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1   **Enriching scientific publications with interactive 3D PDF: An**

2   **integrated toolbox for creating ready-to-publish figures**

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22   o Discussed rendering problems on MacOS systems
23

24   ***Abstract***

25   Three-dimensional (3D) data of many kinds is produced at an increasing rate throughout all
26   scientific disciplines. The Portable Document Format (PDF) is the de-facto standard for the
27   exchange of electronic documents and allows for embedding three-dimensional models.
28   Therefore, it is a well suited medium for the visualization and the publication of this kind of
29   data.

30   The generation of corresponding files has been cumbersome so far. This article presents the
31   first release of a software toolbox which integrates the complete workflow for generating 3D
32   model files and ready-to-publish 3D PDF documents for scholarly publications in a consolidated
33   working environment. It can be used out-of-the-box as a simple working tool or as a basis for
34   specifically tailored solutions. A comprehensive documentation, an example project and a
35   project wizard facilitate the customization. It is available royalty-free and for Windows, MacOS
36   and Linux.

37

38   ***Keywords***

39   PDF; 3D-PDF; Portable Document Format; U3D; Universal 3D; Application

40

Introduction

Throughout many scientific disciplines, the availability – and thus the importance – of three-dimensional (3D) data has grown in the recent years. Consequently, this data is often the basis for scientific publications, and in order to avoid a loss of information, the visualization of this data should be 3D whenever possible **(Tory & Möller, 2004)**. In contrary to that, almost all contemporary visualization means (paper printouts, computer screens, etc.) only provide a two-dimensional (2D) interface.

The most common workaround for this limitation is to project the 3D data onto the available 2D plane **(**Newe, 2015), which results in the so-called "2.5D visualization" **(Tory & Möller, 2004)**. This projection yields two main problems: limited depth perception and objects that occlude each other. A simple but effective solution of these problems is interaction: by changing the projection angle of a 2.5D visualization (i.e., by changing the point of view), depth perception is improved **(Tory & Möller, 2004)**, and at the same time objects that had previously been occluded (e.g., the backside) can be brought to sight.

A means of application of this simple solution has been available for many years: the Portable Document Format (PDF) from Adobe **(Adobe, 2014)**. This file format is the de-facto standard for the exchange of electronic documents and almost every scientific article that is published nowadays is available as PDF – as well as even articles from the middle of the last century **(Hugh-Jones, 1955)**. PDF allows for embedding 3D models and the Adobe Reader (http://get.adobe.com/reader/otherversions/) can be used to display these models interactively.

Nevertheless, this technology seems not to have found broad acceptance among the scientific community until now, although journals encourage authors to use this technology **(Maunsell, 2010; Elsevier, 2015)**. One reason might be that the creation of the appropriate model files and of the final PDF documents is still cumbersome. Not everything that is technically possible is accepted by those who are expected to embrace the innovation if the application of this innovation is hampered by inconveniences **(Hurd, 2000)**. Generally suitable protocols and procedures have been proposed by a number of authors before, but they all required of toolchain of at least three **(Kumar et al., 2010**; **Danz & Katsaros, 2011)** or even four **(Phelps, Naeger & Marcovici, 2012; Lautenschlager, 2014)** different software applications and up to 22 single steps until the final PDF was created. Furthermore, some of the proposed workflows were limited to a certain operating system (OS) **(Phelps, Naeger & Marcovici, 2012)**, required programming skills **(Barnes et al., 2013)** or relied on commercial software **(Ruthensteiner & Heß, 2008)**. Especially the latter might be an important limiting factor which

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75   hampers the proliferation of the 3D PDF format in scientific publishing **(Lautenschlager, 2014;**
76   **Newe, 2015)**.
77   This article presents a comprehensive and highly integrated software tool for the creation of
78   both the 3D model files (which can be embedded into PDF documents) and the final, ready-to-
79   publish PDF documents with embedded interactive 3D figures. The presented solution is based
80   on MeVisLab, available for all major operating systems (Windows, MacOS and Linux) and
81   requires no commercial license. The source code is available but does not necessarily need to
82   be compiled since binary add-on installers for all platforms are available. A detailed online
83   documentation, an example project and an integrated wizard facilitate re-use and
84   customization.

85   ## *Background and Related Work*

86   ### *The Portable Document Format*

87   The Portable Document Format is a document description standard for the definition of
88   electronic documents independently of the software, the hardware or the operating system
89   that is used for creating or consuming (displaying, printing…) it **(Adobe, 2008a)**. A PDF file can
90   comprise all necessary information and all resources to completely describe the layout and the
91   content of an electronic document, including texts, fonts, images and multimedia elements like
92   audio, movies or 3D models. Therefore, it fulfils all requirements for an interactive publication
93   document as proposed by **(Thoma et al., 2010)**.
94   Although it is an ISO standard (ISO 32000-1:2008 **(ISO, 2008)**), the specification is available to
95   the full extent from the original developer Adobe **(Adobe, 2015)** and can be used royalty-free.

96   ### *Embedding 3D Models into PDF*

97   The fifth edition of the PDF specification (PDF version 1.6 **(Adobe, 2004)**), published in 2004,
98   was the first to support so-called "3D Artwork" as an embedded multimedia feature. In January
99   2005, the Acrobat 7 product family provided the first implementation of tools for creating and
100 displaying these 3D models **(Adobe, 2005)**.
101 The latest version (PDF version 1.7 **(Adobe, 2008a)**) supports three types of geometry (meshes,
102 polylines and point clouds), textures, animations, 15 render modes, 11 lighting schemes and
103 several other features. The only 3D file format that is supported by the ISO standard **(ISO, 2008)**
104 is Universal 3D (U3D, see section below). Support for another 3D format (Product
105 Representation Compact, PRC) has been added by Adobe **(Adobe, 2008b)** and has been
106 proposed to be integrated into the replacement Norm ISO 32000-2 (PDF 2.0). However, this

107 new standard is currently only available as draft version **(ISO, 2014)** and has not yet been

108 adopted.

109 Although the first application in scientific context was proposed in November 2005

110 **(Zlatanova & Verbree, 2005)** and thus quite soon after this new technology was available, it

111 took three more years before the first applications were really demonstrated in scholarly

112 articles **(Ruthensteiner & Heß, 2008**; **Kumar et al., 2008**; **Barnes & Fluke, 2008)**. Since then, the

113 number of publications that apply PDF 3D technology either in theory or in practice has

114 increased almost every year (Table 1). The most sophisticated implementation so far is the

115 reporting of planning results for liver surgery where the PDF roots are hidden behind a user

116 interface which emulates a stand-alone software application **(Newe, Becker & Schenk, 2014)**.

117 **Table 1.** Number of publications related to 3D PDFs in biomedical sciences since 2008 (not
118 comprehensive).

Year	Number of publications with embedded/supplemental 3D PDF	Number of publications dealing with/mentioning 3D PDF
2005	-	1
2008	1	-
2009	5	4
2010	2	7
2011	7	6
2012	6	5
2013	7	2
2014	21	7
2015	31	2

119 ***The Universal 3D (U3D) file format***

120 As outlined above, the U3D file format is the only 3D format that is supported by the current

121 ISO specification of PDF. Initially designed as an exchange format for Computer Aided

122 Construction (CAD), it was later standardized by Ecma International (formerly known as

123 European Computer Manufacturers Association, ECMA) as ECMA-363 (Universal 3D File

124 Format). The latest version is the 4th edition from June 2007 **(ECMA, 2007)**.

125 U3D is a binary file format that comprises all information to describe a 3D scene graph. A U3D

126 scene consists of an arbitrary number of objects that can be sorted in an object tree. The

127 geometry of each object can be defined as a triangular mesh, a set of lines or a set of points. A

128 proprietary bit encoding algorithm allows for a highly compressed storage of the geometry

129 data. A number of additional features and entities (textures, lighting, views, animations) can be

130 defined; details are described in previously published articles **(Newe & Ganslandt, 2013)**.

131 The scholarly publishing company Elsevier invites authors to supplement their articles with

132 3D models in U3D format **(Elsevier, 2015)** and many 3D software tools provide the possibility to

133 export in U3D format. However, most of them are commercial software, but open source

134 solutions like MeshLab (http://meshlab.sourceforge.net/) are available as well.

135 ### *Creating 3D Model Files and PDF Documents*

136 Although many tools and libraries are available that support the creation of 3D model files

137 and of final PDF documents, the whole process is still cumbersome. The problems are manifold:

138 some tools require programming skills; some do not support features those are of interest for

139 scientific 3D data (like polylines **(Newe, 2015)** and point clouds **(Barnes & Fluke, 2008)**).

140 Operating system platform support is another issue, as well as royalty-free use.

141 As regards the creation of the 3D model files, most of these problems have been addressed in

142 a previous article **(Newe, 2015)**. The main problem, however, remains the creation of the final

143 PDFs. Specifying the content and (in particular) the layout of a document can be a complex task

144 and is usually the domain of highly specialized word processor software. Figures and

145 supplements for scholarly publications, on the other hand, usually have a specific layout where

146 only the contents of (a limited number of) pre-defined elements vary. There are at least three

147 common elements for a scientific figure: the figure itself, a short caption text and a longer

148 descriptive text. If the figure is intended to be provided as supplemental information file

149 instead of being integrated into the main article text, some additional information is necessary

150 as well: At least a general headline and an optional reference to the main article should be

151 provided. If the document content is modularized to these five key elements (Figure 1), the

152 creation of the PDF itself becomes a rather simple task, because the layout can be pre-defined.

153 One last difficulty arises from a peculiarity of interactive 3D figures in PDF: the number

154 viewing options (e.g., camera angle, zoom, lighting…) is nearly unlimited. Although such a figure

155 is intended to provide all these options, an author usually wants to define an initial view at the

156 objects, if only to simply ensure that all objects are visible. No freely available tool for PDF

157 creation currently provides a feature to pre-define such a view. The movie15 package for LaTeX

158 **(Grahn, 2005)** provides a mechanism do determine the view parameters, but that requires the

159 generation of intermediate PDFs.

160 Finally it must be mentioned that many previously published 3D models are very large –

161 sometimes up to nearly 100 megabytes **(Krause et al., 2014)**. In most cases, this size could (and

162 should) be reduced significantly, because the density of polygon meshes does usually not need

163 to be very high for illustrative purposes.

Newe, A (2016). "Article Title". PeerJ Computer Science. ← Reference

Additional File S1 - Interactive 3D PDF ← Headline

← Figure

Model of an anatomic structure. ← Caption

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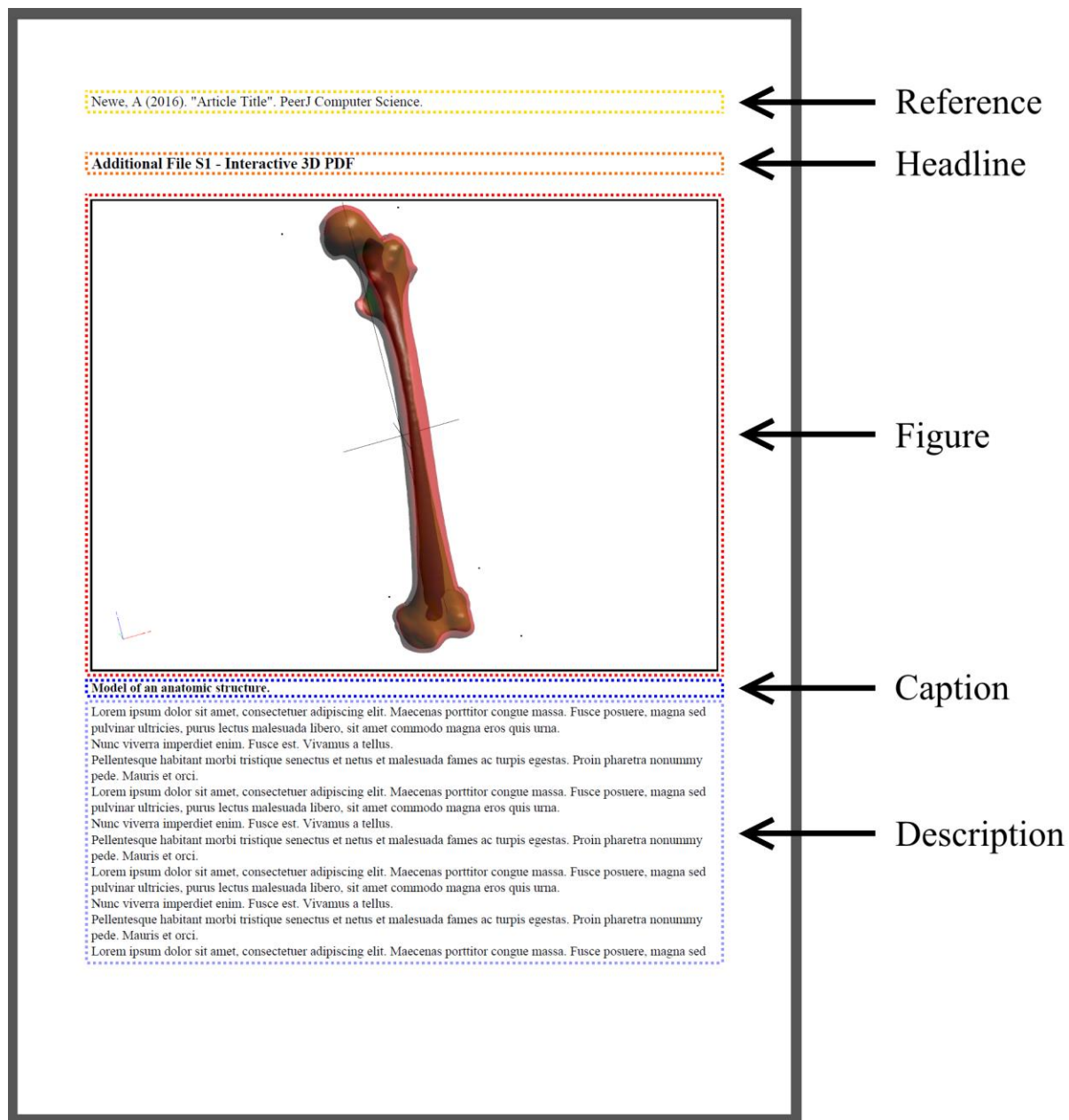
164

Figure 1. General layout of a scholarly figure if provided as supplemental material.

MeVisLab

MeVisLab is a framework for image processing and environment for visual development, published by MeVis Medical Solutions AG and Fraunhofer MEVIS in Bremen, Germany. It is available via download (http://www.mevislab.de/download/) for all major platforms (Microsoft Windows, Mac OS and Linux) and has a licensing option which is free for use in non-commercial

171 organizations and research ("MeVisLab SDK Unregistered" license,

172 http://www.mevislab.de/mevislab/versions-and-licensing/). Besides the development features,

173 MeVisLab can be used as a framework for creating sophisticated applications with graphical

174 user interfaces that hide the underlying platform and that can simply be used without any

175 programming knowledge **(Koenig et al., 2006; Heckel, Schwier & Peitgen, 2009; Ritter et al.,**

176 **2011)**. MeVisLab has been evaluated as a very good platform for creating application

177 prototypes **(Bitter et al., 2007)**, is very well documented

178 (http://www.mevislab.de/developer/documentation/) and supported by an active online

179 community (http://www.mevislab.de/developer/community/;

180 https://github.com/MeVisLab/communitymodules/tree/master/Community).

181   All algorithms and functions included into MeVisLab are represented and accessed by

182 "modules", which can be arranged and connected to image processing networks or data

183 processing networks on a graphical user interface (GUI) following the visual data-flow

184 development paradigm. By means of so-called "macro modules", these networks can then be

185 converted with little effort into complete applications with an own GUI.

186 ### *Methods*

187 ### *Elicitation of Requirements*

188   As described above, the generation of the necessary 3D model data and particularly of the

189 final PDF is still subject to a number of difficulties. Therefore, the first step was the creation of a

190 list of requirements specifications with the aim to create a tool that overcomes these known

191 drawbacks.

192   Two requirements have been identified to be the most important ones: 1) the demand for a

193 tool that creates "ready-to-publish" PDF documents without the need for commercial software

194 and 2) the integration of all necessary steps into a single and easy-to-use interface. Besides

195 these two main requirements, a number of additional requirements have then been identified

196 as well. See Table 2 for a full list of all requirements that were the basis for the following

197 development.

198

199   **Table 2.** Requirements for the development of the software tool. The two main requirements are

200   highlighted in bold font.

ID	Requirement Specification
R1	**The software *shall* create ready-to-publish PDF documents with embedded 3D models.**
R1.1	The software *shall* offer an option to specify the activation mode and the deactivation mode for the 3D models.
R2	**The software *shall* provide an integrated, single-window user interface that comprises all necessary steps.**
R3	The software *shall* be executable under Windows, MacOS and at least one Linux distribution.
R4	The software *shall* be executable without the need to purchase a commerical license.
R5	The software *shall* create 3D model files in U3D format.
R5.1	The software *shall* create view definitions for the 3D model.
R5.2	The software *shall* create poster images for the PDF document.
R6	The software *shall* import mesh geometry from files in OBJ, STL and PLY format.
R6.1	The software *should* import mesh geometry from other file formats as well.
R6.2	The software *shall* offer an option to reduce the number of triangles of imported meshes.
R6.3	The software *shall* offer an option to specify the U3D object name and the color of imported meshes.
R7	The software *shall* import line set geometry from files in text format.
R7.1	The software *shall* offer an option to specify the U3D object name and the color of imported line sets.
R8	The software *shall* import point set geometry from files in text format.
R8.1	The software *shall* offer an option to specify the U3D object name of imported point sets.

201   ### *Creation of an "App" for MeVisLab*

202   MeVisLab-based solutions presented in previous work **(Newe & Ganslandt, 2013; Newe,**

203   **2015)** already provide the possibility to create U3D files without requiring programming skills

204   and without the need for an intensive training. However, they still needed some basic training

205   as regards assembling the necessary processing chains in MeVisLab. Furthermore, the creation

206   of the final PDF was not possible so far.

207   Therefore, a new macro module was created for MeVisLab. A macro module encapsulates

208   complex processing networks and can provide an integrated user interface. In this way, the

209   internal processes can be hidden away from the user, who can focus on a streamlined workflow

210   instead. Designed in an appropriate way, a macro module can also be considered as an "app"

211   inside of MeVisLab.

212   In order to provide the necessary functionality, some auxiliary tool modules (e.g., for the

213   creation of the actual PDF file) needed to be developed as well. Along with the modules for U3D

214   export mentioned above, these auxiliary tool modules were integrated into the internal

215   processing network of the main "app" macro. The technical details of these internal modules

216   are not within the scope of this article. However, the source code is available and interested

217   readers are free to explore the code and to use it for own projects.
218   The user interface of the app was designed in a way that it guides novice users step-by-step
219   without treating experienced users too condescendingly, though. Finally, a comprehensive
220   documentation including an example project, a wizard for creating tailored PDF modules and a
221   verbose help text was set up.

222   **Deployment of Core Functionality**

223   For the creation of the actual PDF files, version 2.2.0 of the cross-platform, open source
224   library libHaru (http://libharu.org/) was selected, slightly modified and integrated as third-party
225   contribution into MeVisLab.
226   Next, the application programming interface (API) of libHaru was wrapped into an abstract
227   base module for MeVisLab in order to provide an easy access to all functions of the library and
228   in order to hide away standard tasks like creating a document or releasing memory. A large
229   number of convenience functions were added to this base module and an exemplary MeVisLab
230   project was set up in order to demonstrate how to use the base module for tailored
231   applications. This base module also served as basis for the PDF creation of the app macro
232   described above. Finally, a project wizard was integrated into the MeVisLab GUI.

233   **Results**

234   **The "Scientific3DFigurePDFApp" module**

235   The new macro module "Scientific3DFigurePDFApp" for MeVisLab provides an integrated
236   user interface for all steps that are necessary for the creation of U3D models files and for the
237   creation of the final PDF documents with embedded 3D models. The model editor part
238   produces U3D model files of geometry data that are compatible with version 4 of the ECMA-
239   363 standard and poster images in Portable Network Graphics (PNG) format. The PDF editor
240   part produces PDF documents that are compliant with PDF version 1.7 (ISO 32000-1:2008). An
241   example PDF is available as Supplemental File S1.
242   The user interface is arranged in tabs, whereas each tab comprises all functions for one step
243   of the workflow. By processing the tabs consecutively, the user can assemble and modify 3D
244   models, save them in U3D format, create views and poster images for the PDF document, and
245   finally create the PDF itself step by step (Figure 2).
246   The raw model data can be collected in two ways: either by feeding it to the input connectors
247   or by assembling it by means of the built-in assistant. The former option is intended for
248   experienced MeVisLab users that want to attach the module at the end of a processing chain.

249　The latter option addresses users that simply want to apply the app for converting existing 3D
250　models and for creating an interactive figure for scholar publishing.

251
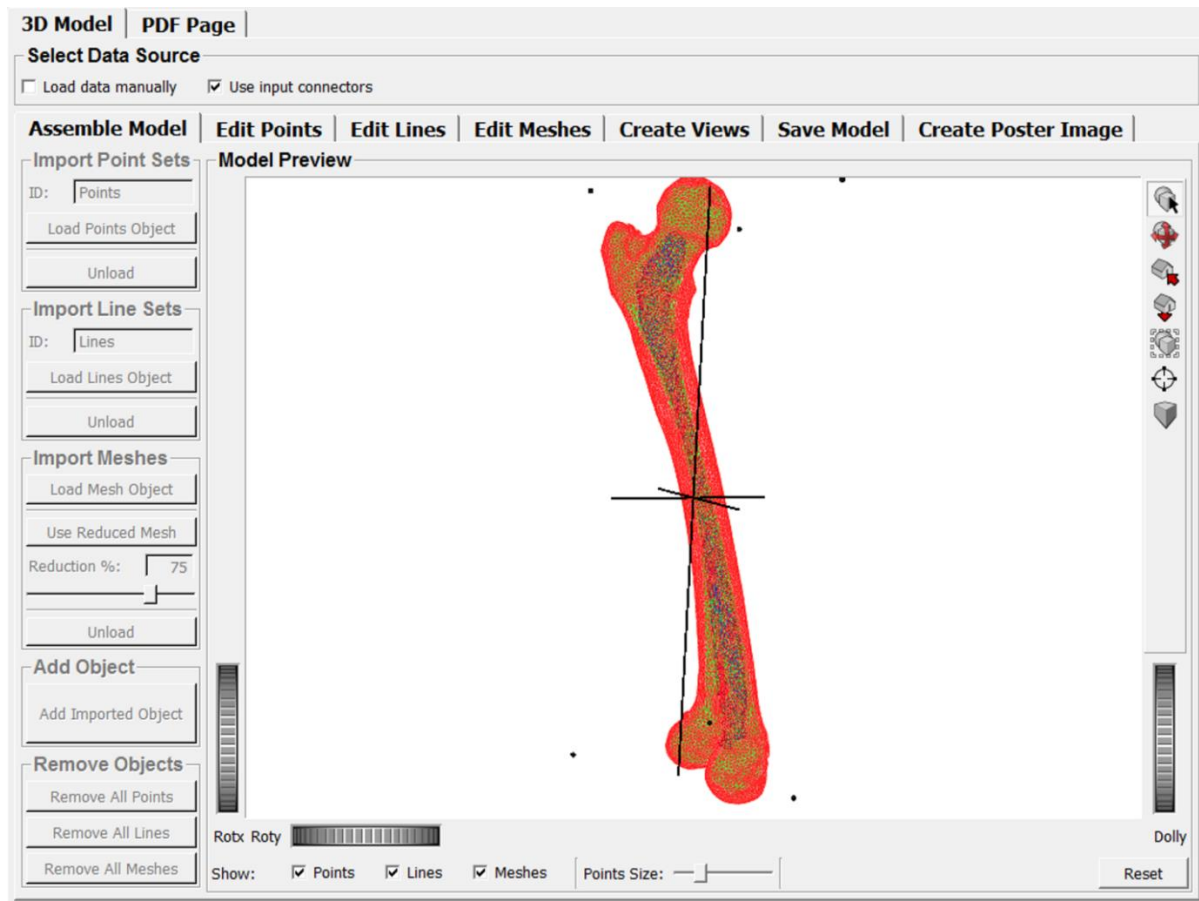
Figure 2. User interface of the app. The user interface comprises all necessary steps for the creation of
3D model files and PDF files. It is arranged in tabs for each step.

254　The software allows for importing the geometry data of 39 different 3D formats, including
255　point clouds and line sets from files in character-separated value (CSV) format (see Table 3 for a
256　full list). The import of textures and animations is not supported.
257　Objects from different sources can be combined and their U3D properties (colour, name,
258　position in the object tree) can be specified. The density of imported meshes can be adjusted
259　interactively and multiple views (i.e., the specification of camera, lighting and render mode) can
260　be pre-defined interactively as well. Finally, it is also possible to create a poster image which
261　can replace an inactive 3D model in the PDF document if the model itself is disabled or if it
262　cannot be displayed for some reason (e.g., because the reading software does not provide the
263　necessary features).

264   **Table 3.** List of supported 3D formats for importing geometry data (textures, animations and other

265   features are not supported).

File format	Typical File Extension(s)
Stereolithography	*.stl
Stanford Polygon Library	*.ply
Wavefront Object	*.obj
Object File Format	*.off
Blender	*.blend
Raw Triangles	*.raw
Raw Point Clouds	*.csv; *.txt
Raw Line Sets	*.csv; *.txt
3D GameStudio	*.mdl; *.hmp
3D Studio Max	*.3ds; *.ase
AC3D	*.ac
AutoCAD/Autodesk	*.dxf
Biovision BVH	*.bvh
CharacterStudio Motion	*.csm
Collada	*.dae; *.xml
DirectX X	*.x
Doom 3	*.md5mesh; *.md5anim; *.md5camera
Irrlicht	*.irrmesh; *.irr;*.xml
LightWave	*.lwo; *.lws
Milkshape 3D	*.ms3d
Modo Model	*.lxo
Neutral File Format	*.nff
Ogre	*.mesh.xml, *.skeleton.xml, *.material
Quake I, Quake II, Quake III	*.mdl; *.md2; *.md3; *.pk3
Quick3D	*.q3o; *q3s
RtCW	*.mdc
Sense8 WorldToolkit	*.nff
Terragen Terrain	*.ter
TrueSpace	*.cob, *.scn
Valve Model	*.smd, *.vta
XGL	*.xgl, *.zgl

266   All functions are explained in detail in a comprehensive documentation which can be

267   accessed directly inside MeVisLab. A stand-alone copy of the documentation is available as

268   Supplementary File S2. In order to use the app, it simply needs to be instantiated (via the

269   MeVisLab menu: Modules → PDF → Apps → Scientific3DFigurePDFApp). A full feature list is

270   available in Table 4.

271   **Table 4.** List of features.

Category	Features
Data Import	Import external data, import MeVisLab data, import point clouds, import line sets, import meshes from 37 file formats, adjust mesh density, preview import
Point Cloud Editing	Specify point cloud name, specify position in model tree, preview settings
Line Set Editing	Specify line set name, specify position in model tree, specify colour, preview settings
Mesh Editing	Specify mesh name, specify position in model tree, specify colour, specify opacity, preview settings
View Specification	Specify view name, specify background colour, specify lighting scheme, specify render mode, preview settings, specify multiple views
U3D Creation	Store model in U3D format, preview scene
Poster Image Creation	Store poster in PNG format, preview scene, specify superimposed text
PDF Creation	Store document in PDF (v1.7) format, specify header citation text, specify header headline text, specify U3D file, specify poster file, specify model activation mode, specify model deactivation mode, specify toolbar enabling, specify navigation bar enabling, specify animation start mode, specify caption, specify description text

272   *Additional Features for Tailored PDF Creation*

273   The abstract module which wraps the API of the PDF library libHaru into a MeVisLab module

274   was made public ("PDFGenerator" module) and can be used for the development of tailored

275   MeVisLab modules. In order to facilitate the re-use of this abstract base module, an exemplary

276   project was set up (/Projects/PDFExamples/SavePDFTemplate). This project demonstrates how

277   to derive a customized module from the PDFGenerator base module and how to specify the

278   content of the PDF file that will be created by means of the new module. The template code is

279   verbosely annotated and includes examples for setting PDF properties (e.g., meta data, page

280   size, encryption) as well as the document content (including text, images, graphics and 3D

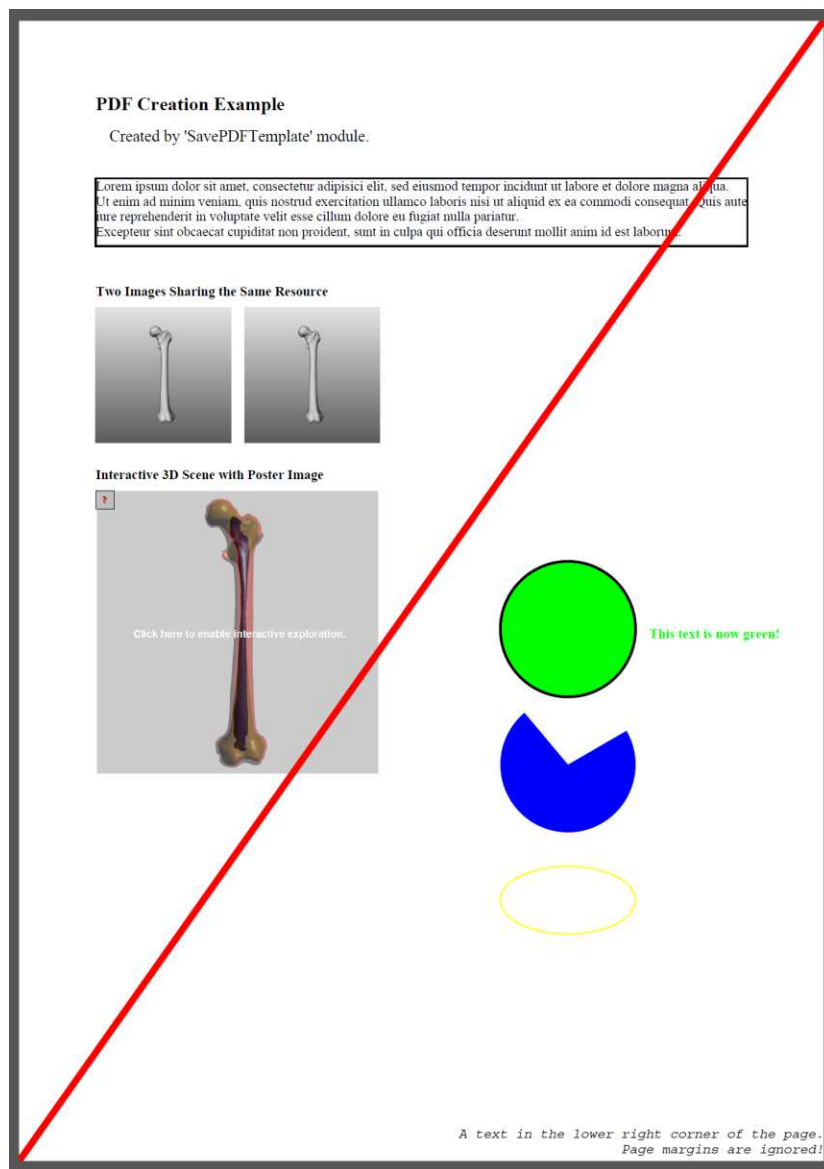281   models). The output of the SavePDFTemplate module is illustrated in Figure 3.

282

Figure 3. Output of the SavePDFTemplate module.

284   Finally, a project wizard was integrated into the MeVisLab GUI. It can be accessed via the
285 MeVisLab menu: File → Run Project Wizard… → PDF Module. The wizard consists of three steps
286 (Figure 4) whereof the second step offers the possibility to include demo code which produces
287 the same PDF file as the SavePDFTemplate module described above. The general usage of
288 project wizards in MeVisLab is explained in chapter 23 of the MeVisLab manual (menu: Help →
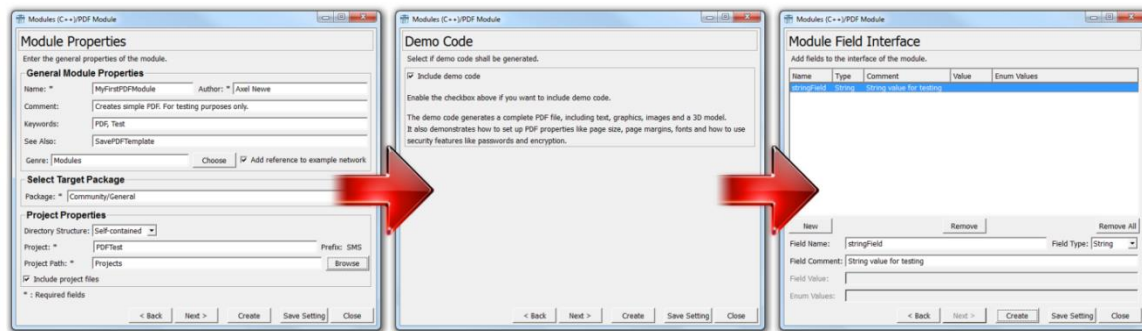289 Browse Help Pages → Using MeVisLab → MeVisLab Reference Manual).

290

Figure 4. Project wizard for creating customized PDF modules.

Availability

293   The whole PDF project for MeVisLab (which includes the Scientific3DFigurePDFApp, the
294   PDFGenerator base module, the SavePDFTemplate project, the project wizard and all source
295   code files) is available for Microsoft Windows, MacOS and Linux (tested with Ubuntu 14.04.2). It
296   requires MeVisLab 2.8 or a later version (http://www.mevislab.de/download/). The Windows
297   version of MeVisLab is available for four compiler versions. This is relevant only if the source
298   code is intended to be compiled manually (see below).

299   There are two approaches to add the app and the other elements to an existing MeVisLab
300   installation: add-on installers and the online repository of the MeVisLab community sources.

301   Installers are self-contained, executable archives that automatically add all necessary files to
302   an existing MeVisLab installation. The target groups for these installers are MeVisLab
303   newcomers and pure users that want to use the Scientific3DFigurePDFApp out-of-the-box. The
304   current version of the installers for all operating systems and all 64-Bit compiler versions can be
305   downloaded   from   the   research   data   repository   Zenodo
306   (http://dx.doi.org/10.5281/zenodo.48758). Installers for the previous version of MeVisLab
307   (2.7.1) are available as well (http://dx.doi.org/10.5281/zenodo.47491), but this version will not
308   be supported in the future. Updates will be made available via Zenodo as well. A dedicated
309   Zenodo Community Collection named "Three-dimensional Portable Document Format (3D PDF)
310   in Science" has been set up for this purpose (https://zenodo.org/collection/user-3d-pdf).

311   All those who are interested in being able to always use the latest version should connect
312   their MeVisLab installation with the community sources which are hosted at GitHub
313   (https://github.com/MeVisLab/communitymodules/tree/master/Community). This approach,
314   however, requires compiling the source code and is intended only for experienced users or for
315   users that are willing to become acquainted with MeVisLab. Note, that there are multiple
316   versions available for Windows, depending on the compiler that is intended to be used.

317   *Discussion*

318   *A Toolbox for the Creation of 3D PDFs*

319   The utilization of 3D PDF technology for scholarly publishing has been revealed and proven
320   both useful and necessary by several authors in the past years. The mainstream application of
321   3D PDF in science, however, is yet to come.
322   One reason might be the difficult process that has so far been necessary to create
323   appropriate data and relevant electronic documents. This article presents an all-in-one solution
324   for the creation of such files which requires no extraordinary skills. It can be used by low-end
325   users as an out-of-the-box tool as well as a basis for sophisticated tailored solutions for high-
326   end users.
327   Many typical problems as regards the creation of 3D model files have been addressed and
328   solved. All steps of the workflow are integrated seamlessly. The software is available for all OS
329   platforms and can import and process objects from many popular 3D formats, including
330   polylines and point clouds (Table 3). The density of imported meshes can be adjusted
331   interactively which enables the user to find the best balance between the desired level of detail
332   and the file size.
333   The main contribution, however, is the possibility to create ready-to-publish PDF documents
334   with a minimum of steps. This approach was proposed to be the ideal solution by **(Kumar et al.,**
335   **2010)**. To best knowledge, this is the first time that such an integrated and comprehensive
336   solution is made available for the scientific community.

337   *Applications*

338   The areas of application (see an example in Supplemental File S1) are manifold and not
339   limited to a specific scientific discipline. On the contrary: every field of research that produces
340   three-dimensional data can and should harness this technology in order to get the best out of
341   that data.
342   One (arbitrary) example for the possible use of mesh models from the recent literature is 3D
343   ultrasound. Dahdouh et.al. recently published about the results of segmentation of obstetric 3D
344   ultrasound images **(Dahdouh et al., 2015)**. That article contains several figures that project
345   three-dimensional models on the available two-dimensional surface. A presentation in native
346   3D would have enabled the reader to interactively explore the whole models instead of just one
347   pre-defined snapshot. Another example is the visualization of molecular structures as
348   demonstrated by **(Kumar et al., 2008)**.
349   Polylines can be used to illustrate nervous fibre tracking. **(Mitter et al., 2015)** used 2D

350   projections of association fibres in the foetal brain to visualize their results. A real 3D

351   visualization would have been very helpful in this case as well: While some basic knowledge

352   about a depicted object helps to understand 2D projections of 3D structures, the possibility to

353   preserve at least a little depth perception decreases with an increasing level of abstraction

354   (mesh objects vs. polylines).

355   This particularly applies to point clouds which can be observed, for example, in an article by

356   **(Qin et al., 2015)**: Although these authors added three-dimensional axes to their figure (no. 6) it

357   is still hard to get an impression of depth and therefore of the real position of the points in 3D

358   space.

359   ***Limitations***

360   Although the presented software pulls down the major thresholds that impede the creation

361   of interactive figures for scholarly publishing, some limitations still need to be considered.

362   A general concern is the suitability of PDF as a means to visualize and to exchange 3D models.

363   PDF and U3D (or PRC) do not support all features that other modern 3D formats provide and

364   that would be of interest for the scientific community (e.g., volumetric models). On the other

365   hand, PDF is commonly accepted and de-facto the only file format that is used for the

366   electronic exchange of scholarly articles. Therefore, PDF may not be the perfect solution, but it

367   is the best solution that is currently available.

368   The presented software requires MeVisLab as background framework and the installation of

369   MeVisLab requires a medium-sized download of about 1 GB (depending on the operating

370   system), which could be considered rather large for a PDF creator. On the other hand,

371   MeVisLab integrates a large library for the processing and the visualization of (biomedical)

372   image data. Furthermore, other frameworks (like MeshLab) do not provide all necessary

373   features (e.g., polylines or point clouds) and therefore were not considered to meet basic

374   requirements for the development of the software tool.

375   The import of 3D models is based on the Open Asset Import Library

376   (*http://www.assimp.org/*) which does not support all features of all 3D formats. For example,

377   textures and animations cannot be imported and should thus not be embedded into a model

378   file that is intended to be imported. However – although the model-editor part of the

379   presented software does not support textures (or animations), the PDF-creator part can still be

380   used to produce scientific PDFs with textured or animated models, if the necessary U3D files

381   have been created with external and more specialized software. In this use case, the

382   Scientific3DFigurePDFApp does not integrate all necessary steps, but it still remains a "few-

383   clicks" alternative for the creation of interactive PDF supplements for scientific publications and

384 it still obviates the need for a commercial solution.

385   Finally, very large model files should be avoided. If a large model fails to import, it should be

386 separated into several sub-models. A mesh reduction can be applied after the import, but a

387 previously reduced mesh speeds up the import process.

Suitable Reading Software

389   The Adobe Reader (http://get.adobe.com/reader/otherversions/) is available free of charge

390 for all major operating systems (MS Windows, Mac OS, Linux). It is currently the only software

391 that can be used to display embedded 3D models and to let the user interact with them

392 (zooming, panning, rotating, selection of components). However, even the Adobe Reader does

393 not support all U3D features **(Adobe, 2007)**, e.g., Glyphs and View Nodes. Furthermore, a

394 rendering flaw has been observed on low-end graphic boards in MacOS hardware (Figure 5).

395 Adobe Reader for MacOS does not render transparent surfaces superimposed upon each other

396 correctly: instead, a strong tessellation effect is visible. This may also occur on other platforms

397 but has not been reported yet. Since this is an issue with the rendering engine of Adobe Reader,

398 there is currently no other solution than using a different render mode (e.g., one of the

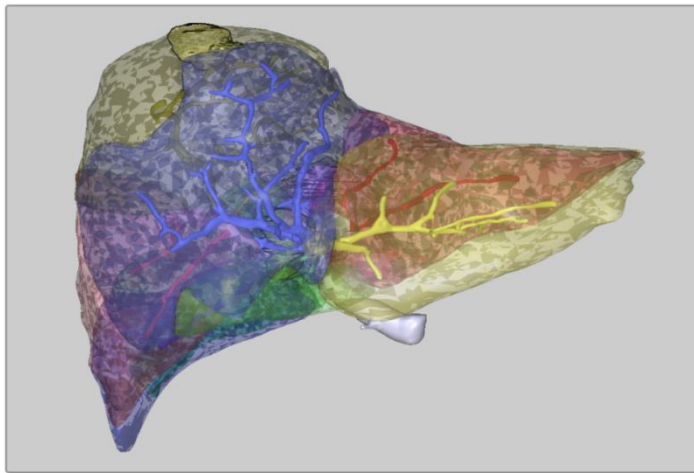399 wireframe modes) or different hardware.

400

401 **Figure 5. Rendering artifacts.** These tessellation artifacts have been observed on MacOS systems with

402 low-end graphic hardware.

403   Experience shows that many users do not expect a PDF document to be interactive.

404 Therefore, possible consumers should be notified that it is possible to interact with the

405 document and they should also be notified that the original Adobe Reader is required for this.

406 Although poster images are a workaround to avoid free areas in PDF readers that are not

407   capable of rendering 3D scenes, missing 3D features of a certain reader could be confusing for a
408   user.

A Basis for Own Modules

410   As pointed out in previous work **(Newe, 2015)**, the authoring of a PDF document is usually a
411   complex task and thus in most cases it cannot be avoided to separate the generation of 3D
412   model data from the actual PDF authoring. Although the software tool presented in this article
413   mitigates this general problem by integrating model generation and PDF creation, it is still
414   limited to a certain use case and a pre-defined PDF layout.
415   However, the API of the core PDF functionality is public and designed in a way that facilitates
416   the creation of own PDF export modules. The large number of convenience functions for the
417   abstract base module (PDFGenerator) facilitates the creation of derived modules. These
418   functions massively lighten the programmer's workload by providing a simple access to routine
419   tasks like writing text at a defined position or like embedding a 3D model which would normally
420   require a whole series of API calls. Finally, the built-in wizard generates all necessary project
421   files and source code files to create a fully functional module barebone which only needs to be
422   outfitted with the desired functionality.

Outlook

424   Although this article represents an important milestone, the development of the PDF project
425   for MeVisLab is ongoing. Future goals are the integration of virtual volume rendering **(Barnes et**
426   **al., 2013)**, animations **(van de Kamp et al., 2014)** and the parsing of U3D files that have been
427   created with external software. The progress can be tracked via GitHub
428   (https://github.com/MeVisLab/communitymodules/tree/master/Community) and updates to
429   the binary files will be published regularly.

Conclusion

431   Three-dimensional data is produced at an increasing rate throughout all scientific disciplines.
432   The Portable Document Format is a well suited medium for the visualization and the publication
433   of this kind of data. With the software presented in this article, the complete workflow for
434   generating 3D model files and 3D PDF documents for scholarly publications can be processed in
435   a consolidated working environment, free of license costs and with all major operating systems.
436   The software addresses novices as well as experienced users: On the one hand, it provides an
437   out-of-the-box solution that can be used like a stand-alone application, and on the other and all
438   sources and APIs are freely available for specifically tailored extensions.

List of abbreviations

439

440 2D – Two-dimensional

441 3D – Three-dimensional

442 PDF – Portable Document Format

443 ISO – International Organization for Standardization

444 U3D – Universal 3D

445 PRC – Product Representation Compact

446 CAD – Computer Aided Construction

447 ECMA – European Computer Manufacturers Association

448 GUI – Graphical User Interface

449 API – Application Programming Interface

450 PNG – Portable Network Graphics

451 CSV – Character-separated Value, Comma-separated Value

452

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453

458

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