sections. This effort resulted in a full fledged 3D human modeling program, which has been named HUMAN. The program has approximately five hundred lines of source codes and it is compatible to Autocad 10 or higher versions.

3. Creation of variable size computer graphic manikins

A 3D manikin is drawn by joining 16 body segments drawings: head, neck, torso, buttock and three segmented upper and lower extremities. The segments are connected to each other at the appropriate articulation joints. The program uses a special master drawing file, that contains two sets of individual body segments drawings of 50th percentile male and female. The body segments are drawn according to the dimensions provided in Humanscale (Diffrient et al., 1974). The individual segment dimensions are not 50th percentile, instead they are proportional to the 50th percentile stature and thus, the assembled segments produce an average and proportional manikin. The individual segment drawings are stored as named blocks and the program uses these blocks to create the manikin.

The outer profiles of the body segments are drawn with planer surface patches which provide the segment drawings with the property to hide the view of the background objects. Normally the segments, and hence the manikin, are displayed in wire-frame mode. Autocad's *Hide* command activates the hiding property of the surface patches, which produces an unambiguous 3D image of the manikin. Internally the segments contain straight line links of proportionate length. They form the kinematic chain of a human body.

It has been previously mentioned that the *Import* command is used to create and insert a male or female manikin within the current drawing. The anthropometry of the manikin can be specified either by the *Gross* percentile of stature or by *Individual* link dimensions. Under the first option, any percentile stature ranging from 0.5 to 99.5 percentile can be specified. Based on the known population mean and standard deviation of stature, a subroutine computes the stature dimension corresponding to the desired percentile value. Based on this computed stature, the program applies appropriate scaling factors to the individual segment dimensions while inserting them to form the manikin. This way the manikin represents a proportional human model representing the desired percentile stature.

When the second option is selected, the user is prompted to supply the individual segment lengths.

These are the link lengths measured between the segment articulation centers. In this case, the scaling factor for an individual segment will be determined from the ratio of the desired link length and the link length of the stored segment in the master drawing. This option provides the flexibility to construct a manikin with any arbitrary body proportion. This type of specification of anthropometry is useful in analyzing multivariate population accommodation (Bittner et al., 1987). Additionally, if a workstation is to be tailor made for a particular person, the actual body measurements of that person can be used to construct the manikin.

After the anthropometry has been specified, the manikin can be inserted in either of the two initial postures: *Seated* or *Standing*. Depending upon the initial posture, the program will prompt to specify the desired seat reference point (SRP) or middle point between the heels, for the insertion of the manikin in the current drawing. The user may indicate the insertion point by entering the desired X, Y and Z coordinates. Alternatively, the user may use the mouse and Autocad's various inbuilt pointing functions to specify the desired insertion point on a drawing. At this point, the program contains all the necessary user inputs and it creates the manikin on a special layer named 'Human'. Different layers act similar to overlays of transparencies. If workstation model needs to be modified, switching off the 'Human' layer will provide an uncluttered screen of the workstation model. If the 'Human' layer is not present the program creates one.

Following is an example of user input (shown in *italics*) and the subsequent system generated prompts in a manikin creation session:

Command: *Import*
Male or Female ⟨M or F⟩: *M*
Gross percentile or link dimensions ⟨G or L⟩: *gross*
Percentile ⟨0.5 to 99.5⟩: *25*
Seated or Standing ⟨SE or ST⟩: *SE*
Coordinate point ⟨X,Y,Z⟩: *25,50,200*

After entering in the command '*Import*', the user enters (1) '*M*' to select the gender, (2) '*Gross*', to indicate the sizing option, (3) '*25*', to specify 25th percentile, (4) '*SE*' (first two unambiguous letters) to indicate seated posture, and finally (5) '*20,50,200*', to indicate the desired coordinate of the SRP of the

manikin. The user will also be able to enter the first three options through the pull down menu. After the last entry, the program will create a 25th percentile male manikin on the VDT screen in seated posture with its SRP at (20,50,200) coordinate location.

Multiple manikins with same or different body proportions can be created by repeated use of *Import* command. By default, the latest created manikin remains active, and the subsequent macro commands will operate on that manikin. *Extract* command is provided to reactivate any one of the manikins in the drawing, which permits the user to work with multiple manikins simultaneously. This command also enables the user to re activate any manikin from a saved drawing for further analysis. Extract routine uses of the invisible attribute feature of Autocad. During the creation of a manikin, the program stores the necessary anthropometric and geometric data on the drawing file as invisible attributes. The *Extract* routine reads these invisible attributes attached to the desired manikin and reactivates it for further manipulation.

4. Positioning and posture control of the manikin

Import command inserts a manikin facing the current Y axis of the workstation drawing. To obtain a specific orientation of the manikin, prior to issuing the *Import* command, the orientation of the global axis system of a drawing has to be changed. The orientation of the global axis system can be changed by using Autocad's basic level commands. As an alternative to this approach, *Hmove* macro command has been provided to change the location and orientation of a manikin which has already been inserted in a workstation drawing. The *Location* option, under *Hmove* command, shifts the manikin from one point to another. Under this option, the user specifies a starting point and a destination point and the program shifts the manikin accordingly, without changing its orientation. The *Angular rotation* option enables twisting of the manikin around its vertical axis. This command provides the flexibility of positioning and orientating the manikin within the workstation drawing, without any change in the relative angles between the manikin's body segments.

The angle between two connected body segments is altered by rotation of the distal segment around its proximal kinematic joint. The rotation of a segment around the X, Y or Z axis of its proximal segment produces a flexion–extension, abduction–adduction or inward–outward rotation motion, respectively. In a complex 3D manikin drawing, this type of manipulation will be extremely difficult to achieve by Autocad's basic level commands. The programmed command, *Posture*, relieves the user from such drudgeries. The *Posture* command needs three inputs from the user: (1) the name of the body segment, (2) the desired axis (X, Y or Z) of rotation, and (3) the angle of rotation in degrees. The *Posture* menu activates the *Segment* sub-menu (Fig. 1), which contains the abbreviated names of the segments. The user can select a segment by clicking on the desired menu box. Alternatively, the posture command produces a list of segment names as the command line prompt. The user may enter the name of the desired body segment from the keyboard. With this information, the program will determine the coordinates of the relevant kinematic joint location, and the angular orientation of the proximal segment. AutoLISP functions have the ability to obtain such data from the current drawing database of Autocad. Additionally, the program will determine which distal body segments should also move along with the selected segment. For example, if left upper arm *(LUarm)* is selected, the program will determine (1) the X, Y and Z coordinates of the current location of left shoulder joint, (2) the angular orientation of the torso with respect to the global axis system, and (3) the left forearm and left palm of the manikin will move along with the left upper arm to ensure simultaneous motion of the connected distal segments. The program will respond by (1) highlighting the selected set of segments, (2) displaying an axes-system icon at the articulation point with appropriate orientation, and (3) issuing a prompt to select the desired axis of rotation. The orientation of the axes-system icon provides a visual cue to the user about the rotational axes. The user enters the letter X, Y or Z to indicate the type of motion and then enters the required angle of rotation. The user may either enter a numerical value of desired change in angle, or may use the mouse to move a cursor in the drawing field. When the numerical value is entered, the program executes
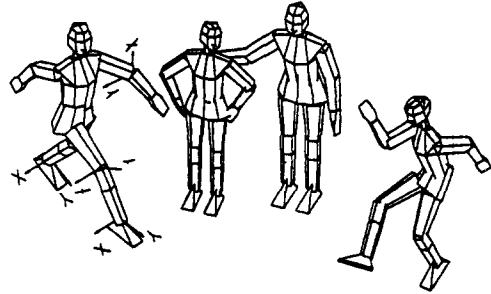

Fig. 2. The flexibility of size and posture of the manikins.

the command by moving the selected set of the body segments of the manikin as specified. When mouse is used, the program shows the dynamic movement of the highlighted selection set according to the changing cursor position. The user can see the effect before accepting the desired posture by clicking the mouse button.

Fig. 2 shows four manikins which have been imported with different body proportions, moved around with *Hmove* command and then their body postures were changed with repeated *Posture* command on different body segments. The manikins illustrate their postural flexibility. The axes-system icons on several articulation joints are shown to illustrate how the program displays the orientation of the distal segments within the global axes system.

5. Ergonomic evaluative functions for workstation design

After a manikin has been inserted and properly positioned within a workstation drawing, *Reach* and *Vision* commands facilitate evaluation of the workstation design in terms of reach and visual abilities of the manikin.

Reach command provides two options to evaluate the reach capability. Under the first option, *Reach to a point*, the user specifies a point within the workstation drawing, and selects left or right arm performing the reach. With this information the program computes the necessary changes in the elbow and shoulder joint angles of the manikin to complete the reach. If the joint angles are within the joint range of motion, the program will execute several *Posture* commands in succession on the upper and forearms

of the manikin. The end result will show that the manikin's hand is in contact with the specified point. If the location of the specified point is too far, or if any joint angle exceeds the joint range of motion, the program will so indicate. If the manikin succeeds to reach a control, then possible interference with other workstation components during the reach, and arm posture required to reach the control can be visually evaluated. With this option, the user may point to the various controls to be reached by the manikin and can evaluate the reach compatibility of the workstation design. The second option, *Reach envelope*, draws a spherical reach envelope of the manikin on the workstation drawing. The program uses the current position of the shoulder joint and the upper extremity length of the manikin to determine the center and radius of the reach envelope, respectively.

Vision command produces a pair of vision cones from the manikin's eye points. The cones represent the human visual field, and the line of sight is determined from the inclination of the manikin's ear–eye plane. The vision cones can be switched on and off by the *Vision* command. For a particular position and orientation of the head of the manikin, the area of the workstation intersecting the vision cones shows the visual range of the manikin. An alternative means is to use Autocad's *Camera* command. This command will produce a perspective view of the environment that will be within the manikin's field of vision. The viewing direction and angle of the visual field can be controlled under this command.

The macro command, *Analyze*, has been provided to obtain quantitative evaluation of manikin's various body segment position. For a given body segment name, the program computes the angular displacements of the segment from the X, Y and Z axes of its immediate proximal segment and the angles are listed out in a text window. After manipulating the manikin's posture, or after the manikin arm has reached a control, this command can be used to obtain the numerical value of the posture angles between the various body segments.

6. Applications of the human modeling program

The effectiveness of the human modeling program is illustrated by two real world workstation design

applications. The first application involved identification of the design deficiency of a grocery checkout stand and subsequent modification to improve human–machine compatibility. To evaluate the existing checkstand, the layout drawing of its components were prepared from the actual measurements taken at site. The two dimensional view of the original checkstand is shown in Fig. 3, with the manikin in the stick figure mode. The position and the orientation of the manikin depicts the actual working position of the cashier. This position was advantageous for the cashiers for bagging and loading the scanned grocery items into the tote box. However, when a reach envelope was drawn with a 5th percentile female manikin with normal upright posture, it revealed that a rather small area on the conveyor belt was within the reach of the manikin. As a result, frequent extreme flexion of the cashier's upper body was inevitable to pick up the grocery items from the conveyor belt. The cash box, keyboard, printer and a code catalogue were placed on the top of a side cabinet. The code catalogue contained the item codes of bulk grocery items. The keyboard and the code catalogue were frequently used by the cashier for sale of such items. From the existing working position, the cashier could only use these components with an awkward turning and twisting of the upper
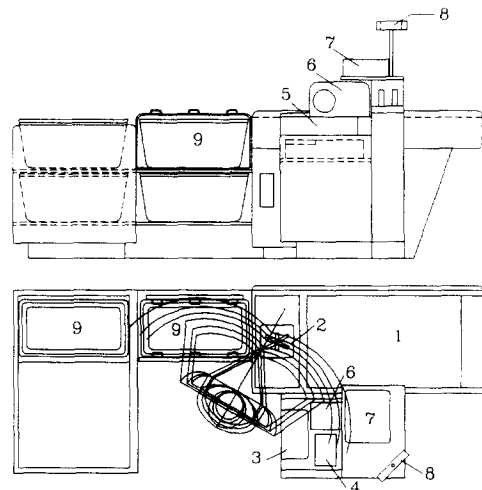

Fig. 3. Layout of the grocery checkstand before modification. Legend: (1) conveyor belt; (2) laser scanner; (3) keyboard; (4) code catalogue; (5) cash box; (6) printer; (7) weighing scale; (8) product price display; (9) tote box.

body. The weigh scale was located on a platform on the top of the cabinet. The height of the platform was above the cashiers shoulder height. Consequently the weighing operation involved lifting the products above shoulder level combined with twisting of torso. The electronic display for the product price was mounted on the top of the platform. During the scanning operation of products, the cashier frequently needed to glance at the display to verify the proper entry of the items. As the display location was behind the normal viewing direction, frequent turning of head was involved to perform such an operation.

The design layout is a good illustration of how a workstation with mostly electronic and technologically advanced components, can create undesirable health hazards to the cashiers. The individual components of the workstation were manufactured by different vendors. The layout design consisted of primarily accommodating the components around the cashier with little or no consideration to ergonomics guidelines for a workstation design. The Autocad drawings with the human model was effective in displaying the design deficiencies to the manufacturer/designer of the checkstand. The upper body posture of a 5th percentile female manikin, while
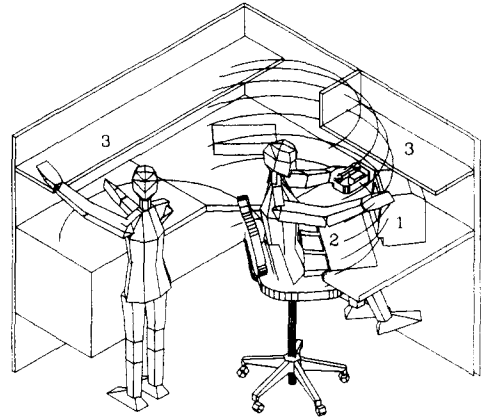

Fig. 5. The office workstation layout. Legend: (1) computer monitor; (2) key board; (3) shelves.

placing a grocery on the weigh scale or while picking up a grocery from the far end of the conveyor belt, displayed the awkward postures of the cashiers in a convincing manner.

Several alternative design layouts were developed in Autocad and the cashier's interactions were demonstrated with the help of the human model. Fig. 4 shows one of the proposed layout model. In this layout, the components that needed frequent operation, were placed in the front of the cashier. The cashier's position was shifted to the right to improve reach function on the product conveyor. Additionally, a deflector was provided to reduce the extreme reach requirement. The width of the laser scanner was reduced to increase reach in the product bagging area at the left. The keyboard and the cash box were designed to project out from the body of the conveyor belt structure. In locating these two items, appropriate clearance from the side of the cashiers body was determined by positioning a 95th percentile female manikin. The printer and the price display unit were placed with in the normal viewing direction of the cashier. In positioning the base unit of the price display, possible interference of the cashier's arm with the structure, while picking up grocery items from the conveyor belt, was verified using the *Reach* command. The upper arm and body postures for bagging grocery items, and operating the keyboard from the working position, were verified by using *Reach*, *Posture* and *Analyze* commands.
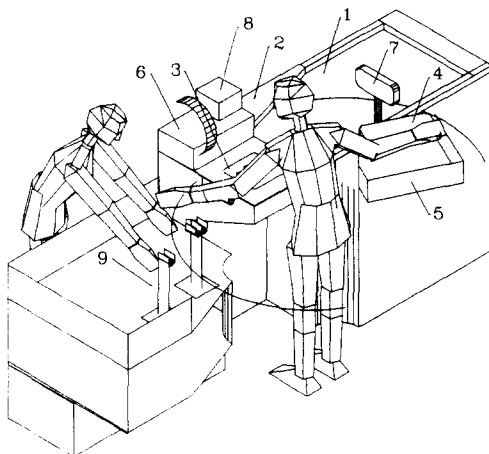

Fig. 4. The human compatibility of the modified layout of the grocery checkstand. Legend: (1) conveyor belt; (2) deflector; (3) laser scanner/weighing scale; (4) key board; (5) cash box; (6) printer; (7) product price display; (8) code catalogue; (9) bag loading area.

The second application involved design of an office workstation for a female employee with low back pain. Due to an automobile accident, the employee experienced back pain after prolonged sitting during office work. The insurance company wanted to try out a sit–stand type office workstation to rehabilitate this employee to normal office work. Fig. 5 shows the office workstation design that was tailor made for the employee. The manikin's body proportion in this design, was based on the measured body dimensions of the employee. The *Individual* link dimension option under *Import* command, was used to create the manikin. The height and depth of the shelves and work surface were determined based on the manikins reach at normal working posture. The manikin at the left of the diagram shows the posture required for filing and shelving operations. The circular arc on the table surface shows her reach ability at this posture. At the right of the diagram, the manikin is shown while working with computer and picking up the telephone. The 3D reach envelope shows the space that can be accessed by the manikin at this posture. With the use of posture and reach routines, positioning the manikin within the 3D workstation drawing, was performed efficiently.

7. Conclusions

In summary, the conclusions reached by this investigation are:

(1) The new human modeling program named HUMAN developed through the use of CAD can generate 3D manikin with any desired anthropometry and allows manipulation of its posture with a few key strokes.

(2) The new system provides the means of performing an ergonomic analysis of human-workstation fit in an efficient and cost-effective manner.

(3) Autocad, a widely used software, with its additional human modeling capability is a low cost but effective alternative for main-frame CAD based workstation design programs.

(4) As the human model works on the Autocad platform, the features of a professional CAD system are simultaneously available to the users.

The program is not yet fully developed for commercial use. However, by using the programming methods described in this paper, it is possible to refine the program further to enlarge its scope and capability.

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