Digital Human Modeling for Design and Evaluation of Human-Machine Systems

ANJA NAUMANN[1] & MATTHIAS ROETTING[2]

[1)] *Deutsche Telekom Laboratories, Technische Universität Berlin*
[2)] *Department of Human-Machine Systems, Technische Universität Berlin*

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Abstract

Digital Human Modeling is an emerging area that bridges computer-aided engineering design, human factors engineering and applied ergonomics. Especially for ergonomics questions, digital humans are already being used. The paper describes different fields for the application of digital human modeling in product design, assembly and manufacturing. Current research on digital human modeling in training, risk assessment of workplaces, hand-object interaction, modeling eye movement, and the assessment of comfort is highlighted. The case is made for a combination of anthropometric models and cognitive models. In addition, the consequences of a wider application of digital human modeling in product design, assembly and maintenance are discussed, especially with regard to the education of engineers and human factors specialists.

1. Why Use Digital Humans in Engineering?

Countless organizations in a variety of industries are facing the same problem: the human element is not being considered early or thoroughly enough in the design, assembly and maintenance of products. More importantly, this is having a devastating impact on cost, time to market, quality and safety. However, for a growing number of organizations, factoring the human element into design, manufacturing and maintenance is no longer a problem but rather a competitive advantage. Using digital human models realizes benefits such as shorter design time, lower development costs, improved quality, and enhanced productivity.

Digital human modeling enables engineers in product development to address questions of ergonomics and human factors early on in the development process. At the same time, digital human modeling reduces the need for the production of real prototypes and can even make it obsolete (Cappelli & Duffy 2006).

In research and development, commercial human models are already being used. These models are up to now mainly restricted to anthropometric issues. Two often used human models are JACK and RAMSIS (Duffy 2006):

- JACK enables users in industry to position biomechanically accurate digital humans of various sizes in virtual environments, assign them tasks, and analyze their performance. The digital humans JACK (and his female counterpart JILL) can tell engineers what they can see and reach, how comfortable they are, when and why they're getting hurt, when they're getting tired and other important ergonomic information. This information helps organizations design safer and more effective products (see also http://www.ugs.com/Products/tecnomatix/human_performance/jack/) faster and for less cost.
- RAMSIS helps manufacturers and engineering services providers to do substantial design studies during the design phase. The core functions of this software are the realistic display of international anthropometric data and the efficient analysis of ergonomic questions concerning, for example, sight, maximum force, reachability, and comfort. RAMSIS is already used by more than 60% of all automotive manufacturers worldwide for the ergonomic design and analysis of passenger compartments and work places (see also http://www.human-solutions.com/automotive_industry/).

In the following, some examples for the use of digital humans in product design and manufacturing will be given.

1.1 Digital Humans in Product Design

During the product design phase, organizations face several key challenges related to the physical attributes and behavior of humans. They need to develop products centered on humans and evaluate designs based on ergonomic factors, account for different sizes and shapes of people, and consider human factors in the design before building physical prototypes. Human simulation allows, for example, questions concerning positioning and comfort to be answered:

- Comfort: Is the design optimized for the comfort of the envisioned user groups?
- Visibility: What can people of different sizes see when they operate a piece of equipment or a vehicle?
- Ingress and egress: Can the target population easily climb in and out of the equipment or vehicles?
- Reaching and grasping: Are controls placed so that everyone can reach and operate them?
- Multi-person interaction: How do multiple people interact with the product?
- Strength assessment: Does operating the product require inordinate strength or create the potential for injury?

1.2 Digital Humans in Manufacturing

Organizations face several key challenges related to the physical attributes and behavior of humans in manufacturing. They need to bring factories on-line faster, to optimize manual workflow, to improve worker safety, and to reduce training costs. In the manufacturing phase of the product lifecycle, human simulation allows the following questions to be answered:

- Work cell layout: Are machines and other equipment positioned to optimize cycle time and avoid hazards?
- Workflow simulation: Are the manufacturing processes designed to eliminate inefficiencies and ensure optimal productivity?
- Assembly accessibility: Can all assembly personnel access the parts and equipment needed to assemble the product?
- Safety analysis: Can all of the assembly tasks be performed safely?
- Lifting: Do all lifting tasks fall within the strength guidelines?
- Energy expenditure: How much energy will workers expend over time as they perform repetitive tasks?
- Simulation based training: How can real-time simulation and virtual reality be used to train workers?

2. Current Research on Digital Human Modeling

Digital human modeling is an emerging area that bridges computer-aided engineering design, human factors engineering and applied ergonomics. It is increasingly getting attention from research and development (Cappelli & Duffy 2006).

Up to now, most research efforts have concentrated on anthropometric aspects of human modeling. Allen, Curless, and Popovic, for example, work on improving models of body shapes. They examined body deformation during movements (Allen, Curless, & Popovic 2002) on the one hand and individual variations in body shapes on the other hand (Allen, Curless, & Popovic 2004).

Besides the continuous optimization of measurement methods and the technical aspects of 3-D-Modeling, one particular research topic is the verification and validation of digital human models. Methods and procedures are thus being developed which make sure that the human models used lead to reliable results. One example is the development and application of digital human models for training purposes, for example, for the development of the diagnostic competence of medical students. In one project, haptic virtual models of the spine serve as educational aids and this especially at early stages of the study of medical science (Howell, Williams, Burns, Eland, & Conatser 2006; Chen, Williams, Conatser, & Howell 2006). One further research topic here is motion analysis for the ergonomic assessment of risky work places or dynamic tasks (e.g. lifting of heavy items; Cappelli & Duffy, 2006).

A relatively new area concerns the modeling of hands and their interaction with objects. An effective ergonomic evaluation often requires a realistic simulation of the hand-object interaction and a reliable estimation of performance. The aim is to use digital mock-ups and digital hand models for usability tests in the early phases of system development. This saves costs and delivers results almost as realistic as from tests with real users (Endo, Kanai, Kishinami, Miyata, Kouchi, & Masaaki 2006). In this way, for example, usage performance, usage durations, and the handling (grasp) qualities of PDAs, mobile phones, and MP3 players can be measured (Endo et al. 2006). In addition, a judgment of shape, color, texture, keys or jog-dials of a mobile device can be made (e.g., DhaibaHand; Miyata, Kouchi, & Mochimaru 2006). Also, based on motion prediction, it can be estimated which elements can be and which can not be reached by finger motion (Grasp Quality Index; Yang, Pitarch, Kim, & Abdel-Malek 2006).

Modeling eye movement deals with the development of adequate models of human vision for the prediction of human behavior using new concepts and technologies. It addresses (amongst other things) basic aspects which are connected to eye movements and the reaction of the person concerned (e.g., worker or operator) to environmental conditions. In this context, examinations are possible into how reading rate, eye movement parameters, light adaptation, planning of eye movements, visibility of objects, and perception of depth and movements are correlated to human movement and posture. Kim et al., for example, examined the role of visual and manual requirements when planning movements (Kim, Martin, Dukic, & Hanson 2006), and the prediction of movements when moving the head (Kim, Martin, & Gillespie 2006). For visibility analyses, commercial digital human models proved to be useful. For example, JACK (see 2.) was used successfully in combination with a CAD model of a car for testing the visibility of a child beneath a car. The deviation of the simulation results from a real situation with a real car and a paperboard model of the child were minimal (Ruspa 2006).

An important research area in the automotive, and more generally in the transportation, sector is comfort and discomfort. Both, drivers and passengers of cars and airplanes expect a high level of comfort. Human-comfort models have thus been developed which can replace test panels for comfort tests (Reynolds & Wehrle 2006; Bidal, Bekkour, & Kayvantash 2006; Parakkat, Pellettier, Reynolds, Sasidharan, & El-Zoghbi 2006). Another important area of research is the modeling of motor behavior and motion sequences, for example for assessing a vehicle, a work place or a task (Monnier, Renard, Chameroy, Wang, & Trasbot 2006; Reed, Faraway, Chaffin, & Martin 2006). Research questions in this context concern, for example, ingress/egress (Cherednichenko, Assmann, & Bubb 2006), driving motions (Parkinson & Reed 2006; Rider, Chaffin, & Martin 2006), accessibility in passenger compartments (Wang, Chevalot, Monnier, & Trasbot 2006), step motions (Wagner, Reed, & Chaffin 2006), and sitting behavior (Wirsching, Junker, & Nitzsche 2006).

First steps towards a combination of anthropometric models and cognitive modeling can be found in the modeling of human behavior. The models used contain representations of the processes how people think and behave. These representations are especially relevant for the planning of operational processes in complex human-machine systems. In recent years, cognitive and behavioral models have become more and more meaningful and allow for human behavior to be modeled at a high level. Using such models, the simulation of autonomous virtual humans in a virtual environment is possible (e.g., Delleman 2006; Rasmussen, Christensen, Siebertz, & Rausch 2006). Thereby, cognitive aspects are already beginning to be considered (e.g., Narkevicius, Bagnall, Sargent, & Owen 2006; Gore & Milgram 2006). In addition, attempts in implementing multitasking models have been undertaken (e.g., Albeck & Badler 2006). Anthropometric models show already a good performance - almost comparable to real humans. However, the combination of cognitive and anthropometric models is not yet powerful enough to be applied and implemented in industry.

3. Prospects of Digital Human Modeling in Human Factors

That digital human modeling is increasingly being addressed by research and development (Cappelli & Duffy 2006), becomes apparent, for example, by the fact that the First International Conference on Digital Human Modeling will be held as a part of Human-Computer Interaction International conference (HCII) in Beijing in 2007 (see http://www.hcii2007.org/home.html).

In addition, in 2006 a new journal titled *International Journal of Human Factors Modeling and Simulation* has been established (see https://www.inderscience.com/www/IJHFMS_leaflet.pdf). This new journal focuses on the development and use of computer simulations and computational algorithms to advance knowledge and understanding in the field of human factors. It puts a particular focus on human factors theory as related to computational models of human performance and interaction with virtual environments, simulator-based evaluations of human factor issues, computer simulation of human behavior and performance, digital human modeling and simulation, developments in simulation and virtual environments to address human factors and ergonomic issues, and the simulation of physiological behavior, measures, and predictions.

Also, a *Handbook of Digital Human Modeling* edited by Vincent G. Duffy, will be published (Duffy 2007). This book will reflect the multidisciplinary perspective required to participate effectively in research and applications in this area (Duffy 2006). The digital human modeling effort will focus on six main areas including the background to digital human modeling, modeling fundamentals, evaluation methods, tools, applications and future work. There are many open questions for researchers and practitioners since there is a tremendous need for the practitioners, especially in ergonomics and human factors engineering, to be able to integrate digital human modeling tools into their everyday work (Duffy 2005). An understanding about the conditions under which certain models can be applied is also important, as well as the respective limitations.

Up to now, human factors specialists have already been included in design teams, but typically they are likely to suggest that a new design cannot work well, without having enough knowledge or tools to suggest possible modifications to make the new design acceptable in terms of human factors and ergonomics (Meister and Enderwick 2001). The digital human modeling community appears to be providing access to a computer-based set of tools to enable an improved contribution from both ergonomists and human factors engineers in engineering design. Attempts are being made to gather the best understanding of the fundamentals, tools and applications in Digital Human Modeling. The results will be made available to researchers and practitioners in applied ergonomics and human factors engineering that may participate in engineering design teams (Duffy 2005). One example for this integration is the Society of Automotive Engineers Digital Human Modeling Conference (SAE-DHM, see http://www.sae.org/events/dhm/). It will be important in the future that the information from this group can be transferred to those involved in human factors engineering. Thereby they will have access to computer-based tools to provide a common platform for their interaction with engineers in other disciplines participating in those design teams. It is also important that the driving forces in this area focus on the scientific fundamentals of this emerging multi-disciplinary field. Human factors and ergonomics is still not required in most engineering curricula. Digital human modeling initiatives provide an opportunity for researchers in human factors engineering and ergonomics to provide additional scientific support. There could be course offerings for undergraduate or graduate students such as *Digital Human Modeling* and *Virtual Interactive Machine Design*. These courses, when taught with a cross-disciplinary perspective, can be of interest to students, for example, in Industrial Engineering, Biomedical Engineering, Mechanical Engineering, Electrical Engineering, and Computer Science as well as Cognitive Science (Duffy 2005). It is clear that without access to the digital mock-ups that include the human aspects of models in advance of workstation and product design, costs will be incurred later, either in retrofit solutions or in lost market opportunities (Duffy 2005).

Until now, applied human models address mainly anthropometric issues. However, in recent decades, the nature of work has changed so that physical demands on workers and users have gotten less and, at the same time, cognitive demands have become more important. This requires new tools when designing products and workstations and consequently will provide more opportunities for cognitive models to be more frequently applied in the workplace and in product design. Thus, the main research challenge currently lies in the development of a combination of cognitive and anthropometric models. It is clear that the three worlds of Digital Human Modeling, Human Factors Engineering and Applied Ergonomics will have great opportunities for synergy (Duffy 2005).

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