Development of the Virtual-Human Santos^{TM}

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Abstract. This paper presents the background and history of the virtual human Santos^{TM} developed by the Virtual Soldier Research (VSR) Program at The University of Iowa. The early virtual human environment was called Mira^{TM}. This 15-degree-of-freedom (DOF) upper-body model with posture and motion prediction was funded by John Deere Inc. and US Army TACOM Automotive Research Center. In 2003 US Army TACOM began funding VSR to develop a new generation of virtual humans called Santos (109 DOFs), which was to be another generation of Mira. Later on, Caterpillar Inc., Honda R&D North Americas, Natick Soldier System Center, and USCAR (GM, Ford, and Chrysler) joined the VSR partnership. The objective is to develop a *new generation* of digital humans comprising realistic human models including anatomy, biomechanics, physiology, and intelligence in *real time*, and to test digital mockups of products and systems before they are built, thus reducing the significant costs and time associated with making prototypes. The philosophy is based on a novel optimization-based approach for empowering these digital humans to perform, un-aided, in a physics-based world. The research thrusts include the following areas: (1) predictive dynamics, (2) modeling of cloth, (3) hand model, (4) intuitive interface, (5) motion capture, (6) muscle and physiology modeling, (7) posture and motion prediction, (8) spine modeling, and (9) real-time simulation and virtual reality (VR). Currently, the capabilities of Santos include whole-body posture prediction, advanced inverse kinematics, reach envelope analysis, workspace zone differentiation, muscle force and stress analysis, muscle fatigue prediction, simulation of walking and running, dynamic motion prediction, physiologic assessment, a user-friendly interface, a hand model and grasping capability, clothing modeling, thermo discomfort assessment, muscle wrapping and sliding, whole-body vibration analysis, and collision avoidance.

Keywords: Virtual humans, predictive dynamics, muscle wrapping.

1 Introduction

Research on digital human modeling and simulation has gained significant momentum in recent years even though several commercial software programs are available, including Jack®, RAMSIS®, and Safework®. Traditionally, digital human modeling and simulation is based on data-driven algorithms. Most models are developed from experiment data and statistic regression. However, computational approaches have been the focus of increasing attention in the human factors and ergonomics community. One reason is that while data-driven approaches can give accurate results for a finite number of tasks, computational approaches can give accurate results for an infinite number of tasks. For example, in posture prediction, we can perform an experiment to obtain data for a finite number of target points and, if the user would like to predict a target point that was not part of the experiment data, the data-driven algorithm would use interpolation to obtain the results. However, computation-based approaches embed the target point in their models.

In this paper, we review the history of the Digital Human Laboratory at The University of Iowa and its research activities. We also introduce the Mira environment from early research results and describe the Santos model and its capabilities.

2 History of Digital Human Lab

The Robotics Lab was launched in 1994 by Dr. Karim Abdel-Malek, and the basic research activities were robotics-related topics such as robotic kinematic and dynamics study, robot control systems, and robotic mechanism design. In 2001 research efforts were extended to human-related studies; for example, studying workstation design for optimal seating position and orientation or studying the difference between how humans and robots move objects. The Digital Human Lab at The University of Iowa was created and included five graduate students and one professor. We had several Unix workstations and PC desktops. We also had Jack software, EON Reality, and a 4-wall virtual reality environment. We developed a digital human environment called Mira, which was financially supported by TACOM Automotive Research Center and John Deere Inc. Research topics included human kinematic model, workspace, posture and motion prediction, biomechanics analysis, placement of manipulators and digital humans for the design, and virtual reality environment. In 2003 the Digital Human Lab was extended to the Virtual Soldier Research (VSR) Program. The research team has 36 members, including faculty, staff, and students. The scope of the research is much more broad, including all topics related to digital human modeling and simulation. The original 4-wall VR system was replaced with a 6-wall Portal system.

3 Mira Environment

The first generation of digital humans developed by the Digital Human Lab is called Mira, and the living environment for this digital human is EON Reality. Figs. 1 and 2 show snapshots of this digital human. This digital human has 15 degrees of freedom (DOFs) from the waist to the right hand, as shown in Fig. 3. It has the following capabilities: (1) posture prediction (Mi et al., 2002; Abdel-Malek et al., 2001), (2) motion prediction (Abdel-Malek et al., 2006), (3) reach envelope analysis (Abdel-Malek et al., 2004; Yang et al., 2005; Yang et al., 2006), (4) placement (Abdel-Malek et al., 2004), and (5) layout design (Abdel-Malek et al., 2005). This approach formulates the design process as an optimization problem. Fig. 4 is a snapshot of the cross section of the workspace for the restrained driver. Figs 5-8 show results for this model where the posture prediction results are compared with IKAN (Tolani et al., 2000).

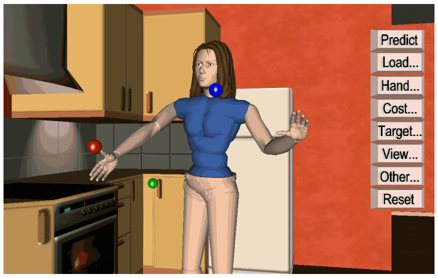


Fig. 1 Mira™ environment Fig. 2 Testing using Mira™

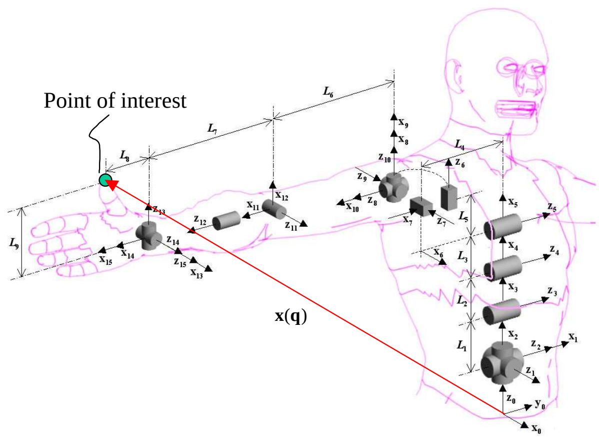


Fig. 3 Model for torso and right upper extremity

4 Virtual Human Santos

In 2003, the VSR team was formed and several large projects were initiated. Sponsors include US Army TACOM TARDEC, Natick Soldier Research Center, Caterpillar Inc., USCAR, Rockwell Collins, and HONDA R&D North Americas. There are fourteen thrust areas for the new digital human modeling and simulation research.

Santos is realistic digital human model that includes anatomy, biomechanics, physiology, and intelligence in real-time. It has 109 DOFs in the kinematic model, thousands of muscle lines in the musculoskeletal model, and a real-human appearance. The kinematic model is shown in Fig. 9, and the musculoskeletal model is shown in Fig. 10. The work to build muscle lines is ongoing, and it is an interactive real-time muscle wrapping model.

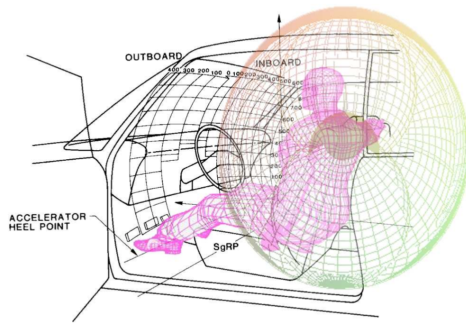
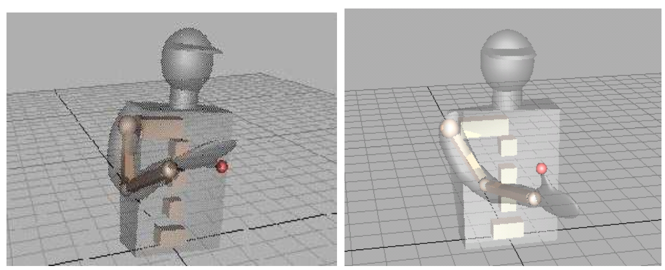
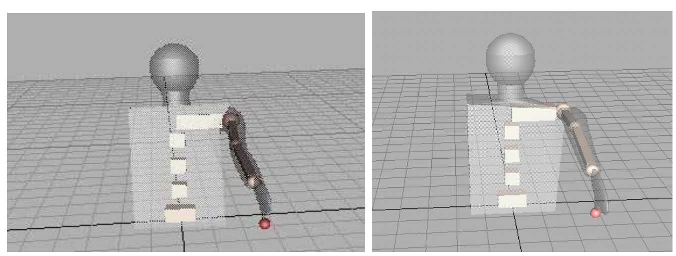


Fig. 4 Cross section of the workspace for the restrained driver



(a) (b)

Fig. 5 Posture prediction example 1 (a) Mira result; (b) IKAN result



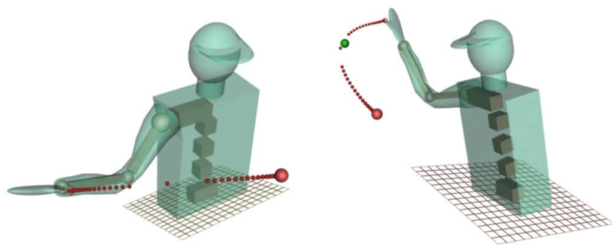
(a) (b)

Fig. 6 Posture prediction example 2 (a) Mira result; (b) IKAN result

Major projects and capabilities are listed as follows:

(1) Real-time VR

A primary focus at VSR is virtual reality (VR), modeling the world on computers with superior realism. However, we continually strive to take VR one step further—to model the world in real time, thus providing instantaneous feedback during human simulations. This allows for additional realism as well as the opportunity for users to actually interact with the virtual world. A key component in our development of premiere virtual reality environments is a state-of-the-art facility, a six-wall, 3-dimensional virtual reality room called the Portal. The Portal is the only PC-based six-wall virtual reality environment in the world. The interior of the Portal is a large 3m x 3m x 3m room. It works with a highspeed native Super XGA DLP projection system with active stereo. Each of the six screens has a resolution of 1024 x 1024 (SuperXGA). The six-screen cube provides a viewing range of 360 degrees horizontally and 360 degrees vertically.



(a) (b)

Fig. 7 Upper body motion prediction (a) Point-to-point; (b) Via-point

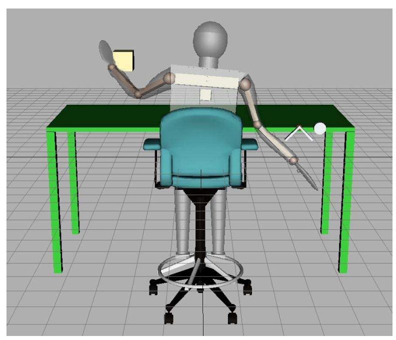


Fig. 8 Layout design

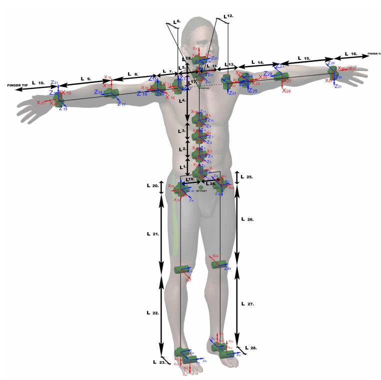


Fig. 9 Santos kinematic model

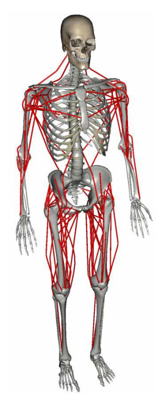


Fig. 10 Musculoskeletal model

(2) Optimization-Based Human Prediction

A key element in our efforts to model humans is a novel optimization-based approach to posture and motion prediction. In fact, much of what we do uses optimization as a foundation. This foundation stems from a solid history of expertise in the field of optimization, not only at the Center for Computer Aided Design (CCAD), but also at The

University of Iowa in general. With this approach, joint angles essentially provide design variables, constrained by joint limits based on anthropometric data as well as other physical constraints. Human performance measures that represent physically significant quantities, such as energy or discomfort, provide the objective functions. We contend that human posture and motion is *task-based*, meaning it is governed by different performance measures, depending on which task is being completed. Using this approach affords the digital human a substantial amount of autonomy, enabling an avatar to react to infinite scenarios rather than having to draw on prerecorded motions. With the optimization approach, incorporating additional capabilities or features is usually a matter of simply introducing new constraints and/or objective functions. In addition, our optimization-based approach allows us to operate in real time. Current digital human modeling methods and commercial codes do not have the capability to actually predict realistic motion in real time.

(3) Rigorous Human Performance Measures
Research concerning the human performance measures addresses fundamental questions about the prediction of human motion, resulting in realistic postures, path trajectories, and locomotion. The primary objective of this work is to mathematically model physically significant quantities. With metrics like energy, the process is relatively simple. However, with more subjective quantities, such as discomfort, the process involves determining which factors have been shown experimentally to contribute to discomfort and then how to represent each factor mathematically. Thus far, we have developed a comprehensive model for energy, discomfort, effort, maximum joint torque, two models for vision (and how the tendency to actually view objects affects posture), and joint displacement. In addition, we are working toward performance measures for muscle fatigue and time to exhaustion. The results of this research are the cornerstone of real-time optimization and real-time kinematics/dynamics models.

(4) Multi-objective Optimization
We recognize that in various situations, posture and/or motion may not be dictated by just one performance measure; it may be necessary to combine various measures. Consequently, we have developed substantial expertise in the field of multi-objective optimization and currently conduct research on how to effectively combine multiple performance measures. With multi-objective optimization problems, there is no single solution point. Rather, there is a set of infinitely many solutions, called the Pareto optimal set, with each point representing a different posture. We are able to depict this set of points and use its structure to glean insight as to how functions should be combined. We have studied more than 60 different methods and have developed new methods as well.

(5) Kinematic Posture and Motion Prediction

Although optimization is used extensively with VSR capabilities, the primary application is with human posture and motion prediction. Currently, we are accelerating toward having the most versatile, extensive, realistic, and computationally efficient posture prediction software package available. In addition to modeling the above-mentioned performance measures, we have developed a new method for dual-arm coordination (predicting posture to multiple kinematic chains that depend on common degrees of freedom, such as the spine). We can constrain any number of end-effectors to any point, line, or plane. We can stipulate the orientation of any local coordinate system. In addition, we incorporate self-avoidance; Santos is essentially aware of himself. All of the features can be applied to the whole body. Currently, we are conducting research on methods for incorporating whole-body movement (as opposed to limb movement with the hip fixed), as when Santos kneels down or leans his whole body forward. Our success with posture prediction is being extended to motion prediction, where optimization is used to predict time-histories of joint angles rather than just a single set of static angles. With notion prediction, time-histories are represented by B-splines, and the parameters for these splines provide the design variables for the optimization problem.

(6) Zone Differentiation

As part of the work with posture prediction, we have developed a novel approach to depicting and analyzing reach envelopes, which not only indicates which points in space are accessible, but also provides contours of values for the various performance measures. Depicting a reach envelope (or workspace) essentially provides a tool for product design. However, the workspace indicates whether or not a point is reachable, but does not necessarily indicate which points are most desirable (most comfortable, require the least effort, etc.). Thus, we have developed an optimization-based approach for workspace zone differentiation. In addition, we are conducting research on voxel processing methods for effectively visualizing 3-dimensional clouds of data, such as those that are provided with our zone differentiation capabilities.

(7) Real-Time Dynamics

This research effort focuses on adding significant capabilities to the motion subtended by digital humans. To date, there is no single digital human modeling program that enables its avatars to act and react to dynamic forces. Tasks such as pulling a lever, feeling the weight of an object, pushing a load, or simply throwing an object of known mass and inertia are not possible. Fundamentally, the optimization formulation for kinematic motion prediction can be augmented by including the equations of motion as constraints. In this way, we avoid cumbersome and time-consuming integration. This optimization-based approach avoids having to use typical forward dynamics or recursive dynamics to solve equations of motion, can easily accommodate highly complex human models, incorporates externally applied loads, and can potentially function in real time. Dynamic motion prediction becomes especially complex for activities that involve gait and balance, such as walking and running. Again, we take advantage of optimization, in conjunction with the Zero Moment Point (ZMP) approach.

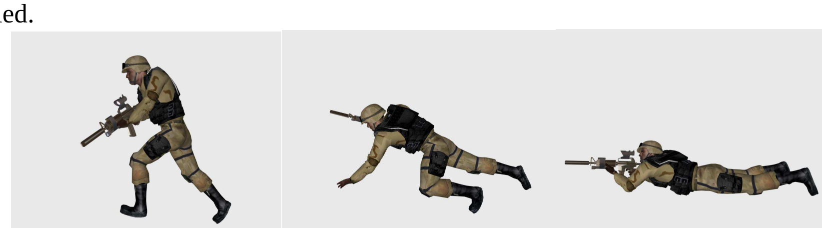
(8) Modeling Physiology

In addition to predicting human motion, we are able to model physiological indices, such as heart rate, breathing rate, oxygen consumption, energy consumption, body temperature, and physiological strain index. Oxygen consumption is a common measure of energy expenditure during sustained tasks in humans. Aerobic mechanisms for the regeneration of the required chemical sources of energy can be maintained for extended periods of time at submaximal levels of exercise. If the limit of aerobic energy metabolism is reached, anaerobic metabolism is required. While this metabolic process is efficient, most individuals cannot maintain it for more than several minutes. Further, time-to-exhaustion is inversely proportional to oxygen uptake. Therefore, the estimation of oxygen consumption provides a method to estimate how long an activity could be maintained and how well it would be tolerated for a variety of task scenarios.

(9) Task-Segmentation

In order to model complex multi-faceted tasks, we are developing a new methodology that involves segmenting motion into smaller subtasks that are simulated using the above-mentioned techniques and then stitched together. The general process is described as follows. First, using motion capture data of a soldier conducting a specific task(s), the motion will be segmented into a series of subtasks. For each subtask, the initial and final configurations for the digital human (a virtual soldier) will be determined and modeled with various constraints. Which constraints are used depends on the nature of the subtask. The digital human is then used to predict the motion between the initial and final configurations within each subtask while providing feedback for various indices. The protocol will be repeated for each subtask so that a user of the final environment will be able to request that the virtual soldier conduct a task under varying conditions of loading and mobility (e.g., different armor configurations and different external loading conditions).

As an example, consider the task outlined in Section 2. Motion capture will provide an understanding of the kinematics performed by a typical soldier for executing this task. The second step will be to segment the task into smaller subtasks as follows: (i) Run for 30 meters from point A to point B, (ii) Change postures from running to a diving position (B to C), (iii) Assume prone position (from diving at C to prone at D). For each of these subtasks, the initial and final conditions are modeled with constraints in the optimization formulation, and which constraints are most appropriate depends on the subtask being modeled.



(10) Mathematical Modeling of Clothing

In many circumstances, clothing can and does impact human performance while also providing protection from exposure to a wide spectrum of external hazards. Our research objective is to describe clothing with computational models and to then exercise these models to realistically predict how different types of clothing (of varying fabrics, cut, and fit) impact human performance when engaging in physical tasks such as running, climbing, and walking. With a knowledge of how clothing impacts human performance, the clothing can be redesigned to improve performance. This research combines many long-standing issues in solid mechanics, such as the following: (i) Modeling flexible systems (clothing) as shells and membranes at arbitrarily large deformations, (ii) Contact modeling between clothing and the human, and self-contact between portions of the same garment, (iii) Developing suitable constitutive models that account for the fibers comprising the fabric, and their evolving woven or knitted structure in the garment.

(11) Hand Modeling
This research addresses the complex biomechanics of the human hand and wrist. The long-term objective of this effort is to develop a three-dimensional model of the human hand and wrist for the purpose of kinematic and dynamic modeling, with the ability to predict grasps autonomously for any type of object. The research will couple digital image segmentation routines, realistic motions, and advanced modeling techniques to determine the joint torques, reaction forces, etc. The ability to incorporate realistic forces and force distributions via a force-feedback system holds the potential to immerse the subject in the virtual task, thereby improving the overall perception of task performance and the overall level of fidelity. A 25-DOF hand model with which users can interact has been developed. Artificial intelligence (AI) is used as Santos's brain to guide him to grasp objects or interact with his environment autonomously.

(12) Skeletal Muscle Modeling and Simulation
Skeletal muscles are important components of a virtual human. It is muscle contraction that causes the movement of the bones and consequently the motion of the body. The stress level in the muscle directly relates to a human's feeling of comfort. The objective of this research is to develop a computational framework that allows for the consideration of skeletal muscle in human modeling. While most commercial digital human environments do not have skeletal muscle modeling capabilities, we believe that this study will be crucial to the development of new capabilities for analysis and simulation.

In order to incorporate the limitations of muscles on the complete body, we have devised a relatively simple but computationally efficient muscle-modeling approach based on readily available data for torque-velocity relationships at various joints. In this way, we simplify the modeling problem by working in the joint space rather than the more complex muscle space.

Muscles are capable of generating more force at lower shortening velocities, and minimal force production at high shortening velocities. A similar trend applies to the relationship between torque and velocity. Validating simulations in joint space is easier than validating the performance of individual muscles, since the determination of joint torque velocity data can be obtained in vivo, whereas force velocity data for individual muscles is not feasible in humans. During the dynamic motion predictions for each subtask, the required joint torques needed to accomplish the predicted tasks are calculated. By plotting the first derivative of the joint angle versus time predictions (angular velocity versus time) against the joint torque versus time predictions we can determine the predicted joint torque versus angular velocity profiles for each subtask. These predicted curves are compared to the standard values for specific joint torque-velocity (T-V) profiles, readily available in the literature, in order to estimate the perceived level of difficulty of a subtask.

5 Summary

This paper reviews the research activities at VSR and the history of Santos, a physical-based digital human environment. Kinematics and dynamics are married with optimization techniques and are the core of this digital human. This is groundbreaking work in the human factors and ergonomics community because traditionally everything comes from experiments. However, we are investigating different human performance measures that govern human motion and formulating the human motion as an optimization problem. We also use experiments to validate our work.

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