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Original Research Article

# Determining the shift of a bronchoscope catheter from the analysis of a video sequence of a bronchoscope video camera

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ABSTRACT

In this study we have proposed an algorithm for automated monitoring of the movements of a catheter used in peripheral bronchoscopy examination. We have shown that the shift of the catheter can be controlled in an automated way with quite a good accuracy by the means of analysis of video sequence recorded by a video camera of a bronchoscope. For a catheter moving between successive frames by no more than 1/3 of the distance between successive markers associated with a catheter the accuracy of a catheter shift measurement was equal to 1% and for a catheter moving between successive frames by no more than 1/2 of the distance between successive markers associated with a catheter the accuracy of a catheter shift measurement was equal to 5%. Visual inspection proved that the observed measurement errors were associated with faster movements of a catheter. Bronchoscope redesign option is proposed to improve catheter shift measurement accuracy. The results of this study demonstrate that application of image analysis techniques to data recorded during bronchoscopy examination can at least support the existing navigation methods for peripheral bronchoscopy with respect to the determination of the location of the catheter distal tip within the lumen of the pulmonary airways.



## 1. Introduction

Bronchoscopy is an endoscopic procedure used to examine pulmonary airways most frequently for the presence of malignant lung lesions [1,2]. It involves inserting a bronchoscope into the trachea and the central airways. The bronchoscope is equipped with a fiber optic bundle what enables illumination and visual inspection of the lumen. The video signal so captured is exported to a video processor and provides cues for a physician to guide the bronchoscope to the target location. The bronchoscope is also equipped with a working channel. Through the working channel a physician inserts additional instrumentation to collect biopsy samples (using a biopsy forceps, a cytology brush, a transbronchial needle aspiration) or EBUS probes.

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Due to the large diameter of commercially available bronchoscopes, video-guided examination of the pulmonary pathways is restricted to their central parts. Commercial bronchoscopes can reach third or at most forth bifurcation of the respiratory tract. Examination of peripheral parts of pulmonary airways requires application of a guide sheath and a guiding device (hereafter we use a term catheter to refer to the unit of a guide sheath and a guiding device). The guide sheath is a flexible plastic tube with a metal marker on its distal end and an external diameter from about 2 to 3 mm. The guiding device is a flexible metal wire with a distal end which can be flexed in a controlled manner using a special handle mounted on a proximal end of the guiding device. The guiding device is inserted into the guide sheath and both are advanced as a whole through the working channel of the bronchoscope and further through the lumen of pulmonary airways. Using the handle mounted on the proximal end of the guiding device a physician rotates the guiding device, flexes its distal end and pushes the guide sheath together with the guiding device to guide both toward the target location. The guide sheath plays thus the role of an extended working channel and targets as far as from 5 to 10 cm from the distal end of a bronchoscope can be reached this way. After reaching the target location the guiding device is removed from the guide sheath and instrumentations of the choice are inserted through the guide sheath. There are no visual cues while advancing a catheter through the lumen of peripheral parts of the pulmonary airways toward the target location. For this reason navigation to the target location without any additional support relies heavily on the skills of a physician performing an examination.

As follows from the above description the final success of a peripheral bronchoscopy depends, among others, on precise determination of the translational movement of a catheter. At present the translation of a guiding device can be controlled in an automated way using electromagnetic navigation bronchoscopy (ENB) [3–5], which – according to the manufacturer – provides accuracy of the translation up to 5 mm. ENB requires however a very specialized hardware and software. In the present study we focus on an alternative approach of determining the translation of a catheter based only on the analysis of a video sequence of a bronchoscope video camera. In contrast to ENB we need only a specially designed software system to determine the shift of a guiding device and a guide sheath – no special hardware is necessary for this purpose. The principal contribution of the present study is the design and tests of a software system specialized for measuring the translation of a catheter.

## 2. Material and methods

### 2.1. Material

A schematic view of a distal part of the video acquisition system is shown in Fig. 1. In basic terms, there are two bundles of optic fibers within a bronchoscope wire. The first one is used to illuminate the lumen of pulmonary airways. The second one is an optic tract of a video camera of a bronchoscope. The sequence of video frames recorded by a video camera is

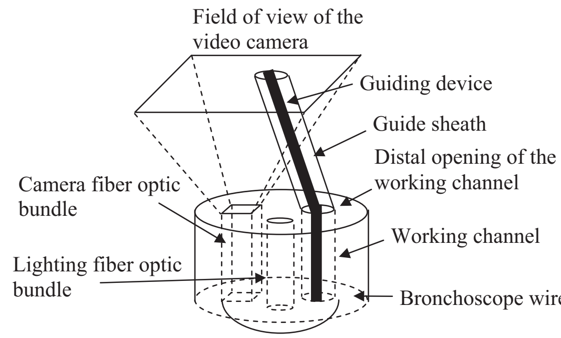


**Fig. 1 – A schematic view of a distal part of the video acquisition system.**

transmitted to a video processor which displays the video on a screen in a treatment room. The video processor has both digital and analog outputs thus providing facilities for recording and on-line capturing and analysis of the video data. The video sequences analyzed in this study were recorded with a bronchoscope model BF-1TH190 (Olympus Co., Tokyo, Japan) and a video processor model CV-190 (Olympus Co., Tokyo, Japan). The video sequences were captured by the video camera at a rate of 30 frames per second. The size of a frame was 720 by 480 pixels. To transmit the video sequence to a PC we used a frame-grabber connected to an analog output of a video processor.

The algorithms developed within this study were tested on three classes of video sequences. The first class was recorded for a catheter (a guiding device inside a guide sheath) advanced through a lumen of a phantom of pulmonary airways (Fig. 2) Ultrasonic Bronchoscopy Simulator LM-099 (Koken Co. Ltd., Tokyo, Japan). The design of this experiment is built upon the construction of a guiding device. The distal part of a guiding device (approximately 10 cm long) is a kind of a spring with loops tightly wrapped around the wires used for flexing the tip of a guiding device. In video images it has an appearance of a periodic pattern – a sequence of strips which can be also observed through transparent walls of a guide sheath (Fig. 3). The light of the bronchoscope illumination

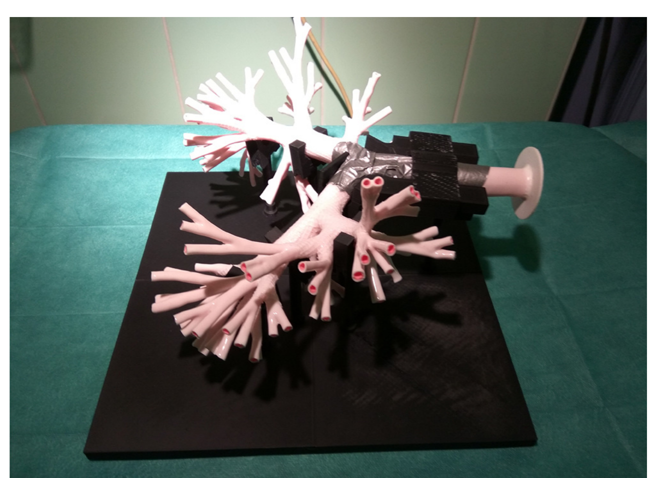

**Fig. 2 – A phantom of pulmonary airways used in the study.**

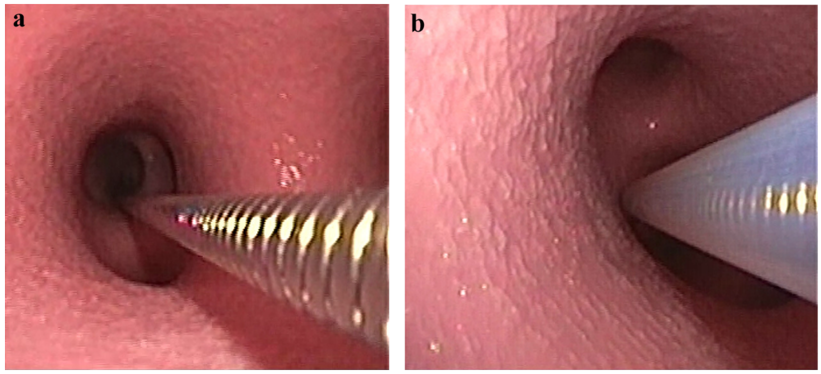


**Fig. 3 – (a) A construction of a guiding sheath; (b) Glares of the bronchoscope illumination at the surface of a guiding device are visible through the walls of a guide sheath.**

system reflected from the surface of a guiding device creates strong glares visible in video images. These glares are also visible through transparent walls of a guide sheath. The algorithm for determining the shift of a catheter is based on detection and tracking of the glares.

The next class of video sequences was recorded during peripheral bronchoscopy examinations of patients. This part of the study was approved by a local bioethical committee. A written consent was received from each patient participating in the study. No special patient exclusion criteria were applied as the experiment differed from a routine treatment only in that the video sequences of the examinations were not only displayed on a screen but also recorded and stored on a hard disk of a computer connected to a video processor. Thus, the experiment did not resulted in an extra burden to a patient. The experiment did not also require any extra engagement of the staff except a few basic operations on the computer.

In the third experiment we designed a special laboratory setting to apply the developed algorithms to determining translations of a catheter with surface covered with a stripped pattern. Because guide sheaths with surface stripped patterns are not available for routine treatment, the experiments were performed in a macroscopic model system build of a camera connected to a PC through a USB port and recording video of an interior of a plastic tube with a diameter of 5 cm and another tube (diameter 1 cm) with a surface covered with a pattern of dark strips (Fig. 4). Video sequences showing shifts of the small tube within the interior of the bigger tube were recorded and analyzed.

### 2.2. *Method*

The general idea behind the bronchoscope video-based monitoring of the translation of a catheter is to analyze the brightness variations at the surface of a guiding device observed through transparent walls of a guide sheath approximately at a fixed distance from the distal opening of the working channel, preferably close the border of the field of view (Fig. 1). These periodic variations of brightness within some region of an analyzed video sequence, which are observed while a catheter is advanced through the pulmonary airways, are related to the movements of the glares of the bronchoscope illumination system at the surface of the guiding device. To find the actual translation of the guiding device (and a guide sheath as well if both are advanced as a whole), we must develop a method for analyzing theses brightness variations while a guide sheath and a guiding device are pushed in or pulled out the working channel.

While guide sheaths used in clinical practice have transparent walls enabling observation of inside movements of the guiding device, it is also possible to develop guide sheaths with surface covered with a stripped pattern. In such a case the shifts of the guide sheath and the guiding device can be measured based either on analyzing the movements of the stripped guide sheath pattern or the movements of the glares at the surface of the guiding device. The pseudo-code of the algorithm for measuring this shift is independent on the actual choice of the traced pattern and is shown in Algorithm 1.

**Algorithm 1.**

```
Retrieve the first video frame from the video sequence;
Determine mask region;
Detect periodic blob pattern of a catheter;
Create a tracker for tracking the rightmost blob of the
periodic pattern of blobs in video frames;
Shift := 0;
while(1) {
  Retrieve a new video frame from the video sequence;
  Determine mask region;
  Detect periodic blob pattern of a catheter;
  Track the rightmost blob of the periodic pattern in the
new frame;
  Update shift based on comparison of the position of the
rightmost blob of the current frame with the tracked
position of the rightmost blob from the previous frame;
  Associate a new tracker with the region of the new
rightmost blob;
}
```

Below we describe the consecutive steps of the algorithm in more detail. In the implementation of the algorithm we use OpenCV version 3.2 [http://opencv.org/].

#### 2.2.1. *Determining the mask region in the video sequence*

The detection of a catheter movement is based on analysis of periodic brightness variations at the surface of a guiding device. An image mask is created to restrict the search for these variations to a smaller region where they can be

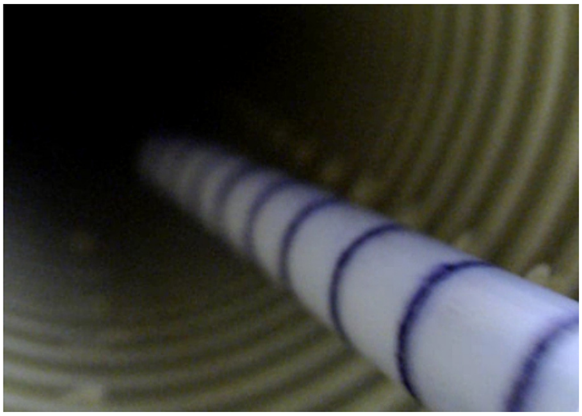

**Fig. 4 – An experimental setting involving tracking of a stripped pattern.**

expected to be observed. The distal opening of the working channel is at a fixed position relative to the center of the video camera field of view. However, although the camera captures images of objects within a 3D region of a broad solid angle, only a part of a catheter beginning at a small distance from the opening of the working channel is visible. For this reason the catheter is not mapped to a fixed position related to the image coordinates. Rather, when a catheter moves in 3D space, we observe it sliding along a video frame edge. As the invisible part of the catheter between the opening of the working channel and the borders of the 3D field of view is small, the movements of a catheter are restricted to a well-defined image region, which can be defined in advance and will be referred to as a primary mask (Fig. 5). This primary mask region is found experimentally and is fixed throughout the algorithm operation. Of course we could use some object tracking algorithm as well but there are no clear benefits from this extra burden.

We further localize the contours of a guide sheath and based on these contours we create the final mask which is defined as the image region within the catheter contours. To detect the contours of the guide sheath in the video image we apply the following processing to the video frames. First, the original RGB frames (Fig. 5) are converted to a gray scale and then we apply a Gaussian blur filter to them (with the kernel size equal to 15 pixels). Then, we apply the Canny edge detector to the image of a catheter (thresholds equal to 5 and 10, the kernel size of the Sobel edge detector equal to 3). Next, all edges return by the edge detector which are outside the primary mask are removed (Fig. 5) and a negative of the edge image is created.

After application of the above listed processing steps, the edges of the guide sheath are always linear black objects over a white background. The edges detected by the Canny edge detector do not form continuous catheter contours. Thus, to detect these contours we apply a variant of Dijkstra's algorithm. In particular a unit level is assigned to all black pixels and a level of 255 is assigned to white pixels. The top and bottom contours of the guide sheath are detected separately. To detect the bottom contour we create a priority queue of pixels with the horizontal coordinate equal to some parameter RIGHT (corresponding to the right edge of the region of interest in the interior of the black padding of images returned by the frame-grabber– see Fig. 5), vertical coordinate in the lower half of the frame and contained within the primary mask. To each of these pixels we assign a ''distance'' equal to the levels within these pixels. Pixels with lower ''distance'' value have higher priority in the queue. All other pixels of the image receive very large distance value. Then, the first element of the queue is popped and its neighbors are eventually assigned a new distance value, according to the Dijkstra's algorithm. The algorithm is stopped after the first pixel P with horizontal coordinate equal to some parameter LEFT (we traced the contours of the guide shift within the right third of the region of interest) is popped from the queue. Then, starting from P, the path is reconstructed to the right border of the primary mask. Analogously we detect the upper contour of the guide sheath but this time we start from a priority queue of pixels with horizontal coordinate equal to RIGHT, vertical coordinate in the upper half of the frame and contained within the primary mask.

### 2.2.2. *Determining periodic blob patterns*

To detect the periodic blob pattern of a catheter we apply adaptive thresholding to an analyzed image (after converting it to gray scale). The thresholding computes for each pixel an average over a square box with size BOX and if the gray level at the pixel is higher than mean plus an OFFSET than the pixel is set white otherwise it is set black. Then all holes within blobs – clusters of white pixels – are filled and the blobs which are not inside the mask are removed. Next, the blobs are labeled and quantitative characteristics are calculated for them (size equal

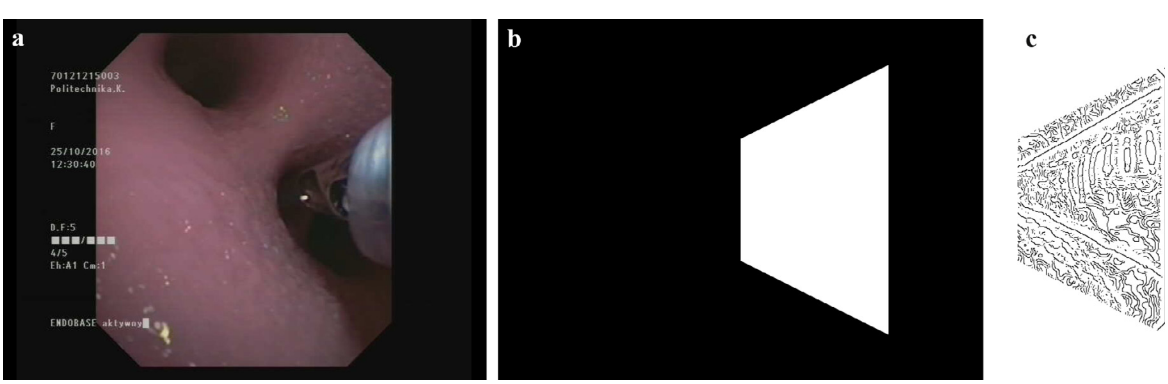


**Fig. 5 – (a) An original image – left; (b) a primary mask region – middle; (c) edges detected by Canny detector – right.**

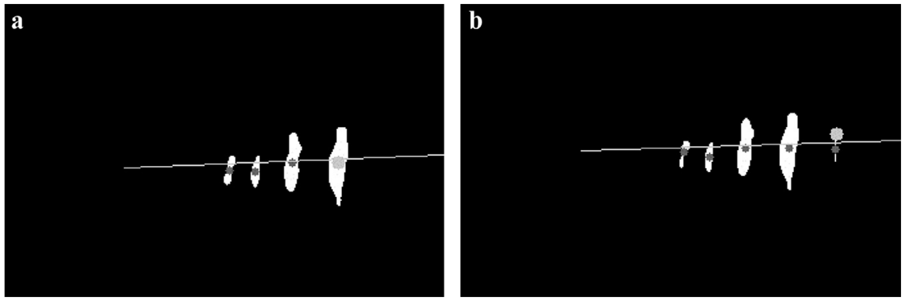


**Fig. 6 – Best line fitted to the centroids (dark gray circles) of the blobs. The centroid of the rightmost blob is designated with a bigger gray circle.**

to pixel count, centroid coordinates and bounding box). Blobs smaller than AREA_THRESHOLD are removed. Then, for the remaining blobs we calculate the best fit line *L*. For this purpose we apply weighted linear regression model to the set of blob centroids and the weights of data points are proportional to the area of the blobs. The distances between blob centroids and *L* are calculated and all blobs at distance from *L* bigger than DISTANCE_THRESHOLD are removed. Then, the best fit line *L* is recalculated (Fig. 6).

After finding the best fit line *L* all the centroids are projected onto *L* and the centroid FIRST which is at the closest distance from the right image edge (as measured along the best fit line) is selected. This part of processing returns FIRST as well as the best fit line *L*.

#### 2.2.3. *Tracking*

At the initialization stage of the processing, after retrieving the first video frame and detecting the rightmost blob, a box enclosing this blob is created for tracker initialization. In the processing we use boxes with fixed size of WIDTH by HEIGH pixels. The movements of the rightmost blob are tracked in original color video frames. The tracking is implemented based on an OpenCV implementation of Kernelized Correlation Filters algorithm [6]. After retrieving a new video frame the tracker is updated and return a new enclosing box of the blob detected in the previous frame. The enclosing box returned by the tracker and thus referring to the rightmost blob detected in the previous frame is tested against the features of the rightmost blob found in the current frame to determine the movement of a catheter, as explained in the next section. Then the tracker of the rightmost blob detected in the previous frame is destroyed and a new tracker is created for tracking the rightmost blob detected in the current frame.

#### 2.2.4. *Determination of a catheter/a guiding device movement*

Given the coordinates of the rightmost blob found in the previous and in the current frame it is first tested if the recorded movement could be accepted (i.e. it is consistent with the overall geometry of the guide sheath). First, the distance between the previous *P* and the current *C* positions of the rightmost blob is calculated. If this distance is smaller than SMALL_MOVE_THRESHOLD then the movement is accepted for further analysis. Otherwise, an angle is calculated between the best fit line *L* and the vector formed by *C* and *P*. The movement is accepted only if the angle is smaller than SMALL_ANGLE_THRESHOLD.

For an accepted movement we test if the box returned by the tracker contains the centroid of the rightmost blob detected in the current frame (Fig. 7). If this is the case, the observed and accepted move is too small to be associated with a new rightmost blob appearing in the field of view or an old rightmost blob disappearing from the field of view and in this case the catheter shift is not updated. Otherwise, either the rightmost blob from the previous frame disappeared or a new

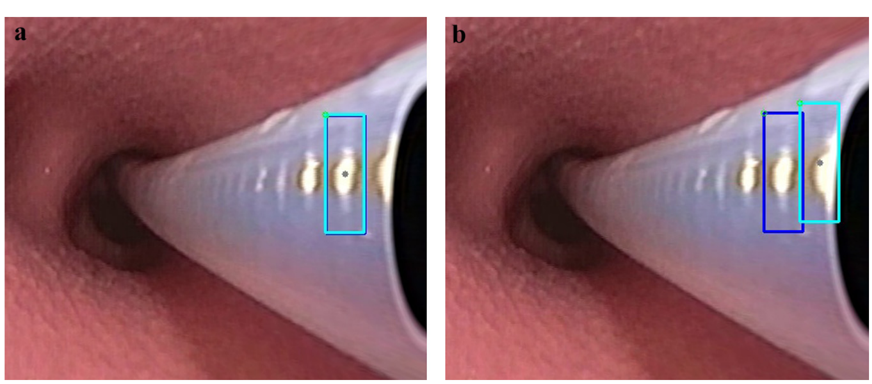


**Fig. 7 – The centroid of the rightmost blob (gray circle), its enclosing box (light blue rectangle) and the enclosing box returned by a tracker (blue). In (a) both boxes almost coincide – there is no new rightmost blob in the current frame as compared to the previous frame. In (b) both boxes are substantially different – a new rightmost blob appeared in the frame.**

rightmost blob is found. Based on the spatial relations between the coordinates of the rightmost blob detected in the current frame and the box returned by the tracker the shift is either incremented or decremented by one. The algorithm returns the number of guiding device turns which passed by the camera.

## 3. Results

The results of the tests of the developed algorithm are presented in Table 1. We recorded four movies for the first experiment, two movies for the second experiment and three movies for the third experiment. In each movie the number *IN* of guiding device loops entering the field of view and the number *OUT* of guiding device loops exiting the field of view were counted visually and in an automated way. The difference *DIFF* between the true (i.e. visually determined) and algorithmically determined values of the `Shift` variable of Algorithm 1 was found. We also determined maximal *MAX* shift (in pixels) of the centroid of the traced blob between successive frames for the case the `Shift` variable of Algorithm 1 is not updated (i.e. the traced blob coincides with the detected rightmost blob, e.g. Fig. 7a) and a mean distance *MEAN* between rightmost blobs detected in successive frames for the case the `Shift` variable of Algorithm 1 is updated (i.e. the traced blob does not coincide with the detected rightmost blob, e.g. Fig. 7b).

The parameters of the algorithm were selected separately for each experiment and were fixed for movies within an experiment.

## 4. Discussion

In this study we have proposed an algorithm for automated monitoring of the movements of a guide sheath and a guiding device used in peripheral bronchoscopy examination. We have shown that the shift of the catheter can be controlled with quite a good accuracy. In the first experiment for a catheter moving between successive frames by no more than 1/3 of the distance between guiding device loops the accuracy of shift measurement was equal to 1% and for a catheter moving between successive frames by no more than 1/2 of the distance between guiding device loops the accuracy of shift measurement was equal to 5%. Visual inspection proved that the observed errors were associated with faster movements of a catheter. The results of the third experiment were even better as accuracy of 0.7% was achieved for a catheter model moving between successive frames by as much as 2/3 of the distance between successive markers. The results of the second experiment demonstrate that with the current settings the accuracy in vivo is two to three times worse than that achievable in vitro.

The clinical application of the proposed method would however benefit from a few improvements. First, the frame rate of the movies recorded in this study was 30 fps. Given the distance between the successive loops of a guiding device equal to approximately 0.5 mm, the safe upper limit for the shift of a catheter is in the range from 2 to 3 millimeters per second which may be too low for comfortable use in clinical settings. For better performance and usability the frame acquisition rate should be thus increased by a factor of 3–4 which is not a technical limitation. Second, the distal part of a guiding device with length approximately 1 cm has no loops. Thus, the algorithm counting loops can start only after a guiding device is pushed into the working channel by a distance sufficiently long to observe guiding device loops in the bronchoscope video images. This initial distance can be predefined and added to the `Shift` variable of Algorithm 1. This problem of course will not be present if guide sheaths with a stripped pattern are used. Finally, the algorithm was tested mostly in an idealized environment. Video sequences recorded during peripheral bronchoscopy examinations prove that mucus present within the pulmonary airways of real patients can potentially disrupt images recorded by the video camera and prevent from detection and tracking of the blobs associated with either the guiding device loops or a stripped pattern of a guide sheath. In such a case an additional burden would be required related to sucking mucus prior to bronchoscopy examination. Alternatively, a distal tip of a bronchoscope can be covered with a transparent layer with thickness of a few millimeters so that the video camera is offset from the distal bronchoscope tip but can still observe lumen of pulmonary airways and the last part of the working channel is within that transparent layer. With that basic redesign the video camera will also observe a part of a catheter inside the working channel. The influence of the conditions external to the working channel e.g. presence of mucus onto the measurement system would thus be minimized.

With the developed method the distance passed by a bronchoscope catheter can be measured with a minimal cost. An ultimate goal of the peripheral bronchoscopy procedure is however collecting biopsy samples. In the case of central parts of the airways typically convex-probe endobronchial ultrasound (CS-EBUS) probes are used to guide biopsy collection. Under ultrasound guidance a physician can direct the biopsy needle toward the lesion which is especially important in cases of lesions located outside the lumen of the pulmonary airways. Recently thin convex-probe endobronchial ultrasound (TCS-EBUS) probes were also introduced [7]. Because of their diameter of these probes can be also used in central parts of bronchial tree. In the case of peripheral sites EBUS miniprobes are used

**Table 1 – Results of the experiments.**

| Experiment | Movie | *IN* | *OUT* | *DIFF* | *MAX* | *MEAN* |
|---|---|---|---|---|---|---|
| 1 | 1 | 61 | 0 | 0 | 13 | 33.3 |
| | 2 | 7 | 34 | 1 | 10 | 31.9 |
| | 3 | 38 | 59 | 1 | 12.2 | 33.9 |
| | 4 | 24 | 24 | 2 | 20.2 | 40.1 |
| 2 | 1 | 20 | 21 | 2 | 10.2 | 31.1 |
| | 2 | 19 | 20 | 1 | 11.1 | 33.4 |
| 3 | 1 | 27 | 28 | 1 | 59.2 | 95.0 |
| | 2 | 25 | 25 | 0 | 58.1 | 98.7 |
| | 3 | 19 | 19 | 0 | 62.6 | 99.6 |

instead [8]. EBUS miniprobes are used in combination with a guide sheath: first a guide sheath together with a guiding device are advanced through a working channel of a bronchoscope toward the target location and next, the guiding device is removed and a EBUS miniprobe is inserted into the guide sheath instead to check if a navigation to a target location is correct. Finally, EBUS miniprobe is removed and an instrumentation for biopsy collecting is inserted into the guide sheath. The final success of the procedure depends on how precisely the tip of the guide sheath is located with respect to the target location. The results of this study demonstrate that application of image analysis techniques to data recorded during bronchoscopy examination can at least support the existing navigation methods because the distance passed by the guide sheath can be measured with good accuracy which has a direct consequence on the precision of the location of the tip of a guide sheath in the lumen of pulmonary airways.

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