Inter-View Depth Consistency Testing in Depth Difference Subspace

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Reading Group Meeting
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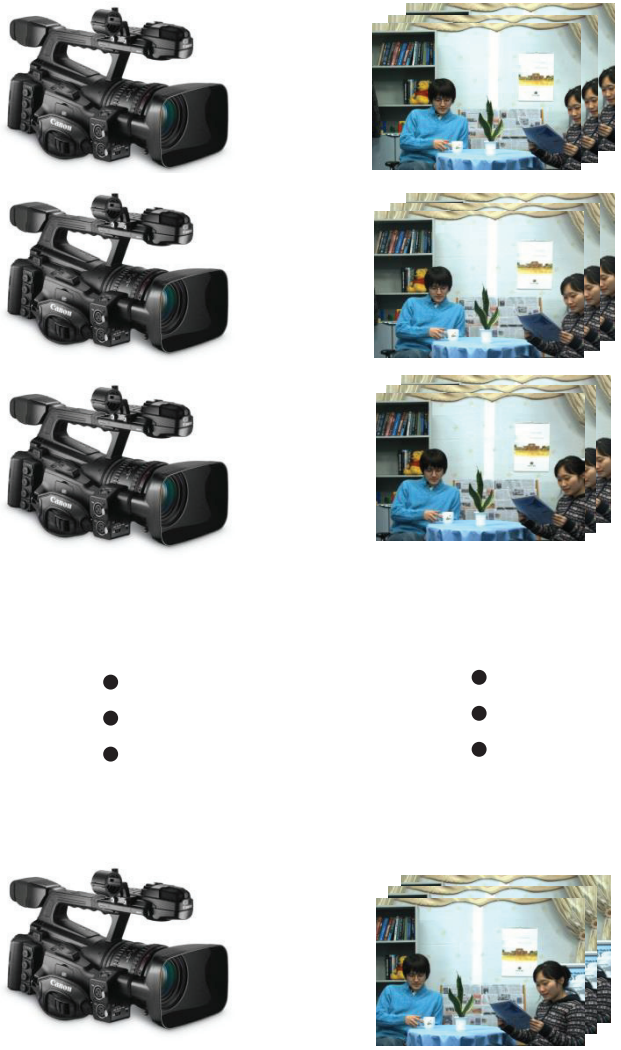
Background and motivation

Free-viewpoint television

User

Display

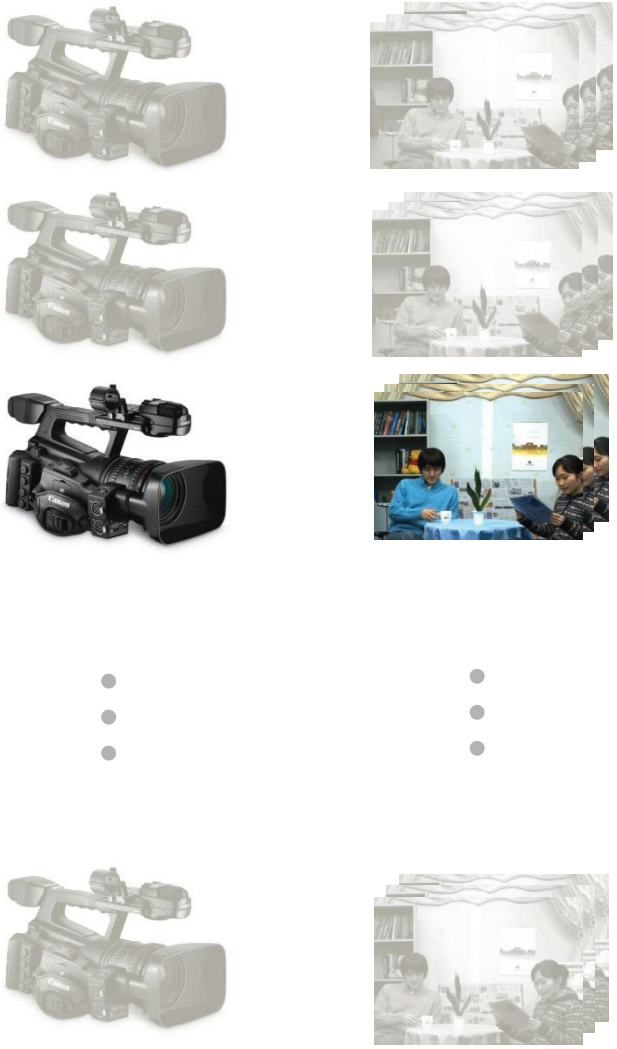


Multiview video imagery

Free-viewpoint television

User

Display

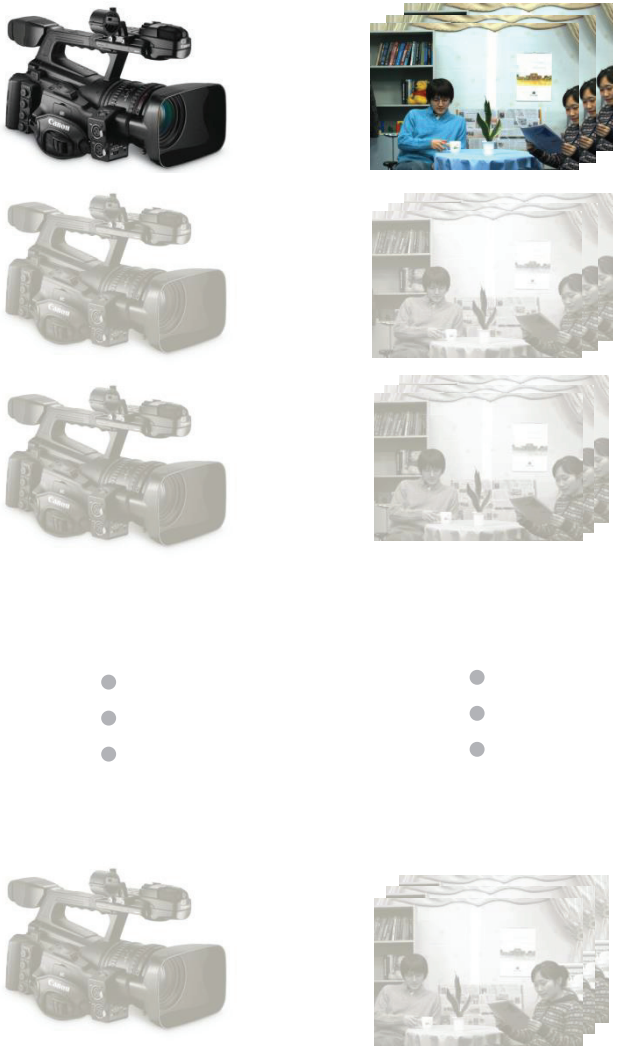


Multiview video imagery

Free-viewpoint television

User

Display

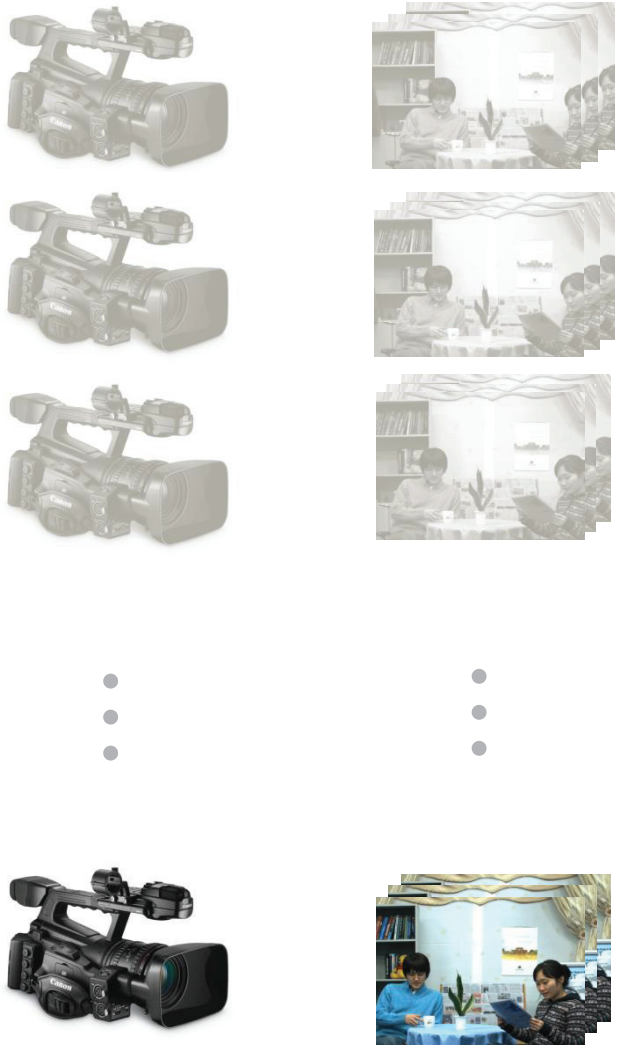


Multiview video imagery

Free-viewpoint television

User

Display



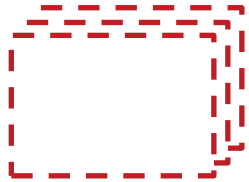
Multiview video imagery

Free-viewpoint television

User

Display

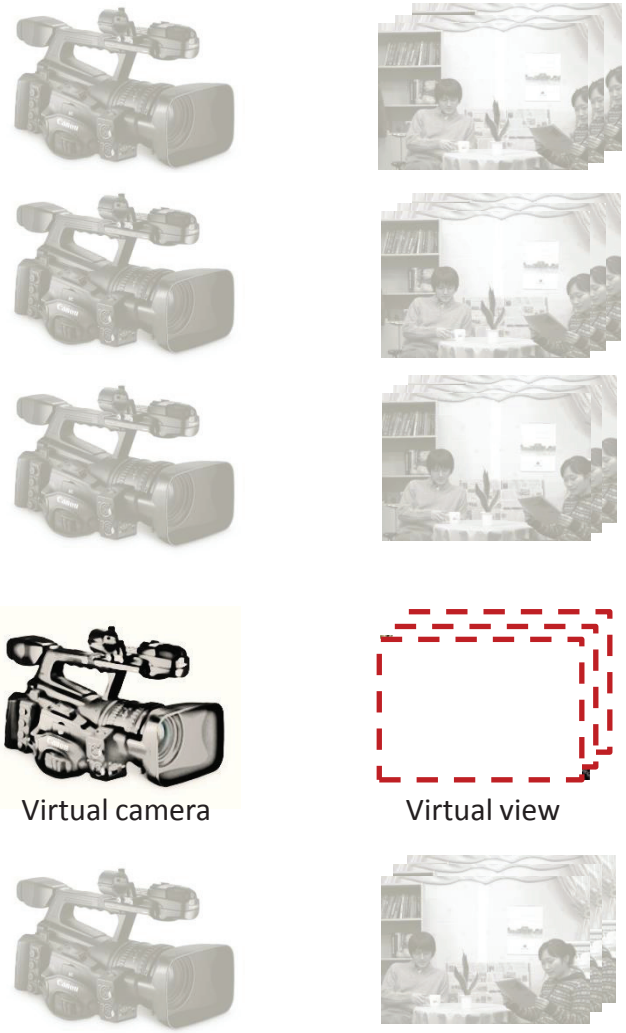
Virtual camera



Virtual view

Multiview video imagery

Depth image based rendering

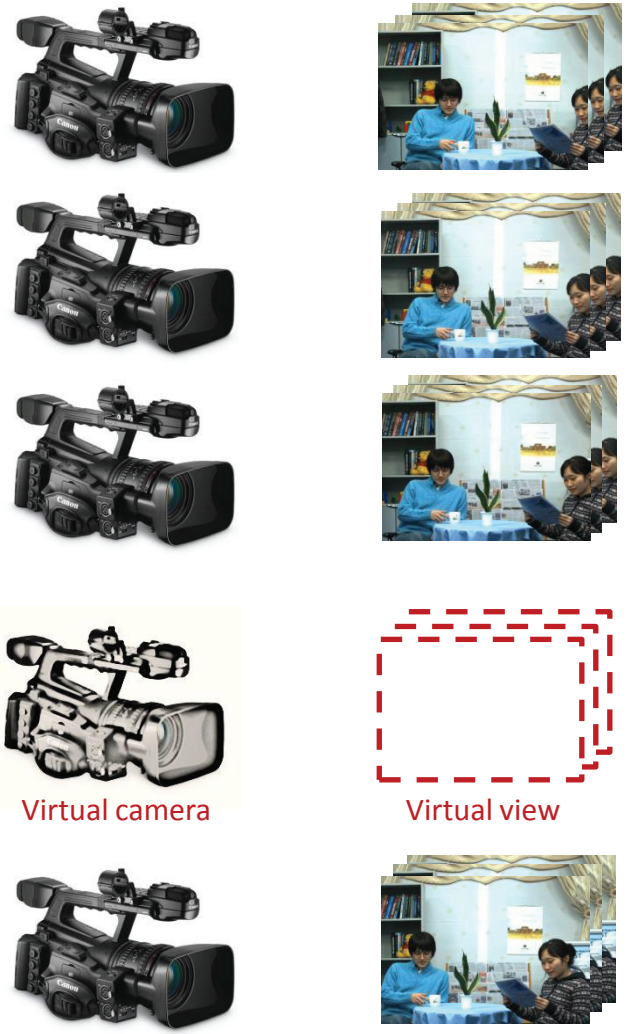


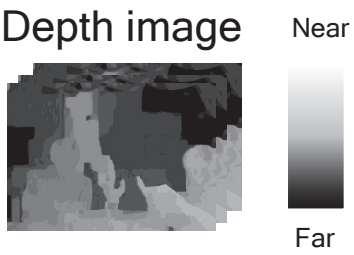
Virtual camera

Virtual view

Multiview video imagery

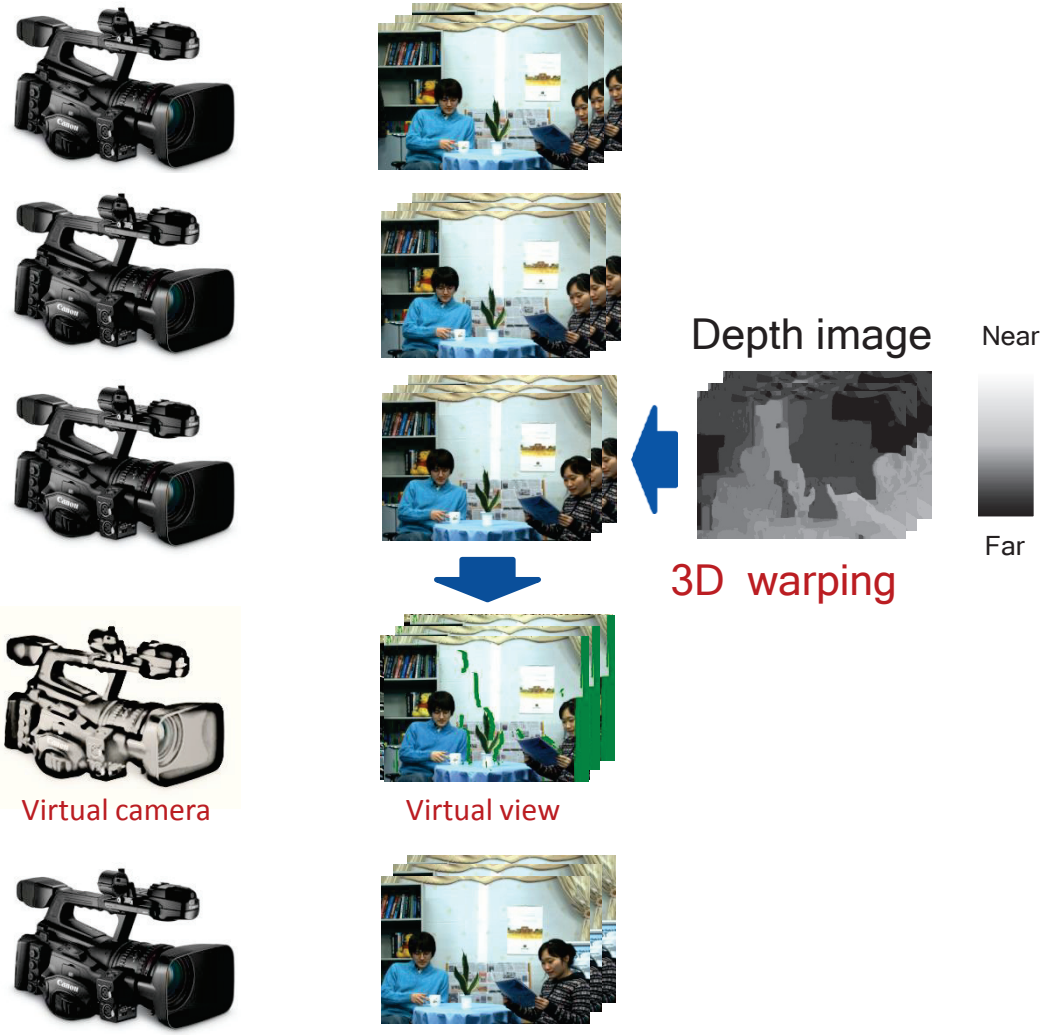
Depth image based rendering





- Depth pixels represent shortest distance between object points and the camera plane
- To be estimated from multiview imagery

Depth image based rendering

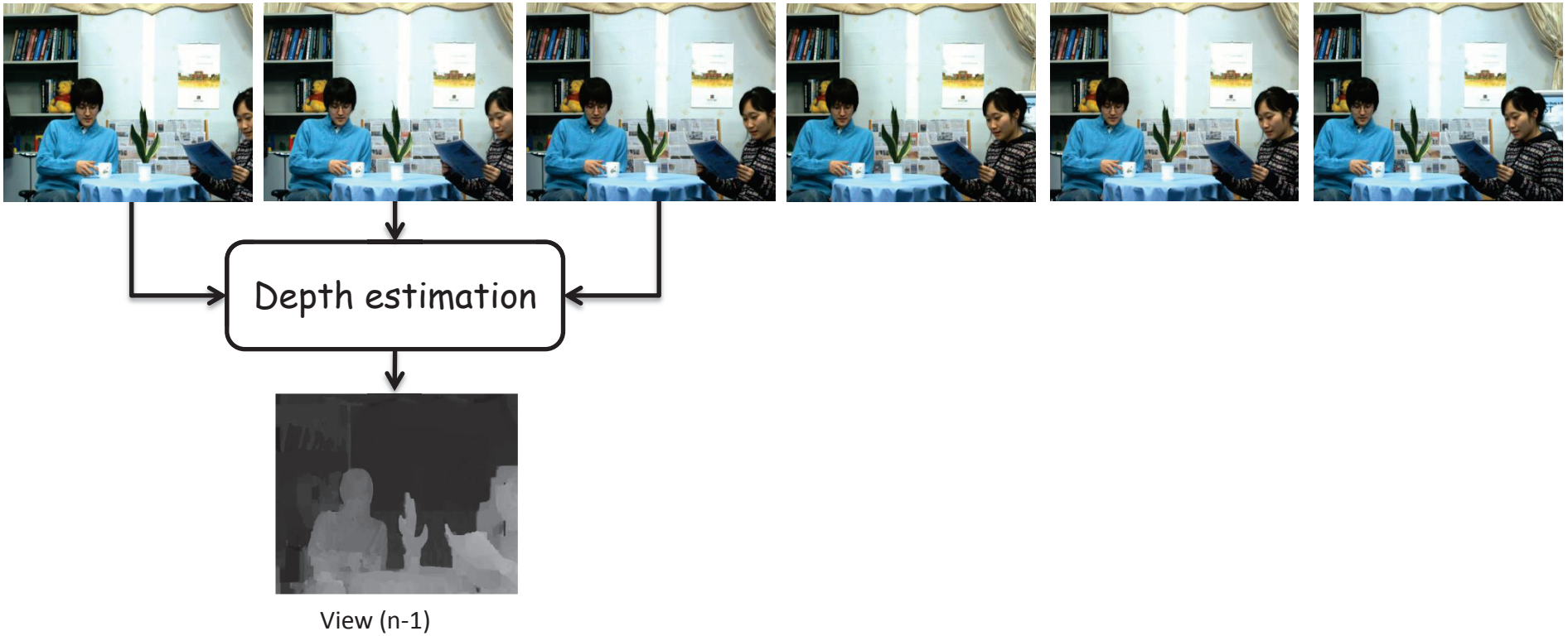


- Depth pixels represent shortest distance between object points and the camera plane
- To be estimated from multiview imagery

Depth estimation

MPEG Depth Estimation Reference Software

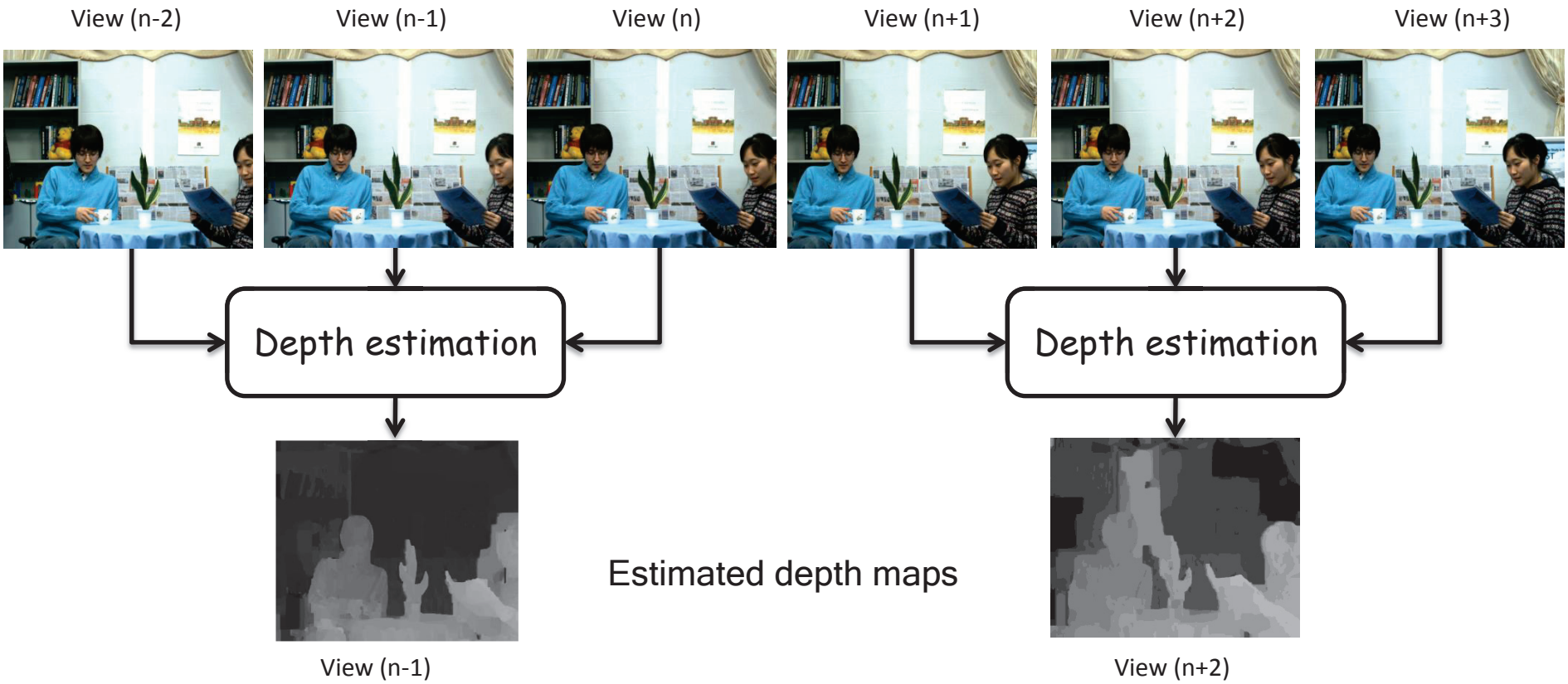
View (n-2) View (n-1) View (n) View (n+1) View (n+2) View (n+3)



Note: we assume a 1D-parallel camera arrangement

Depth estimation

MPEG Depth Estimation Reference Software



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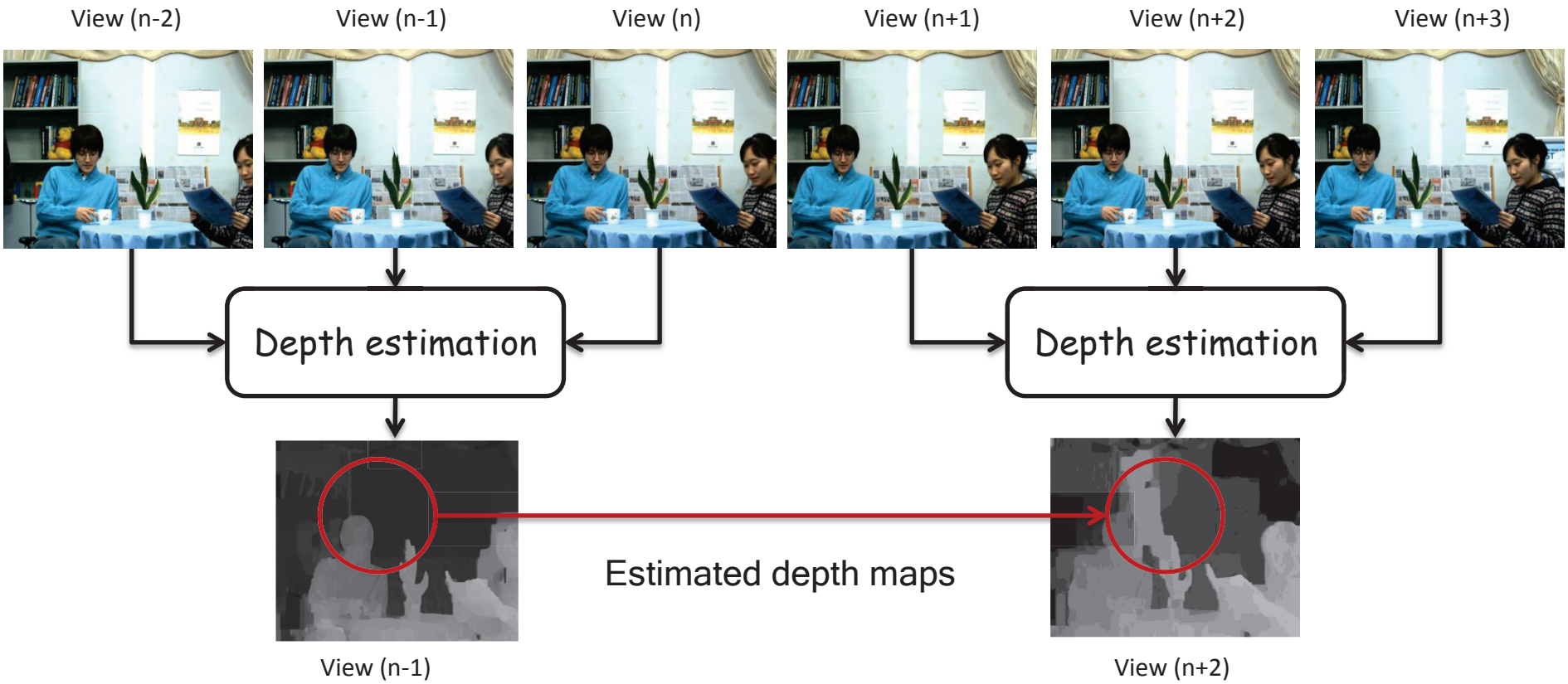
Depth estimation

MPEG Depth Estimation Reference Software



Problem: Inter-view depth inconsistency

Note: we assume a 1D-parallel camera arrangement

Inter-view Depth Consistency Testing

Overview

- Inter-view depth consistency testing
- Applications
- Experimental results

Overview of Inter-view Depth Consistency Testing

- Multiple depth hypotheses
- Consistency analysis
- Testing in depth difference subspace

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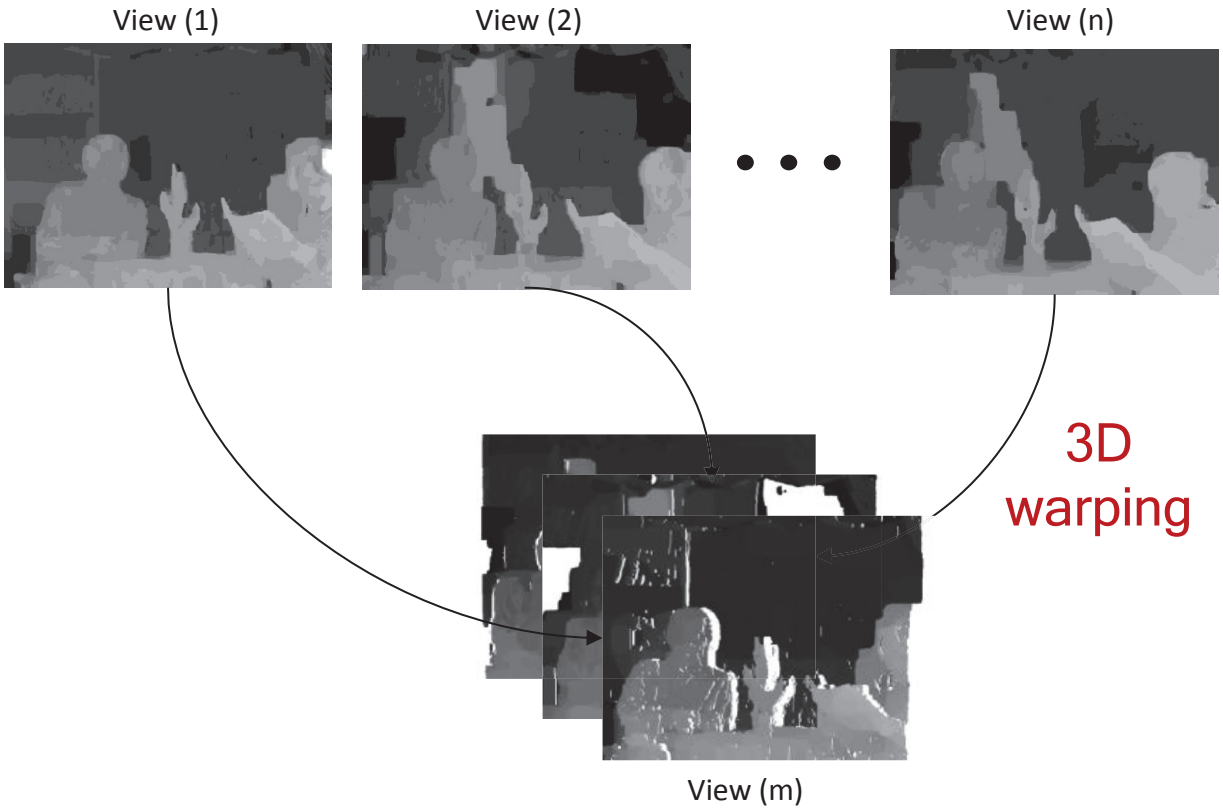
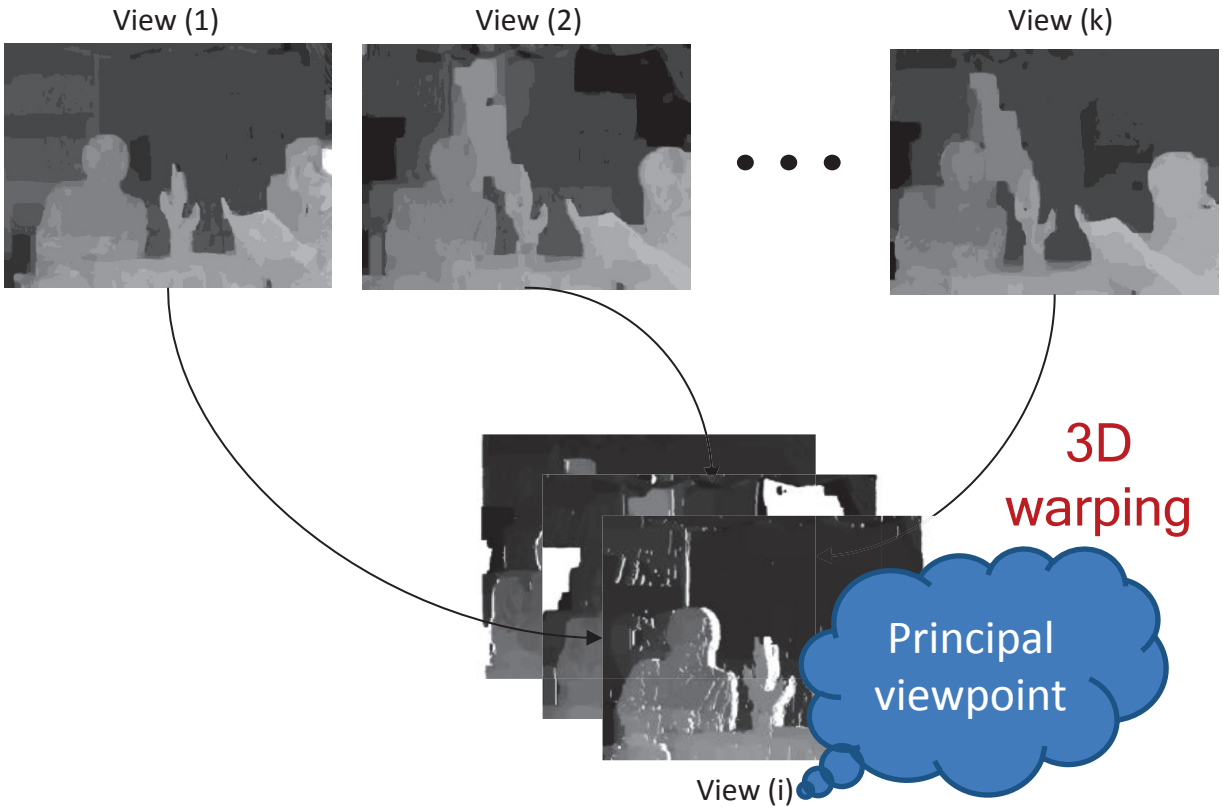
Multiple depth hypotheses



Spatial alignment

[1] P. K. Rana and M. Flierl, "Depth consistency testing for improved view interpolation," IEEE Int. Workshop MMSP, 2010.

Multiple depth hypotheses



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[1] P. K. Rana and M. Flierl, "Depth consistency testing for improved view interpolation," IEEE Int. Workshop MMSP, 2010.

Overview of Inter-view Depth Consistency Testing

- Multiple depth hypotheses
- Consistency analysis
- Testing in depth difference subspace

Consistency Analysis

- At every principal pixel, define a closed loop difference vector

$$\Delta = [\Delta_{12}, \Delta_{23}, \ldots, \Delta_{k1}]^T,$$

where, $\Delta_{ij} = [\hat{d}_i - \hat{d}_j]$ is the *depth inter-view inconsistency evidence*

- Each loop difference vector satisfies zero-sum constraint: $1^T \Delta = 0$
- Elements of a loop difference vector are linearly dependent, and hence, are highly correlated
- Represent the loop difference vector in such a way that its elements are uncorrelated, and that most of energy is concentrated in a low-dimensional subspace

[1] P. K. Rana and M. Flierl, "Depth consistency testing for improved view interpolation," IEEE Int. Workshop MMSP, 2010.

Consistency Analysis

- Linear orthonormal transform

$$\hat{\Delta} = U^T \Delta$$

where $\hat{\Delta} = [\hat{\Delta}_{12}, \hat{\Delta}_{23}, \ldots, \hat{\Delta}_{k1}]^T$ is the transformed loop difference vector in the open loop space

- As the covariance matrix is a symmetric matrix, the spectral theorem holds and there exists an orthonormal basis consisting of eigenvectors of the covariance matrix.

- The loop difference vector can be modeled by a k-dimensional random vector with zero mean and covariance matrix $C_{\Delta\Delta}$

- Assume a wide-sense stationary k-variate normal distribution with covariance matrix $C_{\Delta\Delta}$ and zero mean.
  - the variance is the same for all k elements of the loop difference vector.

- As our method gives no preferences among the individual depth hypotheses in defining the loop difference vector.

Consistency Analysis

- Covariance matrix of a loop difference vector

$$C_{\Delta\Delta} = \sigma^2 \begin{pmatrix} 1 & \rho & \cdots & \rho \\ \rho & 1 & \cdots & \rho \\ \vdots & \vdots & \ddots & \vdots \\ \rho & \rho & \cdots & 1 \end{pmatrix}$$

- By setting the characteristic polynomial of $C_{\Delta\Delta}$ equal to zero

$$p(\lambda) = \det(C_{\Delta\Delta} - \lambda I) = 0$$

- This give following eigenvalues for $C_{\Delta\Delta}$:

$$\lambda_1 = \sigma^2(1 + (k-1)\rho)$$
$$\lambda_2 = \sigma^2(1 - \rho)$$

where λ_1 is a non-degenerate eigenvalue and λ_2 is a (k −1)-fold degenerate eigenvalue

$$\lambda_1 : u_1 = \frac{1}{\sqrt{k}}[1 \quad \cdots \quad 1]^T$$
$$\lambda_2 : 1^T u_l = 0$$

Consistency Analysis

- Difference subspace energy:

$$E_k(\Delta) = \sum_{l=1}^{k} \lambda_l$$

- Zero error event: the depth value for a visible world point across all viewpoints are perfectly consistent

$$E_k(\Delta) = 0$$
$$\Delta_o = [0 \quad \cdots \quad 0]^T$$

- Non-zero error event:

$$E_k(\Delta) > 0$$

  - Reflects inconsistency in the estimated depth values at across multiple viewpoints.
  - the difference subspace energy is directly related to the quality of inconsistency across multiple viewpoints.

Overview of Inter-view Depth Consistency Testing

- Multiple depth hypotheses
- Consistency analysis
- Testing in depth difference subspace

Testing in Depth Difference Subspace

- Inter-view consistency information:
  - It is a binary information which specifies whether k-depth hypotheses at any principal pixel are consistent or inconsistent
  - The inter-view consistency information is obtain by checking the corresponding difference subspace energy

- Inter-view consistency threshold:

$$I_k = \begin{cases} 1 & if\, E_k(\Delta) < \vartheta \\ 0 & otherwise \end{cases}$$

  - *inter-view consistency threshold* (ϑ) is defined as the energy of a subspace in which all the available depth hypotheses at a principal pixel have the desired quality of interview consistency

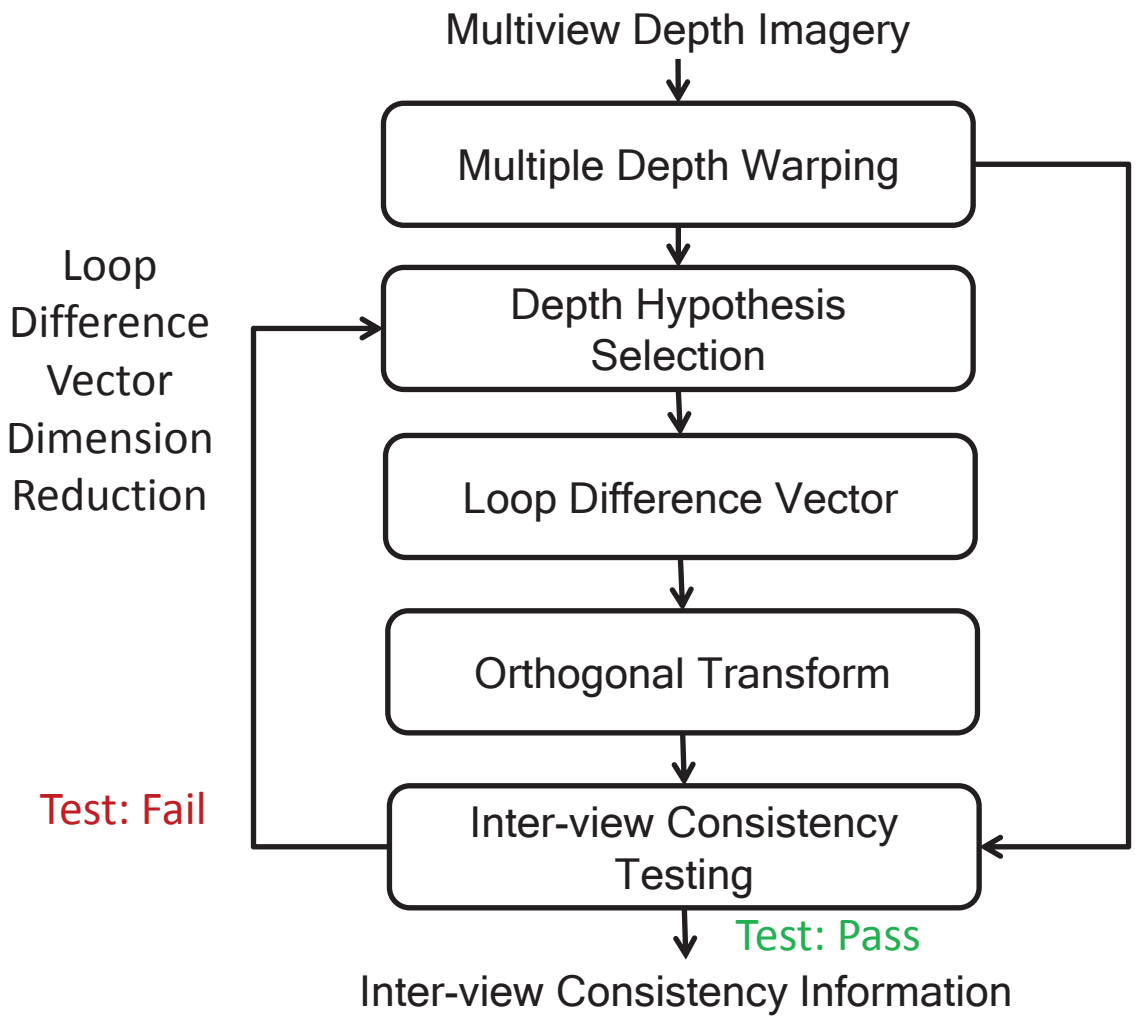
- Single error event: It is a basic error event when only one depth hypothesis out of all available depth hypotheses is erroneous

$$\Delta_| = [0, \cdots, \mu, -\mu, \cdots, 0]^T$$

$$E_k(\Delta_|) = 2\mu = \sigma\sqrt{\frac{k}{k-1}}$$ (In experiments)

$$\vartheta = E_k(\Delta_|)$$

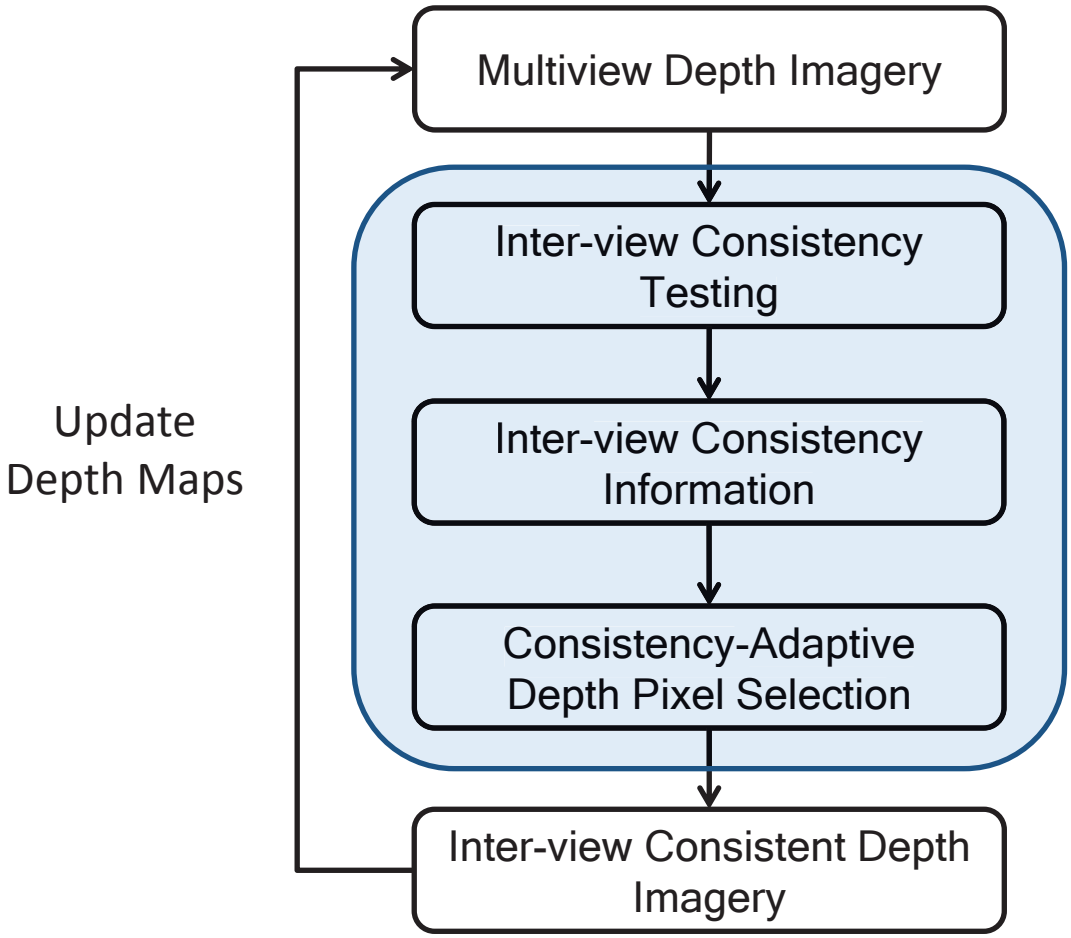
Testing in Depth Difference Subspace



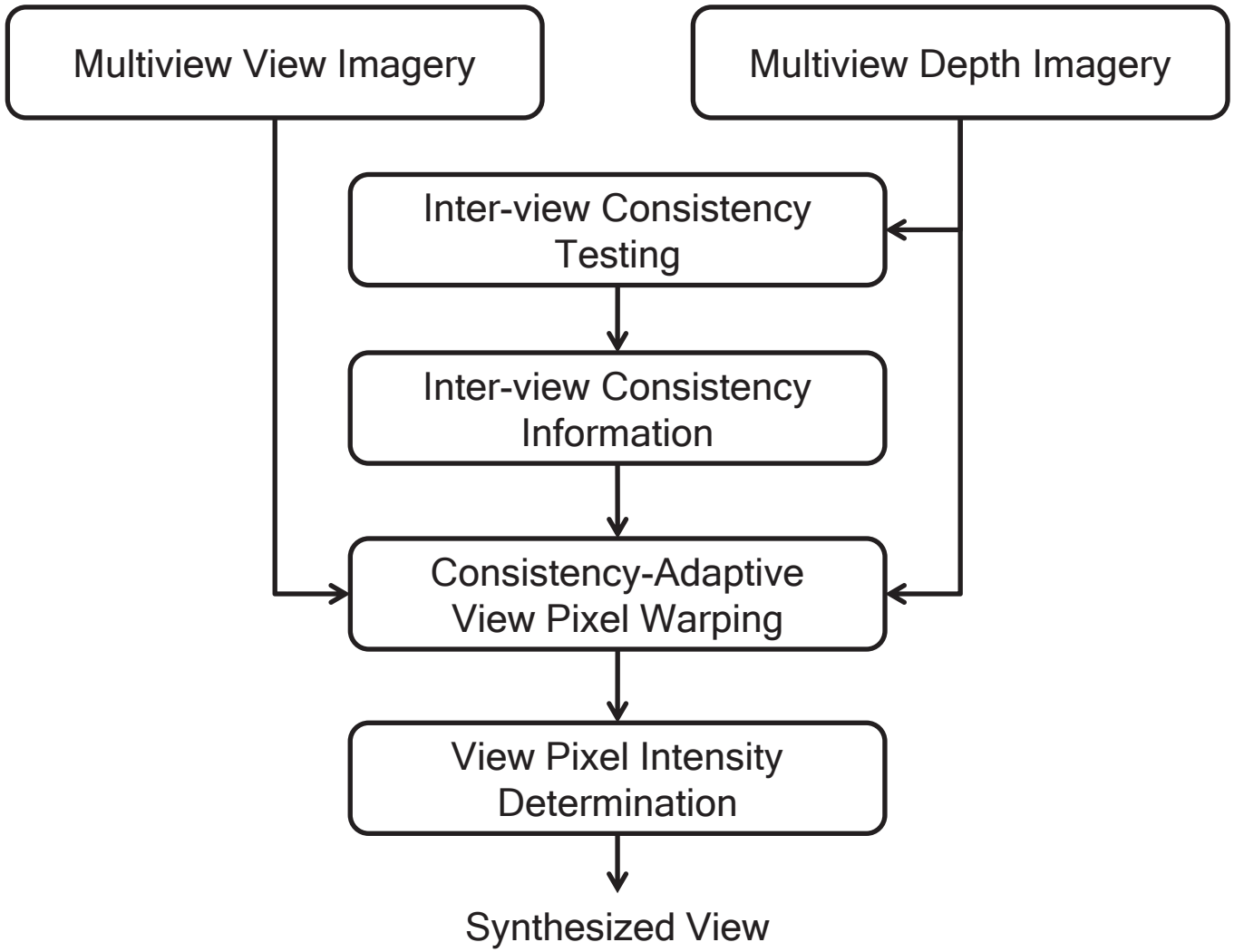
Applications:

- Iterative Inter-view depth enhancement
- Consistency-adaptive view synthesis

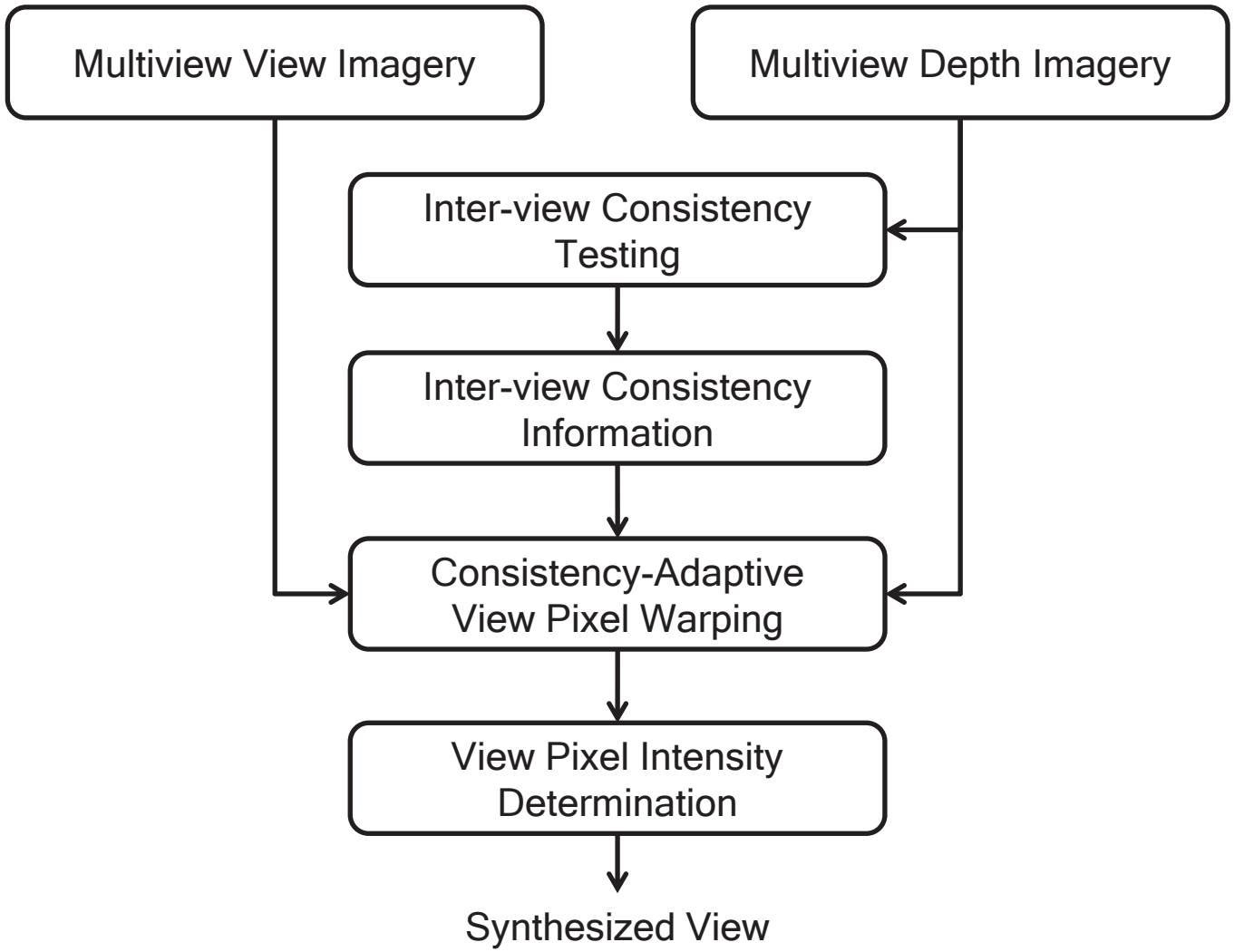
Iterative Inter-view depth enhancement



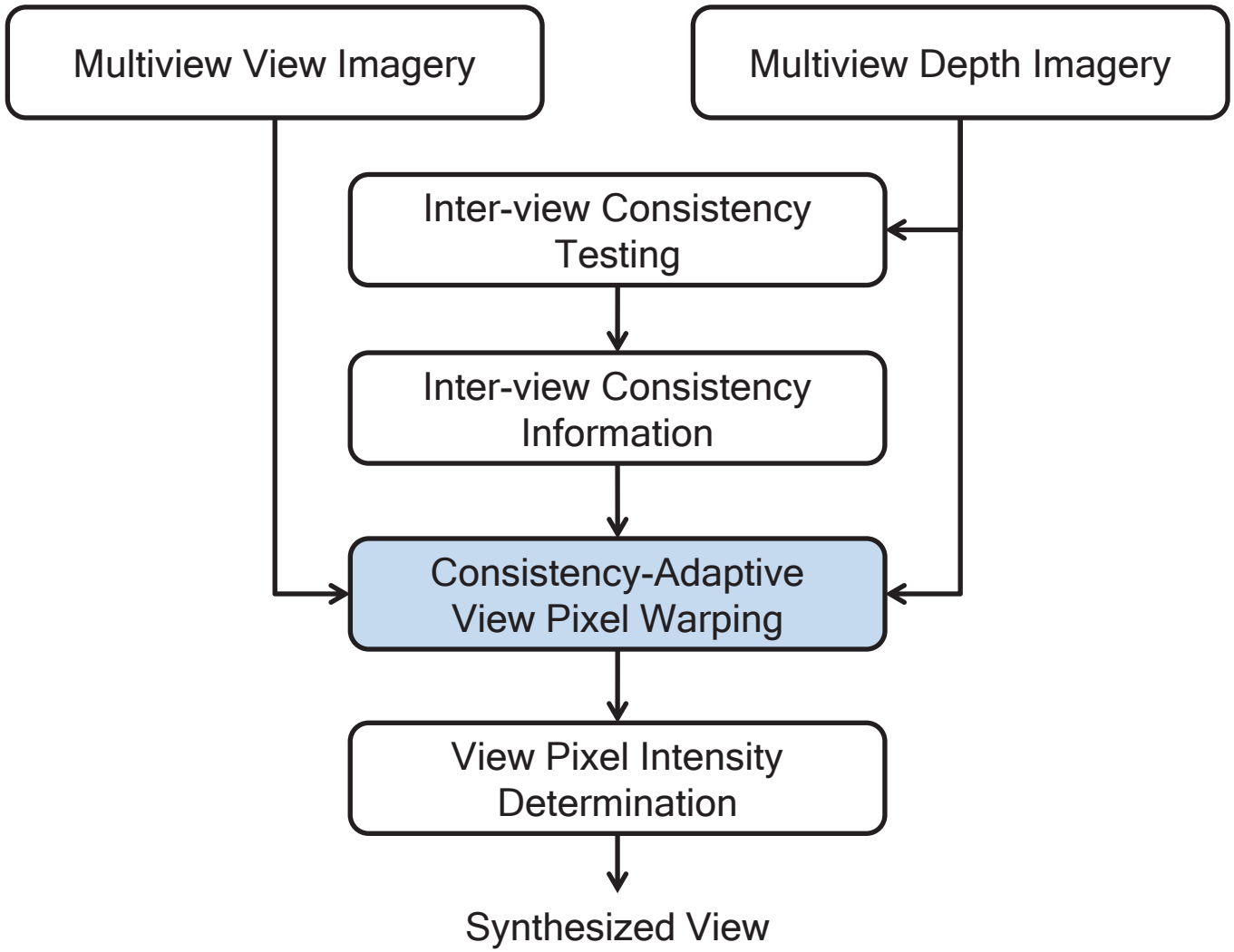
Consistency-adaptive view synthesis



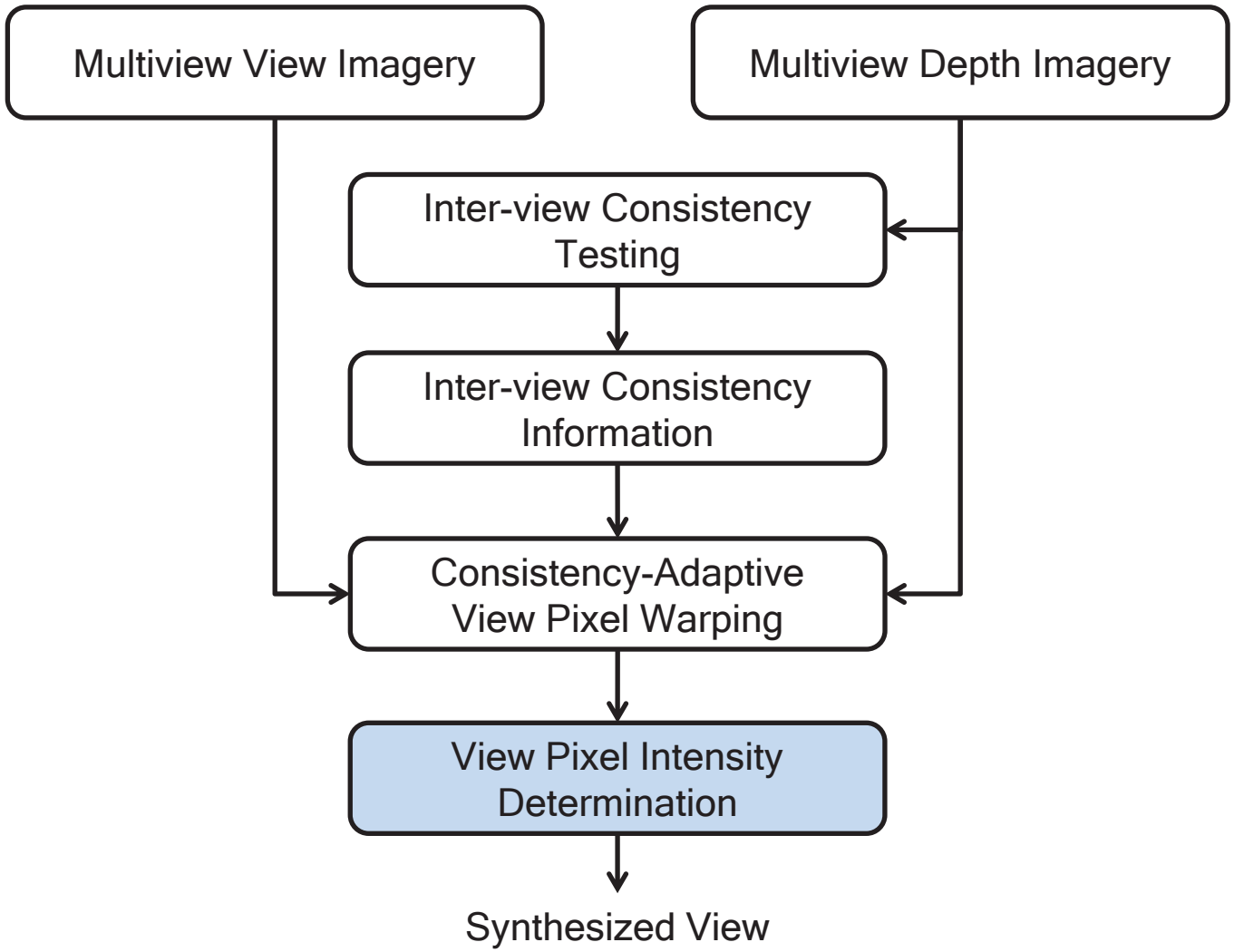
Consistency-adaptive view synthesis



Consistency-adaptive view synthesis



Consistency-adaptive view synthesis



Experimental results

Experimental setup

MPEG 3DTV Multiview Data Set

Newspaper
(1024 X 768)

Lovebird1
(1024 X 768)

Kendo
(1024 X 768)

Balloons
(1024 X 768)

Undo Dancer
(1920 X 1088)

Depth image based rendering

MPEG View Synthesis Reference Software (VSRS) 3.5

Depth map

Left

Depth map

Right

Depth image based rendering

MPEG View Synthesis Reference Software (VSRS) 3.5

Left

Depth map

Reference view

Right

Depth map

Reference view

Depth image based rendering

MPEG View Synthesis Reference Software (VSRS) 3.5

Left

Depth map

Reference view

3D warping

Warped view

Right

Depth map

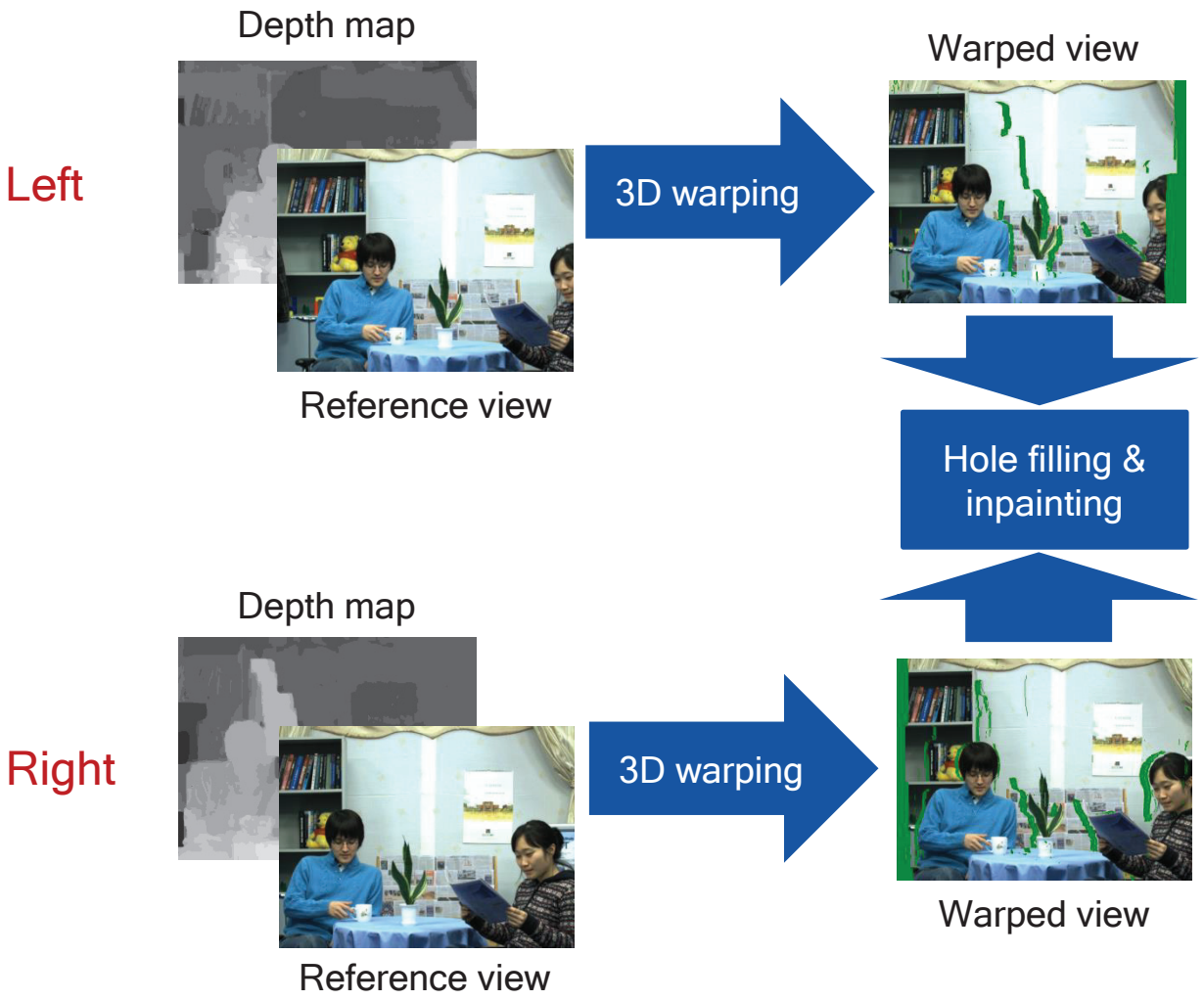
Reference view

3D warping

Warped view

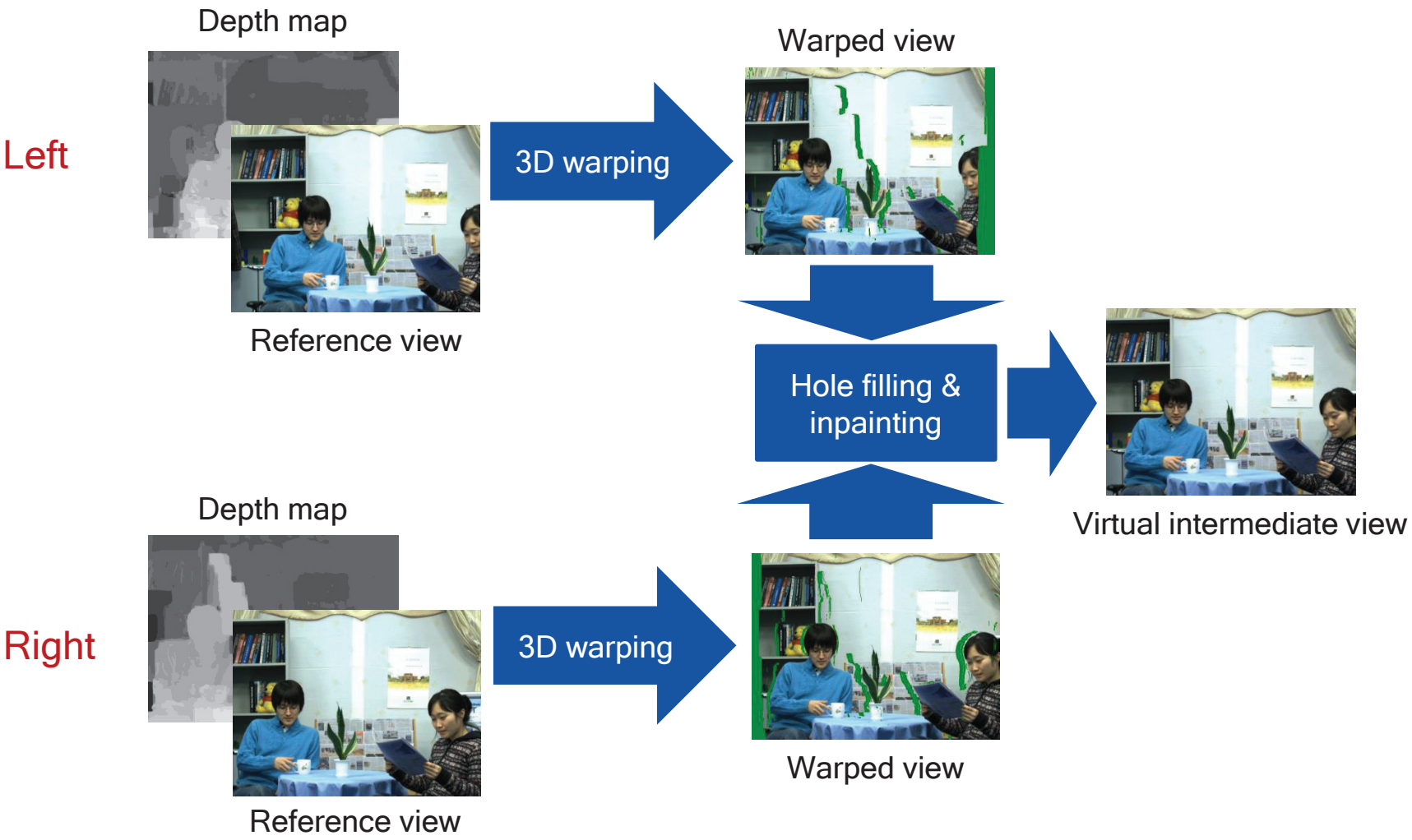
Depth image based rendering

MPEG View Synthesis Reference Software (VSRS) 3.5



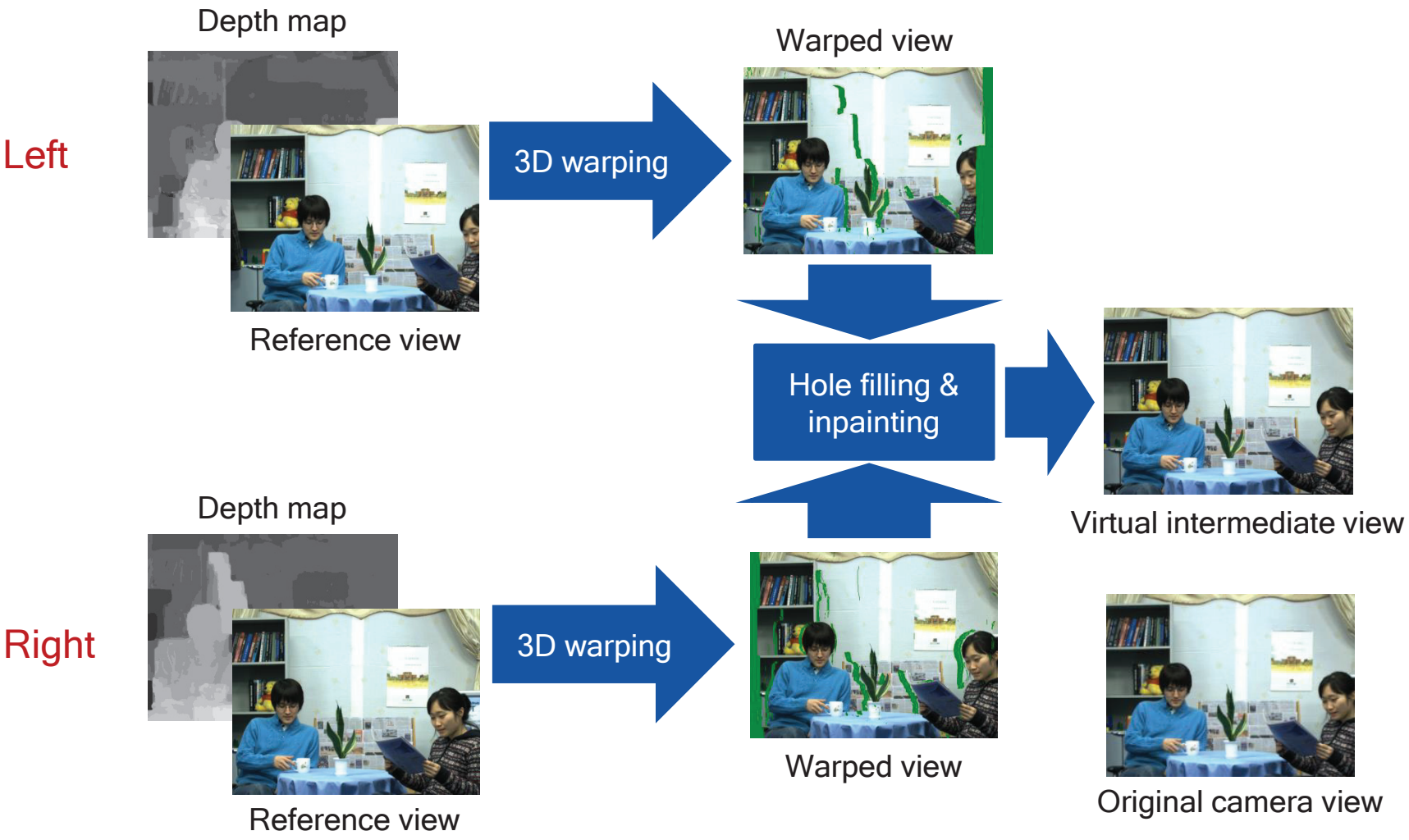
Depth image based rendering

MPEG View Synthesis Reference Software (VSRS) 3.5



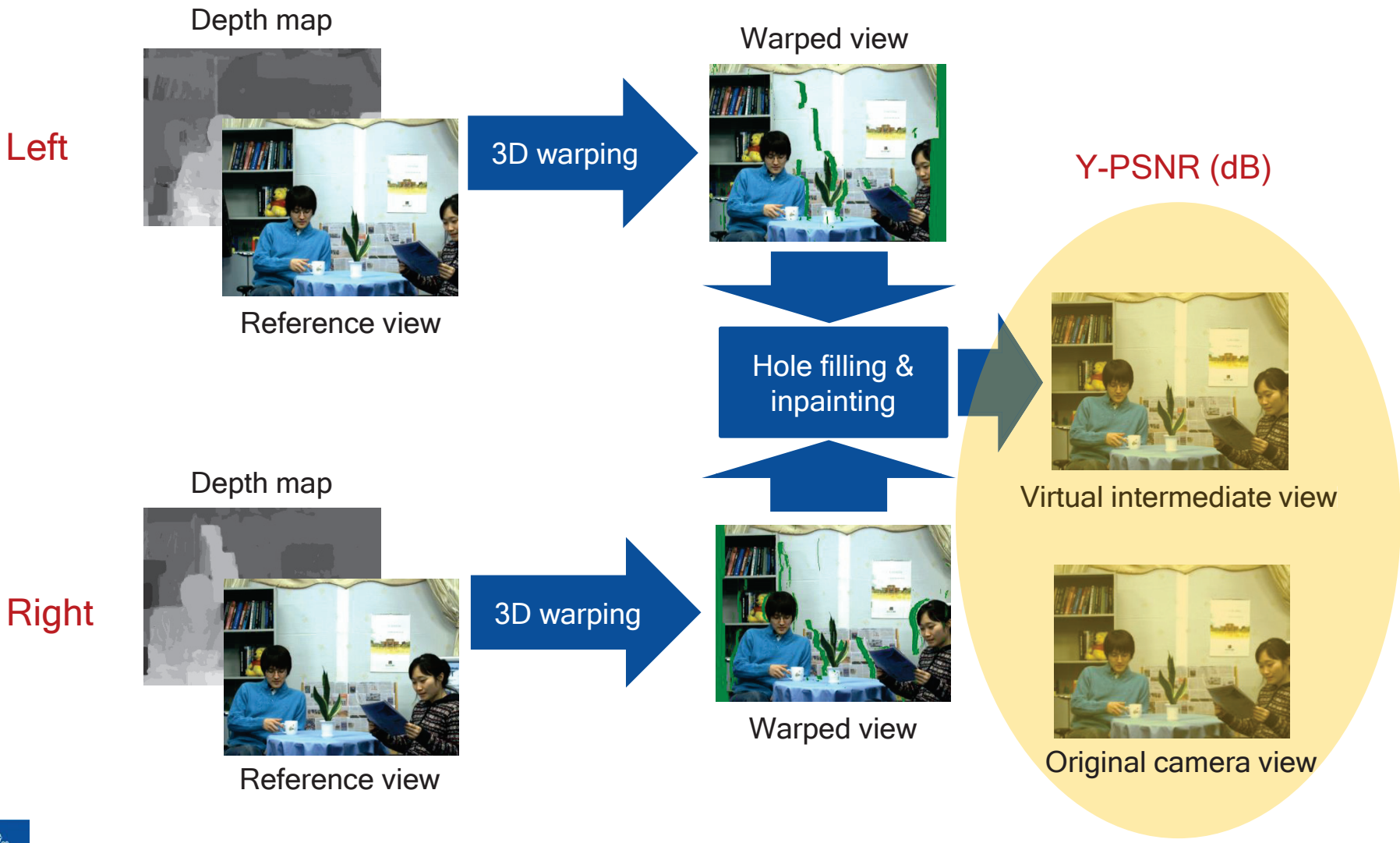
Depth image based rendering

MPEG View Synthesis Reference Software (VSRS) 3.5



Depth image based rendering

MPEG View Synthesis Reference Software (VSRS) 3.5



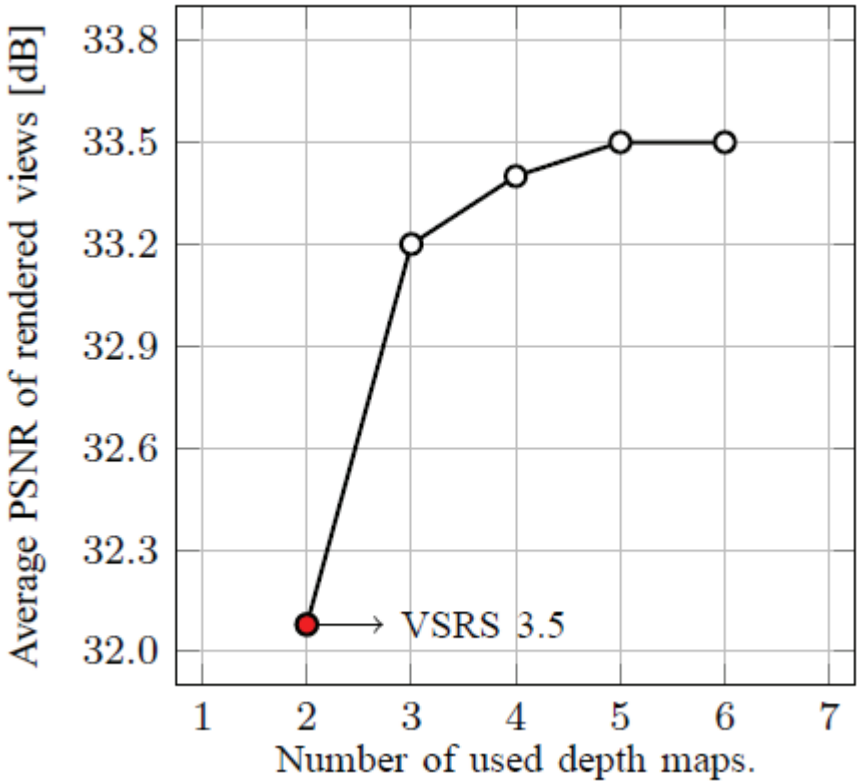
Objective results

Test sequence	Input views		Virtual view	Number of Frames	MPEG VSRS 3.5 [dB]		CAVS [dB]
	VSRS	IVDCT			MPEG Depth Maps	IVDCT Depth Maps	MPEG Depth Maps
Newspaper	4,6	2,4,6	3	300	32.3	33.0	33.5
Kendo	3,5	1,3,5	4	300	37.6	38.2	38.3
Balloons	3,5	1,3,5	4	300	36.6	36.8	37.0
Lovebird1	6,8	4,6,8	7	240	29.0	29.2	29.2
Dancer	2,5	2,5,9	3	250	38.8	38.8	40.0

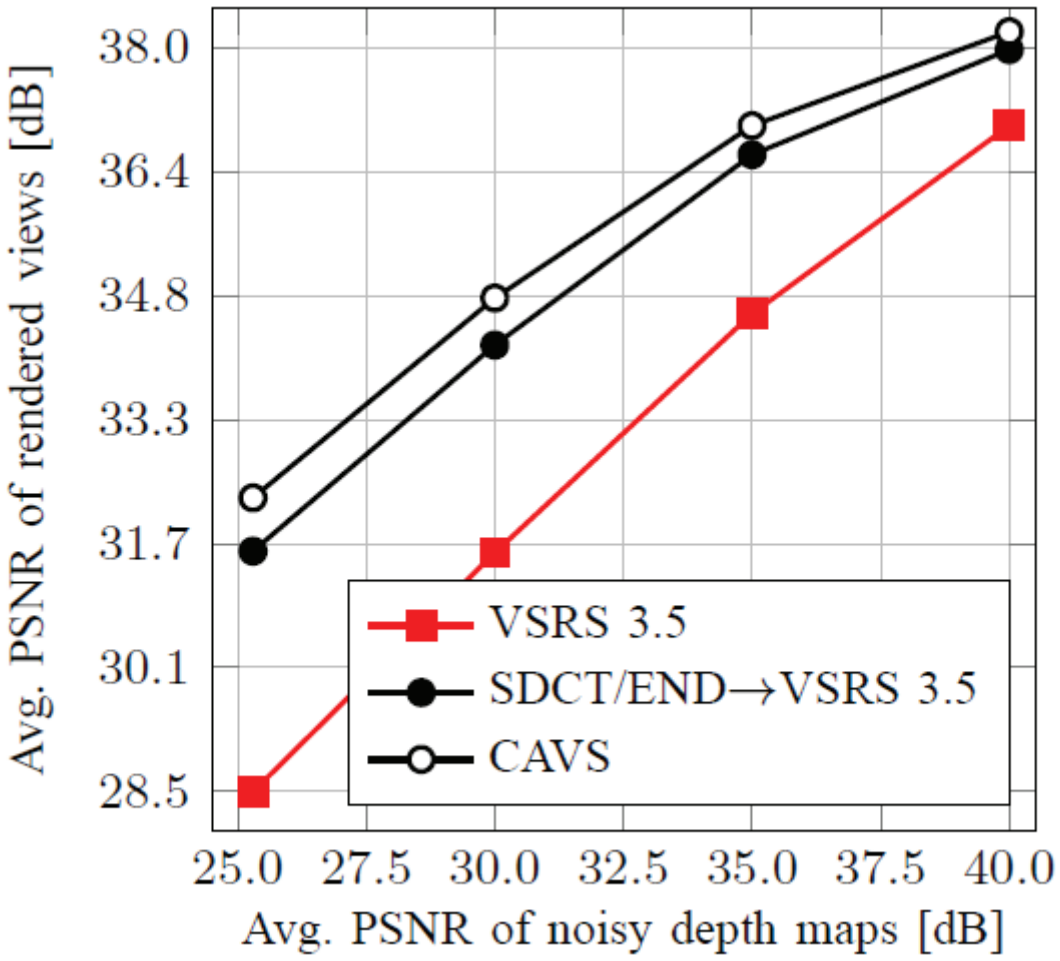
Note: Experimental settings are as per MPEG Call for Proposal on 3D Video Standardization

Objective results

- Quality of synthesized views over the number of depth maps used by CAVS for synthesis

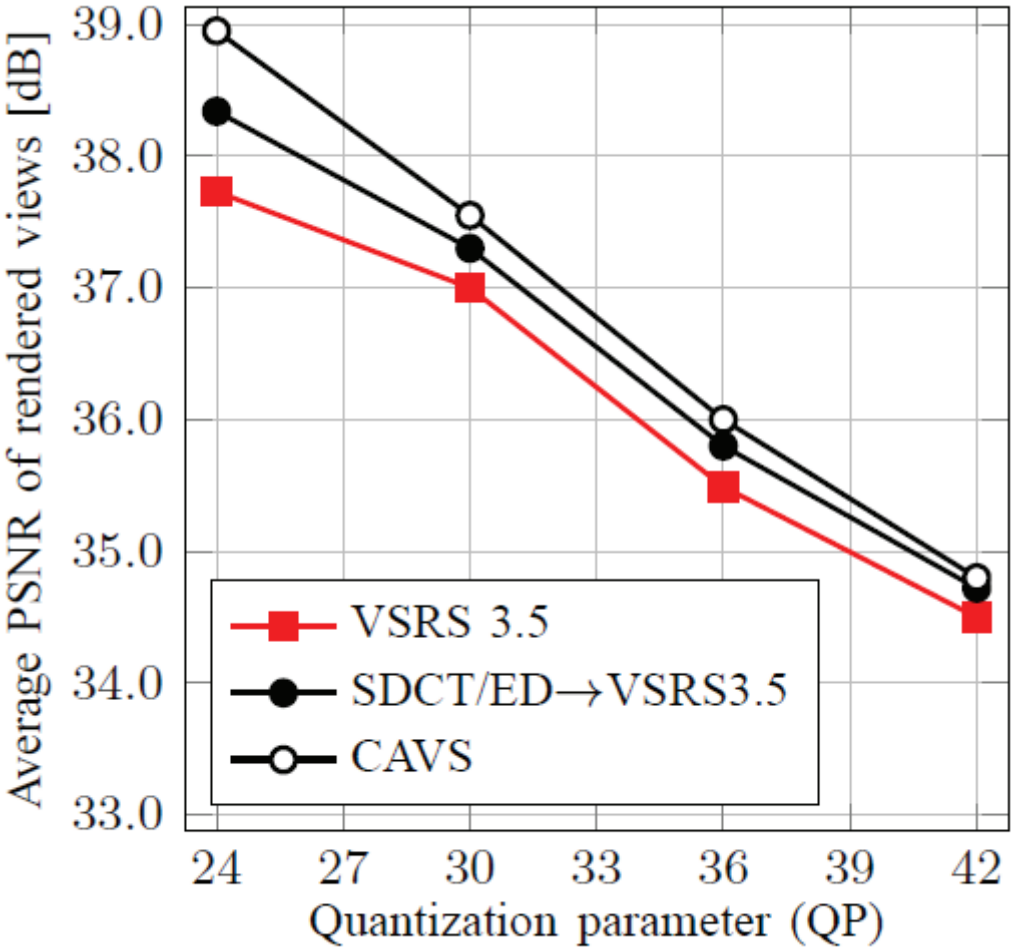


Objective results



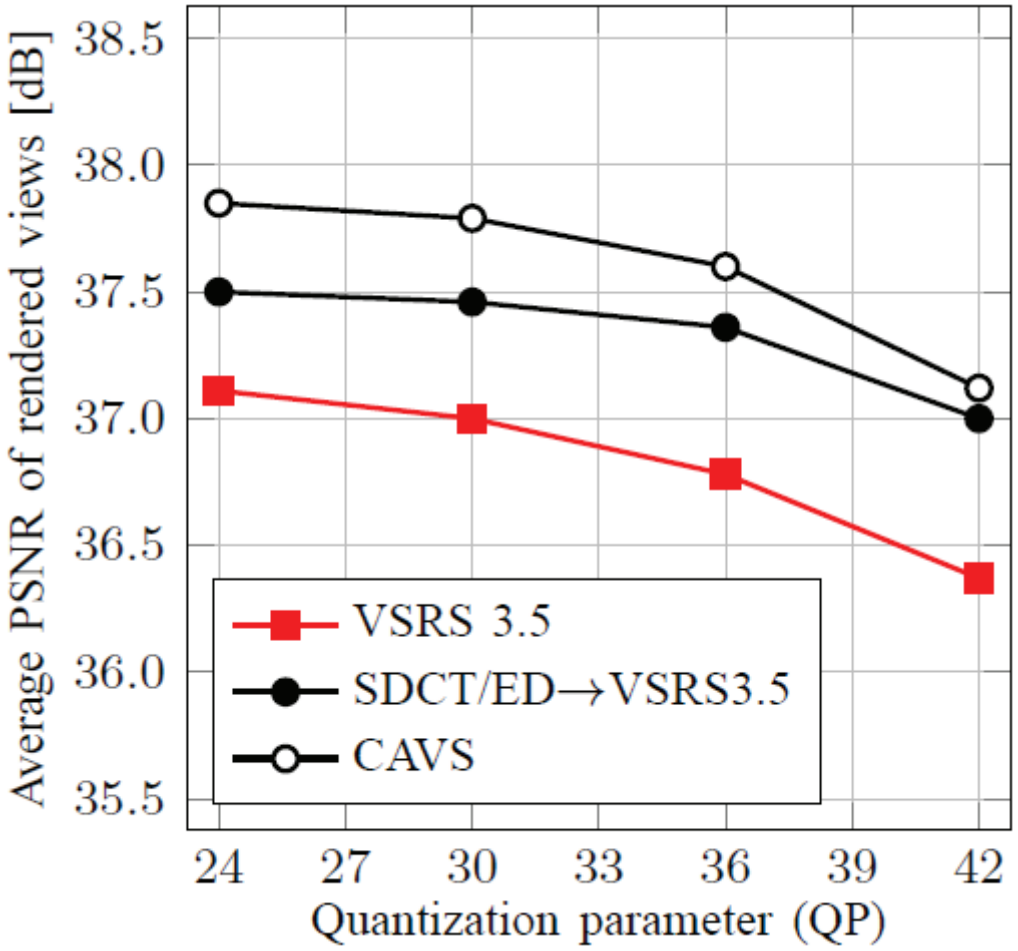
Dancer

Objective results



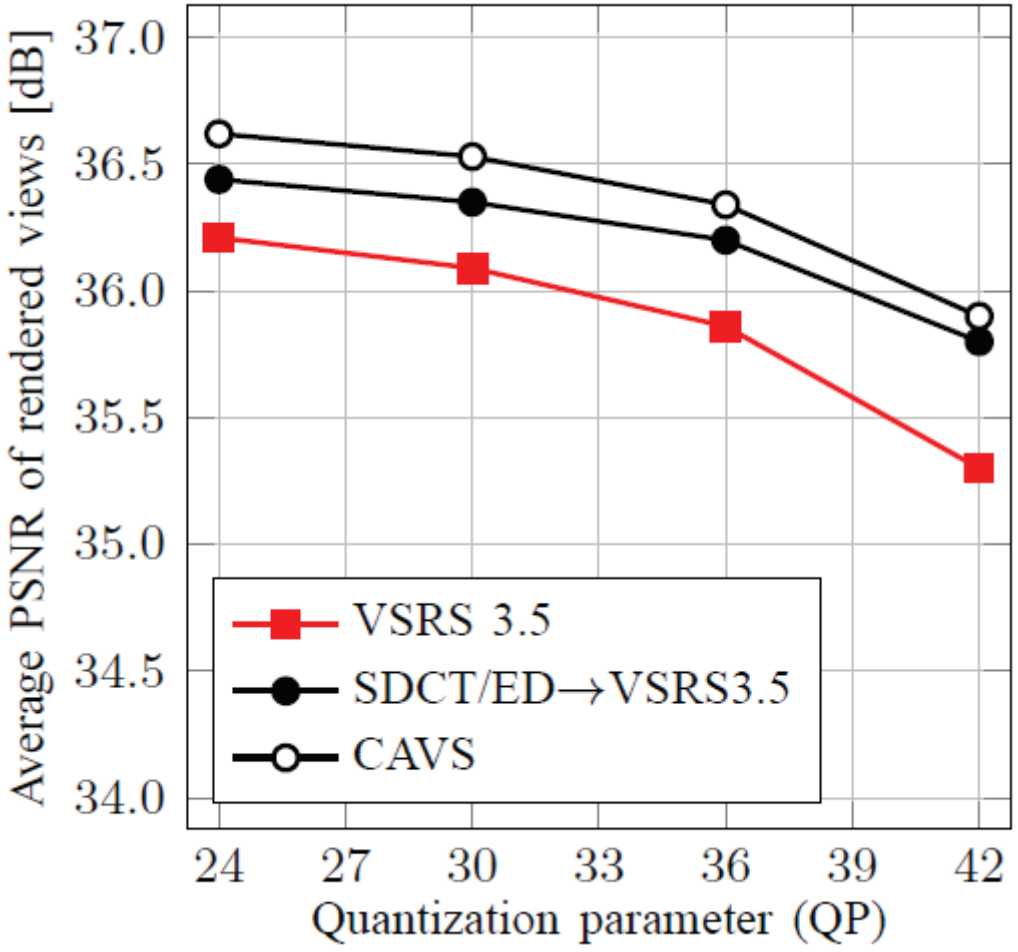
Dancer

Objective results



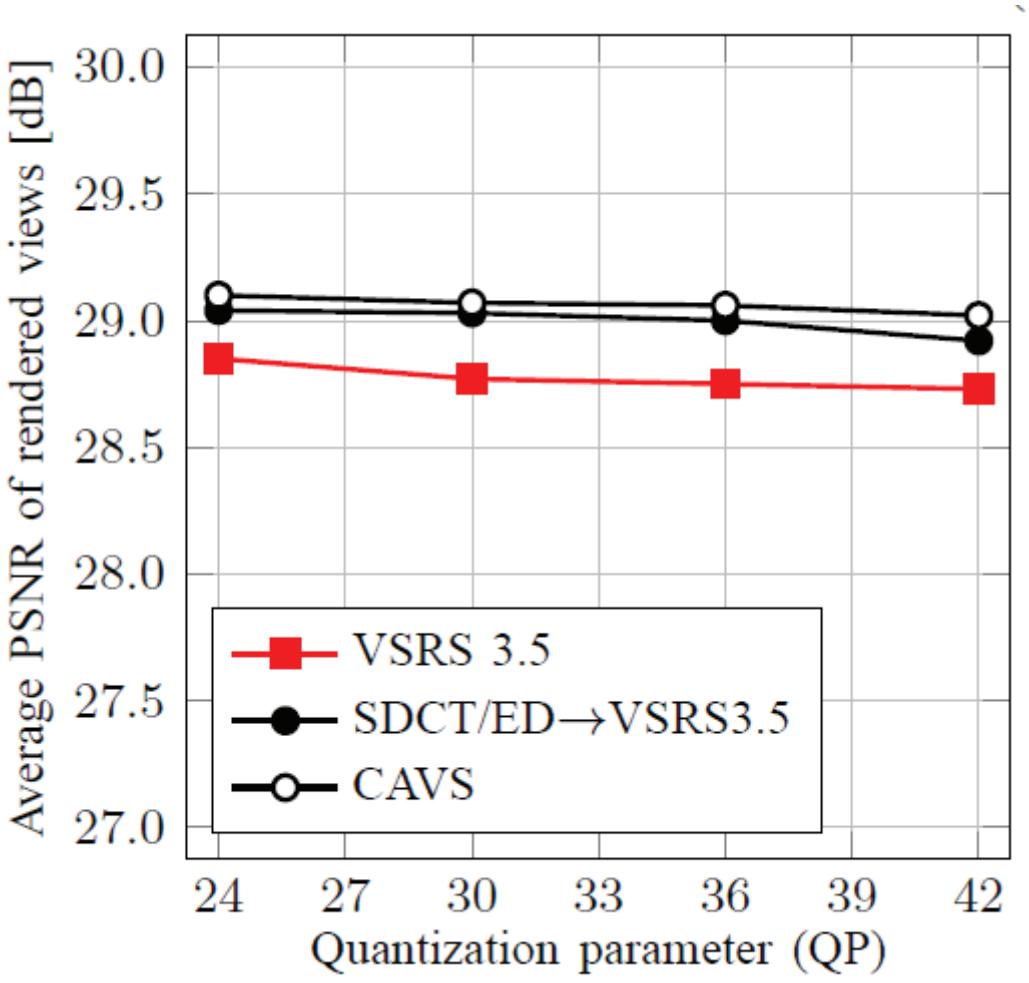
Kendo

Objective results



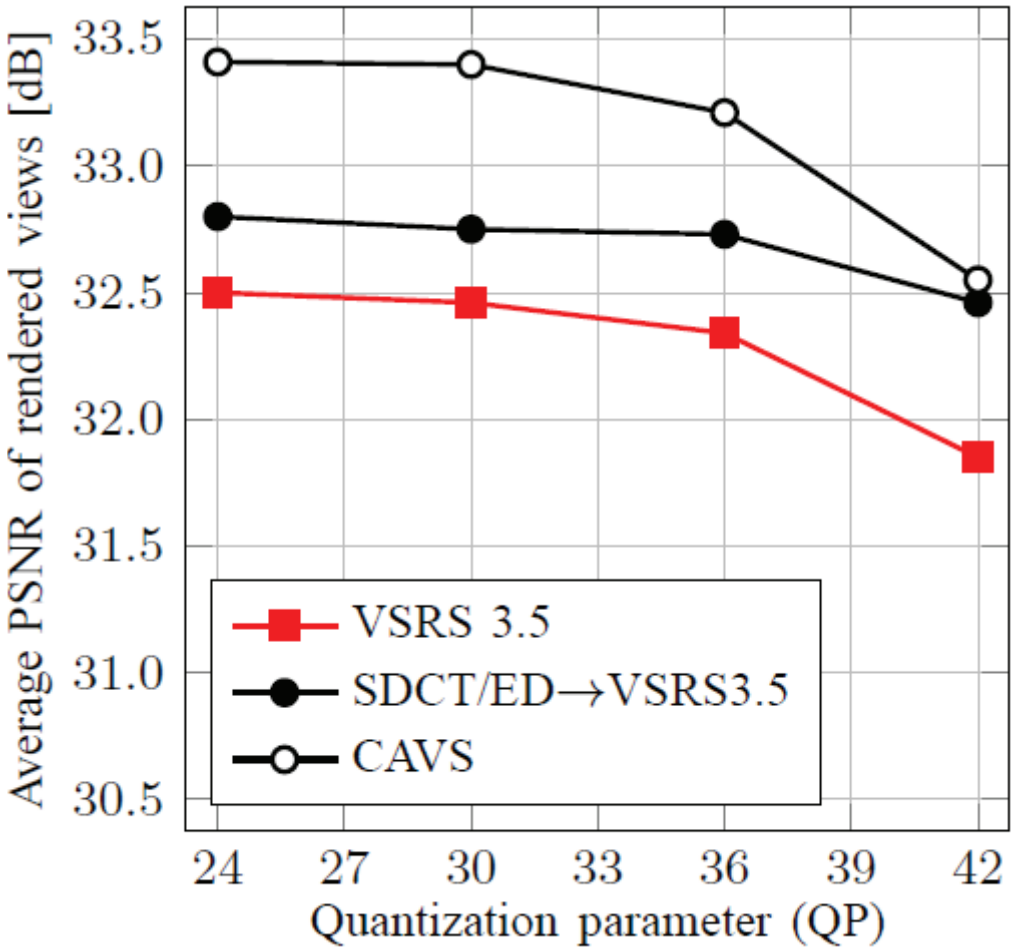
Balloons

Objective results



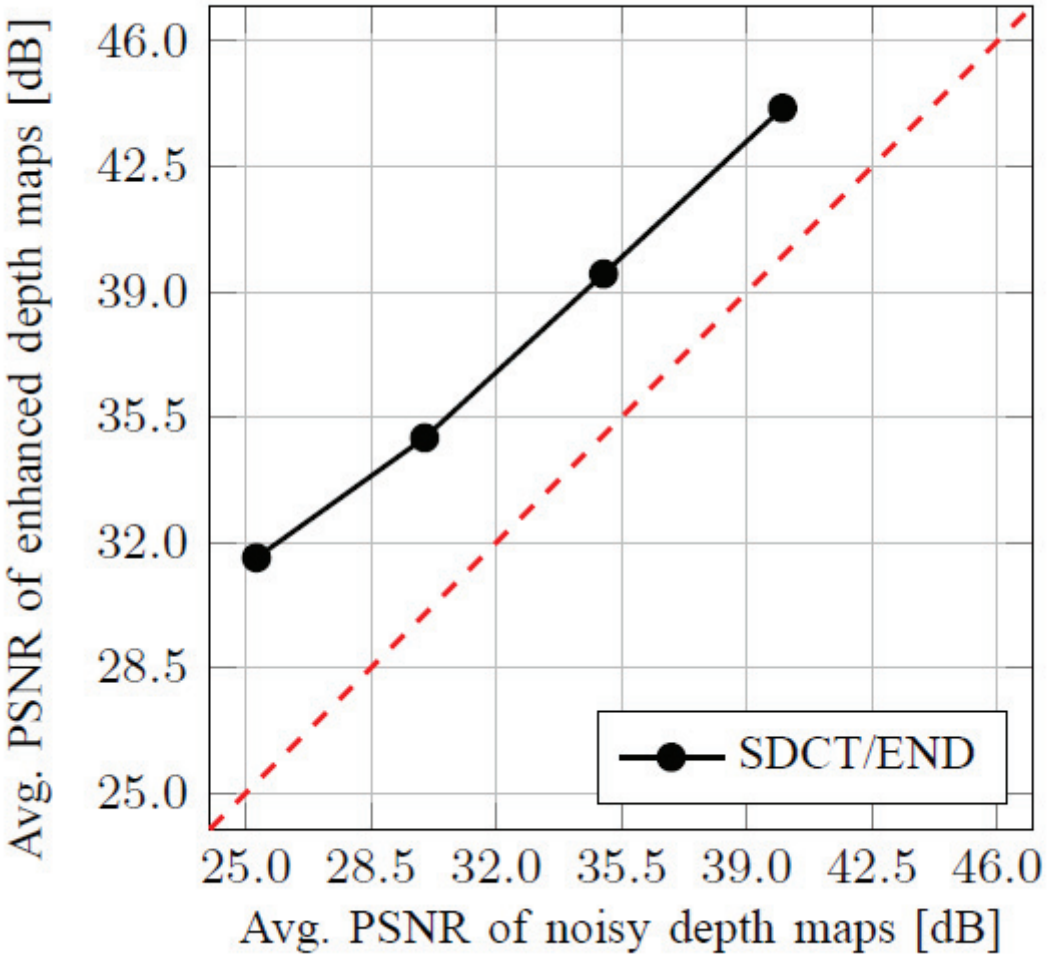
Lovebird1

Objective results



Newspaper

Objective results



Dancer

Subjective results

Sequence: Dancer

Subjective results

Sequence: Dancer

Original

VSRS

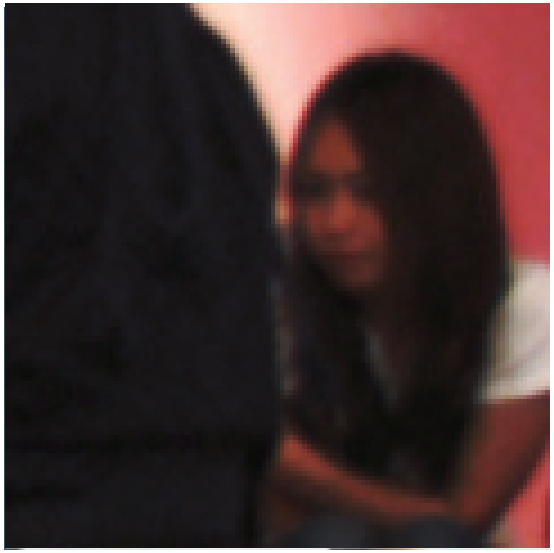
CAVS

Subjective results

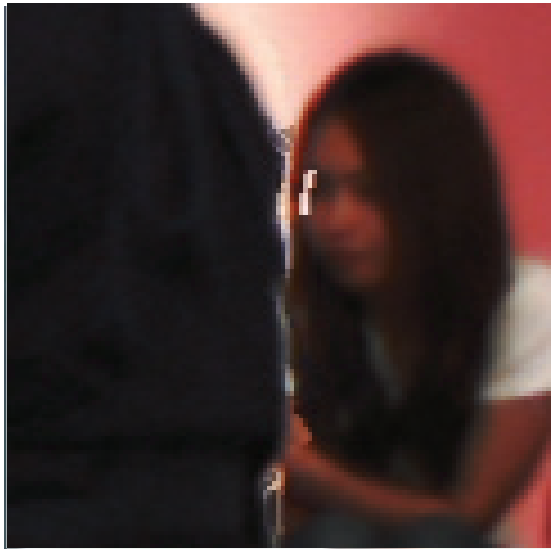
Sequence: Kendo

Subjective results

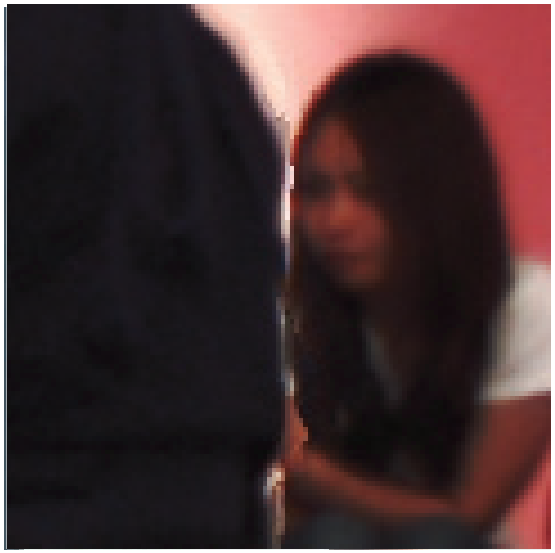
Sequence: Kendo



Original



VSRS



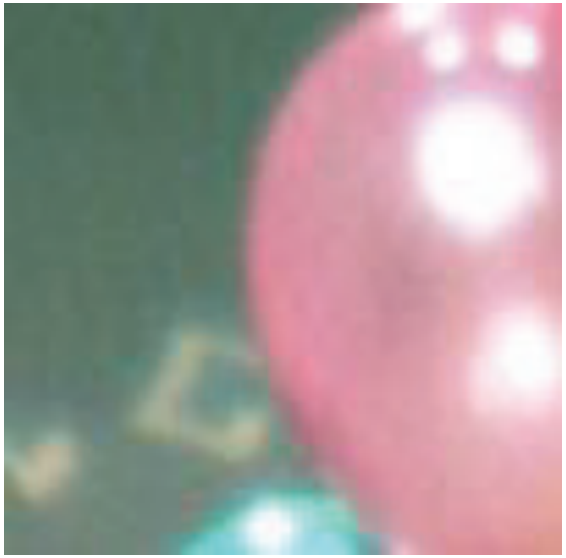
CAVS

Subjective results

Sequence: Balloons

Subjective results

Sequence: Balloons



Original

VSRS

CAVS

Subjective results

Sequence: Lovebird1

Subjective results

Sequence: Lovebird1

Original

VSRS

CAVS

Subjective results

Sequence: Newspaper

Subjective results

Sequence: Newspaper

Original

VSRS

CAVS

Conclusions

- We improved the inter-view depth consistency and hence, enhanced the visual experience of free-viewpoint television
- The consistency testing and information efficiently utilized to enhance the depth representation at multiple viewpoints
- The consistency information is advantageous to improve the visual quality of synthesized views by using conventional depth image-based rendering
- Effectiveness of our approach is demonstrated by both objective and subjective results

References

Publications:

[1] P. K. Rana and M. Flierl: "*Inter-view Depth Consistency Testing in Depth Difference Subspace*", IEEE Transactions on Image Processing, submitted, 2014.

[2] P. K. Rana, J. Taghia, and M. Flierl: "*Statistical Methods for Inter-View Depth Enhancement*", Proceedings of 3DTV Conference, submitted, 2014.

[3] P. K. Rana and M. Flierl: "*Depth Pixel Clustering for Consistency Testing of Multiview Depth*", Proceedings of European Signal Processing Conference, August , 2012.

[4] P. K. Rana and M. Flierl: "*View Interpolation with Structured Depth from Multiview Video*", Proceedings of European Signal Processing Conference, August, 2011.

[5] P. K Rana and M Flierl: "*Depth Consistency Testing for Improved View Interpolation*", Proceedings of IEEE Workshop on Multimedia Signal Processing, October, 2010.

Patents:

[6] M. Flierl, P. K. Rana, I. Girdzijauskas: "*Methods and Processor for 3D Scene Representation*", WO Application No.: PCT/SE2012/050255, 2012, Ericsson AB, Published, Pending.

[7] M. Flierl, P. K. Rana, I. Girdzijauskas, T. Rusert, and A. Georgakis: "*Methods and Arrangements for 3D Scene Representation*", WO Application No.: PCT/SE2010/051294, 2010, Ericsson AB, Published, Pending.

Thank you