# BodySim: A Multi-Domain Modeling and Simulation Framework for Body Sensor Networks Research and Design

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## ABSTRACT

Modeling and simulation are essential techniques for both engineering research and design. They enable many undertakings from early exploration of design concepts to understanding of complex phenomena. Body sensor networks (BSNs) are complex cyber-physical systems where resource-constrained networked computational systems must interact with highly dynamic and complex humans and their environment to achieve system goals of human health monitoring. Modeling and simulation in BSNs have so far been limited to just BSN components or looking at specific cyber-physical interaction issues. In this paper, we present BodySim, a multi-domain modeling framework that allows BSN designers and researchers to explore the cyber-physical issues in various systems scenarios by providing virtual human subject modeling capabilities and interfaces to virtual sensor models to allow experimentation and exploration in virtual space. We describe the architecture and our current instantiation of particular components for this framework. We also illustrate the kinds of explorations that can be done with this framework using our motivating applications in wireless communication and inertial sensing.

## Categories and Subject Descriptors

J.6 [**Computer-Aided Engineering**]: Computer-aided design (CAD); J.3 [**Life and Medical Sciences**]: Medical information systems

## General Terms

Design, Experimentation

## Keywords

Body sensor networks, model-driven design, frameworks

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## 1. INTRODUCTION

Modeling and simulation play important roles in engineering research and design. The semiconductor industry, for example, is heavily dependent on modeling and simulation tools for IC design and fabrication. These techniques are especially helpful in the early phases where limited detail is available about the design and where design changes are less costly. High-fidelity models can be employed at the verification and validation stages to complement testing. Models are also important research tools for understanding complex phenomena.

These techniques typically aid in understanding the relationship between the system being designed and the environment in which the system is intended to operate. Body sensor networks (BSNs) are an emerging class of cyber-physical systems where understanding this relationship is important. Many sensing modalities are directly driven by the dynamics of the user wearing the BSN. Also, the human body itself is a non-uniform environment with many variables of interest exhibiting both spatial and temporal dynamics for any given user state and activity. This makes issues like the effect of sensor location on system behavior important ones to explore. In addition, the behavior of the user and the characteristics of the environment they are in affect other aspects of the BSN, particularly wireless communication.

Previous BSN modeling efforts have typically concentrated on the BSN components (both software and hardware). Examples include exploring particular performance properties like energy consumption [3] and communication quality of service [14]. There has been some limited modeling of the relationship between the BSN and environment [16, 2, 15]. The main drawback of these models is that they typically focus on a specific issue in the BSN and are not easily extensible to consider other issues.

Despite these efforts, there is still a need for model-driven techniques for exploring cyber-physical issues like the effect of the location of the sensor on its output and the effect of particular user activities and environments on communication. Today, these issues are primarily explored using human subject experiments. Such methods are costly, especially for early concept exploration. In addition, there is a limited ability to keep some variables constant while changing others (*e.g.* it is infeasible to have the subject to reproduce the exact same motion while a different sensor location is explored). Lastly, there have been recent calls for patient models compatible with device models to aid in the design of medical cyber-physical systems like BSNs [1, 7].

Our aim is to complement these experimentation techniques and respond to this call for patient models by providing a platform for carrying out experimentation and explorations in virtual space. We envision in the long term a software platform which provides a researcher or designer access to a number of virtual human subjects on which he or she can place sensor nodes of varying capabilities and explore particular properties of interest in the system for various scenarios.

Such a platform can be used in purely virtual fashion or as complement to human subject data. In the purely virtual case, we envision a repository of subjects and their behaviors that users of this platform can select from and run experiments on. In the complementary case, we envision the user of this platform collecting information on a human subject's physical characteristics and behaviors, plugging this information into the software platform to create a new virtual human subject and add virtual sensors to this scenario in order to carry out investigations.

In this paper, we present the architecture and our current instantiation of particular components for a framework that enables the previously described platform. We show the kinds of explorations that can be done using this framework using our motivating applications. A key aspect of this framework is in the acquisition of body geometries for human subjects, and we present our method for rapid acquisition of such geometries. We call this multi-domain modeling and simulation framework, BodySim.

BodySim leverages advances in 3D physical modeling and animation instantiated in open-source tools like Blender [4] and scientific computing tools like MATLAB/Simulink [13, 12] and Python (with appropriate libraries)[10]. We consider BodySim a multi-domain framework because the virtual human subject models describe a physical domain, whereas the models that provide system property information describe the cyber-physical domain interface and the cyber domain of the BSN. Figure 1 shows the BodySim concept.

We must note that BodySim does not seek to supplant previous modeling efforts for BSNs. Rather, it seeks to serve as framework where such models can interoperate and in particular interact with realistic models of human subjects. For example, in this paper, we provide outputs from coupling our developed human models with IMUSim [16], an inertial sensor modeling tool. The focus of this paper is not on the validity or the accuracy of the models like IMUSim used to explore BSN properties, but more to show the kinds of explorations that can been done when such models are coupled properly with virtual human subjects. We envision that BodySim will be a community driven effort, and hence will be making our work available in as open a manner as possible. Our current website for BodySim is `http://wirelesshealth.virginia.edu/content/bodysim`.

## 2. BODYSIM

BodySim requires three components: a human (BSN user) structure model, a human dynamics model, and human-to-system-property relationship model. In this section we describe each of these components and how they are currently implemented in BodySim using our motivating applications in inertial sensing and wireless communication. The current instantiation of BodySim allows the researcher or designer to select a human model (of particular height and other characteristics), select motions and poses, and place sensors on arbitrary locations. BodySim also couples the information generated by this setup to other models that use this input to provide information on system properties of interest like sensor output or communication channel characteristics for the given scenario.

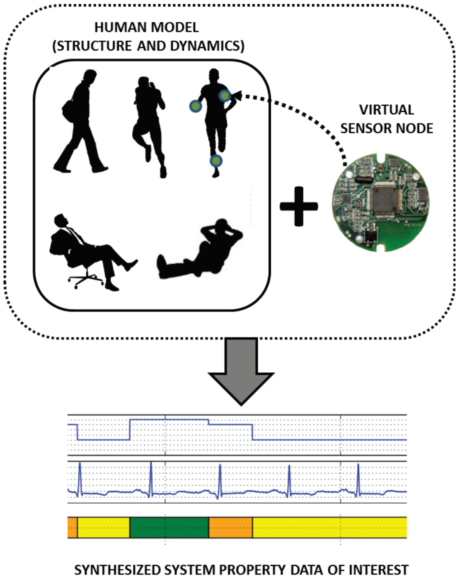

**Figure 1: BodySim Architecture**

### 2.1 Human Structure Model

The human structure describes the 3D features of interest of the human being modeled. In our case, we are particularly interested in the dimensions and the shapes of body segments (limbs, torso, neck and head). These are important because a real human is a 3D object and it is on the surface of this object that wearable sensors are placed. Also, when considering implantable sensors, thickness and structure of segments could be important as well.

Since BodySim relies on Blender, our human structure model is a 3D mesh. To obtain this mesh from a real subject, we use the Microsoft$^{\circledR}$'s Kinect [8] system to capture a depth image from the subject's front and back and use the Point Cloud Library [11] to generate a mesh that can be imported into Blender. Keeping track of actual physical dimensions of the person can be done with information from the depth image and application of triangle relationships (we do not go into detail in the interest of space). Figure 2 shows a human model generated using this process.

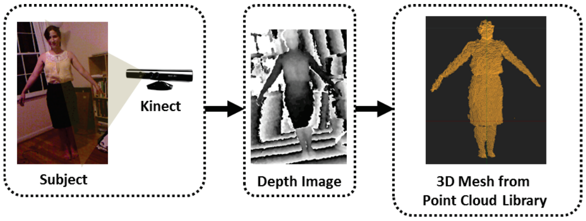

**Figure 2: Human structure model generation.**

## 2.2 Human Dynamics Model

The human dynamics model is intimately tied to the human structure model. The specific nature of the model depends on the particular application being considered. In our case we are interested in human motion, hence our dynamics model describes how the various segments of the body in the human structure model move (or occupy space) over time. For example, the dynamics model could describe how all body segments move while our virtual subject is walking. Non-motion dynamics models will also be tied to structure. An electrocardiograph for example is different at different locations of the body over time. Hence, the signal output must be related to the human structure. Human dynamics models in our framework are in general spatio-temporal models, which describes how the particular phenomena of interest occur at points on or around the body over time.

Currently, BodySim accepts human motion models in the Biovision hierarchical data (BVH) format which describes the human as a skeleton and describes how segments of the particular skeleton move. In Blender, such a model can be combined with a mesh to produce motion for a 3D human structure model. Our motion data is captured using high resolution optical motion capture from Vicon [9], though lower resolution models can be obtained from the Kinect system, or model-generated data can be obtained and converted to BVH from a biomechanics modeling tool like OpenSim [5] (we are yet to explore this option).

## 2.3 Human-to-System-Properties Relationship Model

This model does two things. First, it relates the physical dynamics of the BSN (sensor nodes) to the physical dynamics of the human model by specifying the locations of the sensors on the body and tracking its physical dynamics given these locations (*e.g.* it tracks the movement of a sensor in space given that it is placed on the human's wrist and human is walking). Second, it relates the resulting physical dynamics to property of interest of the sensor nodes (*e.g.* it produces the inertial sensor output data for the resulting movement of the sensor in the previous example).

The first function is currently achieved using features provided by Blender to relate the motion dynamics of one object to another. The second function, in general, has to be developed by the BodySim user for their particular property of interest. The input to the second function are the physical dynamics of interest obtained from the first function. For example, in the inertial sensing case, this is the physical location and orientation of the sensor over time. In a wireless channel case, these could be the distance between two sensor nodes, an indicator of whether line-of-sight exists or not, and the reflectiveness of the particular environment.

We have been able to couple our human structure and dynamics model (generated from real subject data) to IMUSim to generate inertial sensing data for virtual sensors we placed on virtual human subject model. We have also been able to extract data from the virtual subject model to generate wireless attenuation data using a simple distance based model. Figure 3(a) shows the setup for the inertial sensing simulation and 3(b) shows that for the wireless channel simulation. In both figures the black path lines show the trajectories for the virtual sensors attached to the forearm generated by BodySim for a running motion.

In the inertial sensing case the trajectory information is passed to IMUSim which serves as the human-to-system-property model for that case. IMUSim then generates the output of the inertial sensor, which is the system property we are interested in. This output is shown in Figure 4.

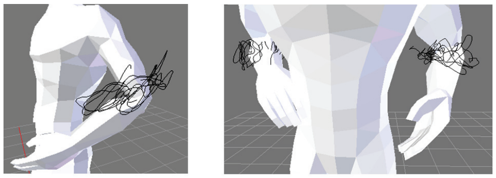
(a) (b)

**Figure 3: Simulation setups for (a) inertial sensor simulation (b) wireless channel simulation. The path lines shown represent the sensor trajectories.**

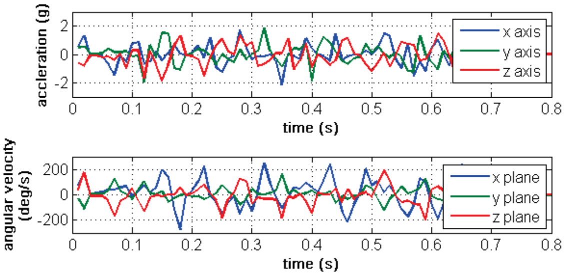

**Figure 4: Inertial sensing simulation using BodySim. The top plot shows the accelerometer data and the bottom plot shows the gyroscope data.**

In the wireless channel case, the two sensor trajectories are passed into a MATLAB model that uses the trace of distance over between the sensors to generate an approximation of the dynamics of the channel attenuation (path loss). The model is a standard attenuation model of the form $PL(d) = a \cdot log_{10}(d) + b + N$, where $d$ is the distance between the sensors, $PL(d)$ is the path loss, $a$ and $b$ are curve fitting parameters, and $N$ is a normally distributed zero-mean random variable. Figure 5 shows the output for this simulation.

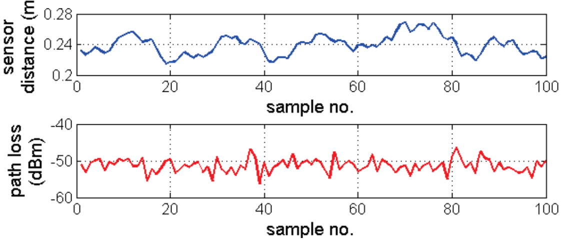

**Figure 5: Simple wireless channel simulation using BodySim. The top plot shows the distance between the sensors over time and the bottom plot shows resulting path loss.**

Using BodySim, we can move the sensors to other locations and observe the new inertial sensor output or predict new path loss curves. These experiments permit the best choice of sensor location for the application of interest.

## 3. DISCUSSION AND CONCLUSION

The current instantiation of BodySim provides us with a virtual experimentation platform for scenarios that would usually require tedious human subject experiments. In order to develop BodySim, however, it is necessary to perform some human subject experimentation, and the models in BodySim can be continuously updated through such experiments. However, the advantage of BodySim is in allowing more explorations beyond what would be feasible in these experiments and to change particular variables while keeping others like the particular subject and their movement exactly the same, an infeasible feat in experimentation.

Our motivations for developing this framework are both research- and design-driven. Our research motivation is in developing accurate intuitive models of the wireless channel around the body explicitly accounting for how the BSN user's structure (physical body parameters), dynamics (movements and postures), environment, and the placement of the sensors on the body affect the resulting channel dynamics.

One key challenge in developing such a model is in accounting for line-of-sight and non-line-sight scenarios. In experimentation, we would have to have video ground truth and manually determine these situations. With BodySim, we can use 3D modeling to recreate our experimental scenario and use scripting to determine these situations allowing us to concentrate on model development efforts.

One design motivation is in developing effective communication strategies for the BSN applications we are interested in. Here we intend to leverage the channel models developed with the aid of BodySim. We are also interested in using BodySim to leverage the capabilities of IMUSim [16] and other models like OpenSim [5] to develop and evaluate inertial sensing systems for a number of medical applications.

Like any framework, BodySim is a work-in-progress. We envision the use of BodySim in exploring other issues like how electrical activity of the heart manifests on various parts of the skin surface, or how the choice of sensor site affects glucose montioring or pulse oximetry. These would require more internal modeling of particular human physiologic structures, however, much is known about such structures and some spatio-temporal models do exists that could be adapted to work in BodySim. Our aim is that the virtual human experimentation and virtual system prototyping that BodySim enables will help with reducing the costs and overheads of early explorations.

Lastly, virtual subject models in BodySim could potentially be used as benchmarks for comparing various systems within the same application. Such benchmarks have been useful in many other industries (*e.g.* the FDA-approved T1DM Simulator for diabetes management technologies [6]) are badly needed since it is usually difficult (and in many cases infeasible) to test different BSN systems which aim to achieve the same goal with the same experimental data from other work.

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