MSMS Software for VR Simulations of Neural Prostheses and Patient Training and Rehabilitation

Rahman Davoodi and Gerald E. Loeb
Department of Biomedical Engineering, University of Southern California

Abstract. In the increasingly complex prosthetic limbs for upper extremity amputees, more mechanical degrees of freedom are combined with various neural commands to produce versatile human-like movements. Development, testing, and fitting of such neural prosthetic systems and training patients to control them effectively are complex processes that cannot be performed efficiently or safely by ad hoc and trial-and-error approaches. We have developed a software tool known as MSMS to enable researchers and engineers to simulate the movement of these neural prostheses and evaluate their performance before they are built and to train the patients in virtual simulation environments to operate their prostheses before receiving them. Further, MSMS facilitates development of interactive virtual reality applications for training, rehabilitation, and treatment of patients suffering from movement disorders.

Keywords. Myoelectric Prostheses, Modeling and Simulation, Virtual Reality, Patient Training and Rehabilitation

Introduction

Computer simulations have become an integral part of the design and development and safe operation of complex systems such as airplanes. In the development stage, different mechanical designs are prototyped virtually and simulated under various operating conditions to optimize performance. And once the airplane is built, its computer simulations are used in the safe environment of the flight simulator to train the pilots to fly the plane and practice emergency procedures that would be impractical with the real airplane. Complex multi-degrees of freedom (DOF) prostheses for upper limb amputees and their operation by neural or myoelectric commands of amputee patients are similarly complex and unintuitive and can benefit from computer simulations in all stages development.

Computer aided design software such as SolidWorks (SolidWorks Corp., USA) is already used to virtually prototype the mechanical design of the prosthetic limbs. These tools help the engineers iterate different design ideas and improve the mechanical design before actual manufacturing. But what remain unknown are the actual performance of the prosthetic limb under various operating conditions and the ability of the patients to operate it successfully. These are important design questions and answers to them can and should influence the design of the prosthetic limbs. Currently, to find out how the prosthetic limb actually performs or whether the patient can learn to operate it successfully, the engineers have to wait until a physical prototype is built and delivered to the patient, when it may be frustrating and even dangerous to identify mistakes and too costly to fix them. Therefore, virtual prototyping of the prosthetic limbs must include not only its mechanical design but also its performance under various operating conditions and evaluation of the ability of the patients to operate them successfully and effectively. In addition, these tools must enable the patients to use the safe virtual environments to practice and learn to operate their prostheses before actually receiving them. These tools are especially important for the new neural prosthesis systems where the combination of a multi-DOF prosthesis with multi-channel neural commands forms a complex system with non-intuitive behavior that is likely to change as the patient gains experience.

Development of neural prostheses to restore movement to the paralyzed limbs faces similar challenges. Patients must produce voluntary command signals to drive the electrical stimulation of a large number of paralyzed muscles, each with highly nonlinear behavior, to move the multi-DOF arm or leg to perform useful functions such as reaching, grasping, and walking. A virtual simulation environment can benefit the development of such complex systems and subsequent training of the patients to operate them effectively.

A number of software tools have been developed over the years to enable virtual prototyping of neural prostheses but none of them support the full cycle of neural prostheses development and delivery. Mechanical design and simulation software such as ADAMS (MSC Software Corp., USA) and Working Model (Design Simulation Technologies, Inc., USA) have been used to simulate neural prostheses for amputees and paralyzed patients. These software packages relieve the user from the error prone and painstaking process of deriving and programming the equations of motion. However, they lack the specialized components specific to physiological systems such as muscles and do not support real-time interactive virtual reality simulations with the patient in the loop. More specialized software such as SIMM[3], OpenSim[2], AnyBody (AnyBody Technology, Denmark) provide tools for building accurate musculoskeletal models of the human limb but they have largely focused on biomechanical analyses such as those in gait labs and do not support development and real-time simulation of sophisticated feedback control systems and practical tasks and work environments.

MSMS on the other hand, is designed to model prosthetic and human limbs and the task environment, and to simulate the limb's behavior under different control inputs and external forces. Further, MSMS simulations can be performed in interactive virtual reality environments where the patients can test drive their neural prostheses and learn to operate them before they are built and delivered to them.

1. Development Methods and Software Architecture

We have used an iterative software development process and applied professional software engineering tools and practices to gradually add, integrate, and test new features in MSMS. Each iteration period adds a small number of features and produces fully functioning and tested software that can and have been used in a number of applications over the course of its development. MSMS's tools for construction, visualization, and rendering of models are programmed in Java and Java3D. The models are stored in XML files where a standard format is defined for storing the parameters of each model component such as a segment or a muscle. The standardized XML format facilitates parsing, validation, and manipulation of model data using readily available tools. The computationally heavy simulations of MSMS models on the other hand, are performed in Simulink where a combination of Simulink library blocks and C programming language are used to speed up the execution of simulations. Simulink provides access to Matlab's toolboxes that can be used to simulate advanced control algorithms. More importantly, the entire Simulink model can be automatically compiled into low-level machine language and executed in a real-time xPC Target PC (Fig. 1). These real-time simulations are essential for building virtual reality simulations with the patient in the loop[4].

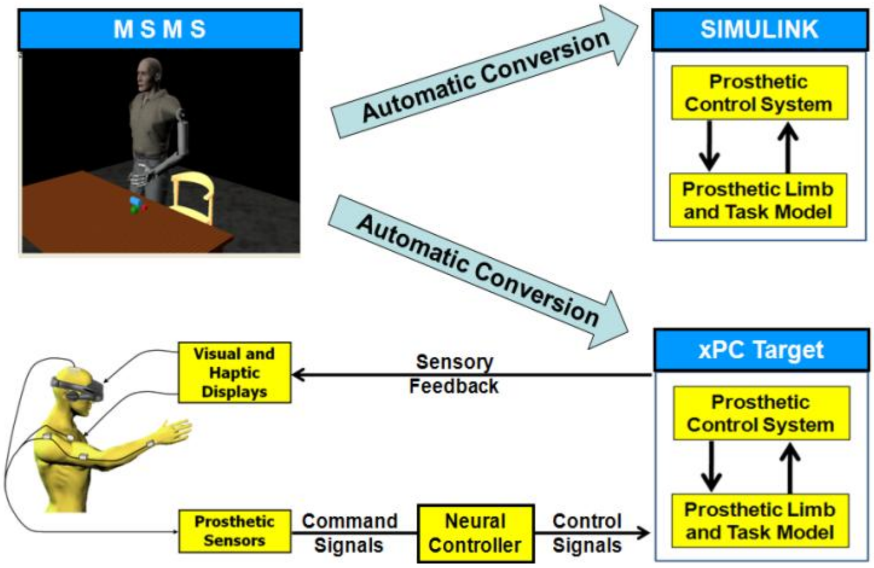

Figure 1. Architecture of MSMS software. Models of prosthetic limbs and rehabilitation tasks are built using MSMS's interactive modeling tools. The models are then automatically converted to a physics-based simulation model that can be run in Simulink or real-time xPC Targert simulation environments. The latter enables the creation of virtual simulation environments for patient training and rehabilitation.

2. MSMS Features and Applications

MSMS is software that is still under development and through our iterative development process is gradually acquiring new capabilities and features. Development to date has already endowed MSMS with enough features and capabilities to support a variety of applications as summarized below.

MSMS has a graphic user interface that allows the users to interactively create, navigate, and edit models of human and prosthetic limbs and the objects in the task environment (Fig. 2). MSMS Models can be edited graphically or directly at the XML files. The latter may be used by more advanced users. To facilitate fast assembly of virtual environments, MSMS allows the users to quickly combine existing models of the limbs and the task environments. Using this feature, a patient may be paired with different prosthetic limbs to find the right match and then allowed to practice operating it in different task environments. Although all model components could be built from scratch within MSMS, it has a utility that allows the users to import existing models built in other popular software tools. These tools allow importing musculoskeletal limb models from SIMM and prosthetic limb models from SolidWorks.

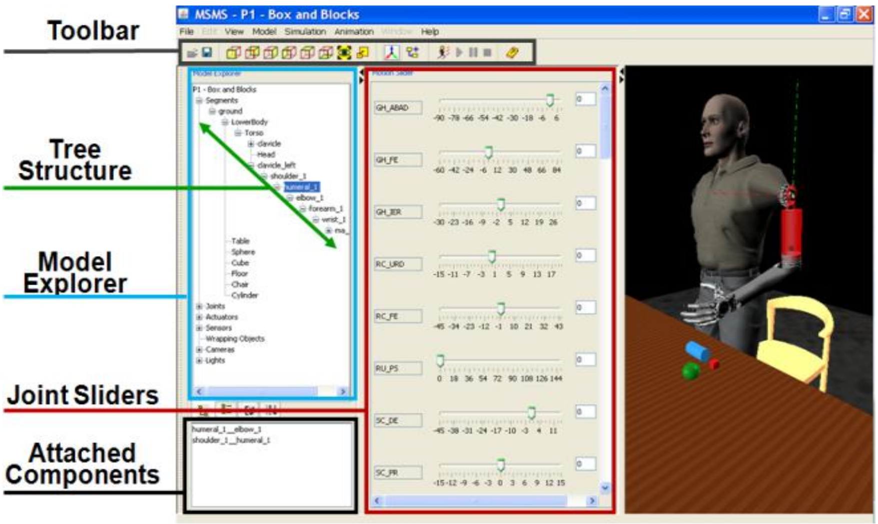

Figure 2. MSMS's Graphic User Interface. MSMS models can be built from scratch, imported from other software environments, and/or assembled from existing models of patients, prosthetic limbs, and rehabilitation tasks.

The physics-based movement of the MSMS models can be simulated in the popular Simulink simulation environment. These simulations can be used to study the movement of the neural prostheses in response to control inputs and external influences thus enabling the user to test the performance of the prosthetic control systems and optimize and fit them to the patients. Further, the Simulink simulations can be automatically compiled and downloaded to a real-time xPC Target PC where it can be executed in real-time (Fig. 1). Predictability and responsiveness of the real-time simulations are essential for construction of rehabilitation and training VR applications that must interact with the patients. These features have been used in Darpa's Revolutionizing Prosthetics Program to model and simulate the myoelectric and cortical control of multi-DOF prosthetic limbs. In our laboratory, we have used these features to simulate normal control of human limbs by the central nervous system and the control of paralyzed human limbs by functional electrical stimulation[5, 6].

Creation of VR applications is facilitated by an extensive set of tools in MSMS such as custom cameras and lights, sound playback, objects of arbitrary shapes and texture, and support for 3D stereoscopic displays that can render and display the VR scene from user's perspective. These tools have been used to build realistic models of human and prosthetic limbs and the virtual task environments simulating realistic rehabilitation tasks (Fig. 3).

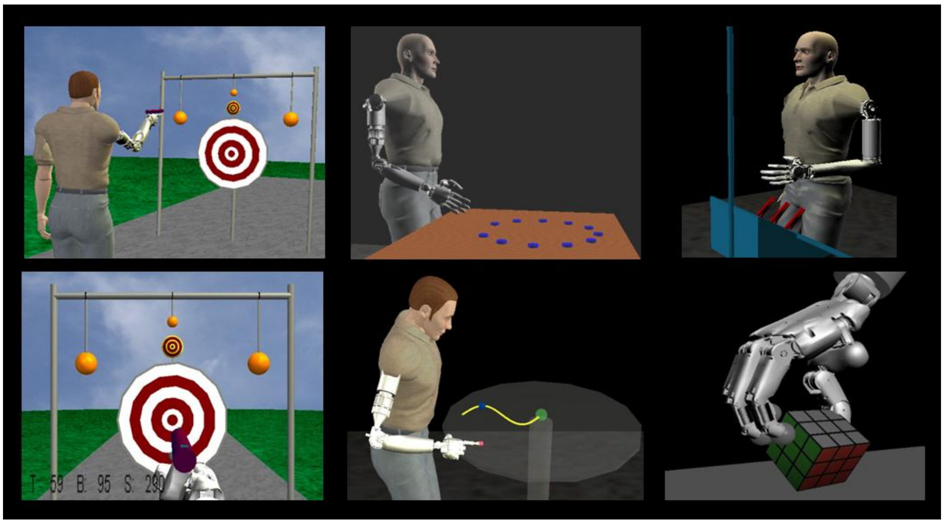

Figure 3. MSMS models of multi-DOF prostheses and the task environments simulating rehabilitation tasks and games.

In MSMS, we have built a set of unique animation tools that are specifically designed to facilitate neural prostheses development and patient training. The animation data can be loaded from a motion file and used to animate a MSMS model. Alternatively, MSMS can receive the motion data from live sources such as a physics-based simulation of the model running in the same PC or a networked PC, or a real-time motion capture system attached to a patient. This allows the creation of interactive VR applications where the motion of the MSMS model is animated in real-time in response to the control actions and patient inputs. These features have been used to develop virtual cortical control experiments where a non-human primate subject produces cortical control signals to control the movement of objects in virtual environment (Fig. 4).

Another animation feature allows non-expert users to develop animations of daily life activities using intuitive PowerPoint interface. Using this feature, primitive movements such as elbow flexion, hand opening, hand closing, etc., can be assembled into a more complex sequence of motions. The order of movement, the precise timing between the primitive motions, and the speed of animation for each motion could be easily modified by simply arranging the order of the slides and editing their properties in PowerPoint (Fig. 5). The resulting motion sequence can be played back in an open-loop manner for training and demonstrations or in a closed-loop interactive environment where the timing and speed of animation can be modified in response to user's actions. This feature is currently used in Walter Reeds Army Medical Center (WRAMC) to study the VR treatment of phantom limb pain in amputee patients.

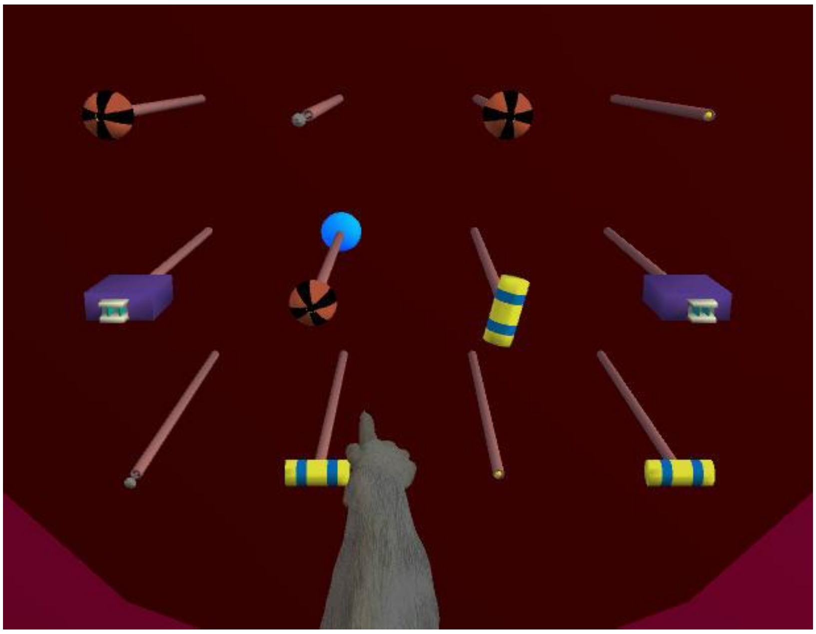

Figure 4. MSMS model of a virtual environment used to study the cortical control of movement by non-human primates.

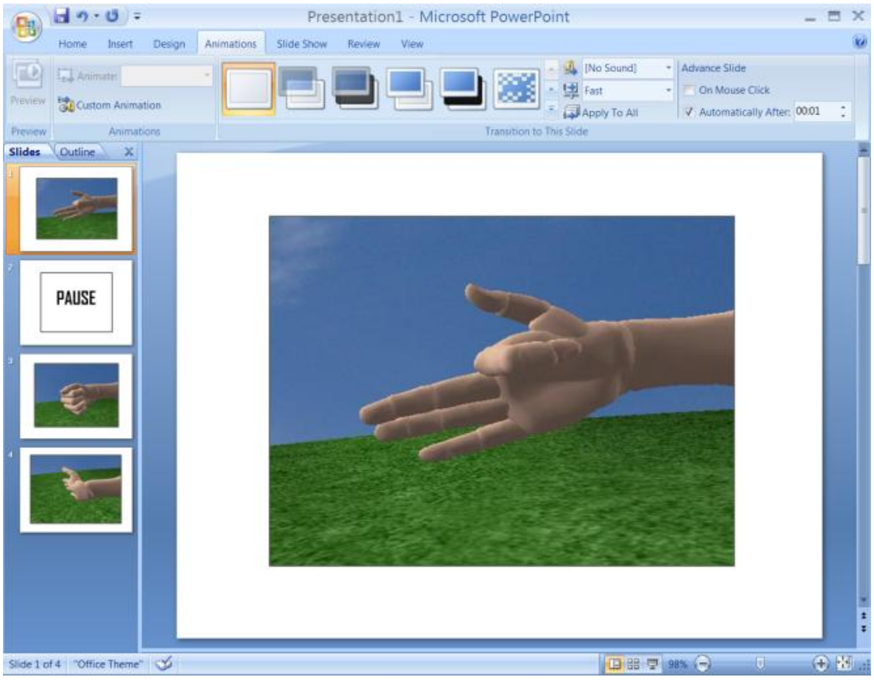

Figure 5. Expert and non-expert users alike can assemble primitive movement animations to build animation sequences with precise timing in Microsoft PowerPoint.

3. Discussion

MSMS provides a comprehensive framework for modeling and simulation of neural prostheses and development of VR applications to rehabilitate and train the patients. To date, the emphasis has been on development of tools for modeling and simulation of prosthetic limbs that has allowed the users to prototype virtual neural prostheses for amputees and develop VR applications to train patients to operate them. MSMS is currently been expanded by adding the tools required for modeling more complex anatomical structures such as the hand and fingers. The inclusion of Virtual Muscle[1] , the most accurate muscle force prediction software, and validated models of proprioceptors[7-9] as an integral part of MSMS will enable us to build accurate simulations of the complete physiological systems. MSMS is available for download at **http://mddf.usc.edu**.

4. Acknowledgement

The development of MSMS is currently funded by DARPA REPAIR program. MSMS development has also been funded in the past by DARPA Revolutionizing Prosthetics Program, NSF Engineering Research Center for Biomimetic MicroElectronic Systems, and Alfred Mann Institute for Biomedical Engineering.

References

[1] E.J.Cheng, I.E.Brown, G.E.Loeb, Virtual muscle: a computational approach to understanding the effects of muscle properties on motor control. *J.Neurosci.Methods* **101** (2000) 117-130.

[2] S.L.Delp, F.C.Anderson, A.S.Arnold, P.Loan, A.Habib, C.T.John, E.Guendelman, D.G.Thelen, OpenSim: open-source software to create and analyze dynamic Simulations of movement. *IEEE Transactions on Biomedical Engineering* **54** (2007) 1940-1950.

[3] S.L.Delp, J.P.Loan, A computational framework for simulating and analyzing human and animal movement. *Computing in Science & Engineering* **2** (2000) 46-55.

[4] M.Hauschild, R.Davoodi, G.E.Loeb, A virtual reality environment for designing and fitting neural prosthetic limbs. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* **15** (2007) 9-15.

[5] R.R.Kaliki, R.Davoodi, G.E.Loeb, Prediction of distal arm posture in 3-D space from shoulder movements for control of upper limb prostheses. *Proceedings of the IEEE* **96** (2008) 1217-1225.

[6] R.R.Kaliki, R.Davoodi, G.E.Loeb, Prediction of elbow trajectory from shoulder angles using neural networks. *International Journal of Computational Intelligence and Applications* **7** (2008) 333-349.

[7] M.P.Mileusnic, I.E.Brown, N.Lan, G.E.Loeb, Mathematical models of proprioceptors. I. Control and transduction in the muscle spindle. *Journal of Neurophysiology* **96** (2006) 1772-1788.

[8] M.P.Mileusnic, G.E.Loeb, Mathematical models of proprioceptors. II. Structure and function of the Golgi tendon organ. *Journal of Neurophysiology* **96** (2006) 1789-1802.

[9] M.P.Mileusnic, G.E.Loeb, Force estimation from ensembles of Golgi tendon organs. *Journal of Neural Engineering* **6** (2009) 036001.