Enriching scientific publications with interactive 3D PDF figures: A complete toolbox

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Three-dimensional (3D) data of many kinds is produced at an increasing rate throughout all scientific disciplines. The Portable Document Format (PDF) is the de-facto standard for the exchange of electronic documents and allows for embedding three-dimensional models. Therefore, it is a well suited medium for the visualization and the publication of this kind of data. The generation of the appropriate files has been cumbersome so far. This article presents the first release of a software toolbox which integrates the complete workflow for generating 3D model files and ready-to-publish 3D PDF documents for scholarly publications in a consolidated working environment. It can be used out-of-the-box as a simple working tool or as a basis for specifically tailored solutions. A comprehensive documentation, an example project and a project wizard facilitate the customization. It is available royalty-free and for Windows, MacOS and Linux.

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Introduction

11 Throughout many scientific disciplines, the availability – and thus the importance – of three-

12 dimensional (3D) data has grown in the recent years. Consequently, this data is often the basis

13 for scientific publications, and in order to avoid a loss of information, the visualization of this

14 data should be 3D whenever possible (**Tory & Möller, 2004**). In contrary to that, almost all

15 contemporary visualization means (paper printouts, computer screens, etc.) only provide a two-

16 dimensional (2D) interface.

17 The most common workaround for this limitation is to project the 3D data onto the available

18 2D plane (**Newe, 2015**), which results in the so-called "2.5D visualization" (**Tory & Möller, 2004**).

19 This projection yields two main problems: limited depth perception and objects that occlude

20 each other. A simple but effective solution of these problems is interaction: by changing the

21 projection angle of a 2.5D visualization (i.e., by changing the point of view), depth perception is

22 improved (**Tory & Möller, 2004**), and at the same time objects that had previously been

23 occluded (e.g., the backside) can be brought to sight.

24 A means of application of this simple solution has been available for many years: the Portable

25 Document Format (PDF) from Adobe (**Adobe, 2014**). This file format is the de-facto standard for

26 the exchange of electronic documents and almost every scientific article that is published

27 nowadays is available as PDF – as well as even articles from the middle of the last century

28 (**Hugh-Jones, 1955**). PDF allows for embedding 3D models and the Adobe Reader

29 (http://get.adobe.com/reader/otherversions/) can be used to display these models

30 interactively.

31 Nevertheless, this technology seems not to have found broad acceptance among the scientific

32 community until now, although journals encourage authors to use this technology (**Maunsell,**

33 **2010**; **Elsevier, 2015**). One reason might be that the creation of the appropriate model files and

34 of the final PDF documents is still cumbersome. Not everything that is technically possible is

35 accepted by those who are expected to embrace the innovation if the application of this

36 innovation is hampered by inconveniences (**Hurd, 2000**). Generally suitable protocols and

37 procedures have been proposed by a number of authors before, but they all required of

38 toolchain of at least three (**Kumar et al., 2010**; **Danz & Katsaros, 2011**) or even four (**Phelps,**

39 **Naeger & Marcovici, 2012**; **Lautenschlager, 2014**) different software applications and up to 22

40 single steps until the final PDF was created. Furthermore, some of the proposed workflows were

41 limited to a certain operating system (OS) (**Phelps, Naeger & Marcovici, 2012**), required

42 programming skills (**Barnes et al., 2013**) or relied on commercial software (**Ruthensteiner &**

43 **Heß, 2008**). Especially the latter might be an important limiting factor which hampers the

44 proliferation of the 3D PDF format in scientific publishing (**Lautenschlager, 2014**; **Newe, 2015**).

45 This article presents a comprehensive and highly integrated software tool for the creation of

46 both the 3D model files (which can be embedded into PDF documents) and the final, ready-to-

47 publish PDF documents with embedded interactive 3D figures. The presented solution is based

48 on MeVisLab, available for all major operating systems (Windows, MacOS and Linux) and

49 requires no commercial license. The source code is available but does not necessarily need to be

50 compiled since binary add-on installers for all platforms are available. A detailed online

51 documentation, an example project and an integrated wizard facilitate re-use and

52 customization.

53 ### *Background and Related Work*

54 ### *The Portable Document Format*

55 The Portable Document Format is a document description standard for the definition of

56 electronic documents independently of the software, the hardware or the operating system

57 that is used for creating or consuming (displaying, printing…) it (**Adobe, 2008a**). A PDF file can

58 comprise all necessary information and all resources to completely describe the layout and the

59 content of an electronic document, including texts, fonts, images and multimedia elements like

60 audio, movies or 3D models. Therefore, it fulfils all requirements for an interactive publication

61 document as proposed by Thoma et.al. (**Thoma et al., 2010**).

62 Although an ISO standard (ISO 32000-1:2008 (**ISO, 2008**)), the specification is available to the

63 full extent from the original developer Adobe (**Adobe, 2015**) and can be used royalty-free.

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

65 The fifth edition of the PDF specification (PDF version 1.6 (**Adobe, 2004**)), published in 2004,

66 was the first to support so-called "3D Artwork" as an embedded multimedia feature. In January

67 2005, the Acrobat 7 product family provided the first implementation of tools for creating and

68 displaying these 3D models (**Adobe, 2005**).

69 The latest version (PDF version 1.7 (**Adobe, 2008a**)) supports three types of geometry (meshes,

70 polylines and point clouds), textures, animations, 15 render modes, 11 lighting schemes and

71 several other features. The only 3D file format that is supported by the ISO standard (**ISO, 2008**)

72 is Universal 3D (U3D, see section below). Support for another 3D format (Product

73 Representation Compact, PRC) has been added by Adobe (**Adobe, 2008b**) and has been

74 proposed to be integrated into the replacement Norm ISO 32000-2 (PDF 2.0). However, this new

75 standard is currently only available as draft version (**ISO, 2014**) and has not yet been adopted.

76 **Table 1:** Number of publications related to 3D PDFs in biomedical sciences since 2008 (not 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

77 Although the first application in scientific context was proposed in November 2005 (**Zlatanova**

78 **& Verbree, 2005**) and thus quite soon after this new technology was available, it took three

79 more years before the first applications were really demonstrated in scholarly articles

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

81 of publications that apply PDF 3D technology either in theory or in practice has increased almost

82 every year (Table 1). The most sophisticated implementation so far is the reporting of planning

83 results for liver surgery where the PDF roots are hidden behind a user interface which emulates

84 a stand-alone software application (**Newe, Becker & Schenk, 2014**).

85 ### The Universal 3D (U3D) file format

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

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

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

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

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

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

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

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

94   proprietary bit encoding algorithm allows for a highly compressed storage of the geometry data.

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

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

97   The scholarly publishing company Elsevier invites authors to supplement their articles with 3D

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

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

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

101   ***Creating 3D Model Files and PDF Documents***

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

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

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

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

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

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

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

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

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

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

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

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

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

115   of being integrated into the main article text, some additional information is necessary as well:

116   At least a general headline and an optional reference to the main article should be provided. If

117   the document content is modularized to these five key elements (Figure 1), the creation of the

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

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

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

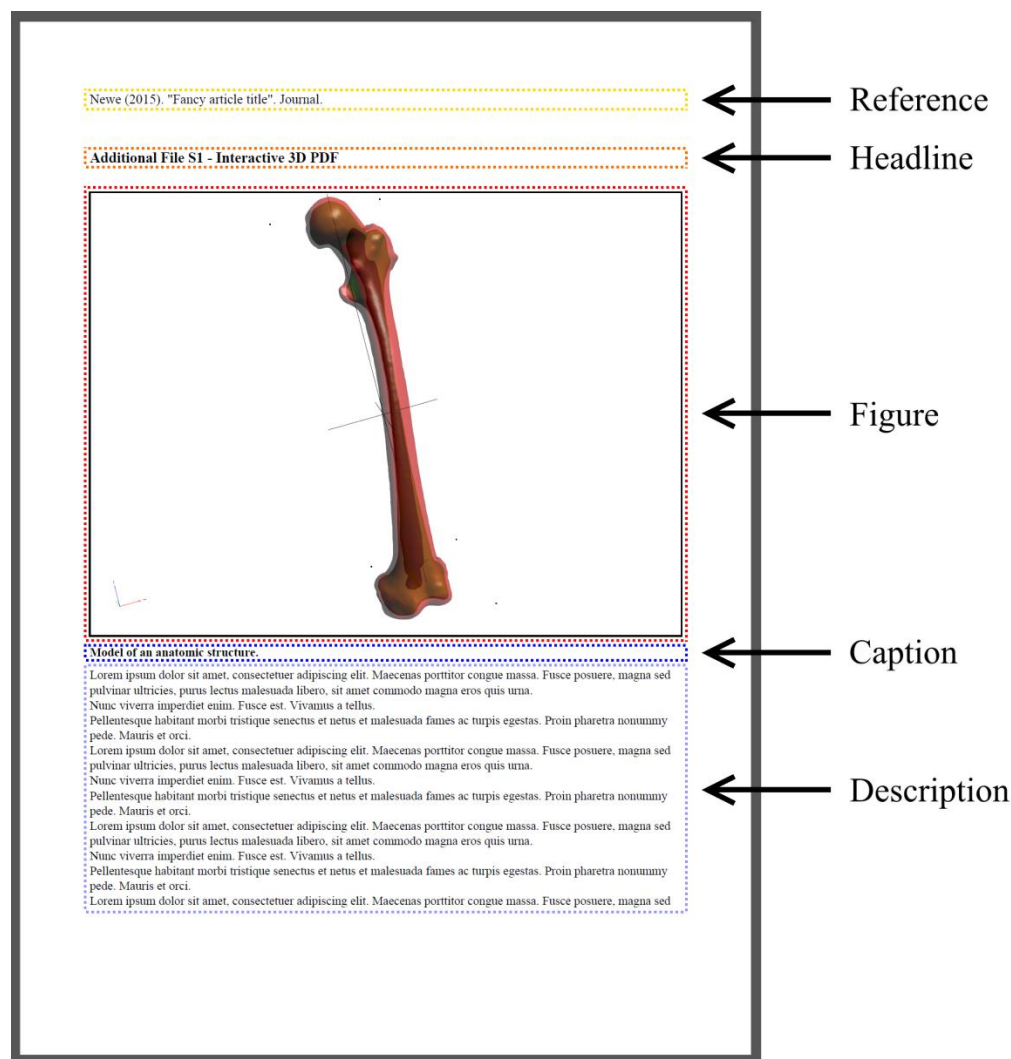
121   is intended to provide all these options, an author usually wants to define an initial view at the

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

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

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

125   generation of intermediate PDFs.

126

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

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

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

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

131   to be very high for illustrative purposes.

MeVisLab

133   MeVisLab is a framework for image processing and environment for visual development,

134   published by MeVis Medical Solutions AG and Fraunhofer MEVIS in Bremen, Germany. It is

135   available via download (http://www.mevislab.de/download/) for all major platforms (Microsoft

136   Windows, Mac OS and Linux) and has a licensing option which is free for use in non-commercial

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

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

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

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

141   programming knowledge (**Koenig et al., 13**; **Heckel, Schwier & Peitgen, 2009**; **Ritter et al.,**

142   **2011**). MeVisLab has been evaluated as a very good platform for creating application prototypes

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

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

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

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

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

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

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

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

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

Methods

Elicitation of Requirements

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

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

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

157   drawbacks.

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

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

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

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

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

163   development.

164   **Table 2:** Requirements for the development of the software tool. The two main requirements are highlighted in
165   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.

166   ***Creation of an "App" for MeVisLab***

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

168   **2015**) already provide the possibility to create U3D files without requiring programming skills

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

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

171   of the final PDF was not possible so far.

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

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

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

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

176   inside of MeVisLab.

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

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

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

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

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

182   readers are free to explore the code and to use it for own projects.

183   The user interface of the app was designed in a way that it guides novice users step-by-step

184   without treating experienced users too condescendingly, though. Finally, a comprehensive

185   documentation including an example project, a wizard for creating tailored PDF modules and a

186   verbose help text was set up.

187   ***Deployment of Core Functionality***

188   For the creation of the actual PDF files, version 2.2.0 of the cross-platform, open source

189   library libHaru (http://libharu.org/) was selected, slightly modified and integrated as third-party

190   contribution into MeVisLab.

191   Next, the application programming interface (API) of libHaru was wrapped into an abstract

192   base module for MeVisLab in order to provide an easy access to all functions of the library and

193   in order to hide away standard tasks like creating a document or releasing memory. A large

194   number of convenience functions were added to this base module and an exemplary MeVisLab

195   project was set up in order to demonstrate how to use the base module for tailored

196   applications. This base module also served as basis for the PDF creation of the app macro

197   described above. Finally, a project wizard was integrated into the MeVisLab GUI.

198   ***Results***

199   ***The "Scientific3DFigurePDFApp" module***

200   The new macro module "Scientific3DFigurePDFApp" for MeVisLab provides an integrated user

201   interface for all steps that are necessary for the creation of U3D models files and for the

202   creation of the final PDF documents with embedded 3D models. The app produces U3D models

203   files that are compatible with version 4 of the ECMA-363 standard, poster images in Portable

204   Network Graphics (PNG) format and PDF documents that are compliant with PDF version 1.7

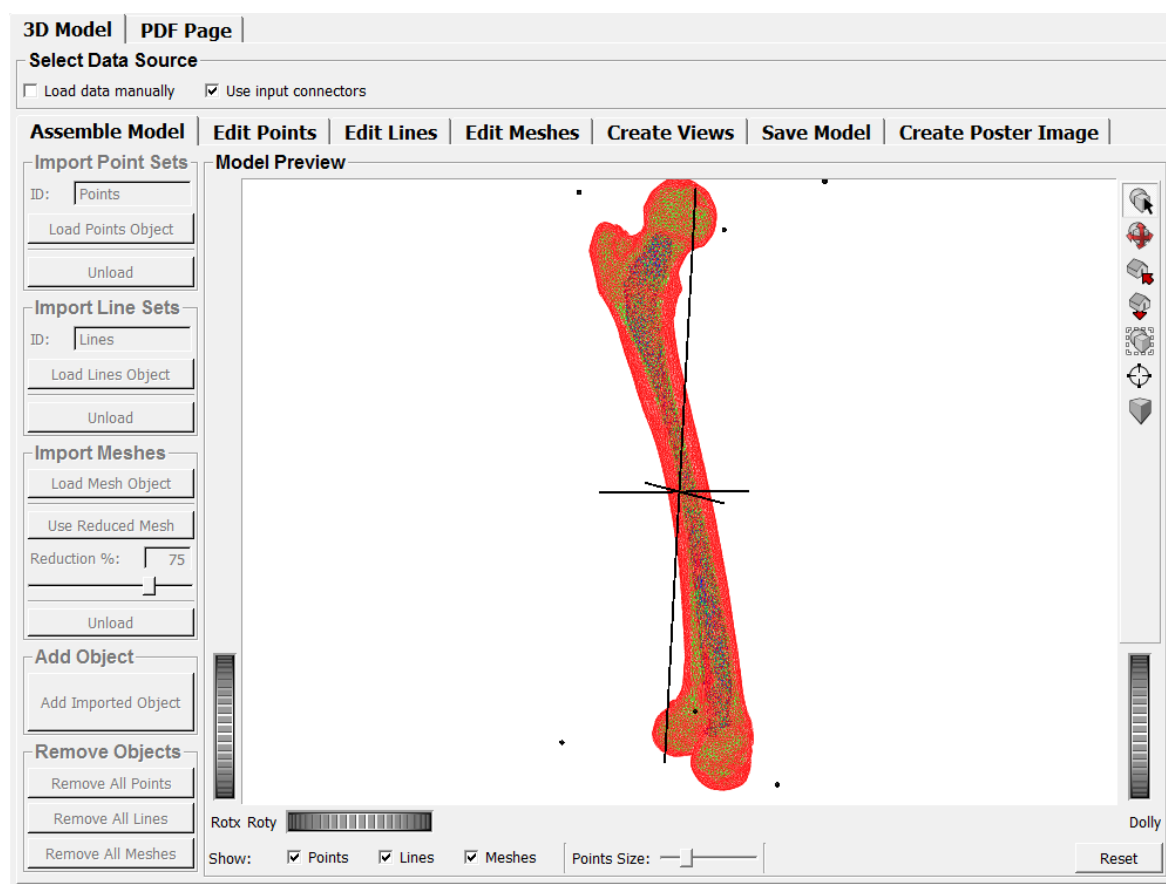
205   (ISO 32000-1:2008). An example PDF is available as Supplementary File S1.

206   The user interface is arranged in tabs, whereas each tab comprises all functions for one step

207   of the workflow. By processing the tabs consecutively, the user can assemble and modify 3D

208   models, save them in U3D format, create views and poster images for the PDF document, and

209   finally create the PDF itself step by step (Figure 2).

210

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

213 The raw model data can be

214 collected in two ways: either by

215 feeding it to the input connectors or

216 by assembling it by means of the

217 built-in assistant. The former option

218 is intended for experienced MeVisLab

219 users that want to attach the module

220 at the end of a processing chain. The

221 latter option addresses users that

222 simply want to apply the app for

223 converting existing 3D models and for

224 creating an interactive figure for

225 scholar publishing.

226 The software allows for importing

227 39 different 3D formats, including

228 point clouds and line sets from files in

229 character-separated value (CSV)

230 format (see Table 3 for a full list).

231 Objects from different sources can

232 be combined and their U3D

233 properties (colour, name, position in

234 the object tree) can be specified. The

235 density of imported meshes can be

236 adjusted interactively and multiple

237 views (i.e., the specification of

238 camera, lighting and render mode)

239 can be pre-defined interactively as

240 well. Finally, it is also possible to

241 create a poster image which can

Table 3: List of supported 3D formats for import.

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 Model	*.mdl
3D GameStudio Terrain	*.hmp
3D Studio Max 3DS	*.3ds
3D Studio Max ASE	*.ase
AC3D	*.ac
AutoCAD DXF	*.dxf
Autodesk DXF	*.dxf
Biovision BVH	*.bvh
CharacterStudio Motion	*.csm
Collada	*.dae; *.xml
DirectX X	*.x
Doom 3	*.md5mesh; *.md5anim; *.md5camera
Irrlicht Mesh	*.irrmesh; *.xml
Irrlicht Scene	*.irr; *.xml
LightWave Model	*.lwo
LightWave Scene	*.lws
Milkshape 3D	*.ms3d
Modo Model	*.lxo
Neutral File Format	*.nff
Ogre	*.mesh.xml, *.skeleton.xml, *.material
Quake I	*.mdl
Quake II	*.md2
Quake III	*.md3
Quake 3 BSP	*.pk3
Quick3D	*.q3o; *q3s
RtCW	*.mdc
Sense8 WorldToolkit	*.nff
Terragen Terrain	*.ter
TrueSpace	*.cob, *.scn
Valve Model	*.smd, *.vta
XGL	*.xgl, *.zgl

242   replace an inactive 3D model in the PDF document if the model itself is disabled or if it cannot

243   be displayed for some reason (e.g., because the reading software does not provide the

244   necessary features).

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

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

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

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

249   available in Table 4.

250   **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

251   ***Additional Features for Tailored PDF Creation***

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

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

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

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

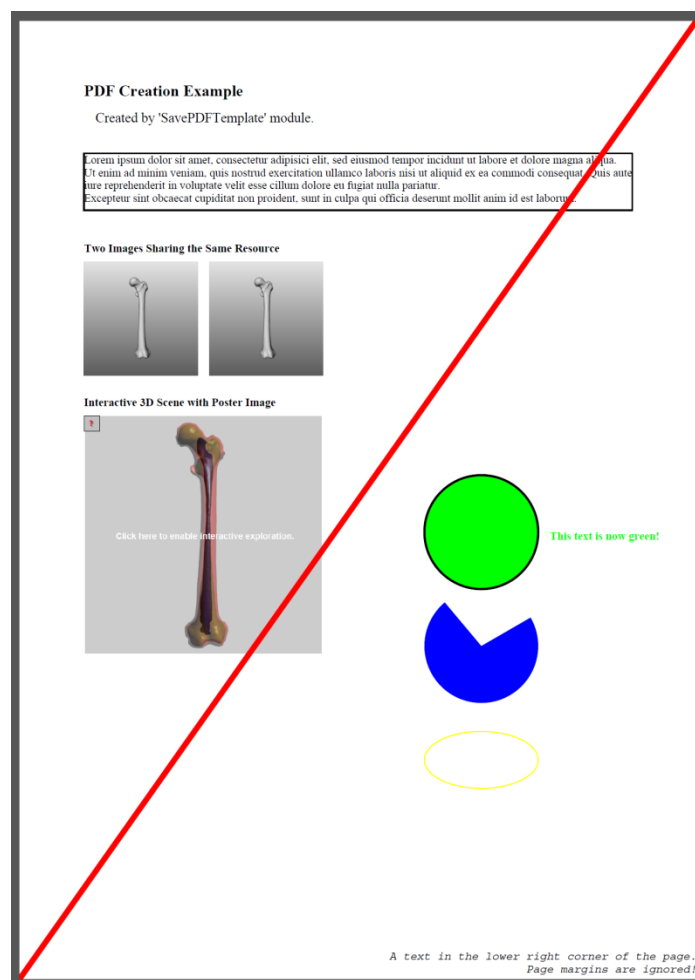
256   to derive a customized module from the PDFGenerator base module and how to specify the

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

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

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

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

261

262   **Figure 3:** Output of the SavePDFTemplate module.

263   Finally, a project wizard was integrated into the MeVisLab GUI. It can be accessed via the

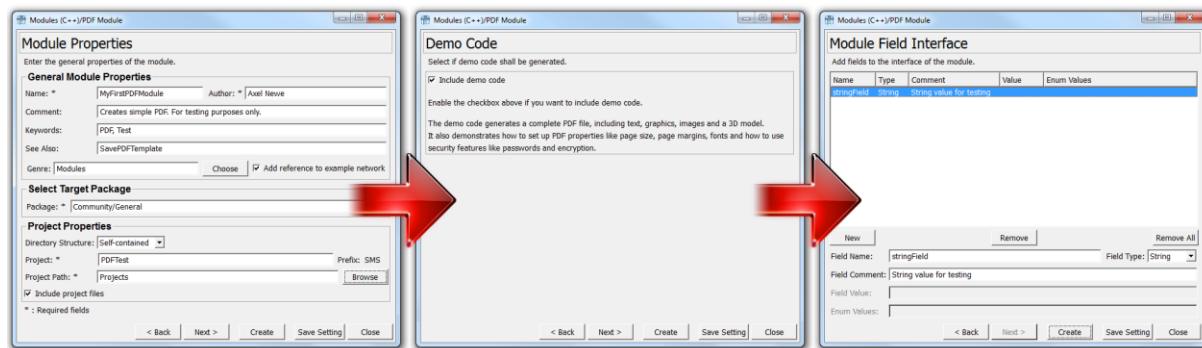
264   MeVisLab menu: File → Run Project Wizard… → PDF Module. The wizard consists of three steps

265   (Figure 4) whereof the second step offers the possibility to include demo code which produces

266   the same PDF file as the SavePDFTemplate module described above. The general usage of

267   project wizards in MeVisLab is explained in chapter 23 of the MeVisLab manual (menu: Help →

268   Browse Help Pages → Using MeVisLab → MeVisLab Reference Manual).

269

270 **Figure 4:** Project wizard for creating customized PDF modules.

271 ***Availability***

272 The whole PDF project for MeVisLab (which includes the Scientific3DFigurePDFApp, the

273 PDFGenerator base module, the SavePDFTemplate project, the project wizard and all source

274 code files) is available for Microsoft Windows, MacOS and Linux (tested with Ubuntu 14.04.2). It

275 requires MeVisLab 2.7 or a later version (http://www.mevislab.de/download/). There are two

276 approaches to add the app and the other elements to an existing MeVisLab installation: add-on

277 installers and the online repository of the MeVisLab community sources.

278 Installers are self-contained, executable archives that automatically add all necessary files to

279 an existing MeVisLab installation. The target groups for these installers are MeVisLab

280 newcomers and pure users that want to use the Scientific3DFigurePDFApp out-of-the-box. The

281 current version of the installers for all operating systems can be downloaded from the research

282 data repository Zenodo (**Newe, 2016**). Future updates will be made available via Zenodo as well.

283 A dedicated Zenodo Community Collection named "Three-dimensional Portable Document

284 Format (3D PDF) in Science" has been set up for this purpose

285 (https://zenodo.org/collection/user-3d-pdf).

286 All those who are interested in being able to always use the latest version should connect

287 their MeVisLab installation with the community sources which are hosted at GitHub

288 (https://github.com/MeVisLab/communitymodules/tree/master/Community). This approach,

289 however, requires compiling the source code and is intended only for experienced users or for

290 users that are willing to become acquainted with MeVisLab.

Discussion

A Toolbox for the Creation of 3D PDFs

The utilization of 3D PDF technology for scholarly publishing has been revealed and proven both useful and necessary by several authors in the past years. The mainstream application of 3D PDF in science, however, is yet to come.

One reason might be the difficult process that has so far been necessary to create appropriate data and relevant electronic documents. This article presents an all-in-one solution for the creation of such files which requires no extraordinary skills. It can be used by low-end users as an out-of-the-box tool as well as a basis for sophisticated tailored solutions for high-end users.

Many typical problems as regards the creation of 3D model files have been addressed and solved. All steps of the workflow are integrated seamlessly. The software is available for all OS platforms and can import and process objects from many popular 3D formats, including polylines and point clouds (Table 3). The density of imported meshes can be adjusted interactively which enables the user to find the best balance between the desired level of detail and the file size.

The main contribution, however, is the possibility to create ready-to-publish PDF documents with a minimum of steps. This approach was proposed to be the ideal solution by Kumar et.al. (**Kumar et al., 2010**). To best knowledge, this is the first time that such an integrated and comprehensive solution is made available for the scientific community.

Applications

The areas of application are manifold and not limited to a specific scientific discipline. On the contrary: every field of research that produces three-dimensional data can and should harness this technology in order to get the best out of that data.

One (arbitrary) example for the possible use of mesh models from the recent literature is 3D ultrasound. Dahdouh et.al. recently published about the results of segmentation of obstetric 3D ultrasound images (**Dahdouh et al., 2015**). That article contains several figures that project three-dimensional models on the available two-dimensional surface. A presentation in native 3D would have enabled the reader to interactively explore the whole models instead of just one pre-defined snapshot.

320   Polylines can be used to illustrate nervous fibre tracking. Mitter et.al. (**Mitter et al., 2015**)

321   used 2D projections of association fibres in the foetal brain to visualize their results. A real 3D

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

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

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

325   (mesh objects vs. polylines).

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

327   Qin et.al. (**Qin et al., 2015**): Although these authors added three-dimensional axes to their

328   figure (no. 6) it is still hard to get an impression of depth and therefore of the real position of

329   the points in 3D space.

Suitable Reading Software

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

332   for all major operating systems (MS Windows, Mac OS, Linux). It is currently the only 100%

333   standard compliant software that allows can be used to display embedded 3D models and to let

334   the user interact with them (zooming, panning, rotating, selection of components). However,

335   even the Adobe Reader does not support all U3D features (**Adobe, 2007**), e.g., Glyphs and View

336   Nodes.

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

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

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

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

341   capable of rendering 3D scenes, missing 3D features of a certain reader could be confusing for a

342   user.

A Basis for Own Modules

344   As pointed out in previous work (**Newe, 2015**), the authoring of a PDF document is usually a

345   complex task and thus in most cases it cannot be avoided to separate the generation of 3D

346   model data from the actual PDF authoring. Although the software tool presented in this article

347   mitigates this general problem by integrating model generation and PDF creation, it is still

348   limited to a certain use case and a pre-defined PDF layout.

349   However, the API of the core PDF functionality is public and designed in a way that facilitates

350   the creation of own PDF export modules. The large number of convenience functions for the

351   abstract base module (PDFGenerator) facilitates the creation of derived modules. These

352   functions massively lighten the programmer's workload by providing a simple access to routine

353   tasks like writing text at a defined position or like embedding a 3D model which would normally

354   require a whole series of API calls. Finally, the built-in wizard generates all necessary project

355   files and source code files to create a fully functional module barebone which only needs to be

356   outfitted with the desired functionality.

357   ***Outlook***

358   Although this article represents an important milestone, the development of the PDF project

359   for MeVisLab is ongoing. Future goals are the integration of virtual volume rendering (**Barnes et**

360   **al., 2013**), animations (**van de Kamp et al., 2014**) and the parsing of U3D files that have been

361   created with external software. The progress can be tracked via GitHub

362   (https://github.com/MeVisLab/communitymodules/tree/master/Community) and updates to

363   the binary files will be published regularly.

364   ***Conclusion***

365   Three-dimensional data is produced at an increasing rate throughout all scientific disciplines.

366   The Portable Document Format is a well suited medium for the visualization and the publication

367   of this kind of data. With the software presented in this article, the complete workflow for

368   generating 3D model files and 3D PDF documents for scholarly publications can be processed in

369   a consolidated working environment, free of license costs and with all major operating systems.

370   The software addresses novices as well as experienced users: On the one hand, it provides an

371   out-of-the-box solution that can be used like a stand-alone application, and on the other and all

372   sources and APIs are freely available for specifically tailored extensions.

373

List of abbreviations

374

375 2D – Two-dimensional

376 3D – Three-dimensional

377 PDF – Portable Document Format

378 ISO – International Organization for Standardization

379 U3D – Universal 3D

380 PRC – Product Representation Compact

381 CAD – Computer Aided Construction

382 ECMA – European Computer Manufacturers Association

383 GUI – Graphical User Interface

384 API – Application Programming Interface

385 PNG – Portable Network Graphics

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

387

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393

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