Supplementary Document on Occlusion Handling in Augmented Reality: Past, Present and Future

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1 Introduction

In this supplementary document, we provide the data, listed in Tables 1, 2, 3, 4, that we have collected for each selected paper, and that support the generation of the charts shown in the main paper. We have not only collected metadata of each selected paper (*e.g.,* title, authors' list, year and local of publication), but we have also extracted the following attributes of each technique:

- **Environment**: Whether the proposed technique runs indoor or outdoor. Possible values: *Indoor*, *Outdoor*;
- Performance (**Perf.**): Evaluated in terms of frames per second (FPS), we follow the classification proposed by related work [1] and check whether the proposed technique achieves real-time performance (equal or above 30 FPS), interactive frame rate (between 6 and 30 FPS), offline processing time (below 6 FPS) or the performance was not reported by the authors. Possible values: ★★★ (real-time performance), ★★☆ (interactive performance), ★☆☆ (offline performance), *NRA* (not reported by the authors);
- **User study**: Whether the proposed technique was validated with a user study. Possible values: ✓ (Yes), ✗ (No);
- **X-ray vision**: Whether the proposed technique was designed to visualize occluded structures in X-ray vision applications of augmented reality. Possible values: ✓ (Yes), ✗ (No);
- **OST display**: Whether the proposed technique was designed to build occlusion-capable optical see-through (OST) displays. Possible values: ✓ (Yes), ✗ (No);
- **Order estimation**: How the technique handles the order problem of occlusion handling. Possible values: *Exclusive* - Rely on a fixed depth order, do not handling the mutual occlusion problem, *Model-based* - Rely on a feature associated with the real world to solve occlusion, *Depth-based* - Rely on depth maps provided or computed from a hardware setup to solve occlusion;

Moreover, for each aspect of the occlusion problem that was handled by each technique, we have also extracted:

- **Model**: Which feature of the real scene is used to solve the order problem of occlusion handling. Only evaluated for model-based techniques. Possible values: *Phantom*, *Background*, *Marker*, *Color*, *Contour*;
- **Depth technology**: Which hardware technology is used to support the order estimation between real and virtual objects. Only evaluated for depth-based techniques. Possible values: *Stereo vision*, *Multi-view stereo*, *Laser rangefinding*, *Structured light*, *Spherical vision*, *Monocular Structure from Motion (Monocular SfM)*, *NRA*;
- **X-ray vision features**: Which features have been used to support the X-ray vision in an AR application. Only evaluated for X-ray vision techniques. Possible values: **A***lpha blending*, **E***dge*, **V***irtual Window*, **SA***liency*, **P***erspective Line*, **M***otion*, **T***exture*, **D***epth*, **SP***atial Manipulation*, **C***urvature*;
- **OST display approach**: Inspired by the classification proposed by Kiyokawa [2], we report the approach used to provide occlusion handling for OST displays. Only evaluated for techniques that solve the visual display problem for OST displays. Possible values: *Pattern illumination*, *Occluder*, *Spatial light modulator*;

It is worthy to mention that none of the X-ray vision techniques listed in Table 3 also solved the occlusion problem for OST displays. Likewise, none of the OST display-based techniques listed in Table 4 also solved the X-ray vision problem. That is why we did not include those attributes in Tables 3 and 4.

References

[1] T. Akenine-Moller, E. Haines, and N. Hoffman, *Real-Time Rendering, Fourth Edition*, 4th ed. USA: A. K. Peters, Ltd., 2018.
[2] K. Kiyokawa, *Occlusion Displays*. Berlin, Heidelberg: Springer, 2012, pp. 2251–2257.

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TABLE 1
An overview of the model-based techniques reviewed in this study, according to their main properties.

Reference	Model	Environment	Perf.	User study	X-ray vision	OST display
Breen *et al.* (1996)	Phantom	Indoor	★★★	✗	✗	✗
Berger (1997)	Contour	Indoor	NRA	✗	✗	✗
Schumann *et al.* (1998)	Phantom	Indoor	NRA	✗	✗	✗
Ong *et al.* (1998)	Contour	Outdoor	NRA	✗	✗	✗
Fuhrmann *et al.* (1999)	Phantom	Indoor	NRA	✗	✗	✗
Vallino and Brown (1999)	Background	Indoor	NRA	✗	✗	✗
Kanbara *et al.* (1999, 2000)	Color	Indoor	★★★	✗	✗	✗
Lepetit and Berger (2000)	Contour	Indoor & Outdoor	NRA	✗	✗	✗
Kiyokawa *et al.* (2000)	Phantom	Indoor	★★★	✗	✗	✓
Inami *et al.* (2000)	Phantom	Indoor	NRA	✗	✗	✓
Kojima *et al.* (2001)	Color	Indoor	NRA	✗	✗	✗
Bimber and Fröhlich (2002)	Phantom	Indoor	NRA	✗	✗	✓
Malik *et al.* (2002)	Marker	Indoor	★★★	✗	✗	✗
Walairacht *et al.* (2002)	Phantom & Background	Indoor	★★★	✗	✗	✗
Ohta *et al.* (2002)	Phantom	Indoor	★★★	✗	✗	✗
Hua *et al.* (2002)	Phantom	Indoor	NRA	✗	✗	✓
McDonald and Roth (2003)	Marker	Indoor	★★★	✗	✗	✗
Fischer *et al.* (2003)	Marker	Indoor	★★★	✗	✗	✗
Klein and Drummond (2004)	Phantom	Indoor	★★★	✗	✗	✗
Lee *et al.* (2004)	Marker	Indoor	★★★	✓	✗	✗
Fischer *et al.* (2004)	Phantom	Indoor	★★★	✗	✗	✗
Lee and Park (2005)	Color	Indoor	★★★	✗	✗	✗
Wang *et al.* (2005)	Background	Indoor	★★★	✗	✗	✗
Fortin and Hébert (2006)	Background	Indoor	★★★	✗	✗	✗
Bichlmeier *et al.* (2007)	Phantom	Indoor	NRA	✗	✓	✗
Gay-Bellile *et al.* (2007)	Marker	Indoor	★★★	✗	✗	✗
Pilet *et al.* (2007)	Marker	Indoor	★★★	✗	✗	✗
Kutter *et al.* (2008)	Color	Indoor	★★★	✗	✓	✗
Pilet *et al.* (2008)	Background	Indoor	★★★	✗	✗	✗
Murase *et al.* (2008)	Phantom & Background	Indoor	★★★	✓	✗	✓
Ventura and Höllerer (2008)	Color	Indoor	NRA	✗	✗	✗
Zhu *et al.* (2008, 2010)	Background	Indoor	NRA	✗	✗	✗
Kakuta *et al.* (2008)	Background	Outdoor	★★★	✗	✗	✗
Kurz *et al.* (2008)	Phantom	Indoor	NRA	✗	✗	✓
Ventura and Höllerer (2009)	Background	Indoor	★★★	✗	✗	✗
Ladikos and Navab (2009)	Background	Indoor	★★★	✗	✗	✗
Tian *et al.* (2010)	Contour	Indoor	★★★	✗	✗	✗
Kim *et al.* (2010)	Phantom	Indoor	★★★	✗	✗	✗
Santos *et al.* (2012)	Phantom	Indoor	NRA	✗	✗	✗
Cordes *et al.* (2012)	Background	Outdoor	NRA	✗	✗	✗
Zollmann and Reitmayr (2012)	Phantom	Outdoor	NRA	✗	✗	✗
Sanches *et al.* (2012)	Marker	Indoor	NRA	✗	✗	✗
Abate *et al.* (2014)	Color	Indoor	★★★	✗	✗	✗
Garrido-Jurado *et al.* (2014)	Marker	Indoor	★★★	✗	✗	✗
Fujimoto *et al.* (2015)	Marker	Indoor	★★★	✗	✗	✗
Narita *et al.* (2015, 2017)	Marker	Indoor	★★★	✗	✗	✗
Zhou *et al.* (2016)	Phantom	Indoor	NRA	✗	✗	✗
Frikha *et al.* (2016)	Phantom & Background	Indoor	★★★	✗	✗	✗
Kasperi *et al.* (2017)	Phantom	Outdoor	★★★	✓	✗	✗
Avveduto *et al.* (2017)	Phantom	Indoor	★★★	✓	✗	✓
Wu and Popescu (2018)	Phantom	Indoor	NRA	✓	✓	✗
Gimeno *et al.* (2018)	Phantom	Indoor	★★★	✗	✗	✗
Battisti *et al.* (2018)	Phantom & Color	Indoor	NRA	✗	✗	✗
Feng *et al.* (2018)	Phantom	Indoor	NRA	✓	✗	✗
Tang *et al.* (2019)	Color	Indoor	★★★	✓	✗	✗
Kilimann *et al.* (2019)	Background	Outdoor	★★★	✗	✗	✗

TABLE 2
An overview of the depth-based techniques reviewed in this study, according to their main properties.

Reference	Depth technology	Environment	Perf.	User study	X-ray vision	OST display
Wloka and Anderson (1995)	Stereo vision	Indoor	★☆☆	✗	✗	✗
Breen *et al.* (1996)	Stereo vision	Indoor	★★☆	✗	✗	✗
State *et al.* (1996)	Laser rangefinding	Indoor	★★☆	✗	✓	✗
Kanbara *et al.* (1999, 2000)	Stereo vision	Indoor	★★☆	✗	✗	✗
Duchesne and Hervé (2000)	Stereo vision	Indoor	NRA	✗	✗	✗
Kiyokawa *et al.* (2001, 2003)	Multi-view stereo	Indoor	★★☆	✓	✗	✓
Kojima *et al.* (2001)	Stereo vision	Indoor	NRA	✗	✗	✗
Ohta *et al.* (2002)	Multi-view stereo & Laser rangefinding	Indoor	★★☆	✗	✗	✗
Schmidt *et al.* (2002)	Stereo vision	Indoor	★★☆	✗	✗	✗
Kim *et al.* (2003)	Stereo vision	Indoor	★★☆	✗	✗	✗
Mulder (2005, 2006)	Multi-view stereo	Indoor	★★☆	✗	✗	✓
Hayashi *et al.* (2005)	Stereo vision	Indoor	★★☆	✗	✗	✗
Fortin and Hébert (2006)	Stereo vision	Indoor	★★☆	✗	✗	✗
Zhou *et al.* (2007)	Stereo vision	Indoor	NRA	✗	✗	✓
Fischer *et al.* (2007)	Laser rangefinding	Indoor	NRA	✗	✗	✗
Li *et al.* (2007)	Stereo vision	Indoor	★★☆	✗	✗	✗
Bartczak *et al.* (2008)	Laser rangefinding	Indoor	★★☆	✗	✗	✗
Wither *et al.* (2008)	Laser rangefinding	Outdoor	★★☆	✗	✗	✗
Ventura and Höllerer (2008)	Stereo vision	Indoor	NRA	✗	✗	✗
Zhu *et al.* (2008, 2010)	Stereo vision	Indoor	NRA	✗	✗	✗
Kakuta *et al.* (2008)	Spherical vision	Outdoor	★☆☆	✗	✗	✗
Hahne and Alexa *et al.* (2009)	Laser rangefinding & Stereo vision	Indoor	★★☆	✗	✗	✗
Koch *et al.* (2009)	Laser rangefinding	Indoor	★★☆	✗	✗	✗
Ladikos and Navab (2009)	Multi-view stereo	Indoor	★★☆	✗	✗	✗
Newcombe and Davidson (2010)	Monocular SfM	Indoor	NRA	✗	✗	✗
Lu *et al.* (2010)	Spherical vision	Outdoor	★☆☆	✗	✗	✗
Ikeuchi *et al.* (2010)	Spherical vision	Outdoor	★☆☆	✗	✗	✗
Newcombe *et al.* (2011)	Structured light	Indoor	★★☆	✗	✗	✗
Izadi *et al.* (2011)	Structured light	Indoor	★★☆	✗	✗	✗
Gimeno *et al.* (2012)	Structured light	Indoor	★★☆	✓	✗	✗
Corbett-Davies *et al.* (2012, 2013)	Structured light	Indoor	★★☆	✓	✗	✗
Yii *et al.* (2012)	Structured light	Indoor	★★☆	✗	✗	✗
Santos *et al.* (2012)	Structured light	Indoor	NRA	✗	✗	✗
Leal-Meléndrez *et al.* (2013)	Structured light	Indoor	★★☆	✗	✗	✗
Seo and Lee (2013)	Structured light	Indoor	NRA	✓	✗	✗
Maimone *et al.* (2013)	Structured light	Indoor	★★☆	✗	✗	✓
Abate *et al.* (2014)	Stereo vision	Indoor	★★☆	✗	✗	✗
Macedo and Apolinário (2014, 2015)	Structured light	Indoor	★★☆	✗	✓	✗
Schöps *et al.* (2014)	Monocular SfM	Indoor	★★☆	✗	✗	✗
Ha *et al.* (2014)	Structured light	Indoor	★★☆	✓	✗	✗
Zhou *et al.* (2016)	Laser rangefinding	Indoor	NRA	✗	✗	✗
Du *et al.* (2016)	Structured light	Indoor	★★☆	✗	✗	✗
Hebborn *et al.* (2017)	NRA	Indoor	★★☆	✗	✗	✗
Wilson and Hua (2017)	NRA	Indoor	NRA	✗	✗	✓
Walton and Steed (2017)	Structured light	Indoor	★★☆	✗	✗	✗
Wu and Popescu (2018)	NRA	Indoor	NRA	✓	✓	✗
Wang *et al.* (2018)	Monocular SfM	Indoor	★★☆	✗	✗	✗
Battisti *et al.* (2018)	Stereo vision	Indoor	NRA	✗	✗	✗
Valentin *et al.* (2018)	Monocular SfM	Indoor & Outdoor	★★☆	✗	✗	✗
Holynski and Kopf (2018)	Monocular SfM	Indoor & Outdoor	★★☆	✗	✗	✗
Roxas *et al.* (2018)	Spherical vision	Outdoor	★☆☆	✓	✓	✗
Feng *et al.* (2018)	Stereo vision	Indoor	NRA	✓	✗	✗
Yang *et al.* (2020)	Structured light & Stereo vision	Indoor	★★☆	✓	✗	✗
Luo *et al.* (2020)	Monocular SfM	Indoor & Outdoor	★☆☆	✗	✗	✗

TABLE 3
An overview of the X-ray vision techniques reviewed in this study, according to their main properties.

Reference	X-ray vision features	Environment	Perf.	User study	Order estimation
Bajura *et al.* (1992)	V	Indoor	★☆☆	✗	Exclusive
Feiner *et al.* (1993)	A, E	Indoor	★☆☆	✗	Exclusive
State *et al.* (1994)	V	Indoor	★☆☆	✗	Exclusive
Webster *et al.* (1996)	A, E, V	Indoor	NRA	✗	Exclusive
State *et al.* (1996)	V	Indoor	★☆☆	✗	Depth-based
Furmanski *et al.* (2002)	V, P	Indoor	NRA	✓	Exclusive
Livingston *et al.* (2003)	A, E	Outdoor	NRA	✓	Exclusive
Bane and Höllerer (2004)	E, V, P	Outdoor	NRA	✗	Exclusive
Kameda *et al.* (2004)	A	Outdoor	NRA	✗	Exclusive
Tsuda *et al.* (2005)	A, E, P	Outdoor	NRA	✓	Exclusive
Bichlmeier and Navab (2006)	V	Indoor	★☆☆	✗	Exclusive
Sielhorst *et al.* (2006)	V	Indoor	★☆☆	✓	Exclusive
Mendez *et al.* (2006)	V	Indoor	NRA	✗	Exclusive
Bichlmeier *et al.* (2007)	V	Indoor	NRA	✗	Exclusive
Bichlmeier *et al.* (2007)	A, V, C	Indoor	NRA	✗	Model-based
Kalkofen *et al.* (2007, 2009)	E, V	Indoor	★☆☆	✗	Exclusive
Avery *et al.* (2007)	V	Outdoor	NRA	✗	Exclusive
Lerotic *et al.* (2007)	A, V, C	Indoor	NRA	✓	Exclusive
Kutter *et al.* (2008)	A, V	Indoor	★☆☆	✗	Model-based
Avery *et al.* (2008)	A, V, P	Outdoor	★☆☆	✓	Exclusive
Bichlmeier *et al.* (2009)	A, E, V	Indoor	NRA	✓	Exclusive
Barnum *et al.* (2009)	A, E, V	Indoor & Outdoor	★☆☆	✗	Exclusive
Sandor *et al.* (2009, 2010)	P, SP	Outdoor	★☆☆	✓	Exclusive
Avery *et al.* (2009)	A, E, V	Outdoor	NRA	✗	Exclusive
Kalkofen *et al.* (2009)	SP	Indoor	NRA	✗	Exclusive
Mendez and Schmalstieg (2009)	A, SA	Indoor	★☆☆	✗	Exclusive
Hansen *et al.* (2010)	A, E, D	Indoor	NRA	✓	Exclusive
Sandor *et al.* (2010)	A, E, SA, M	Outdoor	NRA	✓	Exclusive
Zollmann *et al.* (2010)	A, E, SA, T	Outdoor	NRA	✗	Exclusive
Dey *et al.* (2010, 2014)	A, E, V, P	Outdoor	NRA	✓	Exclusive
Chen *et al.* (2010)	A, E, M	Outdoor	★☆☆	✗	Exclusive
Dey *et al.* (2011)	A, E, SA, M	Outdoor	NRA	✓	Exclusive
Fukiage *et al.* (2012)	A	Outdoor	★☆☆	✗	Exclusive
Santos *et al.* (2013)	A, E, SA, M	Indoor	NRA	✓	Exclusive
Kalkofen *et al.* (2013)	A, E, SA, C	Indoor	NRA	✓	Exclusive
Macedo and Apolinário (2014, 2015)	A	Indoor	★☆☆	✗	Depth-based
Padilha and Teichrieb (2014, 2015)	A, E, SA, M, T	Indoor & Outdoor	★☆☆	✓	Exclusive
Zollmann *et al.* (2014)	A, E, SA, T	Outdoor	NRA	✓	Exclusive
Kersten-Oertel *et al.* (2015)	A, E, V	Indoor	NRA	✓	Exclusive
Marques *et al.* (2015)	A, D	Indoor	★☆☆	✗	Exclusive
Wang *et al.* (2016)	A, E, D	Indoor	NRA	✗	Exclusive
Maia *et al.* (2016)	A, E, V	Outdoor	★☆☆	✓	Exclusive
Özgür *et al.* (2017)	A, E, V	Indoor	★☆☆	✓	Exclusive
Wu and Popescu (2018)	SP	Indoor	NRA	✓	Model- & Depth-based
Eren and Balcisoy (2018)	A, E, V	Indoor & Outdoor	NRA	✓	Exclusive
Roxas *et al.* (2018)	A, SA, D	Outdoor	★☆☆	✓	Depth-based

TABLE 4
An overview of the techniques reviewed in this study that proposed occlusion-capable OST displays, according to their main properties.

Reference	OST display approach	Environment	Perf.	User study	Order estimation
Kiyokawa *et al.* (2000)	Spatial light modulator	Indoor	★★★	✗	Model-based
Inami *et al.* (2000)	Occluder	Indoor	NRA	✗	Model-based
Kiyokawa *et al.* (2001)	Spatial light modulator	Indoor	NRA	✗	Depth-based
Bimber and Fröhlich (2002)	Pattern illumination	Indoor	NRA	✗	Model-based
Hua *et al.* (2002)	Occluder	Indoor	NRA	✗	Model-based
Kiyokawa *et al.* (2003)	Spatial light modulator	Indoor	★★★	✓	Depth-based
Cakmakci *et al.* (2004, 2005)	Spatial light modulator	Indoor	NRA	✗	Exclusive
Mulder (2005, 2006)	Spatial light modulator	Indoor	★★★	✗	Depth-based
Zhou *et al.* (2007)	Spatial light modulator	Indoor	NRA	✗	Depth-based
Murase *et al.* (2008)	Pattern illumination	Indoor	★★★	✓	Model-based
Kurz *et al.* (2008)	Pattern illumination	Indoor	NRA	✗	Model-based
Gao *et al.* (2012, 2013)	Spatial light modulator	Indoor	NRA	✗	Exclusive
Maimone and Fuchs (2013)	Spatial light modulator	Indoor	★★★	✗	Exclusive
Maimone *et al.* (2013)	Pattern illumination	Indoor	★★★	✗	Depth-based
Kakeya *et al.* (2014)	Pattern illumination	Indoor	NRA	✗	Exclusive
Smithwick *et al.* (2014)	Pattern illumination	Indoor	NRA	✗	Exclusive
Yamaguchi and Takaki (2016)	Spatial light modulator	Indoor	NRA	✗	Exclusive
Howlett and Smithwick (2017)	Spatial light modulator	Indoor	NRA	✗	Exclusive
Wilson and Hua (2017)	Spatial light modulator	Indoor	NRA	✗	Depth-based
Itoh *et al.* (2017)	Spatial light modulator	Indoor	NRA	✓	Exclusive
Avveduto *et al.* (2017)	Pattern illumination	Indoor	★★★	✓	Model-based
Hamasaki and Itoh (2019)	Spatial light modulator	Indoor	NRA	✗	Exclusive
Rathinavel *et al.* (2019)	Spatial light modulator	Indoor	NRA	✗	Exclusive
Krajancich *et al.* (2020)	Spatial light modulator	Indoor	★★★	✗	Exclusive
Ju *et al.* (2020)	Spatial light modulator	Indoor	★★★	✗	Exclusive