

Estimation of Mass and Inertia Properties of Human Body Segments for Physics-based Human Modeling and Simulation Applications

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ABSTRACT

This paper describes an effective integrated method for estimation of subject-specific mass, inertia tensor, and center of mass of individual body segments of a digital avatar for use with physics-based digital human modeling simulation environment. One of the main goals of digital human modeling and simulation environments is that a user should be able to change the avatar (from male to female to a child) at any given time. The user should also be able to change the various link dimensions, like lengths of upper and lower arms, lengths of upper and lower legs, etc. These customizations in digital avatar's geometry change the kinematic and dynamic properties of various segments of its body. Hence, the mass and center of mass/inertia data of the segments must be updated before simulating physics-based realistic motions. Most of the current methods use mass and inertia properties calculated from a set of regression equations based on average of some population. In this paper, we calculate avatar-specific mass and inertia properties from the scans of digital human. The mesh of the digital human model is split using equations defined by a plane at each joint. The equation is used to split up the geometry. The resultant geometry is closed to make the mesh hole free. Mass, center of mass (assuming uniform density) and inertia tensor are then calculated using the method described in the paper (Mirtich 1996). The method can be used in all physics-based digital human modeling and simulation software where the scan of the avatar is available. The use of mass inertia properties calculated by this method enables users to customize digital avatar and simulate motions for specifically for that avatar.

INTRODUCTION

Predictive dynamics is the term used for predicting dynamically consistent simulations of virtual human motion. The goal of the project is to simulate human motions for different avatars that are not only visually appealing, but also consistent with the physics constraints. At any given time, a user should be able to change the avatar (from male to female to child to an alien creature). User should also be able to change the various link dimensions, like lengths of upper and lower arms, lengths of upper and lower legs, etc. Once an avatar is selected and its various dimensions fixed, a user should be able to monitor all forces, torques, stress levels, and physiological parameters of the avatar as the avatar performs different tasks. It is well known from the vast literature on robotics and controls that the torques required at each of the joints depend not only on the properties of the task and environment, but also on the properties of self, in this case, avatar. Hence, an accurate estimation of kinematic and dynamic body segment parameters (BSPs) of human body (which is represented by the avatar) is required. Kinematic parameters like the dimensions of various links of the human body will be selected by the user. Dynamic BSPs that include measures of volume (V), mass (M), center of mass (CM), and inertia tensor (I), however, needs to be estimated as accurately as possible to match the dynamic properties of the avatar that is to be simulated.

LITERATURE SEARCH

Since the earlier works of (Borelli, 1680) on prediction of center of mass of human body in stretched condition, many investigators have focused on accurately measuring the mass distribution properties of human body. Most investigators attempted to determine mass distribution properties of human body segments rather than full body in a particular pose. Despite the substantial efforts spent to date, accurately measuring the mass distribution properties of human body segments is still an open problem. Techniques developed to get an estimate of mass and inertia parameters over these years can be classified into two main groups: (i) cadaver segmentation techniques (applied on cadavers); and (ii) image processing techniques (mainly applied on live subjects).

Harless (1860) made the first attempt to obtain comprehensive mass distribution data on cadaver segments based on two male cadavers. Dempster and Gaughran (1967) performed similar studies on nine male white preserved cadavers and compared their results with previous similar studies involving use of cadavers. However, such studies have always used small sample sizes and thus the data obtained from such studies cannot be generalized.

Air Force Research Laboratory (AFRL) developed Articulated Total Body (ATB) (Cheng, Rizer and Obergefel, 1998) software in 1975 to predict gross human body response in various dynamic environments like automobile crash and aircraft ejection with windblast exposure. ATB requires extensive data to describe human geometric and inertial properties. Massive efforts (McConville, Churchill and Kaleps, 1980) (Young, Chandler and Snow, 1983) were undertaken by AFRL to determine the inputs required by ATB such that they correspond to live subjects. It is of the utmost importance that the subject-specific values of these parameters are determined by appropriate (non-invasive) experimental in vivo methods. Hence, they used stereophotometric (also known as biostereometric or photostereogrammetric or photogrammetric) image processing techniques to generate the data. One major contribution of these studies was the development of regression equations that relate the anthropometric data of the segments and their mass distribution characteristics for living subjects. However, while determining the inertia properties from the stereophotometric data, it was assumed that the human body is homogeneous, and thus, each individual body segment is homogeneous and as the same density as all other body segments (Cheng, Obergefell, and Rizer, 1996). The outcome of this effort is Generator of Body Data (GEBOD) program which is an interactive computer program that outputs human body dimensions and inertia properties. Regression equations developed as a part of this research are also used by The AnyBody Modeling System (Rasmussen, 2007).

On similar lines, The 1988 Anthropometric Survey of the U.S. Army was conducted from August 1987 through July 1988. This survey contains 132 traditional two-dimensional anthropometric measurements, and biographical and headboard data for 1,774 male subjects. This survey is widely known as Ansur 88 and is used in Jack Human Simulation Software (UGS, 2007).

In order to get better estimation of inertia properties due to the uneven tissue distribution within the body of living subjects, Magnetic Resonance Imaging (MRI) is another image processing technique that has been widely used. Pearsall et. al. (1994) determined inertial properties of human trunk of males using MRI. They compared their results with existing results based on volumetric estimation methods and segment prediction formulas. While the results from volumetric estimation methods closely matched the MRI results with r^2 values ranging from 0.94 to 0.99, the results from segment prediction formulas matched with r^2 values of 0.76 to 0.81. As a part of this study, it was also concluded that volumetric technique may be effective for deriving BSPs if appropriate density values are used for all the body segments. Hatze (2005) presents a nice review on current state of the art with regards to determination of geometric and inertial parameters determination.

Our approach is based on following algorithmic operations: i) splitting the mesh from the body surface scan of the digital human avatar for each of the body segments, ii) closing the mesh at the ends where it was cut open, and iii) calculating volume, mass and inertia properties for each segments. In the following sections, we explain these three mesh splitting steps and then present initial results of approximating mass and inertia properties for standard objects.

MESH SPLITTING

Dynamic calculation of mass and inertia properties of body parts has been a challenging task in digital human modeling and simulation. A digital human is typically comprised of a single mesh for the entire body with makes it difficult to determine inertia of individual body parts. This limitation can be overcome by either modeling the digital human with multiple mesh segments, but this would make proper skinning (vertex blending) a challenge. Another approach would be to split up a given mesh into multiple meshes based on some splitting paradigm. We present a technique that follows the latter approach in the following sections. Previous work by Rasmussen (2008) illustrates a way of splitting meshes for animation of a virtual mannequin. But this approach is not dynamic and will require manual splitting of meshes to obtain body part meshes.

In this paper, we describe a technique for using plane equations to split up a mesh. This mesh will be used to calculate inertia and mass properties of respective body parts. This approach is independent of the human model being used and would work the same for any given model.

SPLITTING TECHNIQUE

Figure 1 illustrates the mesh splitting technique that is used in this paper. The diagram above illustrates how a given mesh is split. To split a mesh, two plane equations are defined at segments where a split needs to occur. The plane equations are defined at every location at which a mesh split needs to be occurred. These mesh splits can be chained together to get the required number of meshes. The mesh splitting process for the whole body is done by using just two planes. The two planes are relocated to the appropriate location for each segment to be split.

The location of a 3d point in space relative to a plane can be determined by using the plane equation defining the plane. Let us define a point in space O defined by (x, y, z) . x , y and z define the location of the point in space relative to the global coordinate system. Let us also define a plane equation of the form

$$ax + by + cz + d = 0$$

When the values (x, y, z) defining the location of the point O in space are substituted in the above equation, the equation is satisfied (results in value zero as defined) if the point lies on the plane. However, if the point lies on either side of the plane, a non-zero value is returned. This value can be positive or negative depending on the side of the plane the point is on. This characteristic of the plane equation is used in our paper to split a given 3d mesh.

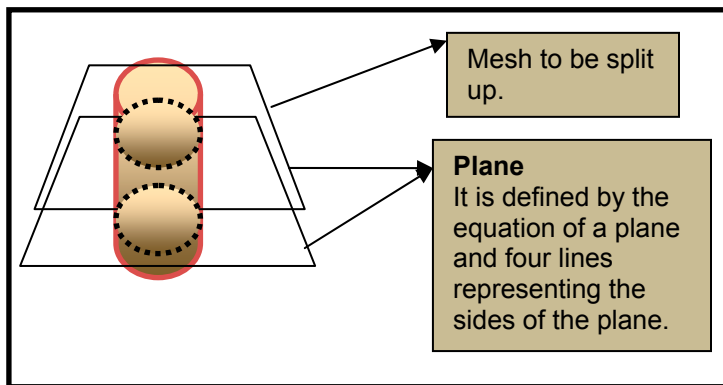


Figure 1: Mesh splitting strategy

The two planes that are used in the simulation have their normals facing each other. 3d coordinates (spatial locations with respect to the global coordinate system) of all the vertices that define the 3d mesh of the digital human model are substituted in the two plane equations to determine what vertices are enclosed by the two planes. If the resultant values of the plane equation are both positive for a given vertex location, the vertex is enclosed by the planes.

All the vertices that are enclosed by the planes are added to a newly created mesh. This is an algorithmic

process and is actually done by iterating through the triangle faces of the mesh. The three vertex locations that define the triangle are substituted in the plane equations. If all three points lie outside the region enclosed by the two planes, the triangle is simply rejected. If the points lie within the region enclosed by the two planes, the triangle is added to the new mesh that is created. There are special cases however.

The special cases occur when one vertex lies on one side of the plane, and the other two, on the other side of the plane. These triangles can simply be rejected, but that would result in a mesh that is slightly smaller than the actual mesh is supposed to be, because of skipped triangle faces.

However, in our technique, we use a simple heuristic to determine the inclusion or exclusion of a triangle face. If two vertices lie in the region enclosed by the two planes, the triangle is added to the new mesh. If only one vertex lies within the region, the triangle is simply rejected. This ensures that the new mesh that is generated is a close approximation of the original geometry. Future work on this technique includes modifying the mesh splitting algorithm to be exact splits at the planes (Jin et. al., 2005).

Figure 2 illustrates the special case splitting process. Here, the blue colored triangles lie within the region enclosed by the two planes. Note that the triangles with two vertices within the enclosed region are colored blue. This indicates that they are also added to the newly generated mesh.

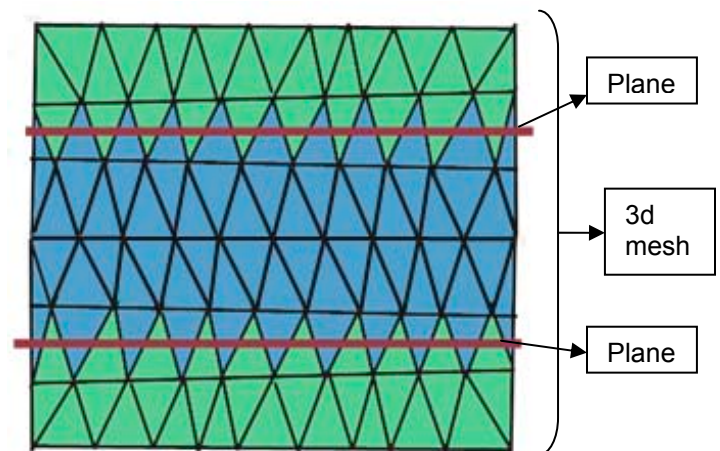


Figure 2: Primitive grouping based on plane equation

Splitting process - Two different planes are used at each end of the section that needs to be split to split the mesh. The normals on the planes face each other. This ensures that points, whose locations yield a positive value after substitution in the plane equation, lie within the region enclosed by these two planes.

A programmed routine uses the main digital human mesh and the two plane equations to split the mesh into a new subsection that is enclosed with the two planes.