ToF Meets RGB: Novel Multi-Sensor Super-Resolution for Hybrid 3-D Endoscopy

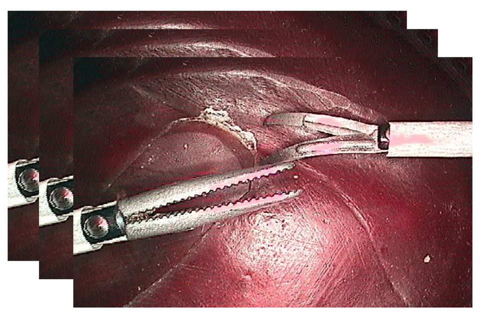
Thomas Köhler[1,2], Sven Haase[1], Sebastian Bauer[1], Jakob Wasza[1], Thomas Kilgus[3], Lena Maier-Hein[3], Hubertus Feußner[4], Joachim Hornegger[1,2]

[1] Pattern Recognition Lab, Friedrich-Alexander-Universität Erlangen-Nürnberg
[2] Erlangen Graduate School in Advanced Optical Technologies (SAOT)
[3] Div. Medical and Biological Informatics Junior Group: Computer-assisted Interventions, German Cancer Research Center (DKFZ) Heidelberg
[4] Minimally Invasive Therapy and Intervention, Technical University of Munich

Hybrid 3-D Endoscopy

Conventional 2-D endoscopy
- Photometric information
- High spatial resolution

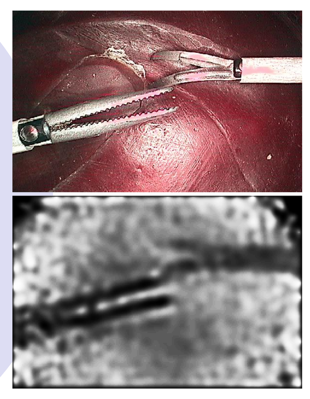
3-D endoscopy (Time-of-Flight, ToF)
- 3-D range data
- Low spatial resolution


(640 x 480 px)

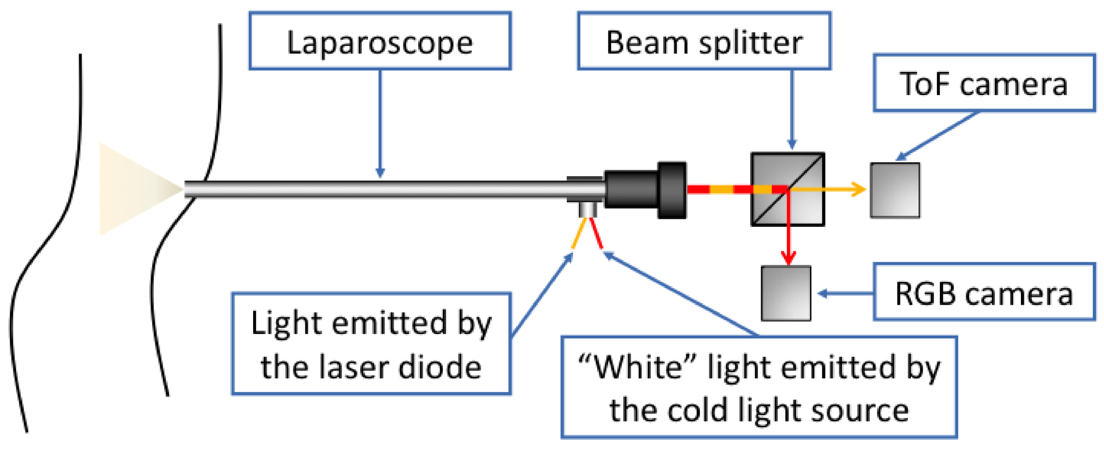
Sensor fusion [1]


(64 x 48 px)

Goal:
- Fusion of RGB and range data
- Enhance low-resolution range data
- Multi-frame range super-resolution guided by RGB data

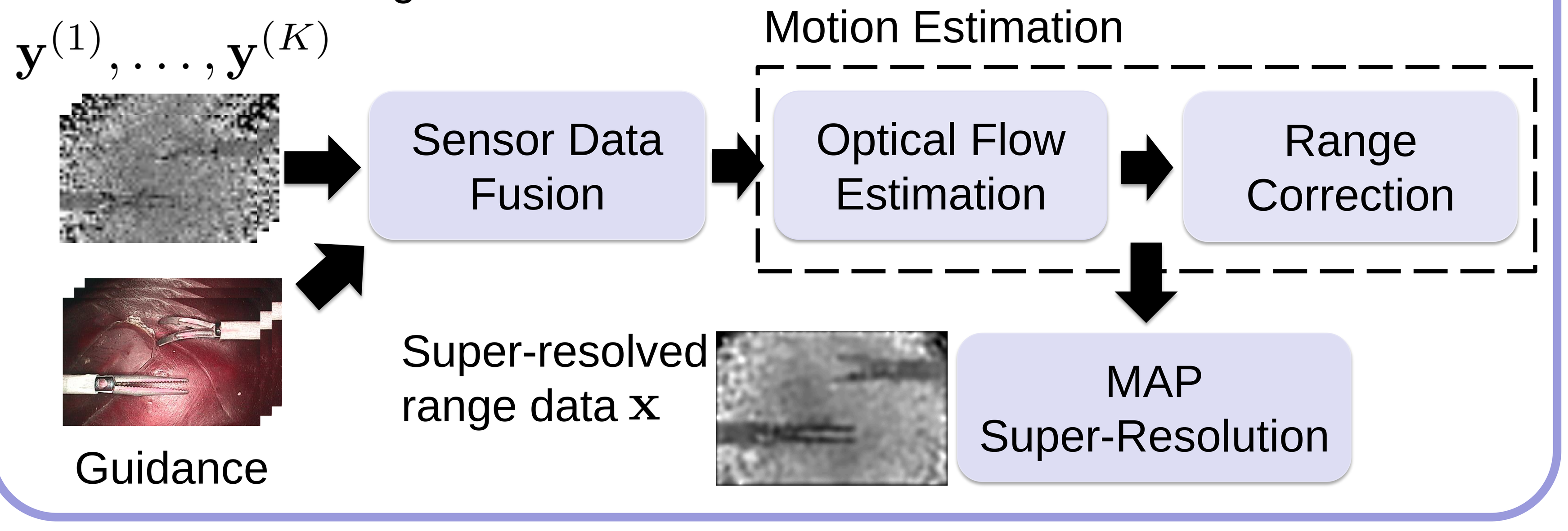


Hardware Setup



Acquire photometric (RGB) and range (ToF) data through a **beam splitter in one single endoscope**

Method Outline

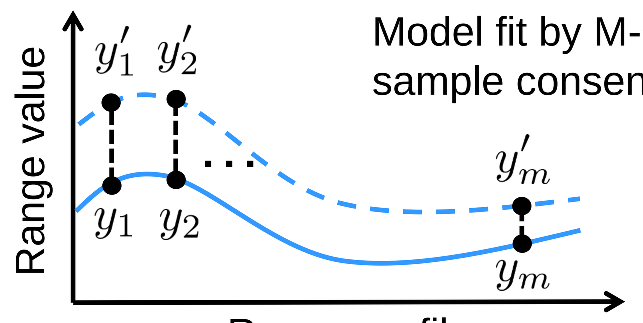


MSR – Multi-Sensor Super-Resolution

Motion Estimation guided by RGB images:
- **Optical flow:** Derive subpixel 2-D displacement fields for range data from optical flow on RGB data
- **Range correction:** Model 3-D out-of-plane motion by affine model (γ_m, γ_a)

$$y_i' = \gamma_m y_i + \gamma_a$$

Corresponding range values (after 2-D alignment)



Maximum a-posteriori (MAP) super-resolution [2]:
- Given: Low-resolution range images $\mathbf{y}^{(1)}, \ldots, \mathbf{y}^{(K)}$
- Objective: MAP estimate for high-resolution image $\mathbf{x}$

System matrix (generative image model)

$$\hat{\mathbf{x}} = \arg\min_{\mathbf{x}} \sum_{k=1}^{K} \left\| \mathbf{y}^{(k)} - \gamma_m^{(k)} \mathbf{W}^{(k)} \mathbf{x} - \gamma_a^{(k)} \mathbf{1} \right\|_2^2 + \lambda R(\mathbf{x})$$

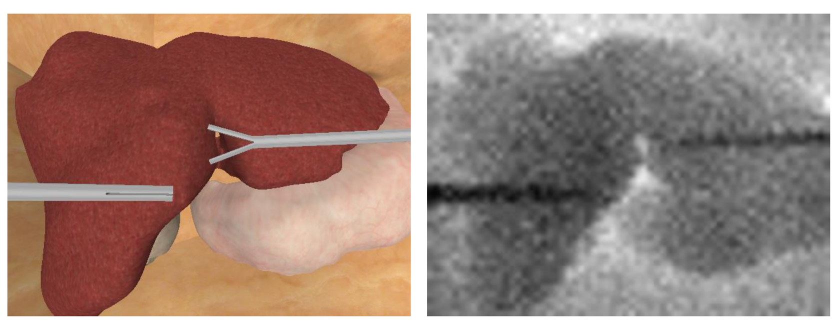
Range correction parameters   Regularizer (Huber prior)

- Huber prior applied pixel-wise: $R(\mathbf{x}) = \sum_n h_\tau(\mathbf{D}\mathbf{x})_n$
  - ➢ Enforce smoothness using Laplacian $\mathbf{D}\mathbf{x}$

Experiments and Results

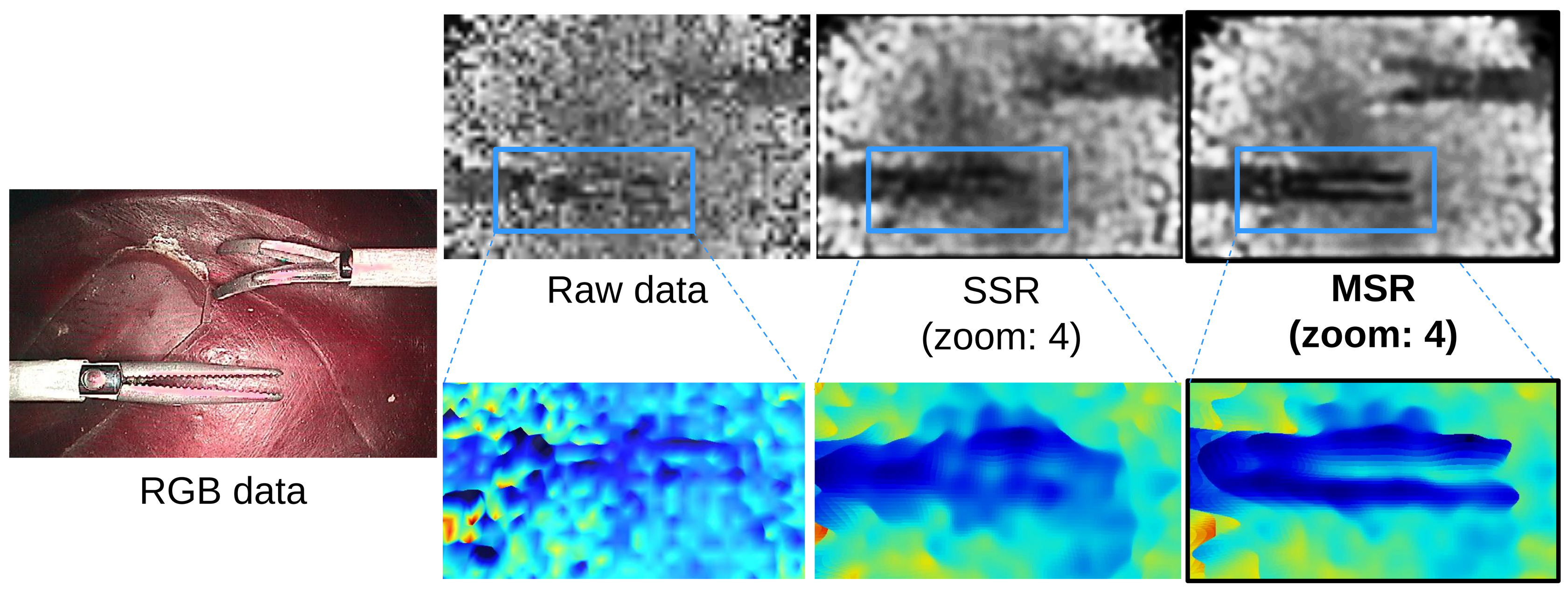
Comparison between single-sensor super-resolution (SSR) and the proposed multi-sensor (MSR) approach:

- **Synthetic data:** 6 sequences for quantitative evaluation (31 frames / sequence)
- **Liver phantom data:** 2 sequences acquired by endoscope prototype (31 frames / sequence)



Metric	SSR	MSR
PSNR [dB]	29.78	**31.38**
SSIM	0.90	**0.92**

Mean peak-signal-to-noise ratio (PSNR) and structural similarity (SSIM) for synthetic data



Generated 3-D meshes

Conclusions

- **Range super-resolution** guided by high-resolution RGB data
- **Improved robustness** compared to single-sensor approach

References

[1] S. Haase et al., *ToF/RGB Sensor Fusion for Augmented 3D Endoscopy using a Fully Automatic Calibration Scheme*, BVM 2012, pp. 467–474

[2] S. Park et al., *Super-Resolution Image Reconstruction: A Technical Overview*, IEEE Signal Processing Magazine, vol. 20, no. 3, 2003, pp. 21–36

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Contact

Thomas Köhler, M.Sc.
Thomas.Koehler@fau.de
http://www5.cs.fau.de/~koehler