

Title: Automated integration of extract-based CFD results with AR/VR in engineering education for practitioners

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Supplementary Material 1

Table 1 Most commonly used 3D data formats in computer graphics.

3D data format	3DS	BLENDER	X3D	FBX	GLTF	OBJ	STL	STEP	DAE	WEBGL	VTKJS
Developer	Autodesk Inc.	Blender Inc.	Web3D consortium	Autodesk Inc.	Khronos Group	Wavefront Technologies	3D Systems	Autodesk Inc.	Khronos Group	Khronos Group	Kitware
Directory (source)	Link	Link	Link	Link	Link	Link	Link	Link	Link	Link	Link
Type	proprietary	neutral	neutral	proprietary	neutral	proprietary	neutral	neutral	neutral	neutral	neutral
ISO standard	-	-	+	-	-	-	-	+	+	-	-
Software development kit (SDK)	+	-	-	+	-	-	-	-	-	-	-
File type	binary	binary and ASCII	binary	binary and ASCII	binary	ASCII	binary and ASCII	ASCII	ASCII	-	-
Utilization in web browser	converter	converter	converter	converter	direct	direct	converter	converter	converter	direct	direct
Initial release	1996	?	2001	2002	2016	1990	1987	1994	2004	2017	2017

Table 2 Data encoding characteristics of 3D data formats.

Data encoding characteristics		3DS	BLENDER	X3D	FBX	GLTF	OBJ	STL	STEP	DAE	WEBGL	VTKJS
Geometry	Approximate mesh	+	+	+	+	+	+	+	+	+	+	+
	Precise mesh		+	+	+	+	+		+	+	+	+
	CSG (constructive solid geometry)		+	+					+			
Appearance	Color	+	+	+	+	+	+ (external)		+	+	+	+
	Material	+	+	+	+	+	+ (external)		+	+	+	+
	Texture	+	+	+	+	+	+ (external)		+	+	+	+
Scene	Camera	+	+	+	+	+				+	+	+
	Light	+	+	+	+	+				+	+	+
	Relative position	+	+	+	+	+			+	+	+	+
Animation	Animation		+	+	+	+				+	+	+

Table 3 A comparison between computational fluid dynamics (CFD) software

CFD software		OpenFOAM	Comsol	Ansys	Star-CCM+	Numeca	Autodesk CFD	SimScale	Flow-3d	OpenLB
Developer		OpenCFD Ltd.	COMSOL Inc.	Ansys Inc.	Siemens	Numeca	Autodesk Inc.	SimScale GmbH	Flow Science, Inc.	OpenLB
Version		v6/2018	v5.4/2018	v18/2017	2019	2019	2019	2019	2019	2019
Directory (source)		Link	Link	Link	Link	Link	Link	Link	Link	Link
Operation	License	open-source	commercial	commercial	commercial	commercial	commercial	commercial	commercial	open-source
	Application programming interface (API)	C++/Python	Java/Matlab	C	Java	C++	QT/Python	C++	Java	optional
	Cloud for clients	outsource	on demand	on demand	on demand	on demand	on demand	+	on demand	outsource
	External execution	C++/Python	Java/Matlab	C/fortran	restricted	restricted	restricted	restricted	restricted	open-field
	Source code manipulation	open-field	restricted but broad	restricted	restricted	no	no	no	no	open-field
	Operating system	Linux/MS/MAC	Linux/MS/MAC	Linux/MS/MAC	Linux/MS/MAC	Linux/MS/MAC	Linux/MS/MAC	web-based cloud	Linux/MS/MAC	Linux/MS
	Parallelization	free	license-required	license-required	license-required	license-required	license-required	license-required	license-required	free
Modeling	CFD	+	+	+	+	+	+	+	+	+
	Multiphysics	+	+	+	+	-	-	-	-	-
Database	File vs Management	file-based	management system	management system	management system	management system	management system	management system	management system	file-based
Support	Benchmark & validation	tutorials	application gallery	tutorials	tutorials	-	tutorials	application gallery	-	-

Table 4 Data import and export options currently provided by CFD software.

CFD software			OpenFOAM	Comsol	Ansys	Star-CCM+	Numeca	Autodesk CFD	SimScale	Flow-3d	OpenLB
Data creation	CAD	Import	Either external or embedded software with several 3D CAD file formats								
		Export									
	Mesh	Import	Either external or embedded software to generate suitable mesh file formats								
		Export									
	Simulation	Import	CPP	Comsol and Nastran	ABAQUS, ANSYS CFD-Post, CGNS, EnSight, Fieldview, Tecplot, Nastran	STAR-View+ and VRML	proprietary formats	proprietary formats	proprietary formats	proprietary formats	open-field
		Export	CPP and txt	mph, mphbin, mphtxt, mphphp, .txt, .csv, .dat, .xlsx, Nastran, vtk	CGNS, HDF, XDMF, NetCFD, EnSight, Fieldview, Tecplot, Nastran, ParaView, csv, txt, xml, cdb, dat, case	Fieldview, techplot, sbd, Nastran, CGNS, HDF, csv, txt, xml	proprietary formats	proprietary formats	proprietary formats	proprietary formats	open-field
	Post-processing	Media file formats	-	+	+	+	+	+	+	+	-
		Text file formats	+	+	+	+	+	+	+	+	+
		3D data formats	-	VRML	VRML	-	-	-	-	-	-

Table 5 Data import and export options currently provided by CFD post-processors.

Postprocessing software		Enight	FieldView	Tecplot	ParaView
Operation	Developer	Ansys Inc.	Vela Software International	Vela Software International	Kitware
	Version	2019	2019	2019	2019
	Directory (source)	Link	Link	Link	Link
	License	commercial	commercial	commercial	open-source
	Application programming interface (API)	Pyhton	Pyhton	Python	Python/C++/Java/Web b
	Source code manipulation	restricted	restricted	restricted	open-field
	Operating system	Linux/MS/MAC	Linux/MS/MAC	Linux/MS/MAC	Linux/MS/MAC
Post-processing	Image and video file formats	+	+	+	+
	Text file formats	+	+	+	+
	Data exchange with other software	Ansys products, ADINA CFD, Barracuda, CFD-ACE+,CGNS,ConvegeCFD,CRUNCH , EDEM, FLOW-3D, KIVA, OpenFOAM, OverFlow, ParticleWorks, Plot3D, PowerFLOW, RADIOSS-CFD, STAR-CCM+, Nastran, MSC, CGNS, HDF, XDMF, NetCFD, VTK	Ansys products, Autodesk Simulation CFD, AVL FIRE, CONVERGE, FLOW-3D, FLUENT, HAVOC, LS-DYNA, NPARC-WIND, OpenFOAM, PATRAN, STL, UH3D, STAR-CCM+,CFD -ACE, ConvegeCFD, CRUNCH, FLOW-3D, KIVA, OpenFOAM, OverFlow, ParticleWorks, Plot3D, PowerFLOW, RADIOSS-CFD, STAR-CCM+, Nastran, Numeca, CGNS, HDF, XDMF, NetCFD, VTK	CGNS, FLOW-3D (Flow Science, Inc.), ANSYS CFX, ANSYS FLUENT .cas and .dat format and polyhedra, OpenFOAM, PLOT3D (Flow Science, Inc.), Tecplot and polyhedra, Enight Gold and HDF5 (Hierarchical Data Format)., HDF.	Ansys, OpenFOAM, Comsol, Star-CCM++, Enight, FieldView, CGNS, HDF, XDMF, NetCFD, VTK
	3D data formats	OBJ, STL, STEP	STL, Parasolids, IGES, Native CAD, XDB	with extension	SVG, GLTF, VRML, X3D,JSON, VTKJS, WEBGL
Immersive visualization	Virtual reality	plugin	plugin	plugin	plugin

Table 6 3D computer graphics software for rendering and data processing.

Application	3ds Max	Blender	Cinema 4D	CLARA.IO	Houdini	Maya
Developer	Autodesk Inc.	Blender	MAXON	Ashlar-Vellum	Side Effects Software	Autodesk Inc.
Version	2019	v8.1/2019	2019	2019	2019	2019
Directory (source)	Link	Link	Link	Link	Link	Link
Platforms	MS	MS/MAC/LINUX	MS/MAC	MS/MAC/LINUX	MS/MAC/LINUX	MS/MAC/LINUX
License	proprietary	open-source	proprietary	proprietary	proprietary	proprietary
Image, video, and audio import	BMP, Cineon, TGA, JPG, PNG, OpenEXR, Cineon, Radiance HDR, SGI, RLA, RPF, AVI, MPEG and QuickTime, GIF, TIFF, PSD, MOV, YUV, DDS	BMP, Cineon, TGA, JPG, PNG, OpenEXR, Cineon, Radiance HDR, SGI, RLA, RPF, AVI, MPEG and QuickTime, GIF, TIFF, PSD, MOV, YUV, DDS	-	-	-	BMP, Cineon, TGA, JPG, PNG, OpenEXR, Cineon, Radiance HDR, SGI, RLA, RPF, AVI, MPEG and QuickTime, GIF, TIFF, PSD, MOV, YUV, DDS
Text file import/export	plugin/coding	plugin/coding	plugin/coding	plugin/coding	plugin/coding	plugin/coding
3D data import/export	FBX, 3DS, PRJ, ABC, AI, DAE, HTR, OBJ, SHP, SKP, STL, TRC, VRML, Openflight FLT, DEM, XML, DDF, DWG, DXF, IGE, IGS, IGES, IPT, WIRE, IAM, LS, VW, LP, SAT, Catia V4/V5, JT, ProE, RVT, PRT, SolidWorks[io 2], STEP, WIRE	DAE, Alembic, FBX, BVH, PLY, OBJ, STL, SVG, DXF X3D, glTF	FBX, OBJ, 3DS, QD3D, STL, DEM, LWO/LWS DXF VRML 1, VRML 2	FBX, OBJ, DAE, MD2, MD3, MD5, 3DS, STL, LWO, GEO, IRR, PLY, POV, SHP, XGL, ZGL, AC, BLEND, BVH, CSM, LWS X DXF VRML, Three.js	-	Maya Ascii, Maya Binary, MEL, FBX, OBJ, STL Openflight FLT DXF, IGES, StudioTools Wire VRML2

Table 7 Game engines that dominant in the gaming industry.

Game engine	Unity 3D	Unreal	Game Maker Studio 2	CRYENGINE SDK
Developer	Unity	Epic games	Yoyo Game Maker	Crytek
Version/released date	v2019.1.0/2019	2019	2019	2019
Directory (source)	Link	Link	Link	Link
Platform	MS/MAC/LINUX	MS/MAC/LINUX	MS/MAC/LINUX	MS/MAC/LINUX
License	free/paid	free/paid	Proprietary	Proprietary
Application programming interface (API)	C#, Java	C++	C++	C++, Lua, C#
Image, video, and audio import/export	+	+	+	+
Text file import/export	plugin/coding	plugin/coding	plugin/coding	plugin/coding
3D Data import/export	FBX, DAE, 3DS, DXF, and OBJ	FBX, DAE, 3DS, DXF, and OBJ	plugin	CGF, CGA, MA, ATOM, DAE, ZIO, FBX, ABC, CBC and CAX
AR support & SDK	ARKit, ARCore, Vuforia, AR Foundation, Magic Leap, Hololens	ARKit, ARCore, Handheld AR, Magic Leap, Hololens	plugin	PlayFusion
VR support & SDK	Stream VR, OpenVR, vivewave, middle VR, oculus vr, samsung gear	Steam VR, Google VR, Oculus VR, Samsung gear VR, Unreal VR engine	plugin	OSVR
Asset store	https://assetstore.unity.com/	https://www.unrealengine.com/marketplace/en-US/store	https://marketplace.yoyogames.com/	https://www.cryengine.com/marketplace

Table 8 3D data formats and the support of platforms. Filled columns show supported format by each software.

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