Robust Incremental Structure-from-Motion with Hybrid Features

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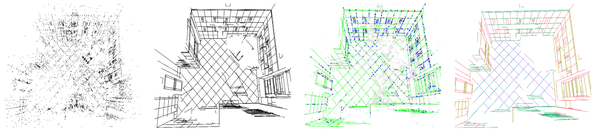
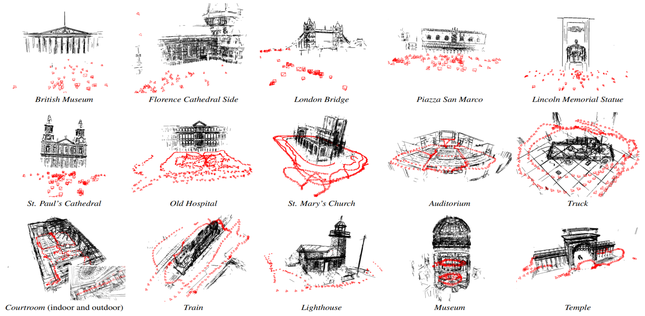
Background – LIMAP (Our past project at CVPR 2023): A toolbox for mapping and localization with line features

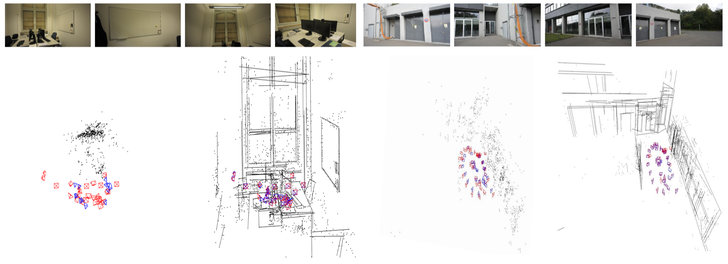


Point mapping · Line mapping · Point-line association · Parallelism & orthogonality



A handful of 3D line segments suffice to describe the geometry!!
------> Feature points are not the only reliable sparse features:)

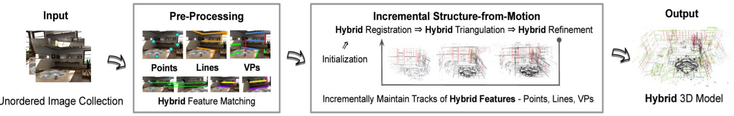
What about a Full SfM system with points and lines together?



Point-alone (COLMAP) · Hybrid (Ours) · Point-alone (COLMAP) · Hybrid (Ours)

Pipeline overview

Start from point-alone COLMAP -> 1) **hybrid** registration 2) **hybrid** triangulation 3) **hybrid** refinement (BA)



Maintaining 3D maps of points, lines, VPs and their relations in the whole pipeline

- **Incremental triangulation**: incremental pipeline as effective as the global triangulator in LIMAP
- **Hybrid registration:** 4 point-line minimal solvers + 2 upright solvers with one VP associated.
- **Hybrid bundle adjustment:**
  - Two-step refinement with selection of 3D points and lines (by uncertainty).
  - Schur complement trick by moving VP to the camera side.

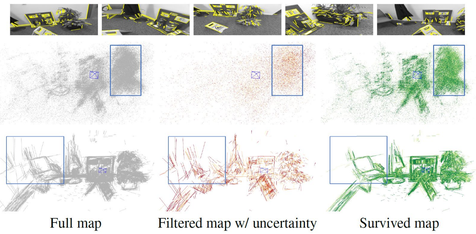
Propagating uncertainty to 3D maps

- Point: trivial with Jacobian-based propagation (supported with ceres)
- **Line: Nontrivial since point-to-line distance is not in least squares form w.r.t. detections!**

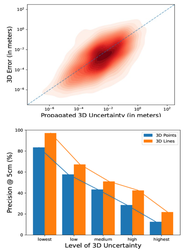
Second-order sensitivity analysis comes to the rescue

$$\frac{\partial E}{\partial \boldsymbol{\Phi}}\Big|_{\boldsymbol{\Phi}=\boldsymbol{\Phi}^*} = 0 \qquad \frac{\partial^2 E}{\partial \boldsymbol{\Phi} \partial \boldsymbol{x}_j^k}\Big|_{\boldsymbol{\Phi}=\boldsymbol{\Phi}^*} = 0$$

Solve for the Jacobian at the optimum!



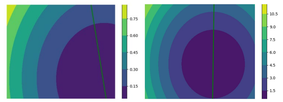
Full map · Filtered map w/ uncertainty · Survived map



Strong correlation between error (e.g., w.r.t. lidars) and uncertainty -> We can Identify noisy parts without GT needed!!

Uncertainty-aware visual localization

- Perform initial localization.
- Compute the reprojection uncertainty for each data point.
- Relocalization by weight correspondences with its reprojection uncertainty.
- State-of-the-art results on 7Scenes and Cambridge.

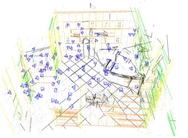


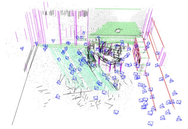
Uncertainty of line reprojection error depends on which point to measure the distance!

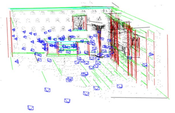
Results

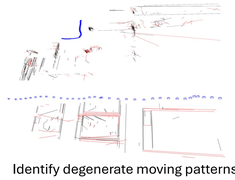
Dataset	Point Feature	Method	AUC @ 1°/3°/5°/10° ↑				Valid Reg. ↑
Hypersim	SIFT + NN	Point	71.3	82.5	85.0	86.8	93.7%
		Hybrid	**82.1**	**86.6**	**87.6**	**88.3**	**93.9%**
	SP + SG	Point	80.1	89.5	91.6	93.2	96.7%
		Hybrid	**87.0**	**92.1**	**93.3**	**94.1**	**97.0%**
ETH3D	SIFT + NN	Point	16.2	26.7	28.1	32.1	46.4%
		Hybrid	**24.3**	**34.8**	**37.4**	**40.8**	**59.4%**
	SP + SG	Point	33.0	54.7	61.1	66.4	69.8%
		Hybrid	**37.3**	**57.9**	**63.3**	**68.8**	**75.3%**

Dataset	Method	AUC @ 1°/3°/5°/10°↑	Valid Reg. ↑
Hypersim	COLMAP [79]	71.3 / 82.5 / 85.0 / 86.8	93.7%
	COLMAP [79] → LIMAP BA [52]	78.6 / 84.2 / 86.5 / 87.3	93.8%
	Ours	**82.1** / **86.6** / **87.6** / **88.3**	**93.9%**
ETH3D	COLMAP [79]	16.2 / 26.7 / 28.1 / 32.1	46.4%
	COLMAP [79] → LIMAP BA [52]	19.2 / 28.3 / 31.1 / 33.8	47.6%
	Ours	**24.3** / **34.8** / **37.4** / **40.8**	**59.4%**

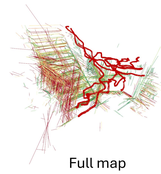






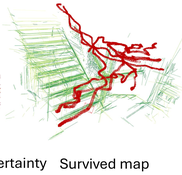


Identify degenerate moving patterns

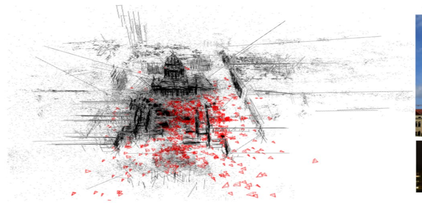


Full map

Filtered map w/. uncertainty



Survived map



Hybrid SfM on Gendarmenmarkt (1,463 images) from 1DSfM

Dataset	Method	Point		Point + Line	
		Med. error ↓	Recall ↑	Med. error ↓	Recall ↑
Cambridge	w/o. uncertainty	7.1 / 0.13	24.3 / 43.1	7.0 / 0.13	25.4 / 45.3
	w. uncertainty	**6.4** / **0.12**	**27.4** / **48.0**	**6.3** / **0.12**	**29.0** / **48.6**
7Scenes	w/o. uncertainty	3.1 / 1.03	51.1 / 76.0	3.1 / 1.01	52.7 / 77.7
	w. uncertainty	**2.9** / **0.95**	**55.6** / **79.0**	**2.8** / **0.95**	**56.5** / **79.5**

Uncertainty-aware visual localization reaches SOTA: better than HLoc and LIMAP

Nerfacto w/ COLMAP

Nerfacto w/ Ours