CAMERA CALIBRATION AND IMAGE DISTORTION CORRECTION FOR SUPERIOR VISUALIZATION IN MEDICAL ENDOSCOPY

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Abstract:

Medical endoscopy is used in a wide variety of diagnostic and surgical procedures. These procedures are renowned for the difficulty of orienting the camera and instruments inside the human body cavities. The small size of the lens causes radial distortion of the image, which hinders the navigation process and leads to errors in depth perception and object morphology. This article presents a complete software-based system to improve the visualization in clinical endoscopy by correcting radial distortion in real time. Our system can be used with any type of medical endoscopic technology, including oblique-viewing endoscopes and HD image acquisition. The initial camera calibration is performed in an unsupervised manner from a single checkerboard pattern image. For oblique-viewing endoscopes the changes in calibration during operation are handled by a new adaptive camera projection model and an algorithm that infer the rotation of the probe lens using only image information. The workload is distributed across the CPU and GPU through an optimized CPU+GPU hybrid solution. This enables real-time performance, even for HD video inputs. The system is evaluated for different technical aspects, including accuracy of modeling and calibration, overall robustness and runtime profile.

Motivation:

Develop a low cost software solution to correct the radial distortion in medical endoscopy in real-time.

Advantages of a software solution:

- Renders geometrically correct perspective images, provided that the RD is correctly modeled and quantified;
- Flexible since it can be applied to any type of endoscopic equipment, regardless of the lens diameter or the image acquisition technology;
- Very cost-effective solution, as long as the computation uses Commercial, Off-the-Shelf (COTS) hardware.

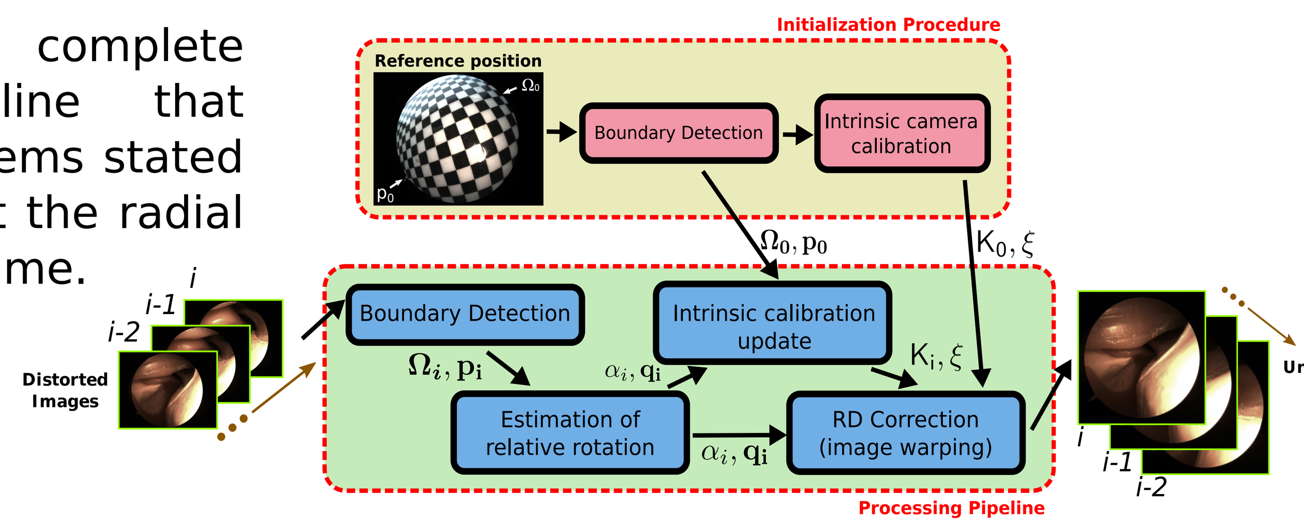
The Problem:

RD correction by software is still not a reality because:

- Camera calibration in the Operating Room (OR): An endoscope cannot be calibrated in advance by the manufacturer because it has exchangeable optics that are usually assembled in the OR before the procedure.
- Changes in the calibration due to lens rotation: The motion between optics and camera sensor changes the projection parameters.
- Execution in real-time: All the computations must be done in real time. This is specially problematic in the case of HD systems providing a frame resolution of 1920 × 1080.

Our Solution:

We present a complete processing pipeline that handles the problems stated above and correct the radial distortion in real-time.



Initial Calibration:

The initial calibration is performed in an unconstrained and completly automatic manner using the SIC algorithm [1] that fully calibrates the endoscope from a single image. This meets the accuracy and usability requirements for a calibration in the OR.

Calibration Results:

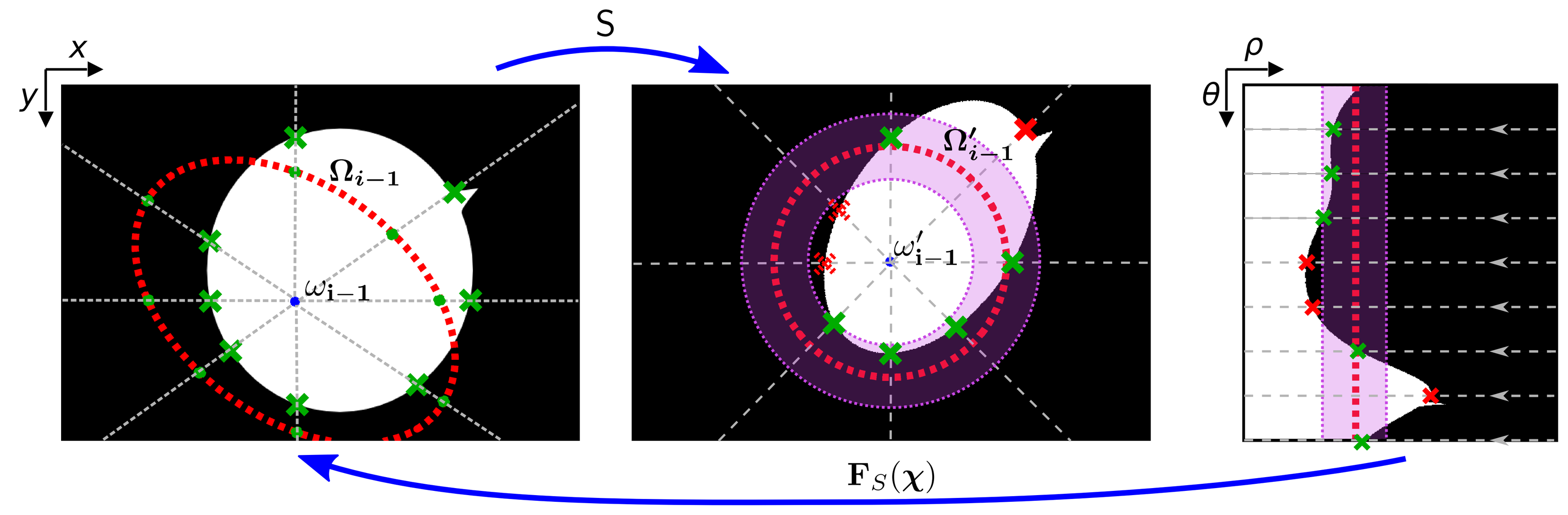
	c_x	c_y	f	ξ
SIC (mean)	595.77	500.14	558.88	-0.527
SIC (std)	7.069	4.889	34.935	0.0066
Bouguet	599.32	497.08	541.90	-0.497

Comparison between SIC (using single images and Bouguet calibration (using 10 images)

Calibration box used to control the lightning conditions

Boundary Detection:

In order to infere the realtive rotation between lens and camera, the meaningful image region has to be segmented at each frame time instant:

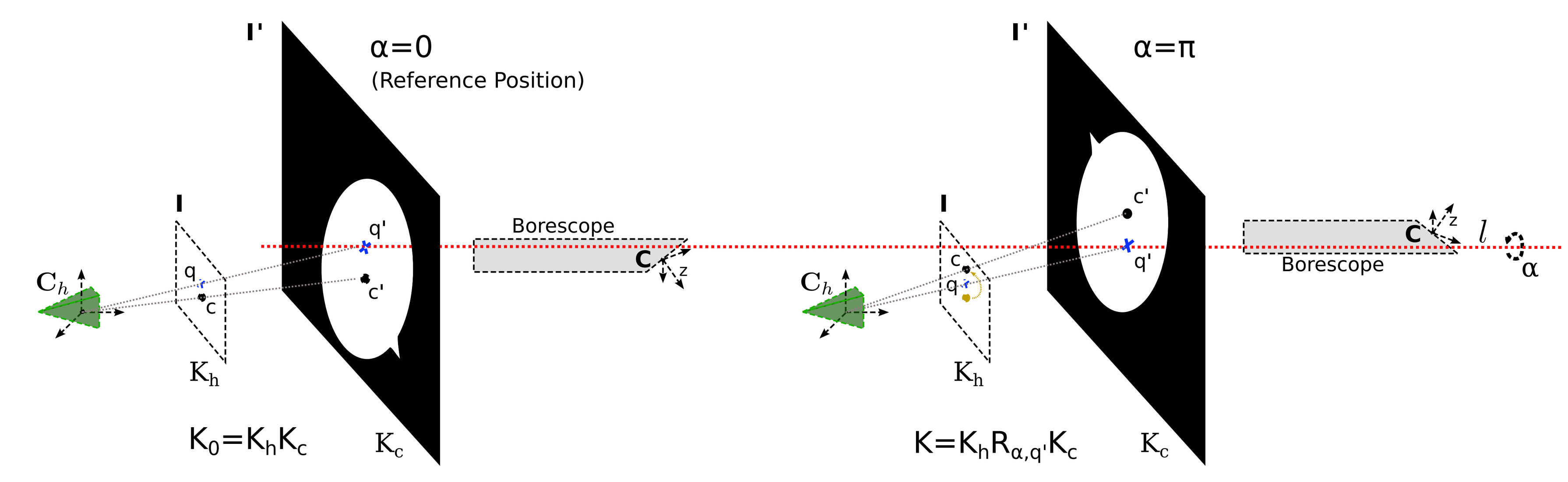


$$\mathbf{x} \sim \mathbf{F}_S(\chi) \sim \mathsf{S}^{-1}\begin{pmatrix}\rho\cos(\theta)\\ \rho\sin(\theta)\\ 1\end{pmatrix} \qquad \mathsf{S} \sim \begin{pmatrix} r\cos(\phi) & r\sin(\phi) & -r\,(w_{i-1,x}\cos(\phi)+w_{i-1,y}\sin(\phi)) \\ -\sin(\phi) & \cos(\phi) & w_{i-1,x}\sin(\phi)-w_{i-1,y}\cos(\phi) \\ 0 & 0 & 1 \end{pmatrix},$$

By changing the image space and performing the tracking of a vertical line we were able to conciliate both robustness and computational efficiency.

Intrinsic Calibration Update:

The lens rotation is modeled as a pure rotation of the image plane around a fixed point not coincident with the principal point of the image.



New Projection Model: $\mathbf{x} \sim \mathsf{K}_i\,\mathbf{\Gamma}_\xi\big(\begin{pmatrix}\mathsf{I}_3 & \mathbf{0}\end{pmatrix}\mathbf{X}\big) \qquad \mathsf{K}_i \sim \mathsf{R}_{\alpha_i,\mathbf{q}_i}\,\mathsf{K}_0$

The rotation point q_i is estimated at each frame time instant using an EKF.

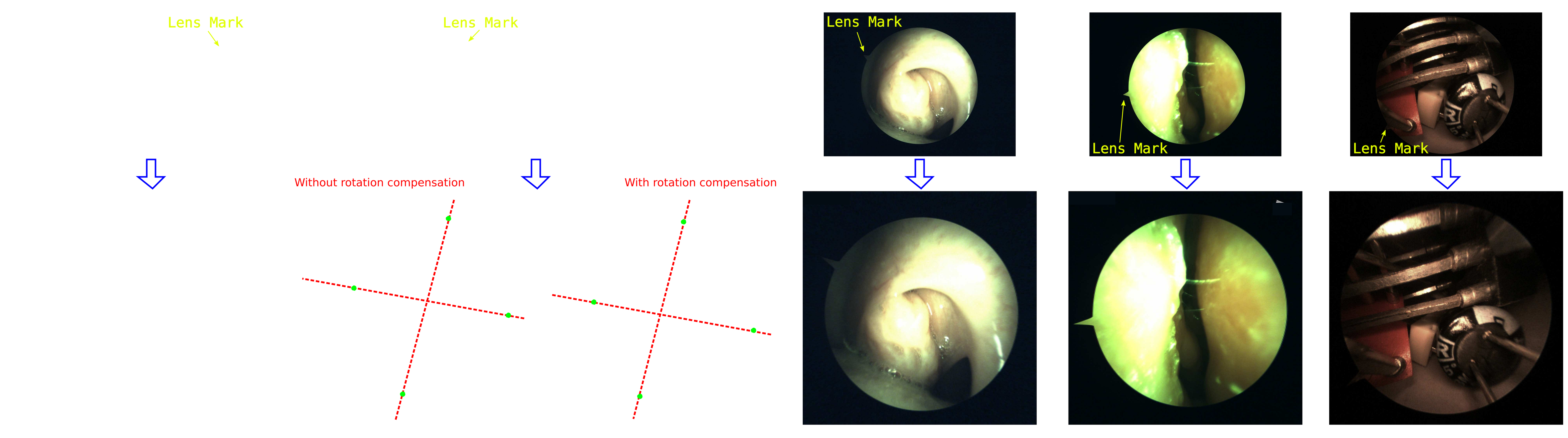
Radial Distortion Correction:

The radial distortion is modelled using the so called *Division Model.*

$$\mathbf{F}(\mathbf{y}) \sim \mathsf{K}_i\,\mathbf{\Gamma}_\xi\big(\mathsf{R}_{-\alpha_i,\mathbf{q}''_i}\,\mathsf{K}_y^{-1}\,\mathbf{y}\big)\,.$$

K_y specifies certain characteristics of the undistorted image (e.g. center, resolution), $R_{-\alpha i\,,q''}$ rotates the warping result back to the original orientation, and q'' is the back-projection of the rotation center q_i.

Results:



(a) Calibration image. (b) Rotation of the lens cylinder. (c) Oral cavity. (d) Nasal cavity. (e)Artificial scene

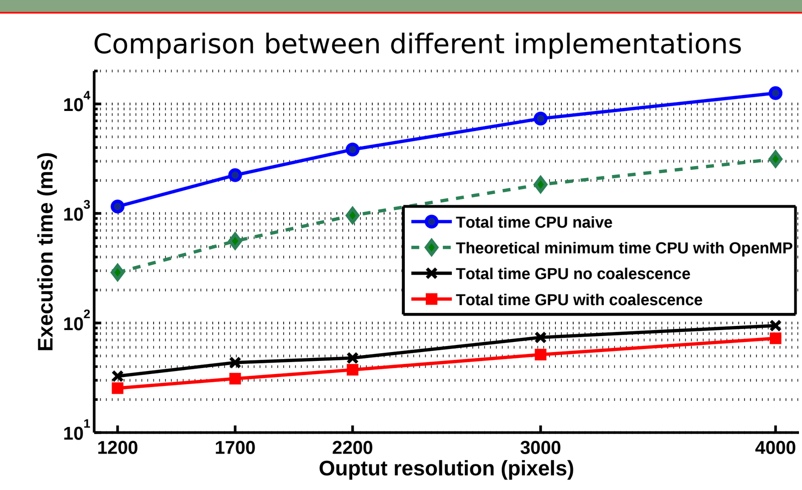


Table 1: Execution times, in milliseconds, and frames per second (*fps*).

Input size	Output size	I.C.	B.E.	R.D.C.	Total (ms)	fps
640x480	700x700	2.53	3.48	2.51	**8.52**	**117**
640x480	1500x1500	2.51	3.15	7.92	**13.58**	**74**
1280x960	2000x2000	9.38	4.52	13.52	**27.41**	**36**
1280x960	3000x3000	9.37	5.36	28.21	**42.94**	**23**
1600x1200	2200x2200	11.86	5.02	17.22	**34.11**	**30**
1600x1200	4000x4000	11.72	4.88	51.39	**67.99**	**15**
2448x2048	3000x3000	30.27	11.89	32.07	**74.23**	**13**
2448x2048	5000x5000	30.17	12.46	79.88	**122.51**	**8**

[1] J. Barreto, J. Roquette, P. Sturm, and F. Fonseca, “Automatic Camera Calibration Applied to Medical Endoscopy,” in BMVC, 2009.