Semi-Automated Location Identification of Catheters in Digital Chest Radiographs

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ABSTRACT

Localization of catheter tips is the most common task in intensive care unit imaging. In this work, catheters appearing in digital chest radiographs acquired by portable chest x-rays were tracked using a semi-automatic method. Due to the fact that catheters are synthetic objects, its profile does not vary drastically over its length. Therefore, we use forward looking registration with normalized cross-correlation in order to take advantage of a priori information of the catheter profile. The registration is accomplished with a two-dimensional template representative of the catheter to be tracked generated using two seed points given by the user. To validate catheter tracking with this method, we look at two metrics: accuracy and precision. The algorithms results are compared to a ground truth established by catheter midlines marked by expert radiologists. Using 12 objects of interest comprised of naso-gastric, endo-tracheal tubes, and chest tubes, and PICC and central venous catheters, we find that our algorithm can fully track 75% of the objects of interest, with a average tracking accuracy and precision of 85.0%, 93.6% respectively using the above metrics. Such a technique would be useful for physicians wishing to verify the positioning of catheter tips using chest radiographs.

Keywords: Digital Radiographs, Catheter, Tracking, Tip Identification, Match Filtering, Template Matching, Computer Aided Detection

1. INTRODUCTION

The most common medical imaging modality is the portable chest x-ray. Its most common use is the identification and localization of catheter tips in the human body. Knowing the location of a catheter tips from chest radiographs is clinically important to patient health as misplaced catheters can lead to complications or death if not detected and repositioned in a timely fashion. The difficulty in analyzing digital radiographs stems from the fact that radiographs are projection images and therefore have no reference gray levels. Another issue is that since these radiographs are acquired using a mobile device, the image quality is also poorer than standard PA radiographs. Both of these effects are illustrated in Figure 1. Due to nature of the portable chest radiographs, readings can be time consuming and often times difficult for a radiologist to perform in a timely manner. By using computer aided image analysis, the efficiency of the radiologist may improve. The purpose of this work is to develop a method for Computer Aided catheter tip localization in digital chest radiographs acquired from portable x-ray machines. The algorithm we are developing seeks to reliably detect the location of catheter tips.

Previous work in the area of catheter location evaluation from radiographs seeks to improve the visualization of catheters, so that radiologists examining the radiographs can better interpret them and more rapidly discern the locations of catheters, by either analyzing various effects and methods for enhancing the appearance of catheters on film or digital chest radiographs[1-3], as well as investigating the efficacy of other techniques, such dual-energy subtraction radiography, versus standard digital radiograph for enhanced visibility of catheters[4]. However, little previous work has been done to develop an automated method of catheter tip identification in standard portable chest radiographs. In this paper the authors discuss a method of determining catheter tip location via tracking catheters from their insertion point in the body to their end point.

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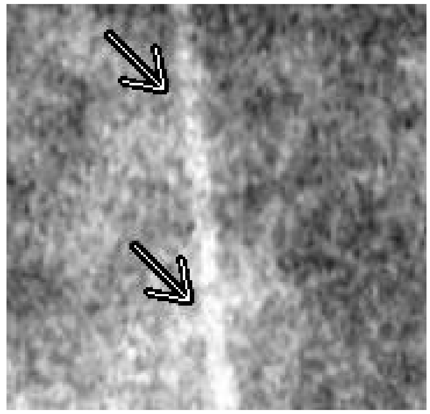

Figure 1: Naso-gastric tube (marked by arrows) as seen in a digital radiograph. Both high levels of noise and variation in object intensity can be seen, making identification of catheters difficult.

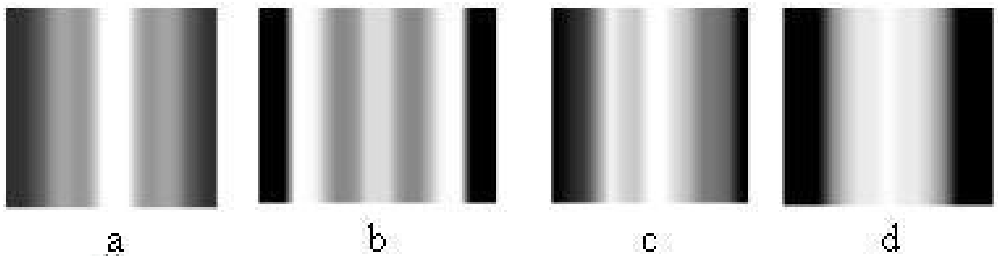

Figure 2: Catheters template samples in a vertical orientation. They are: a) a central venous catheter, b) tracheostomy tube, c) a PICC line, and d) chest tube.

2. METHODOLOGY

2.1 Algorithm design

In order to determine the location of the tips and ends of catheters and other insert-able tubes in the human body, we developed a method to track catheters and tubes in chest radiographs. This method involves a normalized cross-correlation template-matching algorithm similar to the one proposed by Zhou et al.[5] that would find sequential points of best matches to determine the midline of the object to be tracked. However, where as Zhou et al. looked at retinopathy, this work modifies their approach in order to apply the method to the task of tracking. Given that the objects of interest are synthetic; their characteristics can be known a priori. This allows for pre-generation of characteristic templates with which to model the various catheter and tube types. Since the diameter is fixed over the length of the, it also allows for consistent modeling of a catheter or tube anywhere in the human body. Also, since two dimensional chest radiographs have no reference grey levels, a catheter at one point in an image could appear different than the same catheter at any other point in the same image with respect to pixel intensity. Therefore, we chose to implement normalized cross-correlation as the matching metric in order to compensate for the varying background signal. The equation for normalized cross-correlation is

$$\gamma(u,v) = \frac{\sum_{x,y}[f(x,y) - \overline{f}_{u,v}] \cdot [t(x-u, y-v) - \bar{t}]}{\left(\sum_{x,y}[f(x,y) - \overline{f}_{u,v}]^2 \cdot \sum_{x,y}[t(x-u, y-v) - \bar{t}]^2\right)^{0.5}}$$

where $\overline{f}_{u,v}$ is the mean value of the pixels in the template and $\bar{t}$ is the mean of the image pixels in the region being compared to the template. Normalized cross-correlation allows for signal matching invariant to average signal level, which is useful in such instances. Matching would occur centered on the center pixel of each template, therefore template dimensions were kept odd for symmetry.

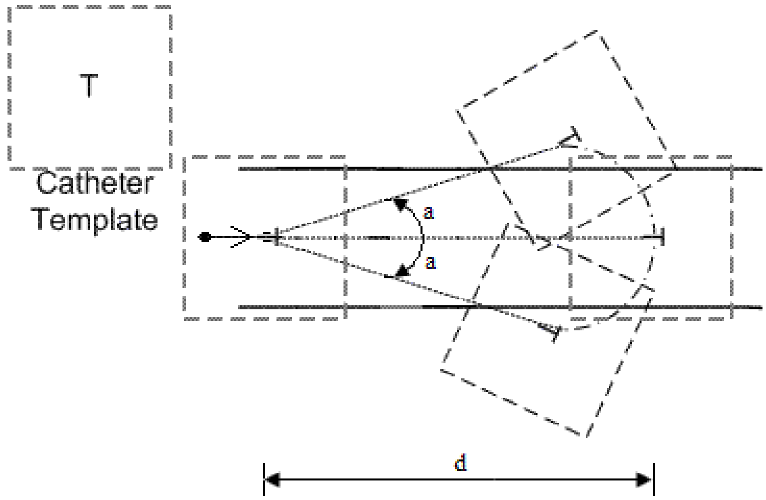

Figure 3: Diagrammatic Representation of a tracking step. From the previously tracked point (small dot on left) and the current point in tracking (the origin of the arc), the direction of catheter travel is determined (arrow point right). From the current point, an arc is then designated as search space, defined by a radius (giving a maximum look-ahead distance) and maximum angle. Every point in search-space is then compared using normalized cross-correlation to an appropriate orientation of the template centered at 'T', and the strongest match that surpasses ncc, the minimum value for continued tracking, is the next point on the catheter midline. If no point surpasses ncc, then tracking ceases at the current point, giving the end point of the catheter.

The templates to be matched were derived by sampling different catheter types representative of the catheters present in the data set. The sampling was done by taking several 1 dimensional profiles of a single catheter, averaging them together, and then extending the profile in the other dimension to generate a two dimensional profile. The profile was then rotated 17 times in 10 degree intervals (to cover the range of 0-170 degrees), so that a total of 18 profiles were generated for each catheter type. Since the catheters have radial symmetry, they have axial symmetry in a projection image, negating the need to provide rotations between 180-360 degrees (i.e. a 180 degree rotation appears the same a 0 degree rotation). Therefore, these rotations then allow template orientation to cover possible catheter template rotations of 0-360 degrees. Four sets of templates were generated in this way, and all objects of interest were set to use one of these profiles. Examples of each catheter profile at a path-angle of 90 degrees can be seen in Figure 2. The average dimension of these templates was 21 pixels x 21 pixels, which is the average width of the catheter profile plus 3 pixels on each side of the profile in order to allow the added attenuation over background to be visible in the template. The template reference point is set to the center point. In this algorithm, the user would specify which template type to use, based on comparing the profile of the catheter to be tracked to the most similar match.

Initially, the user would specify two seed points from which to begin tracking. Because of the fact that a catheter or tube inserted into the body will not bend dramatically over a short distance and can cross periodically attenuated sections, such as if a catheter crosses several ribs, search-space can be limited by both distance and maximum angle of deviation. As seen in Figure 3, template matching would then occur in a forward looking search space defined by the parameter set P(*d,a,ncc)*, where *d* is the maximum look-ahead distance, *a* is the maximum allowed angular deviation from the current path, and *ncc* is the minimum normalized cross-correlation value that needs to be met in order to allow for continued tracking, which serves as a halt criterion. The current path is determined by the current and previous points, indicated in Figure 3 by the two dots and the arrow on the left. At every point in search-space, the template is rotated to be in the same orientation as the proposed new path and the strongest match using normalized cross-correlation, , is kept as the new point for continued tracking. When no point in search-space surpasses P(*ncc*), tracking ceases and the current point is set as the tip.

For considerations of speed, template rotations were performed prior to tracking and the most approximate rotation was used for matching. The algorithm would continue tracking unless the best match found fails to exceed a minimum normalized cross-correlation value. Once the tracking has reached the object of interest's tip, the template would poorly match any point in search space, so tracking would cease.

2.2 Experimental procedure

Initially, we investigated how consistent the profile of a catheter is over its length in order to determine the validity of using a priori information about its profile in order to track catheters. Along the length of the catheter, equidistant points were marked by hand. Then at each point, the previous and next points would be used to bisect the angle at the central point in order to get the cross-sectional profile of the sampled catheter using linear interpolation to determine the relevant pixels. We did this for all 12 objects of interest, and compared the various profiles obtained to determine catheter-profile stability.

In order to validate template based tracking of catheters and tubing from chest radiographs, the algorithm tracked a total of 12 catheters and tubes in 5 chest radiographs and compared these results to the ground truth midline of these catheters as marked by an expert radiologist in order to determine performance. We used two difference metrics to define performance. The first metric we used was correct tracking, which we define as a point on the midline of the catheter or tubing to be tracked being within a certain distance of the tracked path and will be referred to as tracking accuracy in this paper. This can be calculated by the equation

$$Tracking\ Accuracy = \frac{Length(A) \bigcap Length(GT)}{Length(GT)}$$

where length(A) is the length of the algorithm tracked catheter length and length(GT) is length the ground truth marking. For this experiment, we allow the two paths to differ by a set distance, set empirically to be 15 pixels, or 2.55mm given the resolution of the digital chest radiograph, which is the average diameter of the catheters tracked. The second metric used gives the percentage of the tracked midline that lies within a fixed distance of the ground truth midline, empirically set to be 15 pixels, and will be referred to as tracking precision in this paper. The metric would give an indication of the efficacy tracking algorithm to only track the object of interest. This metric can be calculated by

$$Tracking\ Precision = \frac{Length(GT) \bigcap Length(A)}{Length(A)}$$

using the same definitions as above. With these two metrics, we feel one can adequately describe the performance of a tracking algorithm such as this one.

Tracking was accomplished by first defining 4 templates as representative of all catheters and tubing and evaluating the algorithm's performance by comparing the output to the ground truth. Each of the 12 catheters was classified into one of the four representative templates. In order to determine the efficacy of tracking using our proposed method, we perform two experiments on tracking and a third on filtering.

In the first experiment, every catheter is tracked using multiple parameter sets in order to determine how many catheter tips can be identified using our tracking methodology. For each catheter, we varied the search-space parameter set P(*d, a, ncc)*, by allowing the maximum look-ahead distance (*d*) to vary between 50 and 80 pixels in 10 pixel increments, the maximum allowed angle (*a*) of deviation to vary between 15 and 30 degrees in 5 degree increments, and the minimum normalized cross-correlation (*ncc*) to vary between 0.3 and 0.5 in 0.05 increments. We then count the number of catheters whose tips are correctly identified by at least on parameter set. We also investigate the best tracking results of all catheters using the metrics described above, where we report the highest accuracy and the highest precision that level of accuracy can obtain.

In the second experiment, we explore the sensitivity of tracking accuracy and tracking precision to the individual search-space parameters. For this experiment, we varied the best search-space parameter set P(*d*±10*, a*±5*, ncc*±0.05), with the best parameter set defined as the maximum of tracking accuracy obtained given the highest tracking precision for the most detected tip. For each search-space parameter set, we compute the average of each of the two metrics for all the catheters.

We also looked at the effect of image filtering on the tracking algorithm. We evaluate the effect of edge-enhancement filtering the image using edge enhancement to the results of the algorithm without any filtering pre-processing step for the best parameter set determined in the second experiment. Edge-enhancement filtering should improve contrast, which would ideally make tracking simpler by improving the signal of the

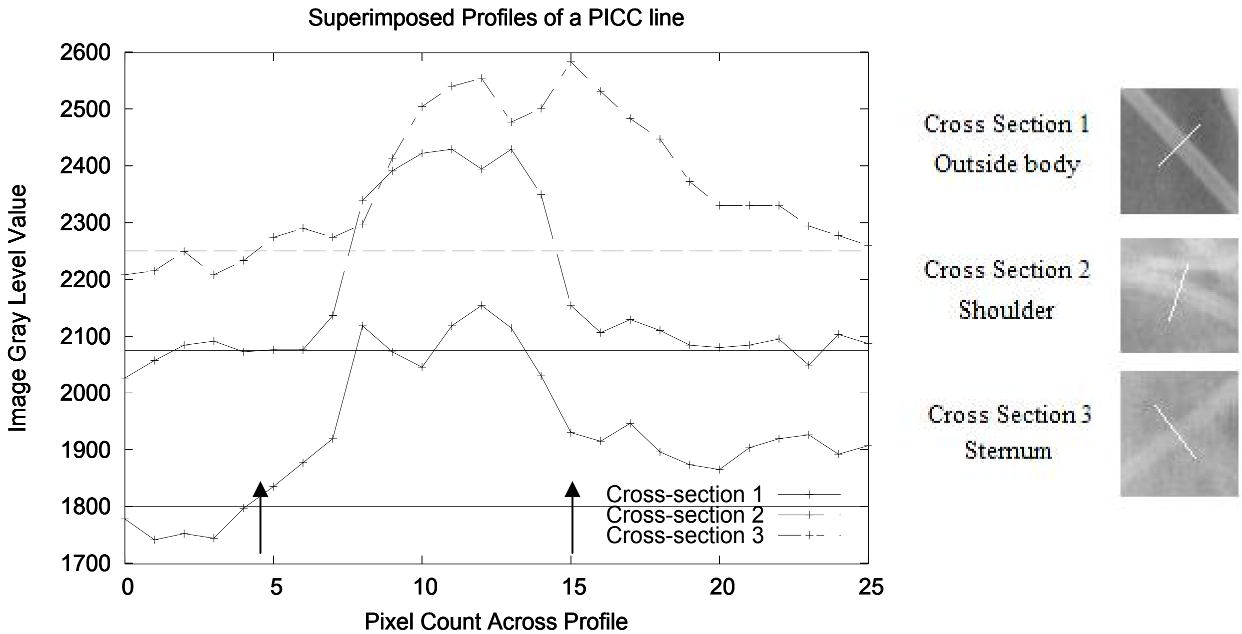

Figure 4: Left)Three 1-D profiles >10% of catheter length apart taken perpendicular to the catheter midline of a PICC line. The pixel values are show with using linear interpolation to connect the points. The mean value for each sampled profile varies over the length of the catheter due to the variation in background attenuation. However, the location of the object of interest is still apparent in the center of the profile sample line where the object is placed, as the signal attenuation due to the object is superimposed on the background signal. Right) The location of the three cross-sections marked on the original digital radiograph

catheters and making it appear more like the idealized templates. We expect edge enhancement to have more of an effect than median filtering, due to the nature of chest radiograph projection images.

3. DATA

Five chest radiographs were obtained from the Weill Medical College of Cornell University from a portable chest x-ray. These radiographs had 12 marked objects of interest, comprised of catheters and tubing that would be desirable to track, marked by an expert radiologist. The objects of interest are a central venous catheter, tracheostomy tube, a PICC line, chest tube. The chest radiograph images were 16-bit images with a resolution of 0.17mm x 0.17mm. The image dimensions were 2500x2050 pixels.

4. RESULTS

4.1 Catheter profile analysis

Review of the sample profiles indicated that the catheters were clearly identifiable at most locations within the image. Figure 4 shows three sample cross-sectional profiles of a PICC line taken along the length of the catheter. The catheter profile has an approximate diameter of 11 pixels and is at approximately centered at the 11 pixel mark. The diameter of the profile is denoted by arrows. The background signal is marked for each cross-section and profiles have an approximate signal strength over baseline of 300 gray levels. The location of where each profile is acquired from the digital radiograph and the anatomical position outside the body, the shoulder region, and under the sternum is shown on the right.

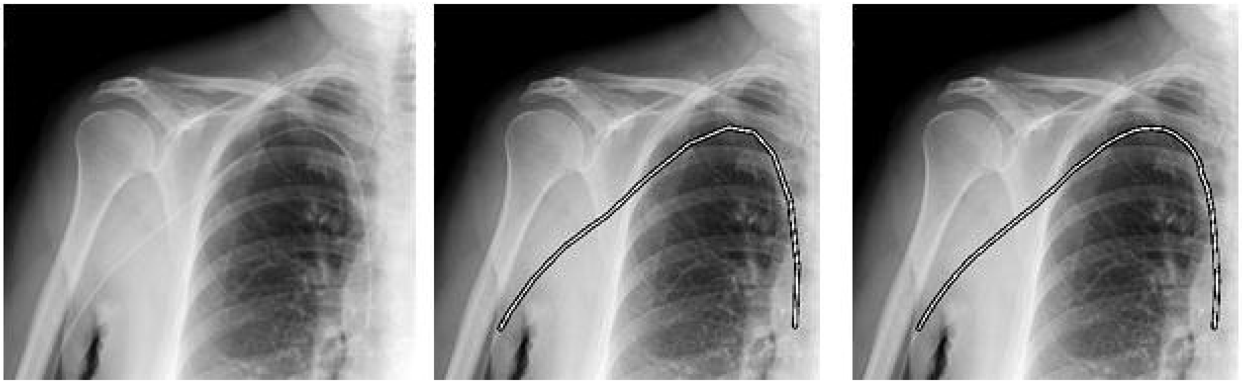

Figure 5: Sample tracking of a PICC line, from left to right: Original digital radiograph, ground truth, tracking algorithm result. On the second and third images, the catheter is marked by a white line.

Table 1: Percentage of accurately tracked object length for optimal search-space parameters by object of interest subtype and ratio of endpoints correctly identified by tracking based on object of interest subtype. Mean tracking accuracy and precision given as percentages of the midline marked by an expert radiologist.

Object of Interest	Mean Tracking Accuracy (Percentage %)	Mean Tracking Precision (Percentage %)	Endpoints Identified (Ratio)
Catheters - 7 objects	90.5%	99.4%	6/7
Tubing - 5 objects	78.6%	93.3%	3/5

4.2 Catheter tracking and tip identification efficiency

We correctly identified the catheter tip (complete tracking) on 75% of the objects of interest using variable search-space criterion and were able to track a mean of 85.0% and median of 99% of the catheter length. This result shows that catheter tip location identification through the algorithm described is a feasible and worthwhile procedure. Figure 5 and 6 show successful tracking and successful tip identification respectively. Table 1 shows tip identification ratios and mean accuracy and precision based on the two primary object classes, catheter and tubing.

Table 1 shows the tracking accuracy and precision of catheter length for each of the subsets of objects of interest, catheters and tubing, using optimal search-space characteristics, as well as the percentage end points correctly identified for each subgroup. A high accuracy indicates that a catheter was tracked to completion, ending within a distance 2.5 mm of ground truth. We found that the maximum time for complete tracking was less than 20 seconds in the worst case and 10-12 seconds on average.

Table 2 was generated by taking the average of each of the two metrics for all tracked objects of interest at specific parameter settings. We found the most effective parameter set to be P(d=70,a=15,ncc=0.35) with a mean tracking accuracy of 79.8% and mean tracking precision of 82.9%. For this parameter set, 8 of 12 objects were successfully tracked. The sample parameter sets are shown in order to illustrate the sensitivity of tracking to the search space parameters.

When the edge-enhancement filter was applied prior to tracking, the tracking precision of the objects of interest increased from a mean of 82.9% to a mean of 86.4% for the P(d=70,a=15,ncc=0.35) search-space parameter setting. However it did not allow for the complete tracking of any additional objects of interest, and decreased tracking accuracy to a mean of 76.9% from 79.8%.

Table 2: Effect of Search-Space Parameter Sets P(*d, a, ncc*) on Tracking Accuracy and Precision. Sample P(*d, a, ncc*) sets are given in order to illustrate individual parameter settings on tracking efficacy.

Search Space Parameters	**Mean Tracking Accuracy (%)**	**Mean Tracking Precision (%)**
d=70, *a*=15, *ncc*=0.35	79.8%	82.9%
d=60, *a*=15, *ncc*=0.35	73.4%	62.4%
d=80, *a*=15, *ncc*=0.35	75.8%	73.1%
d=70, *a*=10, *ncc*=0.35	60.3%	81.2%
d=70, *a*=20, *ncc*=0.35	80.2%	80.4%
d=70, a=15, ncc=0.30	56.2%	56.0%
d=70, a=15, ncc=0.40	79.6%	85.9%

5. DISCUSSION

Figure 4 shows the consistency of the profile of a catheter in multiple sections of the body. The fact that the catheter profile is clearly visible against background signal The consistency of the profile indicates that the deformation of catheters and other objects of interest, such as changing diameter due to constriction, is small *in vivo*. Therefore, we believe a single, fixed template representing the objects profile is sufficient for a tracking algorithm based on registration. However, what is not apparent from this study is how consistent profiles of synthetic objects appear between multiple scans. Variations in this instance could come from multiple sources, such as varied overall signal attenuation between persons scanned, as well as differences in portable scanners, and could require a dynamic definition of the template to be used.

It is interesting to note the relatively lower tracking accuracy and tracking precision for tubing versus catheter as can be seen in Table 1. One possible explanation is that the tubing crosses more high attenuation areas. Another possible that the attenuation signal from the tubing is not strong enough to be detected against background using normalized cross-correlation.

Table 2 shows the performance of the most effective parameter set, P(70,15,0.35) and the variation of performance due to varying search space parameters. We see that tracking accuracy is most sensitive to the maximum look-ahead distance sensitive parameter. Tracking Precision is most sensitive to maximum angle of deviation. However the variations are on average less than 10%, indicating we have reached an optimal operating point. One interesting point is that if the halt criterion (ncc) is set too low, both criterion suffer. This is due to both inaccurate tracking and late stopping.

Edge-enhancement filtering led to a slight increase in tracking precision at the expense of tracking accuracy, meaning less inaccurate tracking and increased incomplete tracking occurred. This indicates that some signal suppression does occur, the edge-enhancement filter alone insufficiently models this problem and the more appropriate filters need to be evaluated for this task.

There are three primary problems that can occur with object tracking. The first is inaccurate tracking, where the tracking algorithm could follow another prominent feature, such as a rib, as is shown in Figure 6. In such instances, it is possible that the two profiles of the objects are similar and when they diverge, the tracking methodology would follow the more prominent one. In our study, we found that we were able to attain high tracking precision, as seen in Table 1, while still identifying catheter tips, implying that our method does not suffer from this issue.

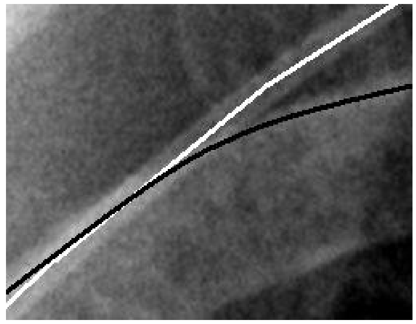

Figure 6: Catheter (white center line) crossing rib edge (black center line). When catheters and other objects of interest overlap or gradually cross prominent anatomical features such as ribs, it can become difficult to determine which object to continue tracking. A long, narrow search-space minimized this effect in this study.

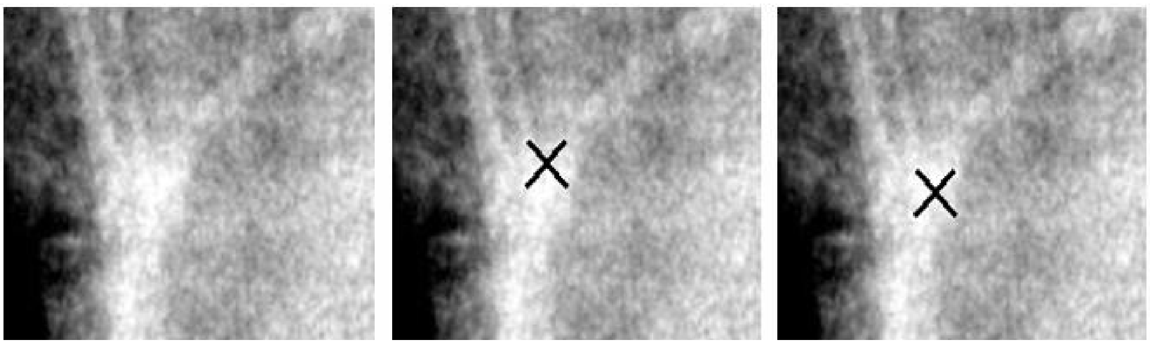

Figure 7: Example of catheter tip identification (marked by a black 'X'). From left to right: Original digital radiograph, ground truth, tracking algorithm result. Catheter tips can lie adjacent or beneath other catheters of objects can be difficult to identify. Tracking with a limited search space and using proper template prevent tracking of other objects.

The second problem that can occur during tracking is premature stopping of the tracking algorithm. Premature cessation of tracking can occur due to high signal attenuation areas preventing the catheter signal from being detected versus background. This problem stems from a selection of a halt criterion that is based entirely on match strength, and would lead to high tracking precision without high tracking accuracy. This issue was the primary cause of failure in 1 of the 12 cases.

The final problem that can occur during tracking is the failure of the algorithm to stop tracking at the end of a catheter. This problem and premature cessation are interrelated by the halt criterion. This is problematic since the halt criterion must be set both low enough to allow continued tracking in high attenuation areas while still requiring a high enough match strength so that similar structures are not tracked. We found that while a minimum normalized cross-correlation value was effective as a halt criterion when the desired profile was no longer present in the image data currently occupied by search-space, which would occur when the tip of the catheter was located, it could fail in preventing tracking of overlapping structures with similar profiles. One instance in which this was a possibility was when a catheter tip may rest near the path of a similar catheter, as observed in Figure 7. In this particular case, the tip rests at an angle similar to other catheter, and the algorithm continues to track this new catheter in error. In the example given, the catheter tip was correctly identified, mainly due to limiting the parameter space to have a small maximum angle of deviation (a=15), which prevented a change in the direction of the tracked path to be at a sharp enough angle to allow continued tracking of the second object. The halt criterion was the primary cause of failure in 2 out of 12 cases. Therefore, an improved criterion will need to be developed and investigated in future work.

6. CONCLUSION

A method for catheter tracking has been presented that takes advantage the synthetic, well defined profile of catheters and other tubes. Template matching using a clean, well-defined prototype was found to be ideal for tracking catheters and identification of catheter tips on chest x-ray images. This method was successful on 9 of 12 cases. This system may be useful in clinical practice due to its ability to rapidly track catheters from their insertion point.

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