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Susanna Guatelli

University of Wollongong, susanna@uow.edu.au

Barbara Mascialino

INFN Sezione di Genova, barbara.mascialino@ki.se

Maria Grazia Pia

INFN Sezione di Genova

Witold Pokorski

CERN

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Abstract

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Keywords

antropomorphic, phantoms, geant4

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Geant4 Anthropomorphic Phantoms

Susanna Guatelli, Barbara Mascialino, Maria Grazia Pia, Witold Pokorski

Abstract— A novel architectural approach to the design of human phantom software models is presented. A detailed design has been developed to enable the adoption of this approach in Geant4-based simulation applications. A few preliminary implementations and application demonstrations are described.

Index Terms— Geant4, Monte Carlo, phantom, dosimetry, simulation.

I. INTRODUCTION

REALISTIC software models of the human body are useful tools in various domains, such as radiation protection, oncological radiotherapy or nuclear medicine. Their most common application is to study the effects of radiation by means of Monte Carlo simulation.

Several models of anthropomorphic phantom have been developed over approximately four decades. They are characterized by two different approaches to the description of body components: their shape is described either through mathematical representations [1]-[2] or through an approximation by means of voxels [3]; a material composition is associated to each of the elementary geometrical components. The issue of which modeling approach is superior has been debated at length in the scientific community: both approaches present advantages and drawbacks [4], which make them suitable to address different application requirements.

Software implementations have been developed based on both approaches. Most of them are not publicly available to the scientific community.

The project described in this paper represents an innovative approach to modeling anthropomorphic phantoms for Monte Carlo simulation. It defines an original architectural design, which enables the implementation and usage of different phantom modeling approaches. The component-based architecture and the object oriented technology adopted make this system open to further evolution.

A detailed design of the system is described, which enables the adoption of the architectural concepts devised in a Geant4 [5]-[6] based simulation application. The system developed is

publicly released for the first time with Geant4 version 8.2; further refinements and extensions will be distributed in forthcoming Geant4 versions.

II. SOFTWARE ANALYSIS AND DESIGN

Geant4 is an object oriented toolkit for the simulation of particle interactions with matter. It provides advanced functionality for all the domains typical of detector simulation: geometry and material modeling, description of particle properties, physics processes, tracking, event and run management, detector response modeling, user interface and visualization. Its advanced geometry modeling capabilities and its versatility to describe materials provide powerful tools for the representation of the human body; its wide physics coverage allows accurate studies of the radiation effects in anthropomorphic phantoms over an extended energy range.

The adoption of the object oriented technology, together with the full-fledged set of modeling tools available in the Geant4 toolkit, allows developing a novel architectural approach to the software modeling anthropomorphic phantom.

The main functional requirement concerning the construction of anthropomorphic phantoms consists in the capability to describe the shape, size, positioning and material composition of the human body anatomy. Characteristics related to the sex and the age of the human model should be taken into account.

The project described in this paper introduced a new significant non-functional requirement: the possibility to model either analytical or voxel phantoms transparently, and even to build phantoms mixing both modeling approaches. Complementary requirements are the possibility to build established phantom models documented in literature, partial phantoms consisting of selected body parts only (for instance, just the torso or the head), and to compose customized phantom models out of a variety of available body component models.

The problem domain decomposition derived from the requirements analysis distinguishes two main abstractions: the process of building a phantom and the model of the human body associated to a phantom. These two abstractions characterize the architecture of Geant4 Human Phantom package.

The process of building a phantom is handled through a Builder design pattern [7]; it is illustrated in Fig. 1 through a UML (Unified Modeling Language) [8] class diagram. The *G4BasePhantomBuilder* base class defines the interface for assembling a phantom and provides dummy implementations of all its public virtual member functions. Derived classes

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S. Guatelli, B. Mascialino and M.G. Pia are with INFN Sezione di Genova, Genova 16146, Italy (phone: +390103536328; fax: +39010313358; e-mail: Susanna.Guatelli@ge.infn.it, Barbara.Mascialino@ge.infn.it, MariaGrazia.Pia@ge.infn.it).

Witold Pokorski is with CERN, CH1211 Geneva 23, Switzerland (phone: +41227672030, fax: +4122767.8130, e-mail: Witold.Pokorski@cern.ch).

provide concrete implementations of the assembly process; they can all be handled polymorphically through the same base class. The Geant4 Human Phantom package includes a *G4PhantomBuilder* derived class and two specializations of it, a *G4FemalePhantomBuilder* and *G4MalePhantomBuilder*. *G4PhantomBuilder* is responsible for assembling the body parts common to both sexes by overloading the respective member functions of its base class; *G4FemalePhantomBuilder* and *G4MalePhantomBuilder* overload the member functions of *G4BasePhantomBuilder* specific to each sex. Alternative assembly processes can be easily customized by deriving classes from *G4BasePhantomBuilder* and overloading the desired member functions. For instance, through this design one can assemble a customized phantom consisting of a torso or a head only, if a partial body representation is sufficient to satisfy the application requirements.

The creation of coherent models of the human body is handled through an Abstract Factory design pattern [7]. A *G4VBodyFactory* abstract base class defines the interface for creating anatomy components. The factory creates products of type *G4VPhysicalVolume*, an abstract class of the Geant4 Geometry package which defines the interface of physical volumes. Concrete factories derived from *G4VBodyFactory* implement the operations to create concrete product objects representing body parts. The class diagram illustrating the creation of coherent phantom models is shown in Fig. 2. Each concrete factory is responsible for the creation of a coherent phantom model, i.e. either one of the specific phantoms documented in literature or even a user-defined one.

A phantom builder may be associated to one or more body factories, thus enabling the assembly of standard phantom models, or of combinations of their parts.

It is worthwhile noting that the fundamental abstractions of the system, their usage in a simulation application and the products of the assembly process are completely transparent to the specific features of the phantom to be modeled, either a mathematical or a voxel one. Since all objects are handled through their abstract interfaces, one can compose a body representation with the greatest flexibility, without being constrained to a specific modeling approach or to a single phantom model in his or her simulation application. The transparent interchangeability of various modeling options opens the possibility for optimization studies, and evaluations of radiation effects in different phantom configurations. This flexibility is especially important in critical studies based on Monte Carlo simulations to estimate possible systematic effects related to the specificity of individual phantom models.

III. IMPLEMENTATION FEATURES

Two concrete factories, corresponding to the MIRD [1] and ORNL [2] analytical phantoms, are publicly released in Geant4 8.2; factories corresponding to other established phantom models will be released in future Geant4 versions. The *G4ORNLBodyFactory* and *G4MIRDBodyFactory* create all the anatomical components as specified in the respective reference phantom models.

The implementation of anatomical components exploits

Geant4 tools for geometry and material modeling. Body parts are characterized by their shape (described through a Geant4 *G4VSolid* object), their sizes, their positioning and rotation with respect to a fixed reference system, and the materials they are composed of.

The geometrical parameters describing the anatomical components are handled through GDML (Geometry Description Markup Language) [9]. This tool allows decoupling the geometrical and material description of the body components from the actual corresponding parameters, which are stored in a file independent from the simulation code. This feature enables modifying any of the geometrical and material parameters freely in the GDML file without requiring the recompilation of the software any time a parameter is modified.

The implementation of a voxel breast reproducing the model described in [10] is included in Geant4 8.2 version. This development has the purpose of demonstrating the capability of the system design to handle mathematical or voxel models transparently and to compose phantoms based on a mixed modeling approach; further more complete voxel phantoms are foreseen for release in future Geant4 versions. It is worth noticing that the implementation of voxel phantoms can exploit powerful Geant4 modeling capabilities for the optimization of the geometry model and the navigation across complex voxel geometries.

IV. DEMONSTRATION OF THE SOFTWARE CAPABILITIES

The realization of a female anthropomorphic phantom corresponding to the ORNL analytical model is shown in Fig. 3; the picture has been produced through Geant4 Visualization package.

Fig. 4 shows a a voxel breast based on [10] embedded in a phantom based on the MIRD mathematical model.

The anthropomorphic phantoms described in this paper can be used in any Geant4-based application; the user can exploit the full functionality of the Geant4 toolkit to study the radiation effects in the body anatomy. For convenience, the Geant4 Human Phantom package provides the option to calculate the dose released in each of the phantom components in a Geant4 simulation; Fig. 5 shows an example of such calculation as a result of the irradiation of a MIRD phantom with a particle beam. In the case of voxel components, the software calculates the dose in each of the voxels (Fig. 6). This versatility allows the user to calculate precise dose distributions based on detailed geometries whenever required, while evaluating the dose globally in less critical organs, thus contributing to the overall optimization of the simulation performance.

V. CONCLUSION

The development of software anthropomorphic phantoms has been addressed through a novel architectural approach. The adoption of the object oriented technology provides the ground for versatile design techniques: thanks to the design

developed, analytical and voxel phantoms can be used transparently in a simulation application. An initial set of phantom models has been implemented; the software design allows the user to construct either established phantoms as documented in literature or customized phantoms consisting of any body components, irrespective of their modelling technique.

Prototype applications have demonstrated the capability of the system developed to allow assembling mixed analytical and voxel phantoms, and to calculate the dose in entire organs or in individual voxels resulting from radiation exposure.

The software described in this paper is open source; it is first publicly distributed in Geant4 version 8.2 in the Human Phantom package of Geant4 Advanced Examples.

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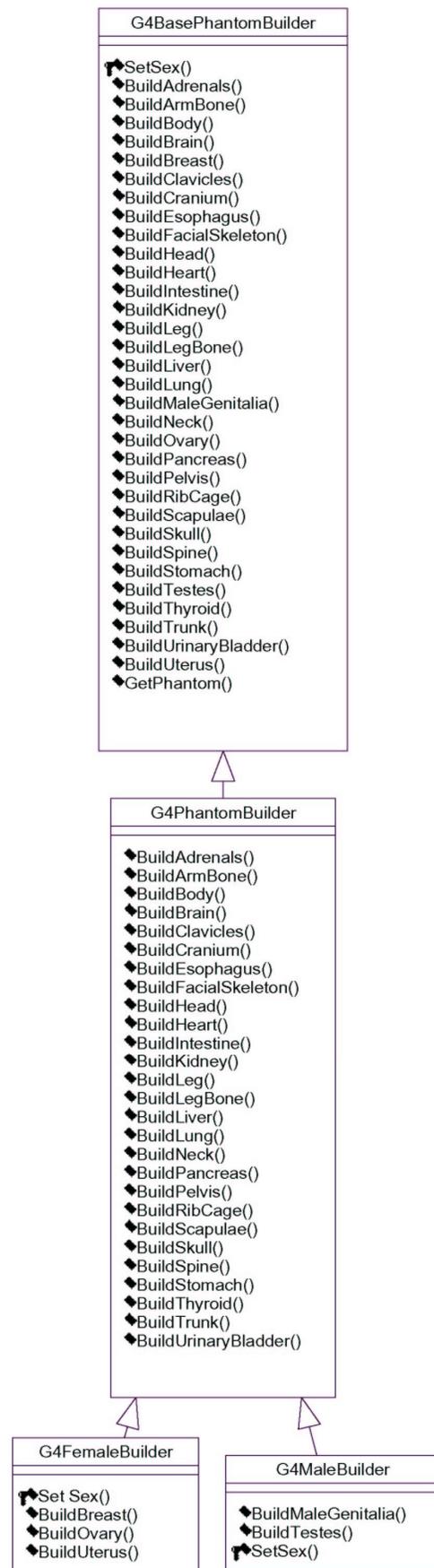


Fig. 1. Class diagram concerning the assembly process of a phantom.

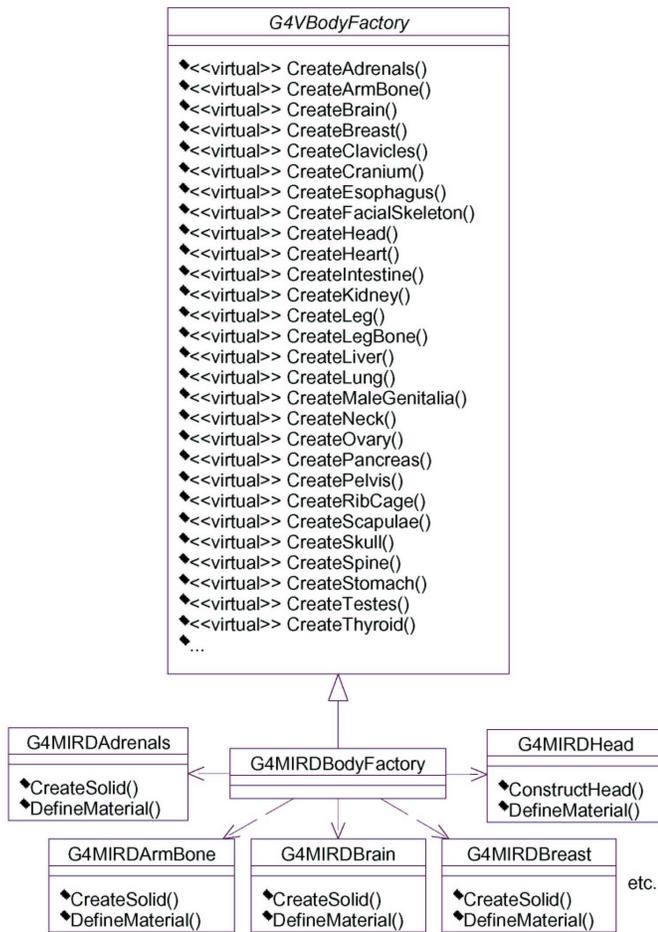


Fig. 2. Class diagram illustrating the creation of coherent phantom models.

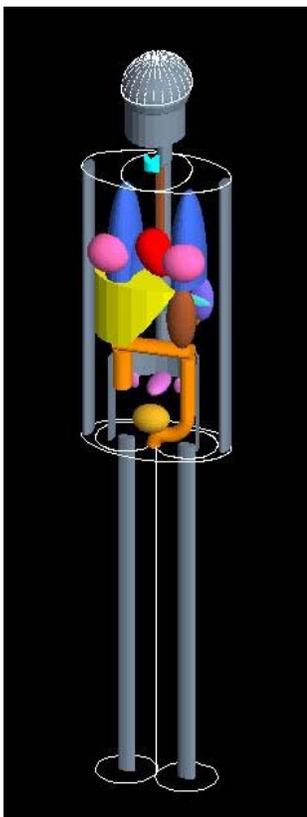


Fig. 3. Visualisation of a ORNL female phantom implemented in Geant4.

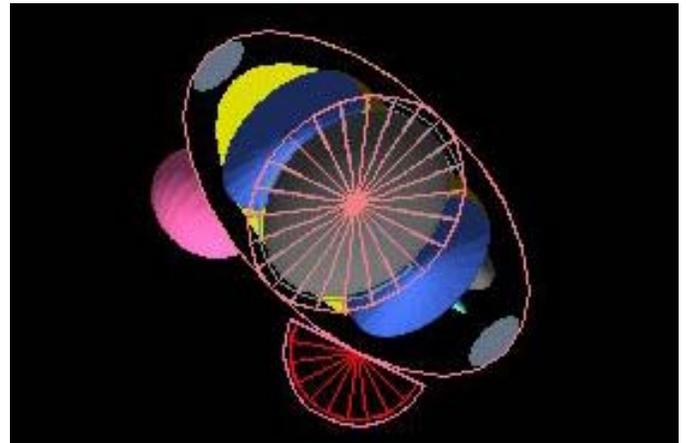


Fig. 4. Visualisation of a voxel breast (red) embedded in a mathematical phantom; the right breast (pink) is represented by a mathematical phantom component.

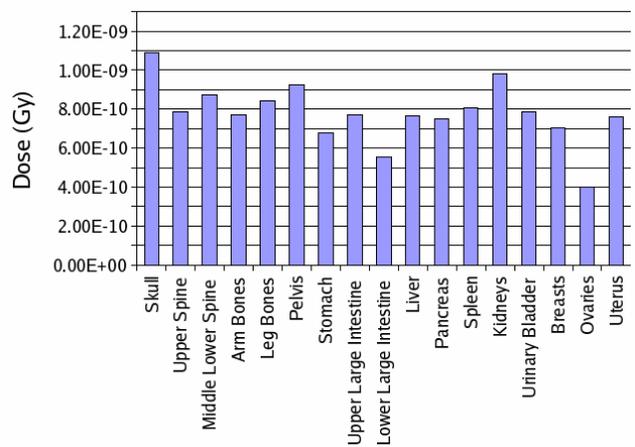


Fig. 5. Dose deposited in various organs of a Geant4 anthropomorphic phantom as a result of radiation exposure.

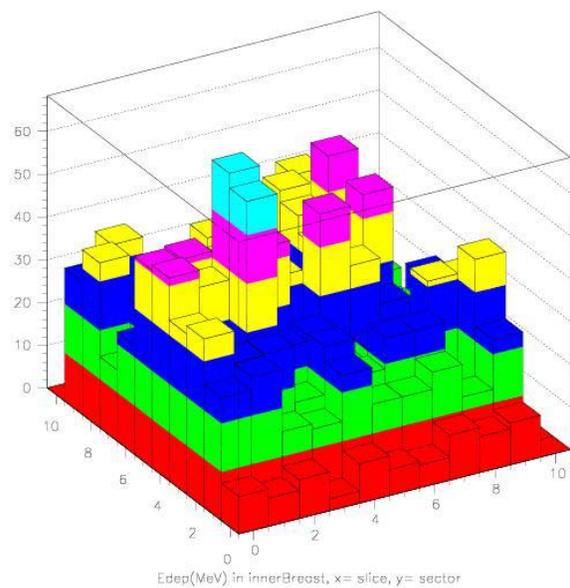


Fig. 6. Dose distribution in the voxels of a breast.