ERGONAUT: A Tool for Ergonomic Analyses in Virtual Environments

Joachim Deisinger, Ralf Breining, Andreas Rößler
Fraunhofer Institute for Industrial Engineering, Nobelstr.12 D-70569 Stuttgart
Germany

email: joachim.deisinger@iao.fhg.de

Abstract. Ergonomic quality is becoming a crucial criterium for the success of many products. The problem of increasing the speed of product development cycles while keeping costs to a minimum could be solved by the possibility of the early evaluation of drafts regarding their ergonomic design. A digital platform is a prerequisite for the analysis of virtual prototypes. The analysis tool ERGONAUT not only fulfills this task in a Virtual Environment (VE) but also makes it possible to combine virtual and real data in a mixed mock-up. This implies that the designer is able to consider the ergonomic point of view at an early stage in the design process. In this context, a project together with the John Deere Company in Mannheim, Germany has been carried out using such an analysis tool in a pilot project. Within this first semi-productive industrial project ERGONAUT has shown its usefulness. It will help companies gain and maintain a long-term leading position in the field of ergonomics and facilitate the integration of VEs in their product development. This paper describes the anthropometric basis for ERGONAUT, its structure and functionality, the different levels of use, the system (User Interface, VE system, etc.) and some experience of the use of ERGONAUT.

1. Introduction

The aim of the John Deere project was to develop the potential of a VE ergonomics tool using an existing tractor driver's cabin as a model. A prototype of ERGONAUT was developed and tested on this model. The ergonomic analysis of the tractor driver's cabin was carried out on different levels of use which were worked out using ergonomic analyzing methods. Three different basic levels were created differing in their structure and the virtual components shown. All three levels have been developed for use in the CAVE [1].

The levels of use also include the mixed mock-up where real and virtual components are combined together in the CAVE. The term mock-up basically describes a full scale model of an object. A mixed mock-up means the combination of both real and virtual models in one complex model. A valuable side effect is the reduction of the amount of data represented in the CAVE. However, the main feature of a mixed mock-up is that it enables the integration of a real operator in the model. To let a real person sit in the driver's cabin a real seat is necessary. This was realized by furnishing

the mixed mock-up with a driver's seat, a steering wheel, a clutch pedal and a control console. The single components can be combined differently, all parts can be put in the CAVE, together or just the seat without the other operational elements.

2. Related Work

Regarding the simulation of human motion there is a lot of research going on. Also there are some real-time human models available, like 'VirtualMan' by Safework or 'Jack' by EAI. They are different in behavior, amount of body segments, variables and features. VirtualANTHROPOS [2] is a human model that has been developed since 1996 by the Fraunhofer Institute for Industrial Engineering (IAO) in close cooperation with the company IST GmbH. IST developed the 2D System ANTHROPOS whereas VirtualANTHROPOS is intended for use in a VE. The high level of functionality of ANTHROPOS makes desktop-based ergonomic analysis possible. VirtualANTHROPOS can be represented using. different percentiles e.g. 2,5 - 97,5 percentile. Representations can be varied according to sex, weight and body volume; even different clothing is available. Collision detection is not yet available but can be approximated by the fact that parts of the body can be virtually supported at 6 points. A support of hands, legs, back and hip can be simulated this way.

3. Ergonomic Basis

Apart from a range of animation possibilities VirtualANTHROPOS also provides basic ergonomic tools and values which can be used for both immediate and offline analysis. Torque, joint resistance and discomfort value as well as the visualization of ergonomic categories can be used for direct analysis.
Anthropometric data sets are the basics for the behavior and the proportions of VirtualANTHROPOS. The body weight is calculated relatively to the body height based on an average man.
This normalized weight multiplied by diverse factors results in the overall body weight with regard to the chosen somatotype. For further considerations not only the overall body weight is necessary but also the weight of single body parts. These can be approximated using the body-segment factors based on the NASA Study 3000 Vol. 1 [4]. Figure 2 shows the classification of the segmentation. The segmental weight can be determined by distributing factors to the various segments. The center of gravity point for each joint can be found in the NASA Study 3000, depending on the body height. The center of gravity points can thus be defined generally and independent of the human percentiles.
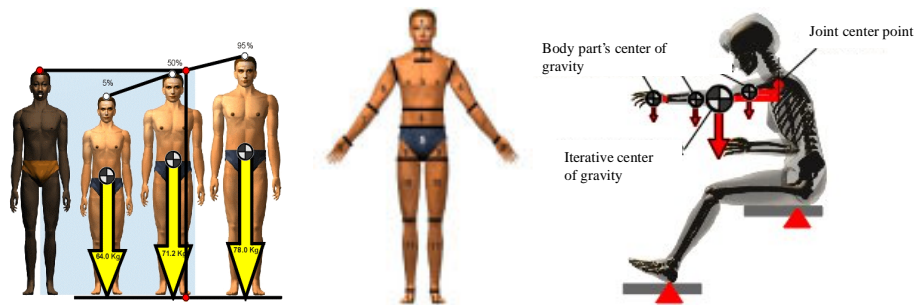
Fig. 1. ANTHROPOS Somatotypes, Segmentation and Determination of Torque [3]

The static torque due to the tare weight in every joint can be determined for every posture. For the given example in Figure 2 the torque in the shoulder joint is determined by the iterative center of gravity, the lever arm and the iterative chain weight. The torque in the given joint gives a first idea of the local strain.

In VirtualANTHROPOS body elements like arm, leg, hip, and back can be supported which is an important factor in determining torque and strain of the joints. This feature implies that e.g. the virtual hand can be supported by the steering wheel or the rump by a seat which could have a significant impact on the torque results.

As a normalized posture VirtualANTHROPOS uses the so called NASA-Neutral-Posture (NNP) where the body experiences zero load [4]. This posture would be taken by persons in weightless space without employing any muscular power. Figure 4 shows a normal seat posture in comparison to the NNP.

Based on the NNP a point of joint resistance is determined for each body joint by estimating the utilization ratio of the joint angular field in percent. Figure 5 shows the principle for the determination of the so called discomfort value. This value varies between zero and one where one is the critical value from the ergonomic point of view. The discomfort value of different joints can thus be compared directly on a quantitative basis.
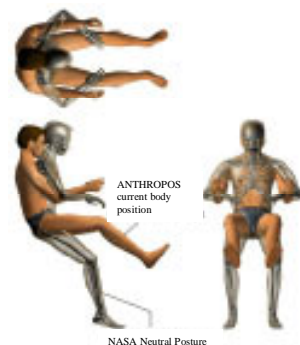

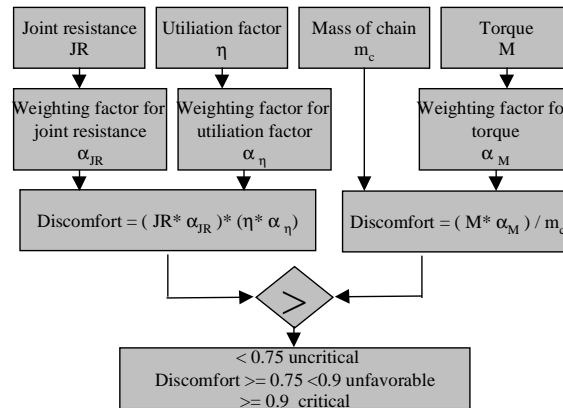**Fig. 2.** Current Posture vs. NNP [3]

Joint resistance JR | Utiliation factor η | Mass of chain m_c | Torque M

Weighting factor for joint resistance α_{JR} | Weighting factor for utiliation factor α_η | Weighting factor for torque α_M

Discomfort = (JR* α_{JR})* (η* α_η) | Discomfort = (M* α_M) / m_c

\>

< 0.75 uncritical
Discomfort >= 0.75 <0.9 unfavorable
\>= 0.9 critical

Fig. 3. Determination of Discomfort [3]

4. ERGONAUT Structure and Functionality

Transferring ANTHROPOS to a real-time version for VE makes great demands on the user interface. However, due to the 3D interactive and fully immersive environment a great potential for using new analyzing techniques can be created. Ergonomic features such as reach envelopes and visual fields but also force isodynes have been modeled and implemented in ERGONAUT for the analysis of objects

Reach Envelopes A reach envelope is defined as that space in which you can touch, grasp or move objects with your hands. Different reach envelopes in ERGONAUT are described by ball segments referring to elbow and shoulder joints which are estimated to be sufficiently exact for practical use [5], [6]. In ERGONAUT the five classes of reach envelopes [7] are categorized and split into two files representing the small and the wide reach envelope (see figure 5).

Visual Fields The whole field of view is subdivided in several visual fields [8], that is, the optical field as well as the fields of vision and periphery. They differ basically in their ability to focus objects. The difference between monocular and binocular view has not yet been taken into consideration since an exact focus on the objects is not necessary for the analysis of handling controls.

Force Isodynes The forces of the human body play an important role when using the handling controls. As they depend on many influence coefficients it is not possible to indicate any exact figures. There are only a few references in literature that mention the maximal forces [9]. The results of these investigations are the force isodynes, i. e. lines of equal force that are indicated in so called force maps. Six different force directions (FD) are distinguished, the force of the arm straight up, straight down, away from and towards the body axes, and the horizontal force on the palm and the back of the hand. Since the analysis will be carried out in a VE, the 3D force isodynes

have been modeled on the basis of 2D force isodynes which all have the same maximal force value (see figure 6). These lines can be used to estimate the maximal force value that can be used at a single handling control positions. The quantitative statement about the maximal value is only of minor importance. However, one can determine with the help of this force and the force direction if there is a more suitable force direction where the human maximum force is stronger.
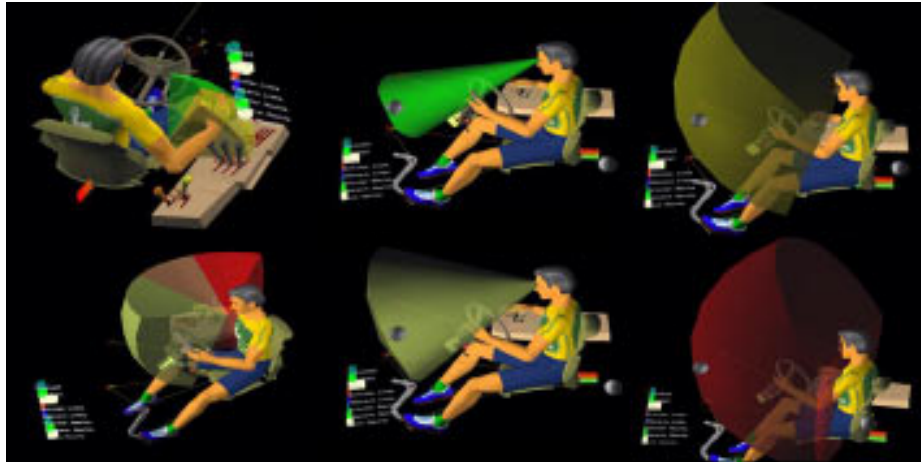

Fig. 4. Reach Envelopes and Visual Field Categories

Discomfort Value Bar charts for selected joints provide a quick overview of the current constitution of VirtualANTHROPOS. The bars show the discomfort values for selected joints. Short bars characterize little discomfort and long bars show where body joints are stressed most. Figure 6 gives a qualitative view of the man model about to grasp one of the controls. The hand is being held in a significant position. Therefore the discomfort in hand and shoulder appear higher (below bars) than for the other represented joints.

Further Features In a driver's cabin the seating comfort for variously sized people depends on foot pedal operation and the seat position. In ERGONAUT, the seat can be moved freely within its adjustment range. The basis of VirtualANTHROPOS can be linked to the seat, which means that when the seat is moved the man model will follow its movement. This link enables a kinematic relation between different elements, i. e. moving single elements will have a direct effect on linked elements. Additionally, all controls can be switched into the different gearing positions.
A data set with the data of all joints can be saved for any posture. The visualization in the offline analysis is improved by a snapshot function which generates images of the current scene dependent on your viewing direction. There are 81 different values resulting from joint resistance, torque and discomfort. These values are available for detailed quantitative analyses and documentation at a later date.

Fig. 5. Examples for Force Isodynes and Bar Chart

5. An Approach for Ergonomic Optimization

5.1. First Level of Use (Rough Analysis)

The first level of use serves as rough analysis and as practice for the assignment to be analyzed. All physical elements of the mock-up have to be placed in the CAVE. The user can employ various elements in order to get accustomed to the assignment. The movement of hand and arm is transferred real-time by trackers to the posture of VirtualANTHROPOS. The man model is constantly adjusted according to the user's posture but is not visualized in the CAVE. The position of the reach envelopes, the visual fields and the force isodynes can be visualized relative to the user. This first level not only determines the categories for the reach envelope and visual fields in which the single handling control can be found but also determines the different percentiles. Finally this level is useful for pinpointing any ergonomically weak features.

5.2. Second Level of Use (Detailed Analysis)

VirtualANTHROPOS is moved by the user via a button device which also analyzes single leverage positions. The analysis is done by the evaluation tools of VirtualANTHROPOS, i. e. torque, joint resistance and discomfort values. All values are dependent on the analyzed percentiles. This detailed analysis gives quantitative information about the ergonomic quality of control column positions in a given project. It also shows which control columns are installed in an ergonomically unfavorable position.

5.3. Third Level of Use (Design Optimization)

The objective of this level is to quickly create variants to improve any weak points identified in previous levels of usage. Single elements such as the seat, the clutch pedal and the steering wheel are placed in the CAVE. The control console is represented virtually. It is now possible to change the position and orientation of single parts of the console and to check the effects in the ergonomic analysis immediately.

VirtualANTHROPOS need not necessarily be visualized but will nonetheless serve as basis for the analysis. Interaction is tracking-based as described in the first level of use. The newly defined positions are checked quickly by means of the defined chain value where the joint angles and joint resistance can also be retrieved. This is how different design variants are worked out. Coordinates and images can be saved and examined more thoroughly in an offline detailed analysis.

6. Technical Realization

6.1. User Interface

The user interaction in ERGONAUT is realized by a mixture of 3D widgets in the CAVE, a 2D desktop window and speech recognition. This mixture has been chosen to control the complexity of the application without at the same time frustrating the user in the CAVE. Figure 6 shows parts of the 3D User Interface in the CAVE. VirtualANTHROPOS is portrayed on a digital mock-up.

The 2D menu also provides interaction possibilities for a second person, it is simple to handle and includes functions which are in many cases not necessary or need only be set once at the start of each session. VirtualANTHROPOS can be directly manipulated within the CAVE. It has seven relevant reference points for manipulation. These points are marked by red rings and can be selected and moved with the MIKE II device [11]. The head-ring indicates the line of sight. One reference point moves the whole VirtualANTHROPOS in the current body posture. Besides this, the controls can be moved to different positions. A red ring on each control enables the selection of the shift positions in order.

6.2. Speech Recognition

Loading applications and configuring the projection system in general can be controlled by speech recognition. Specific to the application, menu commands such as resetting the man model's posture or taking snapshots can also be shortcut. But the major advantage of speech recognition is that it greatly facilitates object selection. Object selection can be a major problem if objects overlap, interfere or are located very close together. With speech recognition the user is provided with a tool which can select all reference points controlling VirtualANTHROPOS as well as menus and

functions redundant to tracking and desktop-based selection. Speech recognition in ERGONAUT has been implemented based on the IBM ViaVoice Executive 98. ViaVoice provides a user independent speech recognition that functions after a single training without any major problems for those users speaking similar accents of the same language. ViaVoice does not react if the user speaks without intending to give a command. However, the user has to take into account that before the tool recognizes a command it requires a speech pause of about 2 seconds. This needs a little practice since it is easily forgotten in the heat of an ongoing analysis. Furthermore, the speech recognition tool is equipped with a wireless microphone system which has proved to be very resistant to background noise, e.g. other people talking in the CAVE. A client server connection transfers the commands to the VR system Lightning (see 6.3) and is interpreted there. Both the application and the sound server are controlled in this way.
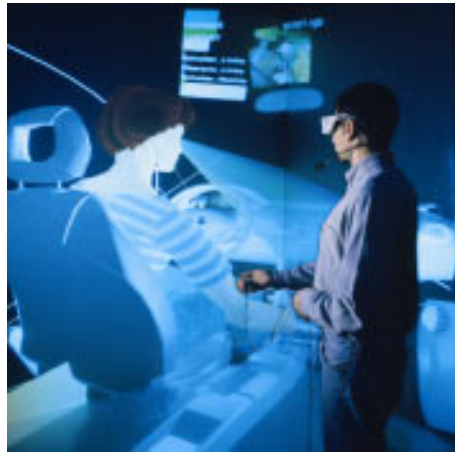

Fig. 6. ERGONAUT User in the CAVE

6.3. Lightning

The VE system Lightning was developed at the Fraunhofer Institute (IAO) and was first presented in 1996 [10] as a rapid prototyping tool for VE applications. Since then it has evolved into a mature tool for interactive engineering environments where the prototyping of 3D user interfaces have become an important issue. Lightning provides an open application framework for the efficient development of interactive high-end VE applications. Lightning is available as a development or as a runtime option. The system supports the UNIX based high-end graphic workstations of SGI. Lightning provides modules for the definition of virtual environments and their functionality as 3D objects, input/output support, function blocks and communication mechanisms (dataflow oriented). The application programmer is able to create and combine all these features easily.

A key feature of Lightning is its extensibility. All application objects are accessible via the TCL interface. Behavior scripts can be developed to define the functionality of applications. New applications can be built completely on this layer.

7. Experiences in Use

Real-time ergonomic analyses have proved to be very time and cost effective when evaluating and comparing design variants. An application which provides a full scale 3D immersive representation clearly has its advantages.. The necessary high level of functionality is a challenge that can be met with the help of a very flexible and effective tool like VirtualANTHROPOS. The high grade of complexity makes massive demands on the design of the user interface. On the other hand, it makes no sense to put all options on top of the 3D interface. Most of the man model characteristics like age, gender, height, nationality, body volume and percentile are better controlled by a 2D desktop interface. This interface offers furthermore all other functions in addition and therefore, together with speech recognition, provides the user with two levels of redundancy that in practice enable a second person to support the design engineer in handling the application. This feature has had a great impact on user's acceptance since it implies that for the important features two users can launch a single function in three different ways.

The posture variability of VirtualANTHROPOS and the implementation of different ergonomic categories, such as reach envelope, visual fields and force isodynes, comprise a very complex and interactive real-time application that is already in semi-productive use. This means that an industrial application as performed successfully but the technical equipment was used at the research institute. Specific results in the project with the John Deere Company were the analyses and the creation of variants of a driver's cabin.

Since the analyses were carried out on a cabin which was already in mass-production, proposals for design changes had to be kept within specific limits set by the John Deere Company. These limits included maintaining the existing space as well as other restrictions due to service/operating elements. Furthermore, there were restrictions related to the kinematics of the shifting elements. Modifying these elements would have had a major impact on technological and economical factors. In collaboration with John Deere designers, two variants were developed and consequently tested.

The results of the analysis show that ERGONAUT enables the user to create ergonomic design variants and generate reproducible results. Furthermore, results can then be compared and analyses results and quantitative improvements can be shown. ERGONAUT's progression from prototype stadium to the finished product will involve the systematic eradication of errors and the long-term testing of the application.

8. Conclusion

Using the application showed that a VE ergonomic tool is able to support analysis and optimization and offers the aforementioned advantages over desktop solutions. The tools produced an ergonomic analysis and the proposed improvements were implemented. VE technology is well on the way to being considered the standard technology in industry. The potential of ergonomic tools in a virtual environment as demonstrated in the pilot project have been described in this paper. A man model application opens perspectives not only in the design and the rapid development of products but also in the fields of manufacturing, maintenance and training.

VEs have many clear advantages over an ergonomic CAD desktop analysis solution. The main advantage is the real-time fully immersive and interactive visualization that, in this case, can be experienced in full scale. Any problems with the ergonomic analysis and optimization are depicted quickly and clearly and the designer is able to work with a realistic representation of a digital model. It is also possible to analyze a combination of virtual and real models on a single platform. This facilitates, for example, the examination and comparison of competitors' products that are not digitally available. A mixed mock-up also reduces the problems arising from a lack of force feedback. Finally, the application provides the user with valuable hands-on experience with VE technology.

9. References

1. Cruz-Neira C., Sandin T.A., De Fanti R.V.: Surround Screen projection based virtual reality: the design and implementation of the CAVE. Proceedings of SIGGRAPH 1993, pp. 135-142.
2. Lippmann, R.; Rößler, A.: Virtual Human Models in Product Development. In: Göbel. M.; Lang, U.; Landauer, J.; Wapler, M. (Hrsg.): Proc. of Virtual Environments. Springer, Stuttgart, 1998, pp. 53/1-4.
3. IST: ANTHROPOS 5 das Menschmodell der IST GmbH. Manual 2 Interaktionen. IST GmbH, 1998.
4. NASA: NASA-STD-3000, Man-Systems Integration Standards, Vol. I, Rev. B., NASA Johnson Space Center, Houston, TX, 1995.
5. Schmidtke, H.: Lehrbuch der Ergonomie. 3. Auflage. Hanser, München / Wien, 1993.
6. Bullinger, H.-J.: Ergonomie Produkt- und Arbeitsplatzgestaltung. Teubner, Stuttgart, 1994.
7. Diffrient, N.; Tilley A. R.; Harman D.: Humanscale 4/5/6. Massachusetts: MIT Press, 1981.
8. DIN 33 414: Ergonomische Gestaltung von Warten, Sitzarbeitsplätzen, Begriffe, Grundlagen, Maße.
9. Rohmert W.: Körperkräfte. In: Arbeitsgestaltung in Produktion und Verwaltung. Hrsg. Vom Institut für angewandte Arbeitswissenschaften e. V. Köln: Wirtschaftsverlag Bachem, 1989.
10. Blach, R., Landauer J., Rösch A., Simon, A.: A flexible Prototyping Tool for 3D Realtime User-Interaction. In: Virtual Environments: Conference and 4th Eurographics workshop / IEEE YUFORIC Germany '98; 16-18 June 1998, pp 195-203. Germany, Stuttgart/ Eds.: Martin Göbel et. al. Stuttgart, 1998.
11. Häfner, U.; Doulis, M.; Simon, A.: Evaluation of Complex CAD Data in a Virtual Environment in 3. International Immersive Projection Technology Workshop, 10.11. May S. 157-165 1999 Stuttgart Springer Verlag Berlin.