SurgIPC: a Convex Image Perspective Correction Method to Boost Surgical Keypoint Matching

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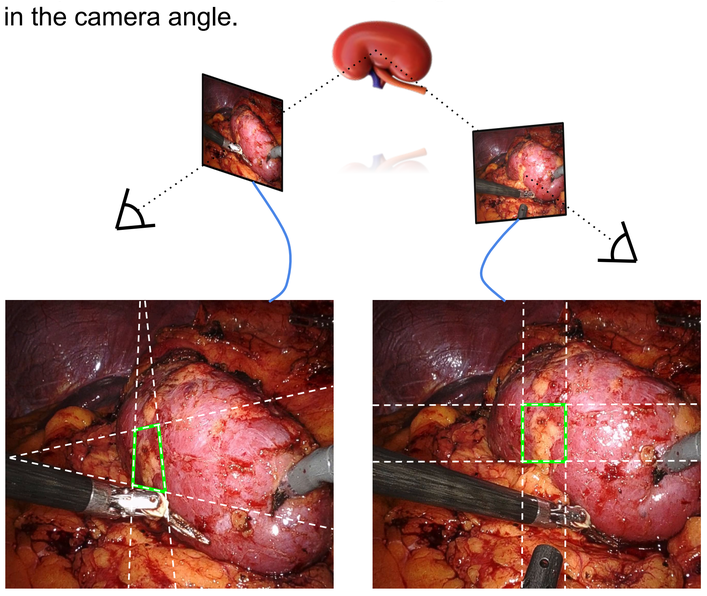
Overview

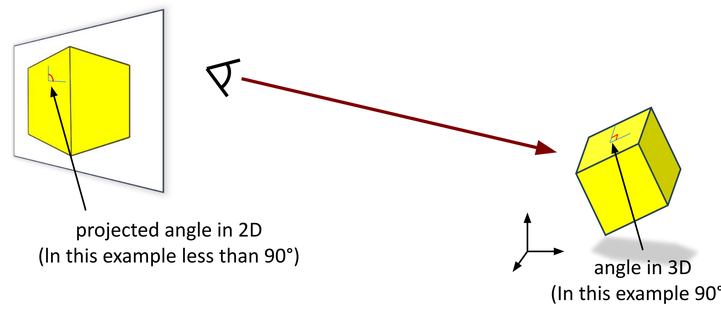
- Perspective distortion is caused by organ movement or variations in the camera angle.



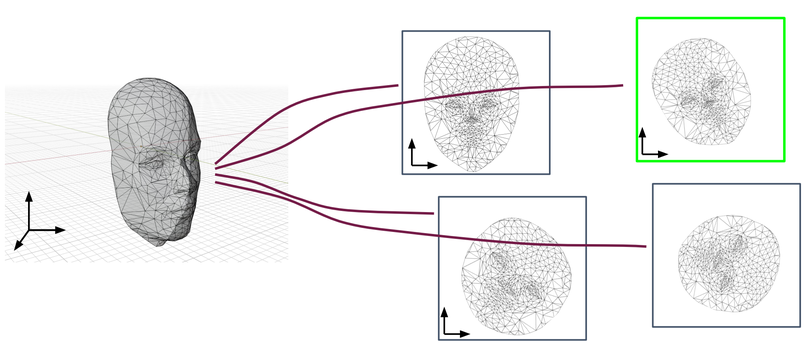
- Existing methods for Keypoint matching often struggle in the presence of extreme perspective distortion. This can be mitigated by applying perspective correction to the input image prior to keypoint detection.
- We propose a convex method, specifically a linear least-square (LLS) one, applicable to non-developable yet smooth surfaces.
- Experiments on downstream tasks, including keyframe matching and 3D reconstruction using SfM, highlight significant performance gains.

Methodology

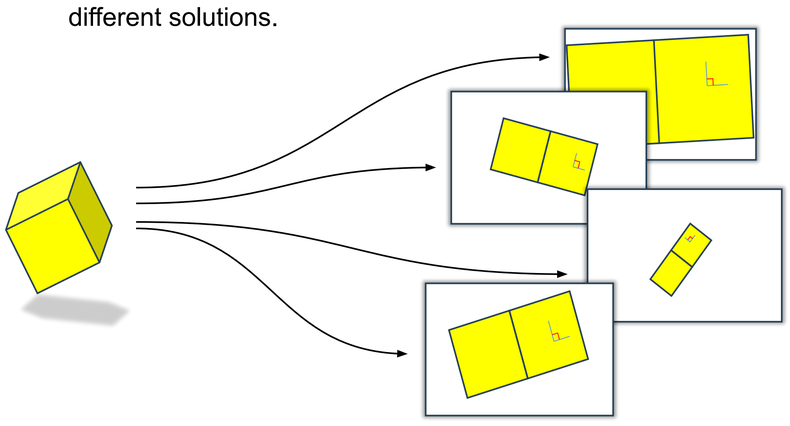
- The perspective effect distorts 3D angles.



- If we could create a virtual image preserving the 3D angles, we would remove perspective.
- In computer graphics, 3D shapes require flat parameterisation to enable texture mapping.

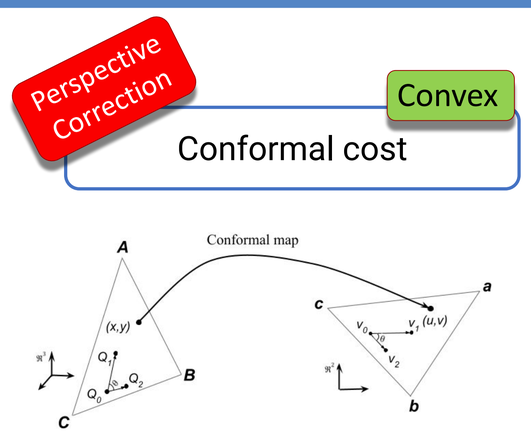


- One of the parameterisations, known as conformal flattening, specifically minimises angle distortions
- It has the capability to transform a 3D mesh to a 2D flat domain while preserving angles [1].
- Challenges of using conformal flattening for images, compared to texture mapping are:
  - 1- Object identification → Segmentation
  - 2- 3D computation → Monocular/Stereo depth estimation
  - 3- Image resampling: conformal transformation can result in different solutions.



- SurgIPC adapts texture mapping from CG to CV.

Mathematical formulation



Conformal mapping between two triangles with angle preservation

- According to Riemann's theorem:

"Any surface homeomorphism to a disk can be represented by a planar conformal parameterisation".

- We establish a linear system for the conformal transformation between the two triangles.

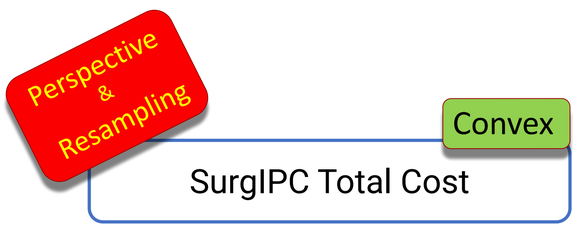
$$M_t p_t = 0$$

- The mapping between these two triangles is affine and conformal if and only if the angles between their corresponding edges are equal.
- To establish conformality for the entire 3D mesh, we minimise the violation of equation in least squares manner, for the entire 3D mesh:

$$C_{conf}(p) = \Sigma_{t \in T_{3D}} \|M_t p_t\|^2$$

- We mathematically model resampling with Integral pixel displacement.
- We measure the extent of pixel displacement from their original positions using a 2D grid within the image:

$$C_{disp}(p) = \|P_{init} - p\|^2$$

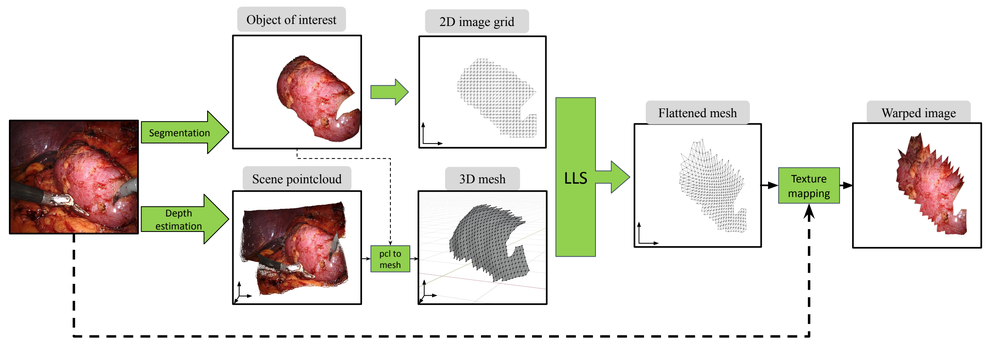


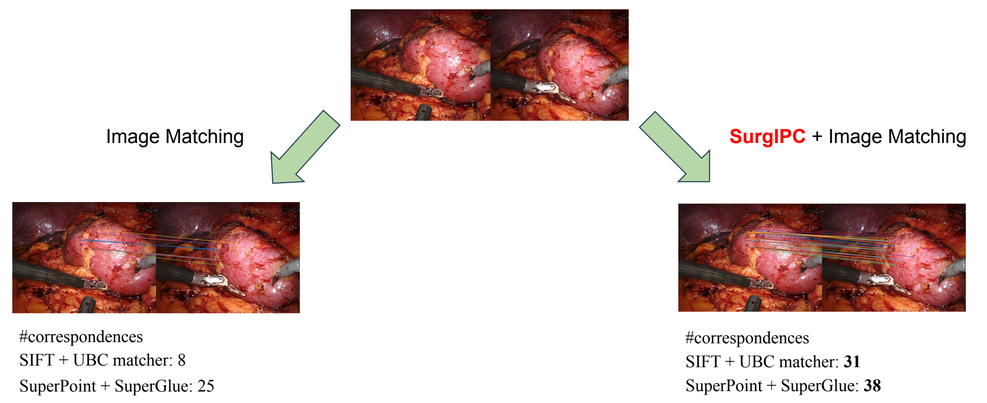
- We combine the 3D conformal and image displacement costs to achieve the simultaneous preservation of 3D angles and the prevention of resampling:

$$C_\lambda(p) = \lambda \mu_{conf} C_{conf}(p) + (1-\lambda)\mu_{disp} C_{disp}(p)$$

- The compound cost is convex, specifically linear least-squares.
- The hyperparameter λ is adjusted between zero and one to balance between preserving 3D angles and resampling.
- In our experiments, λ was selected empirically and remained fixed during the evaluations.

SurgIPC pipeline



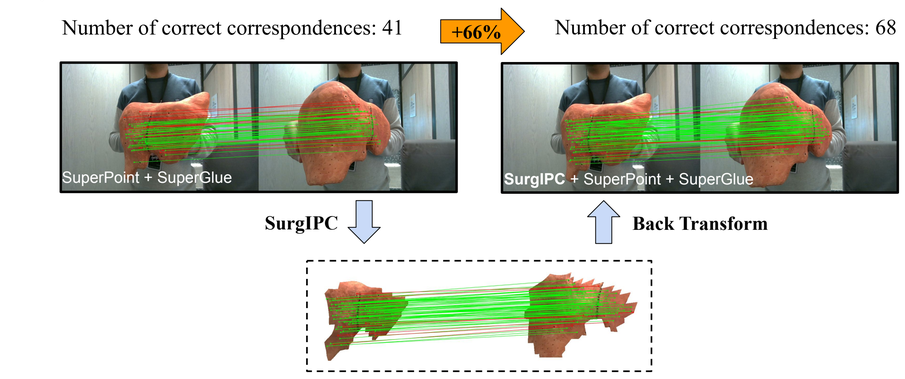


Experiments

Experiments with Liver phantom

- A 3D-printed and painted liver phantom with known camera pose gt

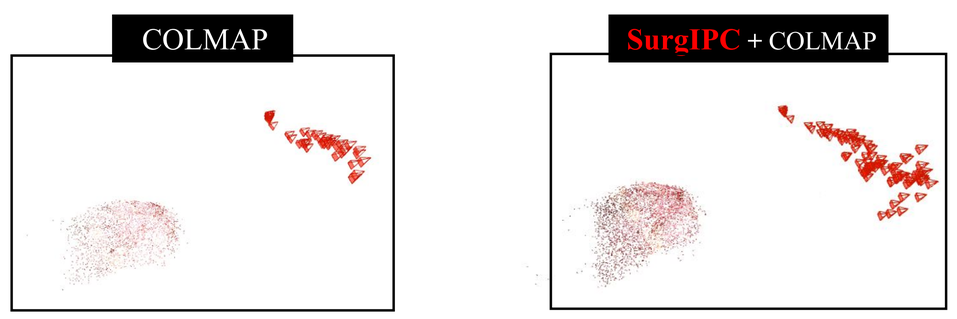
• Qualitative results



• Quantitative results

	#Crsp. ↑		#C. Crsp. ↑		Precision ↑		Recall ↑	
	easy	*hard*	*easy*	*hard*	*easy*	*hard*	*easy*	*hard*
SIFT+UBCMatcher	49	12	45	2	0.92	0.17	**0.80**	0.06
SurgIPC+SIFT+UBCMatcher	**50**	**24**	**47**	**12**	**0.94**	**0.74**	0.70	**0.32**
ORB+NN	**145**	0	94	0	0.65	0.00	**0.45**	0.00
SurgIPC+ORB+NN	142	**5**	**96**	**2**	**0.68**	**0.40**	0.36	**0.08**
SuperPoint+SuperGlue	**137**	53	**135**	41	**0.99**	0.52	**0.90**	41
SurgIPC+SuperPoint+SuperGlue	136	**76**	133	**68**	0.98	**0.65**	0.88	**68**
LoFTR	318	206	295	161	0.93	**0.81**	0.64	0.38
SurgIPC+LoFTR	**324**	**343**	**301**	**264**	0.93	0.77	**0.65**	**0.70**

3D reconstruction



Method	#Cameras	#Registered Imgs.	#Points	Reproj. Error (px)	Time (min)
COLMAP	37	37/95	3303	**0.87**	3.28
SurgIPC + COLMAP	**88**	**88/95**	**4976**	1.02	**1.55**

Conclusions

- SurgIPC boosts the performance of existing keypoint matching in the presence of extreme perspective distortions.
- Proposed method corrects perspective distortions by preserving 3D angles and minimising image resampling.
- Importantly, the method is convex, is adaptable to non-planar scenes, and can effectively use various depth estimation methods as input.

SurgIPC code is available here.

References

[1] Lévy, Bruno, et al. "Least squares conformal maps for automatic texture atlas generation." Seminal Graphics Papers: Pushing the Boundaries, 2002.
[3] SuperPoint: DeTone, D., et al., Superpoint: Self-supervised interest point detection and description. CVPRW, 2018
[4] SuperGlue: Sarlin, P.-E., Superglue: Learning feature matching with graph neural networks. CVPR, 2020

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