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Paper: "Anatomical Reconstructions of Pediatric Airways from Endoscopic Images: A Pilot Study of the Accuracy of Quantitative Endoscopy"

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A. Intent

Traditional methods of laryngeal surgery involved disruption of the laryngeal framework which then led to motor and sensory deficits of the patients. Attempts to improve and possibly avoid such external invasive procedures led to advances in endoscopic laryngeal surgery that access the endolarynx through the mouth of the patient. Despite the enhancements to the endolaryngeal surgery triggered by improvements in microlaryngeal instrumentation and endoscopes, the current set up of endolaryngeal surgery continues to have disadvantages. Currently, there does not exist a non-invasive way to measure the airway. Treatment requires accurate measurement of airway caliber and shape. Current methods for pediatric airway assessment use endoscopy to gather measurements of airway size and shape using computed tomography with thin spiral scan technology. The drawbacks of such approach include exposure to ionizing radiation with small but finite oncologic risk. The most commonly used method for airway assessment is serial placement of endotracheal tubes of ascending size. Surgeons repeat this process while making note of the ability to pass the tube and also leak air around the tube during peak inspiration. One of the shortcomings of the procedure is that the approach itself may alter the target that it is trying to measure and cylindrical endotracheal tubes are not completely apt for sizing airway.

The authors of the paper have proposed and tested a novel system to size the airway by processing a video sequence taken intra-operatively using a rigid airway endoscope. The authors named this process 'quantitative endoscopy' (QE). The study compared the results obtained by QE to the measurements obtained by CT readings. QE does not involve radiation and is not physically traumatizing to the airway. The main contribution of the study is a prototype system that combines multiple images from a moving rigid endoscope with an attached external tracking system. Such a system is capable to producing accurate scaled 3D representation of the inner surface of the airway.

B. Technical Summary

In order to accurately reconstruct a 3D structure from 2D images, the authors used binocular image pairs to determine the distance from the camera to an object. Before the start of the quantitative endoscopy study discussion, the authors described the general properties of a standard camera model and how the real world view is transformed into an image. Next, the authors explained the geometry of the imaging process to constrain the 3D structure of the images. Finally, the data contained in the images was fused with the relative locations of the camera to generate measurements.

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B.1 Pinhole Camera Model

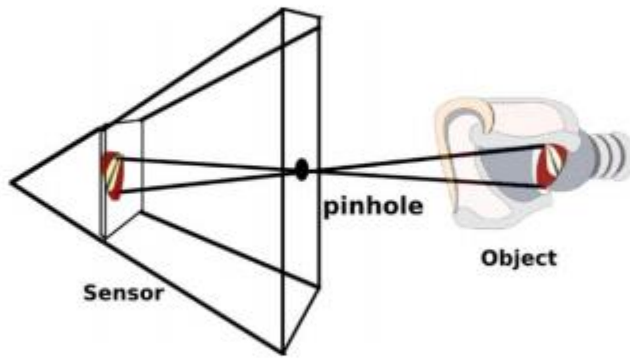

Figure 1.The pinhole camera model

Pinhole camera model is described in figure 1. Cameras can be characterized by this model if image distortion caused by the camera lens itself is addressed and the image is un-warped before any image processing is done with the acquired image. The model has an inconvenient ambiguity known as scale. The authors describe the scale ambiguity in a following way: Given a point *P* in 3D, the model projects the point onto the 2D image plane of a camera. Consider the light ray that is reflected by point *P* which enters the camera through the pinhole. Point *P* can then move along that line and the location of the imaged point *p* will remain constant even though the real world coordinates of *P* has changed. This is called scale ambiguity.

B.2 Stereo Vision

To address the scale ambiguity, consider a system with two cameras.

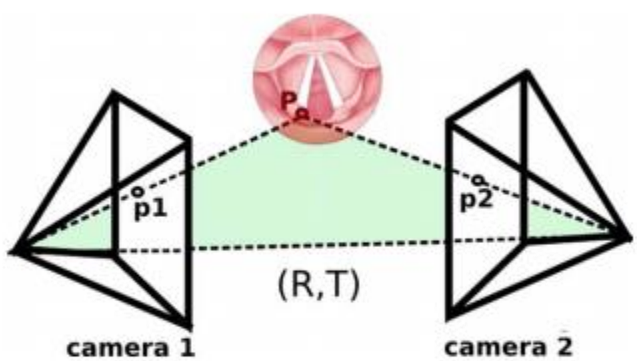

Figure 2. Geometry of stereo vision.

Using two cameras, the goal is to measure the location *P* using the two image projections *p1* and *p2.* The line connecting the two cameras forms a triangle. Given two known projective cameras (calibrated cameras) and the relative position of the two cameras, the 3D location of the scene point can be determined by triangulation. The main technical challenge with stereo vision system is to accurately take a location in the first image *p1* and find the corresponding location in the second image *p2.* Additionally, the relative camera poses must be figured out as well in order to make assessments about the airway. Instead of using two cameras in a narrow airway, the authors use a system with only one camera to achieve stereo vision. Under the static scene assumption, it is trivial to note that stereo vision can be achieved by a single moving camera. Stereo vision from a single moving camera is illustrated in the figure below.

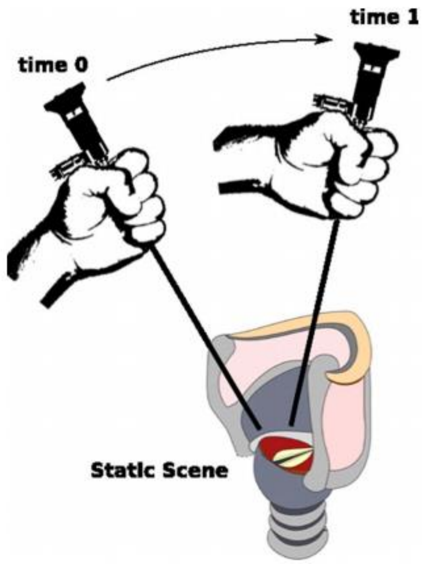

Figure 3. Static scene imaged over time by a moving camera.

Figure 3 shows a rigid endoscope imaging a static scene. If the scene is non-moving, an image taken from the camera at a given time can be considered an image from a unique camera. In conclusion, assuming the 3D scene does not change over time, a moving projective camera can be used to reconstruct a scene from 2D images of the camera.

B.3 Materials and Methods

The quantitative endoscopy study was performed under IRB approval. Subjects from the Johns Hopkins Pediatric Otolarygology department included five children who required direct laryngoscopy, rigid bronchoscopy and computed tomography.

B.4 Procedure

The authors present the following procedure for their quantitative endoscopy system:

1. An operating room capable of collecting data was prepared with Aurora electromagnetic measurement system, a data collection computer, and a sterilizable endoscope tracker.
2. Electromagnetic measurement tracker was attached to the endoscope to record the endoscope's motion. The instrument of choice was Karl Storz 5 mm Hopkins rod endoscope with Stryker or Karl Storz high-definition video tower.

3. Subjects' CT scan was obtained from the Johns Hopkins Department of radiology's PACs server.
4. Enrolled subjects underwent routine video endoscopy.
5. All imaging and endoscope motion measurements were time stamped.
6. Using the time stamp from both sets of data, authors determined the relative position of the endoscope at the moment the image was recorded.
7. Recover scale from EM tracker position data meaning that translational motion between two given camera positions is calculated.
8. Compute feature points in images. Match feature points and the scale information from the EM tracker to generate triangulated 3D feature points.
9. Compute a surface as a function over the triangulated feature points using thin-plate spline models deformation technique. The result is a 3D surface representation of the inner surface of the airway.

B.5 Outcome Measure

The airway cross-sectional area and the airway diameter as a function of depth and position were the measure of accuracy and potency of the new system. The ground truth measurements were provided by CT scan data of the subjects. For comparison purposes, the authors extracted an isosurface of the trachea beginning in the subglottic region and extending to the bifurcation. Then, authors manually aligned the CT extracted volume with the QE computed volume in the depth dimension. The alignment was refined using iterative closest point algorithm. The authors measured surface area of the two volumes (resulting from both QE and CT) at pediatric intervals along the z-axis which generates 2D contour lines. The areas inside of the contour lines were computed using Green's theorem.

B.6 Results

The result data is presented in the table below.

TABLE I.
Statistical Results for Area and Diameter Measurements.

Sample	Mean Area Error (mm2)	Std	Mean Diameter Error (mm)	Std
Set 1	−2.24	±33.59	−0.029	±2.54
Set 2	−8.88	±35.198	−0.312	±2.42
Set 3	14.27	±30.38	0.810	±2.22
Set 4	5.78	±35.07	0.400	±2.62

The table presents the mean difference between area and diameter from 2 subjects. Sets 1 and 2 correspond to the first patient and the sets 3 and 4 are from the second patient. The results show that the mean difference is consistently closed to zero compared to the diameter. A small mean difference suggests that QE is very accurate and has an error with diameter less than a 1 mm compared to ground truth data provided by prior CT scans of the patients.

C. Significance

1. The work presented by the authors demonstrates a proof of the concept of quantitative endoscopy.
2. The method requires little overhead and does not disrupt the already existing intra-operative surgical workflow.
3. The quantitative endoscopy allows for assessment of a structure without radiation or physical manipulation of the target.
4. The presented system can be broadly applied to other non-airway systems for assessment.

D. Relevance

	Our Project	Reviewed Project
Similarities	Attempts to achieve non-invasive intra-operative measurement of an inner structure.	
	Uses stereo vision techniques to match feature points and generate depth value.	
Differences	Flexible endoscope	Rigid endoscope
	Cannot use external tracker to gather position data of the camera at a given time.	Uses EM tracker to gather camera pose information.
	Robot manipulates the scope.	Hand manipulated scope.

E. Critique

Strengths	Weaknesses
The authors make a very clear statement of the problem.	The variance of the measurements seems relatively too high.
Very extensive and thorough background information on a pinhole camera model and stereo vision.	Given the inherit small baseline values, the error due to external tracker might have a reasonably big error in the assessment of the airway.
The surgical procedure is laid out very clearly.	Static scene assumption may be a too strict of an assumption. The airway might be moving due to subject's lung or cardiac movement.
The authors included intuitive and high-quality diagrams to aid their background summary.	The authors use CT scan data as the ground truth. However, the subject's airway structure might be different during a CT scan and during a QE.
	Minimal mathematical and technical details about the actual algorithms for feature detection, matching, 3D reconstruction and

	bundle adjustment techniques. (I actually found a draft of a paper that describes the mathematical background and the technical summary of the algorithm. The paper is not published)
	Even though the study was a pilot study, the number of test subjects could have been more.

F. Citation

Eric M. Meisner, Gregory D. Hager, Stacey L. Ishman, David Brown, David E. Tunkel, Masaru Ishii (2013). Anatomical Reconstructions of Pediatric Airways from Endoscopic Images: A Pilot Study of the Accuracy of Quantitative Endoscopy. The Laryngoscope, 123, 2880-2887