Towards an easy generation of scientific three-dimensional models for embedding into 3D PDF (Portable Document Format) files

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The Portable Document Format (PDF) allows for embedding three-dimensional (3D) models and is therefore particularly suitable to exchange and present respective data, especially as regards scholarly articles. The generation of the necessary model data, however, is still challenging, especially for inexperienced users. This prevents an unrestrained proliferation of 3D PDF usage in scientific communication. This article introduces a new module for the biomedical image processing framework MeVisLab. It enables even novice users to generate the model data files without requiring programming skills and without the need for an intensive training by simply using it as a conversion tool. Advanced users can benefit from the full capability of MeVisLab to generate and export the model data as part of an overall processing chain. Although MeVisLab is primarily designed for handling biomedical image data, the new module is not restricted to this domain. It can be used for all scientific disciplines.

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Introduction

Science produces a large amount of three-dimensional (3D) data, especially in the biomedical field. Although the visualization of this data should be 3D as well to avoid a loss of information (Tory & Möller, 2004), almost all contemporary visualization means (paper printouts, computer or television screens) only provide a two-dimensional (2D) interface. This limitation makes it necessary to project the 3D data onto the available 2D plane, which results in the so-called “2.5D visualization” (Tory & Möller, 2004). While there are many technical approaches to overcome this issue (stereoscopy, anaglyphs, head-mounted displays), they all require special equipment and do not eliminate the problem that objects can occlude each other if they lie on the same optical axis. A simple but effective solution is interaction: by changing the angle of a 2.5D projection, depth perception is improved (Tory & Möller, 2004), and masked objects can be brought to sight. Finally, the possibility to interact with the data representation might trigger the consumer’s curiosity, which then may lead to a more detailed exploration (Ruthensteiner & Heß, 2008).

The Portable Document Format (PDF), which is the de-facto standard for the exchange of electronic documents with more than 500 million users worldwide (Adobe Systems Incorporated, 2014a), is the best way to exchange respective data (Newe, Becker & Schenk, 2014). A PDF file describes the layout of an electronic document and can comprise all necessary resources for its reproduction without the need of external resources. Although there is a considerable number of publications in this field ((Ruthensteiner & Heß, 2008; Danz & Katsaros, 2011; Ziegler et al., 2011; Kumar et al., 2010; Vasilyev, 2010; Quayle et al., 2014; Sharp, 2014) and others), and although even journals encourage authors to embed 3D data directly into their publications (Maunsell, 2010), the usage of 3D-PDF has not yet found its way neither into the publishing routine nor into the clinical routine.

One reason might be that the generation of the necessary data can still be challenging, especially for the inexperienced. This constitutes an inhibition threshold, which stands in the way of a further proliferation of 3D PDF usage in science and medicine. In this article, a highly advanced version of a previously described tool for the generation of 3D data for embedding into PDF (Newe & Ganslandt, 2013) is presented. It is available free of charge for all major operating systems, can be used out-of-the-box for biomedical and other science disciplines, and requires no programming skills.

Background and Related Work

Using 3D PDF for the Exchange of Scientific and Medical Data

The Portable Document Format is a standard (ISO 32000-1:2008, (International Organization for Standardization (ISO), 2008)) for the definition and reproduction of electronic documents. It ensures independence from the creating, displaying and printing hardware and software and fulfills all requirements for an interactive document as defined by (Thoma et al., 2010). The specification is freely available and very well documented. Although it is an ISO standard, it can be downloaded and used free of charge (Adobe Systems Incorporated, 2014b; Adobe Systems Incorporated, 2008).

The Adobe Reader (http://get.adobe.com/reader/otherversions/) is currently the only 100% standard compliant software that allows to correctly display 3D models (meshes with solid or transparent surfaces, wireframes, line sets and point clouds) embedded into PDF documents and to let the user interact with them (zooming, panning, rotating, selection of components). By means of embedded scripting, animations and interaction with other components (e.g. control elements like clickable buttons) of the respective PDF document are possible. Adobe Reader that is available for free for all major operating systems (MS Windows, Mac OS, Linux).

Furthermore, respectively formatted PDF documents are particularly suitable for the representation and exchange of medical data if compliant with the PDF Healthcare (PDF/H) standard published by the Association for Information and Image Management (AIIM) and the American Society for Testing and Materials (ASTM) (Association for Information and Image Management, 2008a; Association for Information and Image Management, 2008b).

In addition to that, Supplement 104 (DICOM Standards Committee, Working Group 6, 2005) of the DICOM (Digital Imaging and Communications in Medicine) standard describes how to encapsulate PDF documents into a DICOM data structure, so that they can be stored and exchanged using the appropriate DICOM Service Classes.

3D Model Data

Two different file formats can be used to embed 3D models into PDF: the Product Representation Compact (PRC) format and the Universal 3D (U3D) format. They are not arbitrarily exchangeable since they differ in some features (Visual Technology Services Ltd., 2014a; Visual Technology Services Ltd., 2014b). PRC (Adobe Systems Incorporated, 2014c) is the older format and published as ISO 14739-1 (International Organization for Standardization (ISO), 2012), but U3D seems to have become more popular since it is available as export format for many 3D software tools. The U3D specification is published by the Ecma International as the ECMA-363 (Universal 3D File

Format) standard (ECMA International, 2007).

There are a number of tools and libraries available for the creation of either PRC or U3D files. Most of them are commercial software, but open source solutions like MeshLab (http://meshlab.sourceforge.net/) are available. However, using these tools needs a considerable amount of training. Furthermore, certain features those are of interest for scientific 3D data like point clouds and line sets (polylines) are often neglected by these tools. Free libraries that provide the full feature range are available, e.g. the Visualization and Computer Graphics Library (http://vcg.sourceforge.net/) or the U3D Reference Implementation Library (http://u3d.sourceforge.net/). Barnes et. al. (Barnes et al., 2013) have presented a comprehensive library that creates PRC data for scientific purposes. The drawback of using such libraries, however, is that they often require programming skills. Furthermore they are only suitable for converting existing 3D data that need to be generated intermediately using another software like Amira (http://www.vsg3d.com/amira/).

MeVisLab

An alternative to 3D data processing applications and libraries is the use of MeVisLab (http://www.mevislab.de/, German web address, but English language) since it combines the advantages of both. MeVisLab is an image processing framework, developed by MeVis Medical Solutions AG and Fraunhofer MEVIS in Bremen, Germany. The core feature of MeVisLab is its module concept: All included algorithms and functions are represented and accessed by "modules", which can be arranged and connected to image processing networks on an intuitive graphical user interface (GUI) following the visual data-flow development paradigm. These networks can then be converted with little effort into complete applications for a convenient re-use. For simple tasks like creating or converting 3D model data, this requires no writing of software code.

MeVisLab is available for all major operating systems (MS Windows, Mac OS and Linux, http://www.mevislab.de/download/) and offers a free license for use in non-commercial organizations and research (“MeVisLab SDK Unregistered”, (MeVis Medical Solutions AG & Fraunhofer MEVIS, 2014a)). The usage of MeVisLab is explained in its easy-to-understand documentation (http://www.mevislab.de/developer/documentation/). Especially the “Getting Started Tutorial” is recommended for newcomers. It can be accessed via MeVisLab itself (Menu “Help” → “Show Help Overview” → “Getting Started”) or as downloadable version (MeVis Medical Solutions AG & Fraunhofer MEVIS, 2014b). Further support can be obtained from an active online community (http://forum.mevis.fraunhofer.de/index.php).

The current version 2.6.1 of MeVisLab has included more than 1000 pre-defined standard modules. Another 1800 additional modules completely wrap the Insight Segmentation and Registration Toolkit (ITK, http://itk.org/) and the Visualization Toolkit (VTK, http://vtk.org/), which makes the total module base very comprehensive.

Material & Methods

Creation of an Improved U3D Export Module

The standard distribution of MeVisLab comes with the WEMSaveAsU3D module, which is described in detail in (Newe & Ganslandt, 2013). This module is capable of exporting triangular surface meshes to U3D file format and has proven to be suitable for use in reporting of surgery planning results in clinical routine (Newe, Becker & Schenk, 2014). However, it was limited to triangular meshes – other geometry definitions could not be exported, although U3D allows for embedding point clouds and line sets (polylines) as well. In addition to that, the definition of object model trees was not possible and the specification of object properties (like name, color etc.) was somewhat cumbersome. Finally, the re-use of geometry data for multiple objects was not possible.

In order to compensate these shortcomings, a new Module named “SaveU3D” was created. The source code was written in C++ using Microsoft Visual Studio 2010 and contains the full set of constant definitions (e.g. lighting attributes or material attributes) of the ECMA-363 Standard. Although not necessary for the end-user, the code was extensively annotated in order to simplify the understanding and the potential expansion of the implementation.

To facilitate the generation of the necessary object definitions, the GUI of the final module was enriched by a convenience window that allows for an easy assembly of the respective informations. This part was written in the Python programming language.

Validation of the New Module

The new SaveU3D module was validated against the old WEMSaveAsU3D module and the reference implementation of the U3D standard (http://u3d.sourceforge.net/).

Using only features that the WEMSaveAsU3D module already supported (triangle mesh geometry, lighting, cameras), the output files of the SaveU3D and WEMSaveAsU3D were equal.

The output files of the reference implementation and the SaveU3D module were binary compatible, i.e. both produced the same geometry models after import into a PDF document.

Results

The SaveU3D Module

The new module produces ECMA-363 compliant U3D files that contain point clouds, line sets, triangle meshes and meta data annotations. Each object that shall be exported can be specified using a simple description syntax that resembles the well-known Extensible Markup Language (XML) (Figure 1, left). A Specification Generator (Figure 1, right) facilitates the creation of the necessary specifications.

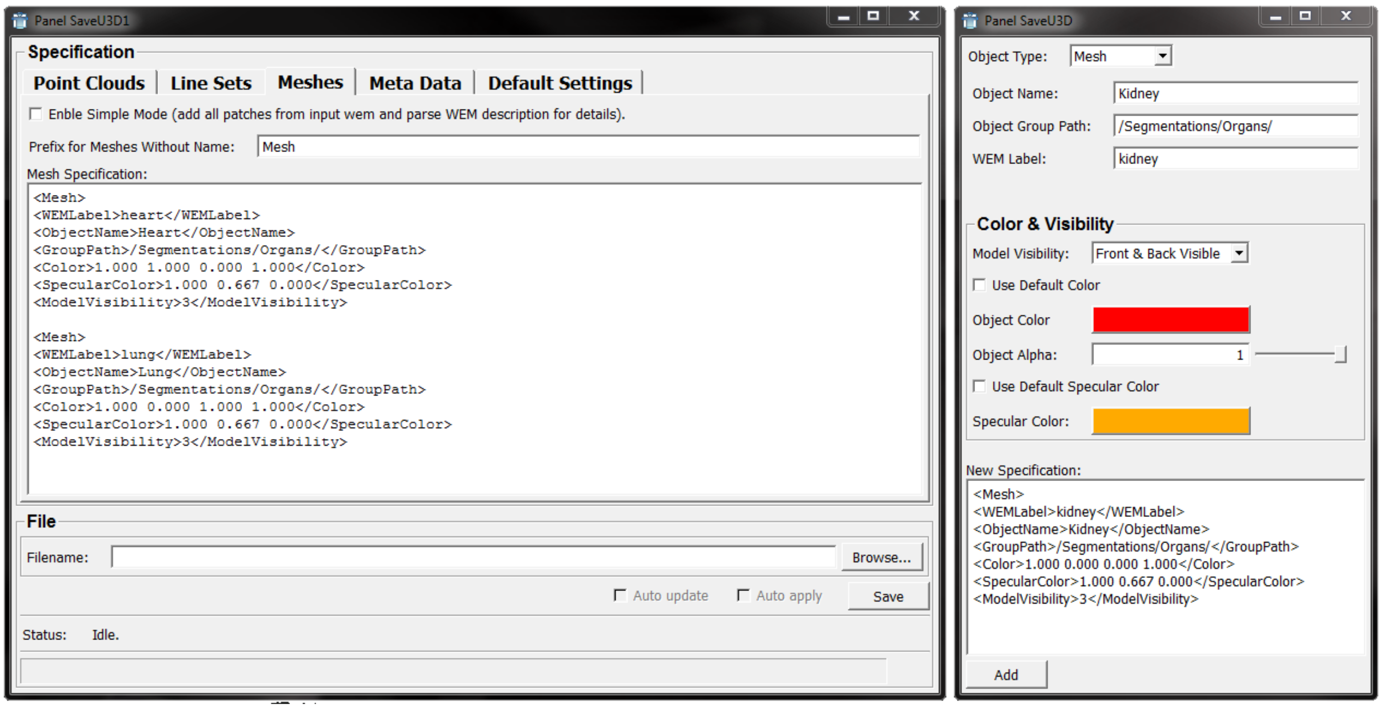

Figure 1: Panels (Windows) of the SaveU3D module. Left: Main panel of the U3D module where the object specifications are entered. Right: Panel of the Specification Generator which facilitates the assembly of valid object specifications.

While the objects to be exported are specified directly in the GUI of the module, the underlying geometry data must be provided by other modules. This can be modules that load existing data from a storage medium or modules that create the data themselves. This concept gives the user the full flexibility to either re-use data that has been created using other software or to use MeVisLab itself to generate the data.

Usage of the Module

MeVisLab novices should read the “Getting Started” tutorial mentioned above to get familiar with the basic concepts of MeVisLab and to learn how to create modules and how to assemble them to networks. Using the module itself requires no programming. It simply needs to be created (“instantiated”) using the MeVisLab GUI. A detailed description of the module and its usage is available with the module documentation. An example network that demonstrates all features is also available. The module documentation and the example network can be accessed by right-clicking any instance of a SaveU3D module and selecting “Show Help” or “Show Example Network” from the context menu.

Two steps are required to export 3D objects: first, the geometry data must be connected to the inputs of the module, and second, the objects must be specified using the module GUI. The specifications can be entered manually using the XML-like Syntax or by using the Specification Generator. The latter can be opened by right-clicking the module and selecting “Show Window” → “Specification Generator Panel” from the context menu. Deleting unwanted or erroneous specifications can only be done directly in the GUI. The specification syntax is described in the module documentation.

Point Clouds

Point Clouds are the simplest type of objects. They only consist of points in 3D space. Therefore, the geometry data only consists of a list of point positions that need to be connected to the “inPointPositions” input of the module.

Line Sets

Line Sets consist of nodes that are connected by edges. The geometry data must be provided by two lists: the positions of the nodes (“inLinePositions” input) and the description of the edges (“inLineConnections” input), that indicates which nodes (positions) are connected by an edge. The latter list can be omitted – in this case the connections are automatically calculated by simply connecting each node with the next in the list.

Meshes

Meshes are the most complex type of objects since they consist of nodes, edged, faces, and some more attributes. MeVisLab uses the Winged Edge Mesh (WEM) format (Baumgart, 1972; Baumgart, 1975) to store meshes. Therefore, the geometry data for meshes needs to be provided as a WEM and connected to the “inWEM” input. MeVisLab provides about 50 modules for the import, creation, manipulation and visualization of WEMs.

Availability

The source code (http://sourceforge.net/p/mevislabmodules/code/HEAD/tree/trunk/Community/General/Sources/ML/MLPDF/ and http://sourceforge.net/p/mevislabmodules/code/HEAD/tree/trunk/Community/General/Modules/ML/MLPDF/) of the SaveU3D module is available at the MeVisLab Community Sources (http://mevislabmodules.sourceforge.net/), hosted by Sourceforge.net. It is part of the MLPDF project and requires another community project (MLBaseListExtensions). Binary versions of the modules for the current MeVisLab version 2.6(.x) and instructions how to add them to an existing MeVisLab installation are provided as Supplemental S1. Binaries for future releases of MeVisLab can be requested from the author or the MeVisLab community.

Discussion

An Easy-to-Use Tool

While the predecessor module WEMSaveAsU3D (Newe & Ganslandt, 2013) was already a big relief compared to other solutions, the new SaveU3D module simplifies the generation of biomedical 3D models for embedding into PDF even further. In addition to that, new geometry model types (point clouds and line sets) can now be exported using MeVisLab in the same simple and user friendly way as meshes.

Line sets can be used for the visualization of nervous fiber tracking, vessel centerlines or as pointers to structures of interest. Another use case is the interactive visualization of vectorcardiograms (VCG, Figure 2 and Supplemental S2). Traditional methods of plotting VCGs onto a 2D surface come with an inherent loss of information unless a high number of plots with different viewing angles is presented. Using Adobe 3D PDF technology, only one representation of the VCG data needs to be included in a document and the user herself or himself can find the best way to display the respective graph according to his or her question.

Finally, point clouds (or single points) can be used to mark or highlight points of interest (Figure 2 and Supplemental S2). To stay with the example of VCGs: points or point clouds could be used to mark the amplitude values or to set fiducial markers.

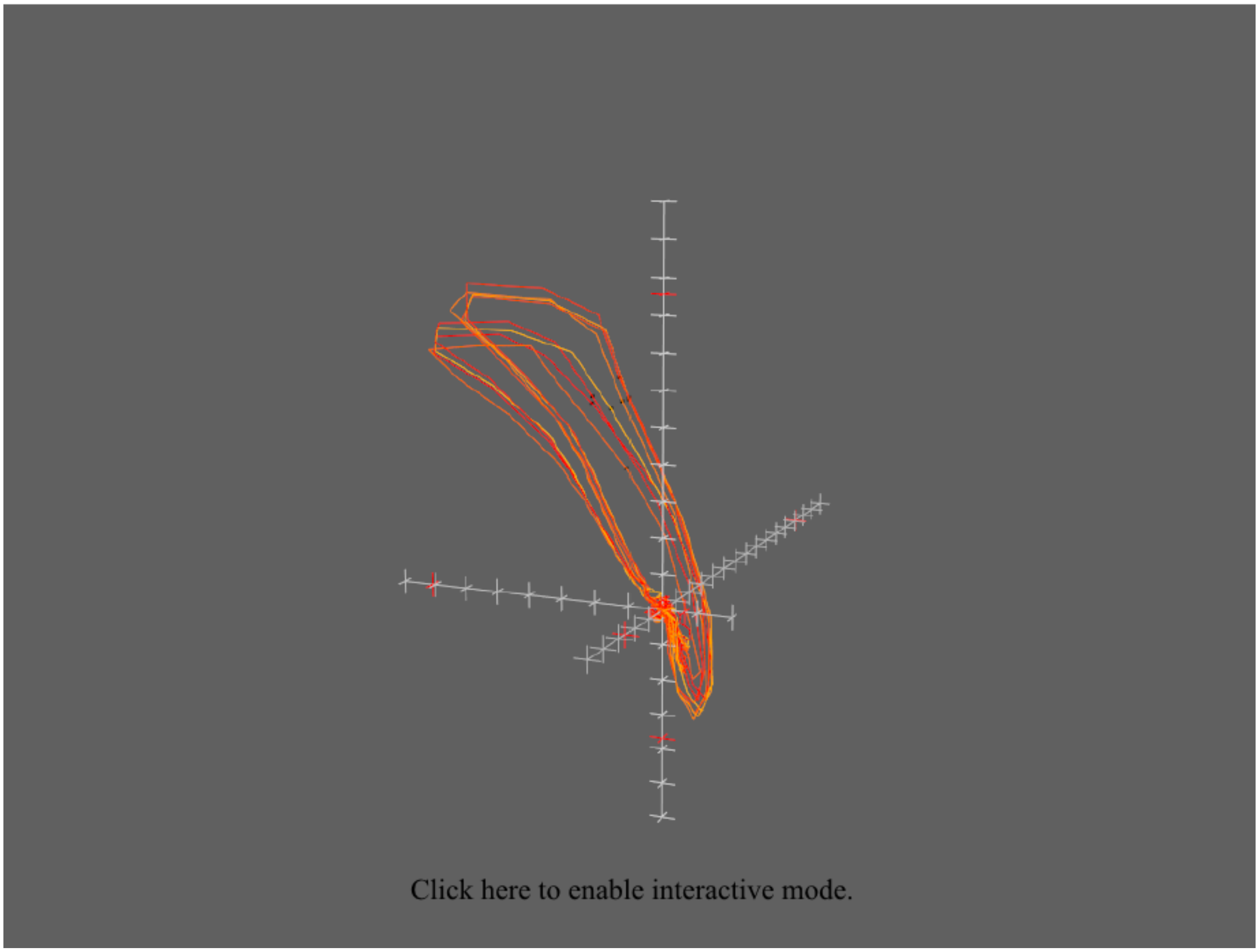

Figure 2: Example of a 3D vectorcardiogram exported by SaveU3D module. Shows an 8-beat vectorcardiogramm with fiducial markers at the x-axis amplitude as displayed in Adobe Reader. A coordinate system is integrated into the 3D scene. (Click to enable interactive mode.)

This support for point clouds and line sets is a unique feature of the SaveU3D module for MeVisLab, compared with other integrated tools like MeshLab. Some libraries do support point clouds and line sets (e.g. S2PLOT (Barnes et al., 2013)), but they require programming. The SaveU3D module works "out-of-the-box" and without the need to write any software code. The generation of the geometry data can be handled within MeVisLab or be loaded from external sources, alternatively. Therefore, this solution provides the possibility to make use of both approaches: on the one hand, the SaveU3D module could be used as a simple conversion tool (Figure 3 and Supplemental S3); on the other hand, it can be used as final step in an arbitrarily complex image or data processing pipeline.

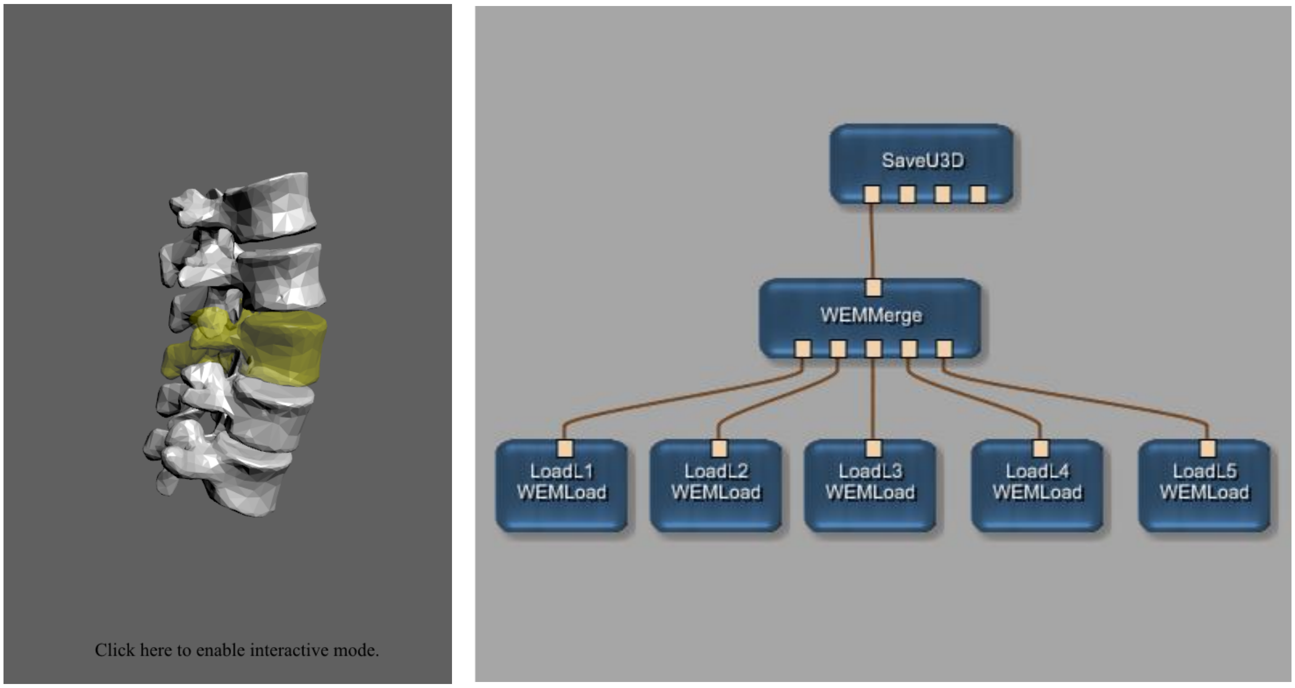

Figure 3: Example of 3D surface meshes converted by MeVisLab using the SaveU3D module. Left: The exported meshes as displayed in Adobe Reader. One mesh has been exported using color and transparency. Right: The MeVisLab network used to load and to export the five meshes. The original mesh data was downloaded in Wavefront OBJ file format from BodyParts3D, The Database Center for Life Science (Mitsuhashi et al., 2009) and is licensed under Creative Commons Attribution-Share Alike 2.1 Japan. See also Supplemental S3. (Click left image to enable interactive mode.)

MeVisLab is available for free and for all major operating systems (Windows, Mac OS and Linux). U3D models produced with the SaveU3D module can be processed by free PDF authoring tools like LaTeX (http://www.latex-project.org/) in conjunction with the media9 package (http://www.ctan.org/pkg/media9) or like the iText library (http://itextpdf.com/) to create the final PDF document.

Ongoing Development

The SaveU3D module will be extended. A major feature that is still missing is the application of textures onto models. Using textures would allow for creating simulated volume rendering visualizations. Although this simulated volume rendering would be limited to a fixed windowing, it would offer a new way of publishing biomedical 3D images.

Unfortunately, PDF does not support another feature of U3D: glyphs. Glyphs could be used to apply label text directly within the 3D scene, but since PDF ignores U3D glyphs, it is not planned to add support for glyph to SaveU3D. However, using textures for labeling objects in the 3D scene can serve as a workaround as shown in (Barnes et al., 2013). Especially PDFs with an educational purpose (e.g. for teaching anatomy to medical students) could benefit from an undoubtful labeling of structures with complex spatial relationships.

Additional Export Formats

SaveU3D is part of the MLPDF project. In the long term, this project shall provide all modules that are needed to create PDF documents using MeVisLab. One of the next steps is the implementation of a module that exports 3D objects in PRC format. Finally, the creation of actual PDF files is on the agenda for future development.

Another MeVisLab project deals with the implementation of the DICOM Surface Segmentation Storage SOP Class (DICOM Standards Committee, Working Group 6, 2008). As soon as the respective modules for loading and saving DICOM Surface Segmentation objects are available, the gap between generic DICOM segmentation results and their conversion into files for embedding into PDF will be closed.

Beyond Biomedical Data

Although it is their primary purpose, MeVisLab or the SaveU3D module are not limited to biomedical data. The 3D objects used for Figure 3 could also be representations of rocks from geological sciences or chemical molecules. Lines or point clouds as shown in Figure 2 could be derived from physics models or statistical distributions of any science discipline.

Conclusion

Modern science in general and the biomedical sciences in particular produce three-dimensional data at an increaing rate. The Portable Document Format provides the means to distribute and visualize this data without the need for additional dedicated software. The new SaveU3D module for MeVisLab presented in this article allows even novice users to generate the necessary file format without requiring programming skills and without the need for an intensive training. Advanced users can benefit from the full potential of MeVisLab to generate and export the model data to U3D as part of the overall processing chain. Only one additional PDF authoring tool is then required to generate the final PDF document. For most uses cases, a replacement of this authoring tool seems not reasonable since the ability to set text layout, process screenshots etc. is an application domain of its own. Therefore, in most cases, the separation of model data generation and PDF authoring cannot be avoided anyway.

List of Abbreviations

2D – Two-dimensional

2.5D –Three-dimensional reduced to two-dimensional

3D – Three-dimensional

AIIM – Association for Information and Image Management

ASTM – American Society for Testing and Materials

DICOM – Digital Imaging and Communications in Medicine

GUI – Graphical User Interface

ITK – Insight Segmentation and Registration Toolkit

PDF/H – PDF Healthcare

PRC – Product Representation Compact file format

SOP – DICOM Service-Object-Pair

U3D – Universal 3D file format

VCG – Vectorcardiogram

VTK – Visualization Toolkit (VTK)

XML – Extensible Markup Language

Competing interest statement

None declared.

Authors' contributions

AN engineered the software, conceived the study, drafted and wrote the manuscript.

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Supplemental Information

Supplemental S1. “Package.zip”.

Binary files, module definition files and installation instructions. Using these files, the SaveU3D module can be added to an existing MeVisLab 2.6(.x) installation without the need to compile the source files.

Supplemental S2. “VCG-Example.zip”

An example U3D file of a vectorcardiogram and the resulting 3D PDF.

Supplemental S3. “Vertebrae-Example.zip”

An example U3D file of lumbar vertebrae and the resulting 3D PDF.