On-line Supplement for IEEE Transactions on Biomedical Engineering paper entitled "Hands-Free System for Bronchoscopy Planning and Guidance"

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Section II-B supplemental material:

Algorithm 1, presented in Section II-B, forms the basis of our approach for computing navigation plans. As an example of how **Algorithm 1** derives a rotate-flex-advance maneuver sequence for branch $\mathbf{b}_j$, consider the situation of Fig. 2. As shown in Fig. 2a, suppose the next branch $\mathbf{b}_{j+1}$ appears in the left-half of the image plane at an angle $\theta = 200°$. Then, the following extrema arise, depending on the wrist position α:

- Hand in neutral position: $\alpha = 0°$
  - $\theta_1 = 110°,\ \theta_2 = 70°,\ right =$ FALSE
  - $T_j = \theta_2 = 70°$ CW rotation, $M_j =$ Down (Fig. 2b)
  - new wrist position $\alpha = 70°$ after rotate-flex-advance sequence
- Wrist at CW limit: $\alpha = +90°$
  - $\theta_1 = 110°,\ \theta_2 = 70°,\ right =$ FALSE
  - $T_j = -\theta_1 = -110°$ CCW rotation, $M_j =$ Up (Fig. 2c)
  - new wrist position $\alpha = -20°$
- Wrist at CCW limit: $\alpha = -90°$
  - $\theta_1 = 110°,\ \theta_2 = 70°,\ right =$ FALSE
  - $T_j = \theta_2 = 70°$ CW rotation, $M_j =$ Down ; i.e., $\mathbf{b}_{j+1}$ appears at the bottom of $I_{\mathrm{CT}}^{\Theta_j}$ (Fig. 2b)
  - new wrist position $\alpha = -20°$

Note that while the neutral position is not an extremum within the context of **Algorithm 1**, it does give a useful instructive situation.

Figs. 7-9 give enlarged versions of Figs. 4-6 appearing in Section II-C.

A video is also available demonstrating the complete guidance process for the example of Fig. 4 (Fig. 7).

Figs. 10-11 provide additional demonstrations of the position-verification mechanism and follow directly after the guidance position of Fig. 4c.

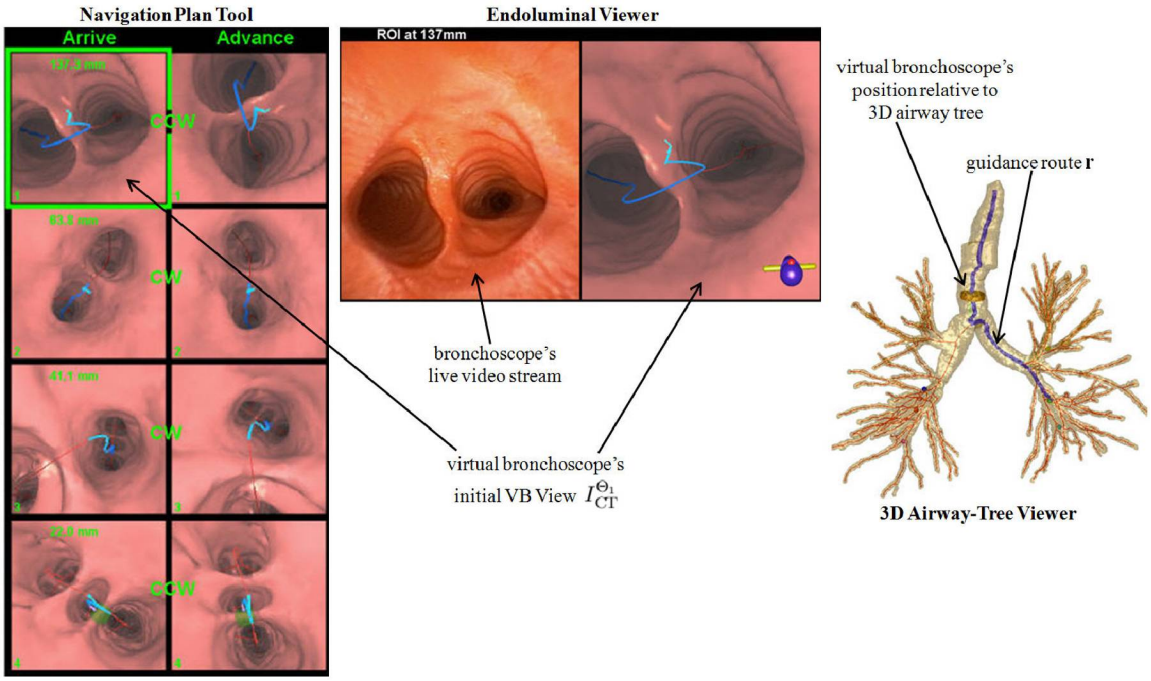
With respect to Fig. 10, the physician invokes the "verify" foot-switch command. This results in a set of concentric targeting circles appearing superimposed on the video-stream view in the Endoluminal Viewer. The physician now adjusts the bronchoscope as needed so that the perimeter circumscribing a nearby airway bifurcation fits in between the two circles. Fig. 10a illustrates these operations, starting from the concluding position of Fig. 4c (also Fig. 7c).

Conversely, Fig. 11 illustrates another situation, also starting from Fig 4c, where the physician evidently flexed and advanced the bronchoscope into an incorrect branch. The physician again invokes "verify,"

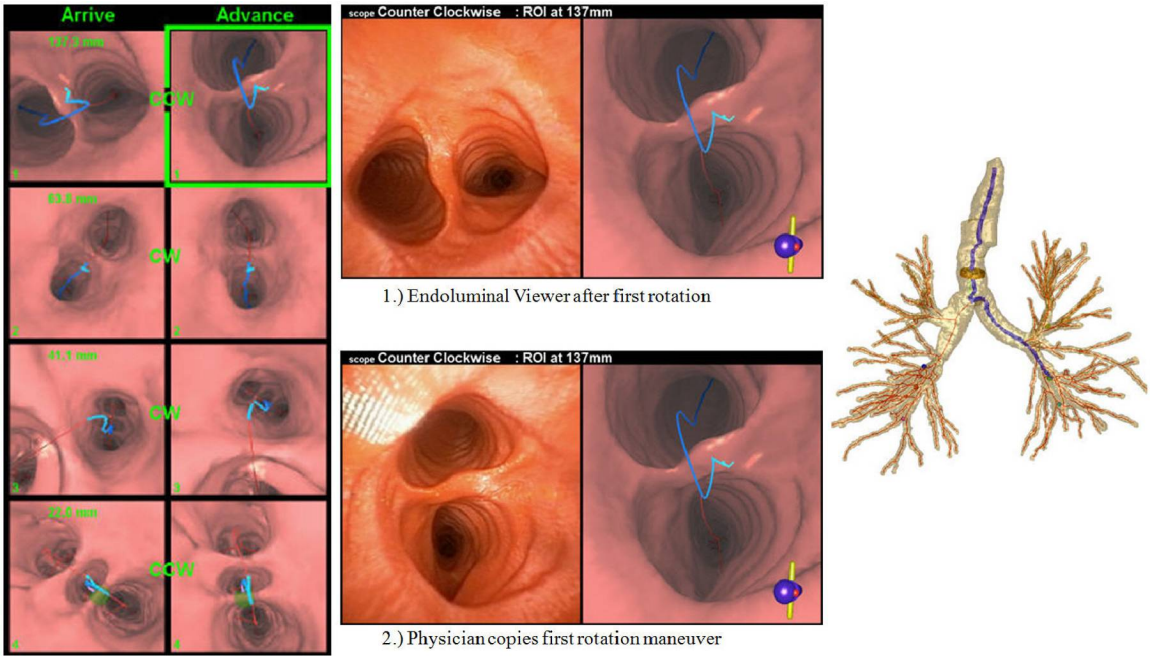
causing the targeting circles to appear on the video frame (Fig. 11a). After adjusting the bronchoscope as needed so that the displayed bifurcation accommodates the limits set by the concentric circles, a second invocation of "verify" produces the result depicted in Fig. 11b. The revised base-camp pair clearly shows a correct real- and virtual-space registration at a location that is off the desired blue route — significantly, the blue route does not appear in either base-camp view. In addition, the message "Off Path! Fall back 2 generations!" appears. To correct this navigation error, the physician follows the given instruction by pulling back the bronchoscope 2 airway generations until returning to the closest correct branch on the route. Navigation can then proceed — the system now waits until the next "rotate" command is invoked.

The physician next invokes the "verify" command again. This causes an automatic registration to occur between the current video view I_{V} and CT-based virtual space, focused on a sub-tree around the current branch $\mathbf{b}_j$. For the example of Fig. 10a, this involves a global registration relative to $\mathbf{b}_1$; the result is shown in Fig. 10b. The Endoluminal Viewer's revised base-camp pair now shows that the bronchoscope's position is in fact correct and asserts this conclusion with the message "On Path. Move forward." The base-camp pair also fuses the blue guidance route $\mathbf{r}$ onto the frozen video view to further assert this conclusion [16]. For the situation of Fig. 10, the physician has successfully verified his/her current position: navigation can now proceed confidently.

With respect to the Study 1 results in Section III-A1, Fig. 11 actually simulated a coughing event, whereby we shook the phantom while the bronchoscope was inserted. As the figure shows, the system's position verification mechanism successfully detected the erroneous position and suggested an appropriate corrective action. Cooperation and care, however, are required in using this feature, as discussed in Section IV.

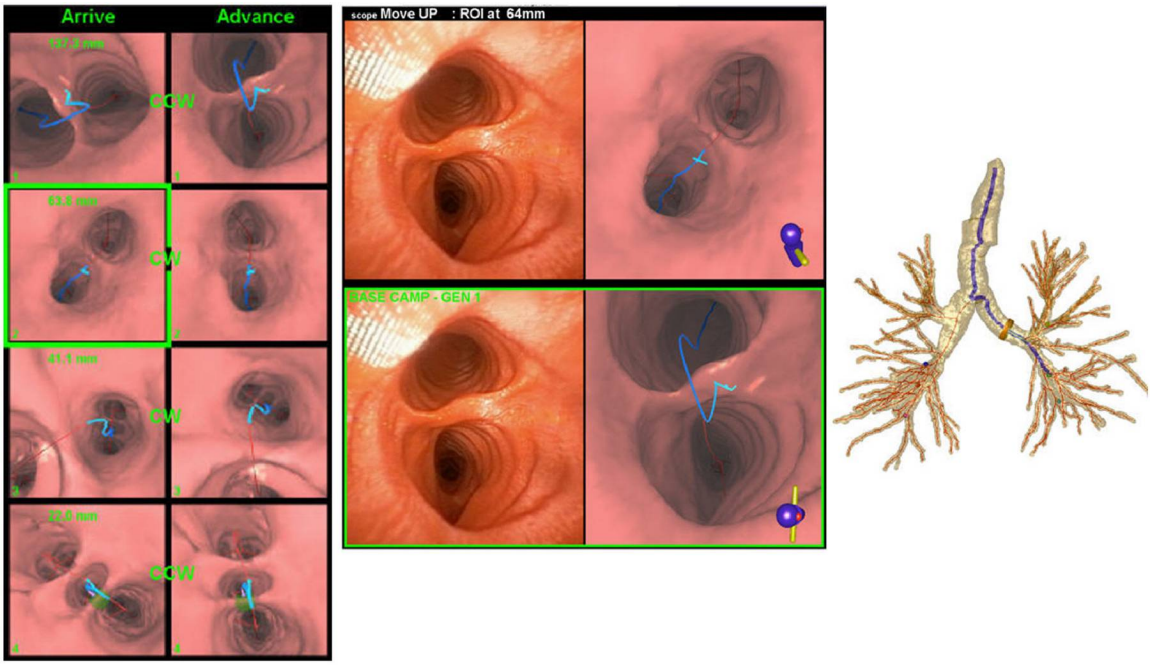


(a) Initial position for first branch $\mathbf{b}_1$ (the trachea)



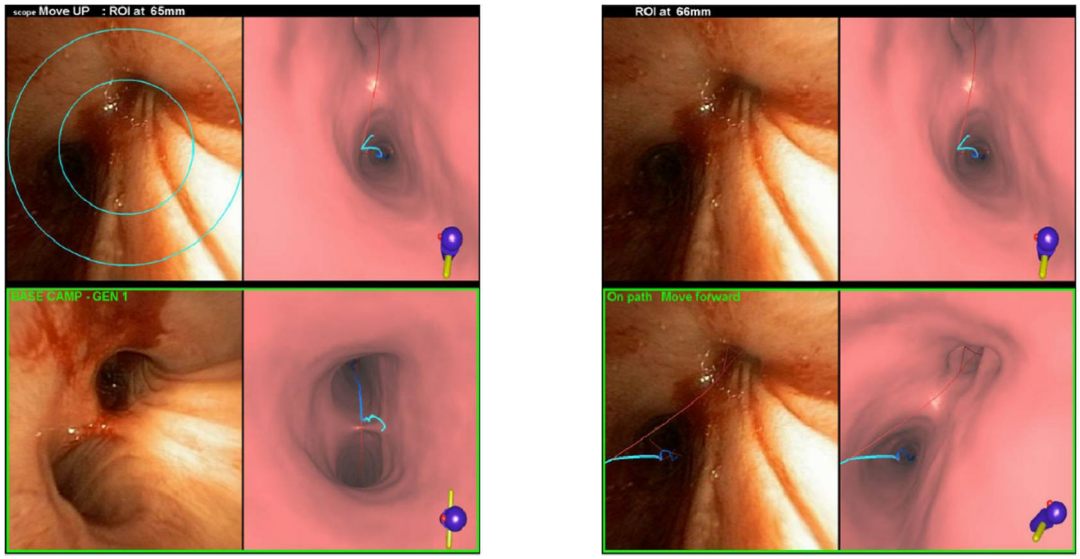
(b) Completion of first rotation for $\mathbf{b}_1$

Fig. 7: Demonstration of the first complete rotate/flex/advance maneuver per **Algorithm 2** (case B — see Table I) [enlarged version of Fig. 4]. (a) System GUI display in preparation for the first rotation. (b) Display after completing the rotation. Endoluminal Viewer labeled "1.)" indicates the state of this tool after invoking the "rotate" foot-switch command, while the panel labeled "2.)" shows the tool's state after the physician rotates the bronchoscope as instructed. The views of the other two tools do not change during this maneuver.



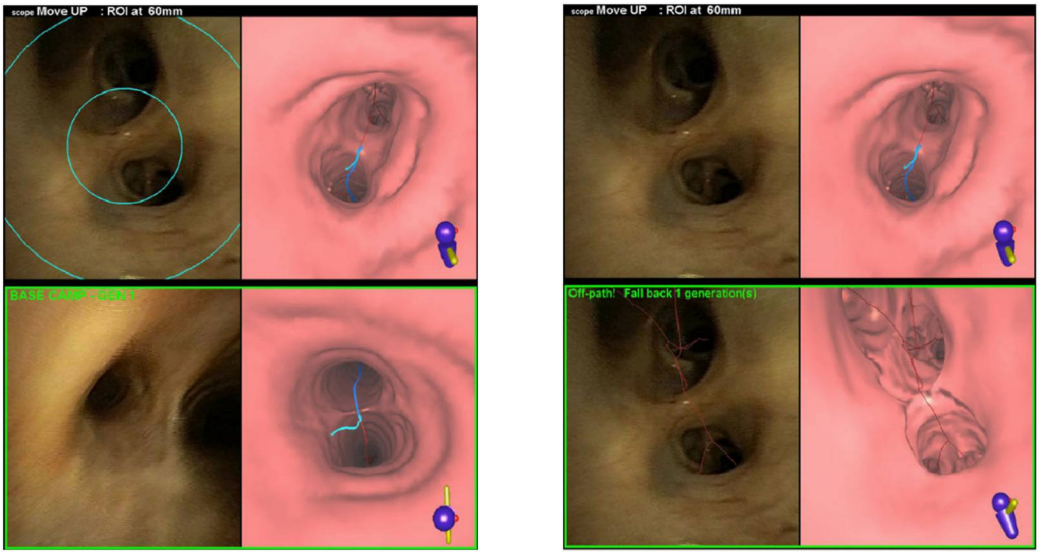
(c) First flex-advance maneuver for $\mathbf{b}_1$

Fig. 7: (continued) (c) System GUI state after invoking the "advance" foot-switch command — instructions appear for performing the required flex-advance command.



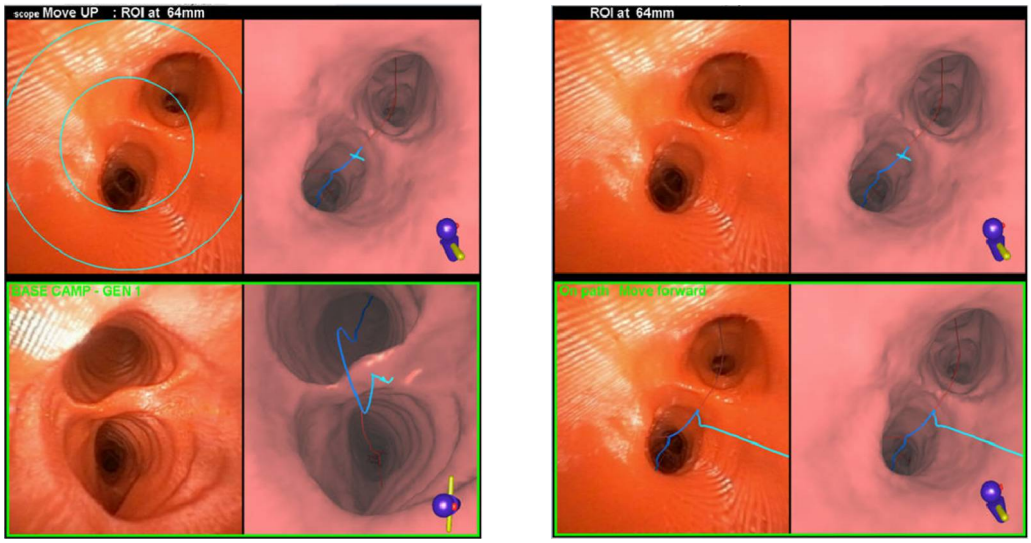
(a) Targeting circles appear for branch $\mathbf{b}_2$ (b) Correct position confirmed after second "verify"

Fig. 8: Use of the position verification mechanism for route $\mathbf{r}_8$, human case D (see Section III-B) [enlarged version of Fig. 5]. (a) The physician appears to have maneuvered the bronchoscope incorrectly into branch $\mathbf{b}_2$, as shown by the base-camp pair. Thus, the physician invokes the "verify" command and adjusts the bronchoscope so that the bifurcation fits between the targeting circles. (b) The physician again invokes the "verify" command — the system's base camp reports "On path. Move Forward." As it turned out, the physician did have the bronchoscope in the correct airway originally, but did not rotate the bronchoscope properly for the branch $\mathbf{b}_2$ maneuver.



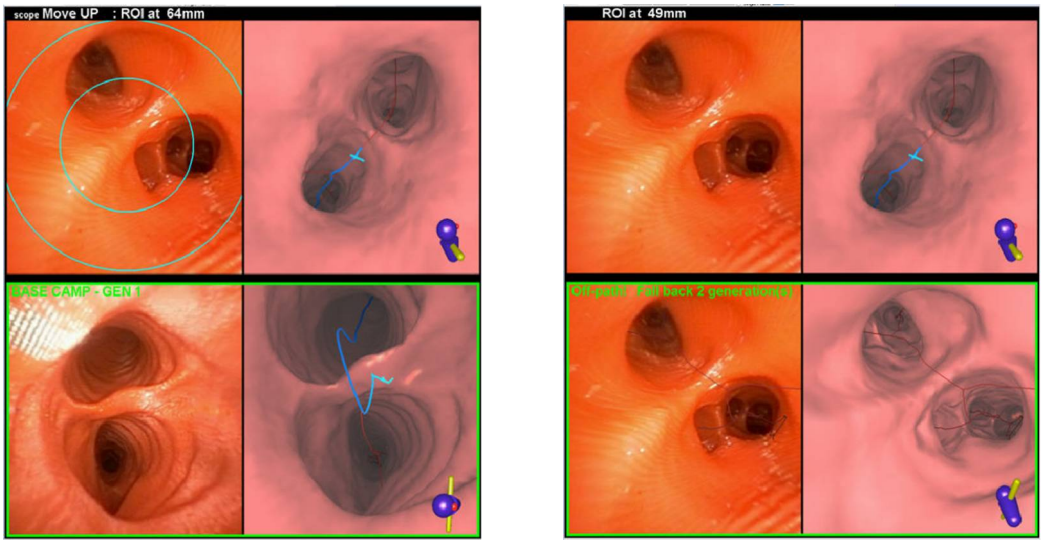
(a) Targeting circles appear. (b) Position error detected after second "verify"

Fig. 9: Error detection example for route $\mathbf{r}_2$, human case F [enlarged version of Fig. 6]. (a) The base-camp view pair shows that the physician has maneuvered off the correct route; because this location is clearly incorrect, the physician invokes the "verify" command. (b) After adjusting the bronchoscope to fit the observed bifurcation within the targeting circles and invoking "verify" a second time, the system correctly indicates the bronchoscope's erroneous position and gives the directive "Off path. Fall back 1 generation(s)" for correcting the error.



(a) Targeting circles appear (b) Endoluminal Viewer after second "verify"

Fig. 10: Demonstration of the position verification mechanism. (a) Starting from position of Fig. 4c (Fig. 7c), the physician invokes the "verify" command and adjusts the bronchoscope's position as needed so that a bifurcation fits in between the targeting circles (this represents the completed flex-advance maneuver for branch $\mathbf{b}_1$). (b) The physician again invokes the "verify" command — the system reports "On path. Move forward" in the base-camp view pair and the blue guidance route appears fused on the video view.



(a) Targeting circles appear (b) Position error detected after second "verify"

Fig. 11: Error detection using the position verification mechanism. (a) Beginning again from the position of Fig. 4c (Fig. 7c), the physician moves the bronchoscope to the position shown — this view evidently seems incorrect — and then invokes the "verify" command. (b) After the physician invokes "verify" a second time, the base-camp view pair clearly shows that the physician has maneuvered off the correct route; the system confirms this with the message "Off path! Fall back 2 generation(s)"; in addition, notice that the registered VB view only shows red centerlines, denoting off-route airways, instead of the correct blue-line route.

Section III-B supplemental material:

Regarding the human studies of Section III-B, Fig. 12 illustrates the extra guidance information presented by the system when navigation reaches the end of a route. As discussed more fully in Gibbs *et al.*, when approaching the final destination, the ROI (green) begins to appear in the VB view. In addition, a large arrow also appears indicating the final airway position for performing a possible needle biopsy [16].

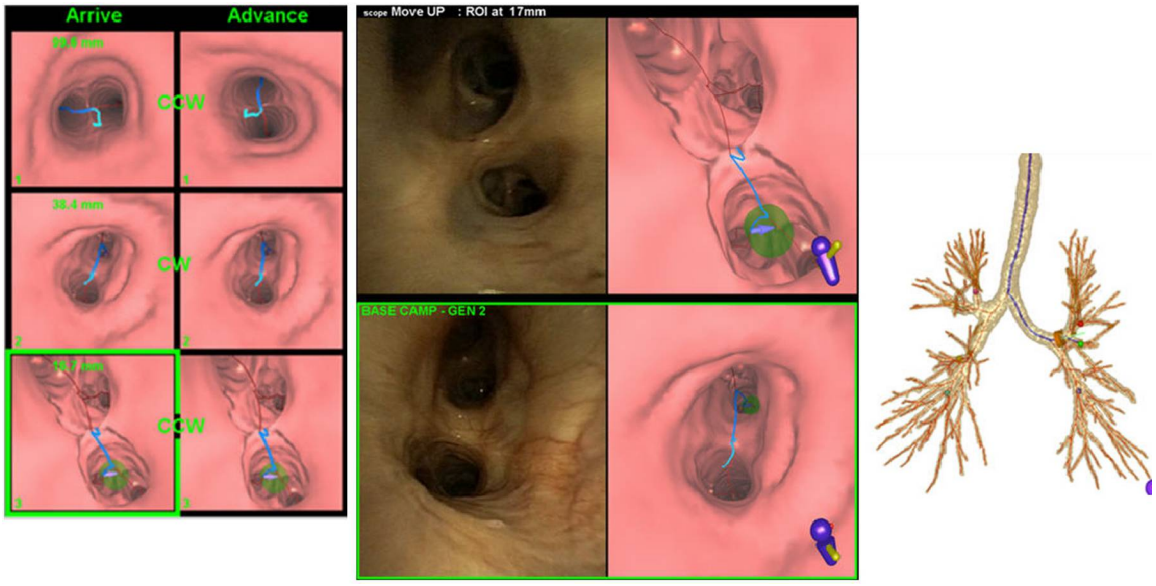


Fig. 12: Nearing the end of bronchoscope navigation for $\mathbf{r}_2$, cases F. After correcting the error highlighted in Fig. 6, the physician correctly navigates into the final route airway, where target localization information begins to appear.

Section III-C supplemental material:

TABLE VI: Ergonomic study of the proposed system. "No. of Routes" refers to the total number of routes considered for a case. "Total Branches" gives the total number of airway branches constituting a case's routes. "Total Maneuvers" gives the total number of maneuvers constituting the system's computed navigation plans for a case. "Acceptable Maneuvers" denotes the portion of these maneuvers deemed acceptable by the physician. "Acceptable Plans" refers to the number of precomputed navigation plans found to be 100% acceptable (all route maneuvers acceptable). "Physician Predict" equals the number of routes the physician correctly predicted to have occurred during the live procedure.

Case #	No. of Routes	Total Branches	Total Maneuvers	Acceptable Maneuvers	Acceptable Plans	Physician Predict
C	4	20	17	10	2	4
D	4	19	17	14	2	2
E	4	14	14	14	4	4
F	4	13	13	10	2	4
G	6	33	27	24	5	4
H	5	24	18	18	5	4
I	5	26	19	15	3	4
J	5	29	20	13	3	4