Reconstruction of 3D Catheter Paths from 2D X-ray Projections

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Abstract. The diagnosis and therapy of intensive care patients requires the usage of several catheters inside the patients chest. The information about the position and path of the catheters inside the patients body is important for the doctor, but is nowadays not part of the clinical routine. One possible source of this information are CT or NMR scans, which lead to an organizational overhead and additional stress for the intensive care patient. To minimize the overhead we implemented an algorithm to extract the 3D path of catheters in the body of the patient from two or more standard X-ray images. The approach is based on only few assumptions, runs completely in three dimensions, and uses the X-ray images only as a guideline for the path reconstruction process. It shows an inherently robust behaviour against misleading structures in the X-ray images, like loops and intersections. The algorithm has been tested with a selection of test images, including images from the clinical routine.

1 Introduction

Intensive care patients often need a multitude of catheters, for example, the central venous catheter for intravenous drips, pulmonary artery catheters to monitor the heart functions, and pleura drainages in case of lung injuries. What all of these examples have in common, is that the exact position of the catheters cannot be verified in the clinical routine. On the other hand the exact position and 3D path of the catheters is important information for the doctor: the risk of lung injuries caused by the catheter, and the success of the pleura drainage depends very much on its position, so knowing the first placement of pleura drainage makes the second placement more apparent. As a second example, the signals of a pulmonary artery catheter which monitors the heart functions, depend very much on its position. The exact position of the catheter tip relative to the heart cannot be controlled without knowing the catheter path and comparing the catheter path with the anatomical situation around the patients heart.

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One source of the 3D path information of the catheters are CT or NMR scans. In practice, scanning every patient with catheters to control the position and path of the catheters would introduce a tremendous organizational overhead and additional stress for the intensive care patient. Therefore, CT or NMR scans cannot become part of the standard diagnostic process.

In contrast, 2D X-ray images, even if two or more images from different directions exist, are not the best help to identify the position and path of the catheters in relation to the patients anatomy.

As a result, there are no alternatives to the 3D reconstruction of the catheter position and path to give the doctor additional valuable information about the catheters he has placed. The 3D reconstruction gives the doctor the possibility of viewing the reconstructed catheter path in 3D from all directions, in combination with the X-ray images of the patient.

In this paper we present a method to extract the curve of one or more catheters in 3D space from two or more X-ray images, which is suited in principle for the clinical routine. A special emphasis has been put on the minimization of the number and restrictness of preconditions to allow the algorithm to work with standard X-ray images.

2 Problem Specification and Related Work

Figure 1 shows a typical set of X-ray images from a rotating monoplane X-ray system, which is a standard device to deliver two or more X-ray images of one patient from different directions. Typical catheters can be recognized as tubes with constant thickness and hardly visible edges. In many cases, especially when the catheters are of interest for the doctor, a special strip with high X-ray contrast is added inside the catheters to give a good signal in the X-ray image. The signal of the strip can be used to detect the path of the catheter. The white line, representing the catheter path, is typically not visible in all parts of the image; for example, it can be covered by bone, which absorbs X-ray images as well or better than the catheter material or the contrast strip does.

Because catheters follow anatomical structures and are primarily not intended to be bent, we assume that the 3D catheter path has a restricted curvature. In addition we assume that the geometric parameters of the image producing device are known; especially the projection parameters and the geometric correlation between the single images of the set of X-ray images are important for the catheter path reconstruction process.

As a result we can summarize the following preconditions:

- The catheters itself or a contrast strip appear as one line or two parallel lines with nearly constant thickness or distance in the X-ray images.
- The catheters or the contrast strip are visible in most parts of the X-ray images, and they have detectable edges.

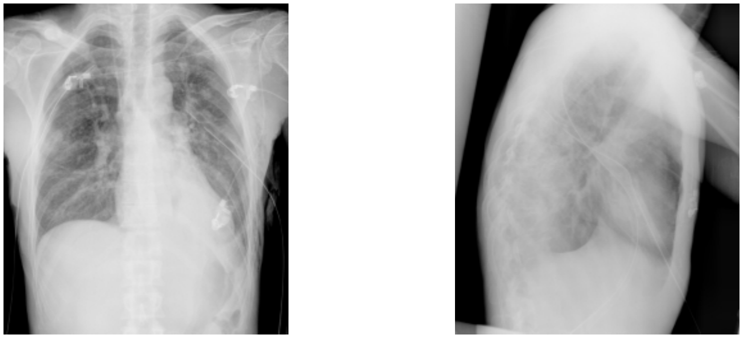

Fig. 1. An example set of X-ray images from a human chest. The pleura drainage at both sides can be recognized, because they contain a strip with good X-ray contrast, visible as thin white lines with constant thickness. The central venous catheter does not contain a contrast enhancing strip and can be seen partly in the upper image, but can only be anticipated in the bottom image.

– The 3D path of the catheters has a restricted curvature. [1]
– The geometric parameters of the X-ray image generating unit are known.

The reconstruction process of 3D paths of catheters out of 2D X-ray images is not a well known topic in literature. Most work related to the position control of catheter inside the human body, describe the reconstruction of the catheter tip only, or describe methods to control the catheters tip with external devices [1][7].

On the other hand, the reconstruction of 3D catheter paths can be compared with technical similar problems like the vessel reconstruction from angiographic images [2][8]. This problem has a similar setup: the goal is to find the 3D path of vessels, which can be seen as a kind of "lines" in the 2D angiographic images. Typical solutions for the vessel reconstruction problem are divided into the distinct steps "preprocessing", "segmentation of the vessels in the 2D images", and "path reconstruction". Because the catheter reconstruction problem does not have to deal with problems of vessel reconstruction like vessel branches and variating diameter of vessels, we decided to combine the "segmentation" of the catheter in the 2D images with the path reconstruction in one iterative algorithm.

3 Catheter Path Reconstruction

3.1 Preprocessing

The algorithm can be divided into two main steps, the preprocessing and the reconstruction loop. The reconstruction process uses the local gradient magni-

[1] This need not to be true for the 2D X-ray projections. See Fig. 4 as an example: the 3D helix with low curvature in 3D has a sinus function with much higher curvature as possible 2D projection.

tude in the X-ray images for the catheter edge detection. The preprocessing step basically has the goal of delivering these gradient magnitude images in a suitable form. To eliminate the usually contained high-frequency noise, first a Gaussian filter is applied to the original images; in addition the images are median filtered, which gives the desired effect that this filter removes noise without destroying the edges of the catheter or its contrast strip. The gradient images are then calculated out of the smoothed images; the absolute value of the gradient is used to produce the gradient magnitude images.

3.2 Catheter Path Reconstruction

The main loop of the catheter path reconstruction process is an iterative process. The main data of the algorithm is a set of points which describe the path of the catheter. The iterative algorithm assumes that a certain amount of points is already available to reconstruct the next point. This is not the case at the beginning of the algorithm; the initial condition of the algorithm is discussed at the end of this section.

The iterative reconstruction process can be divided into the following major steps:

1. Estimation of the catheter direction in 3D and estimation of a new 3D point along the catheter direction.
2. Correction of the 3D point position:
   (a) Projection of the 3D point to the 2D images.
   (b) Detection of the catheter edges in the neighbourhood of the 2D points, giving a corrected catheter centre position in the 2D images.
   (c) Backprojection of the corrected 2D points to form a new 3D point of the catheter path.

The first step is to estimate an actual catheter direction in 3D and a new vertex on the centre of the catheter along its direction. The new vertex is computed in a constant distance to the last known vertex on the catheter centre so that it lies in the actual catheter direction (see Fig. 2). The estimation of the actual catheter direction is done using a main axis transformation of the point cloud containing the last recently generated points of the catheter path.

Since the algorithm works in 3D to use the information of all X-ray images, it is necessary to transform the 3D vertices to the images. This is is done by a homogeneous coordinate transformation using a 4×4 matrix for each image [4], which makes it possible to provide the typical conical geometry setup of X-ray image producing devices (see Fig. 2). In addition, the usage of a homogenous coordinate transformation allows it to consider the angle between the X-ray images, as well as other linear coordinate transformations.

After transforming the estimated vertex and the actual direction to the image, the algorithm searches for the edges of the catheter in the local neighbourhood. The search is located on a line, which is orthogonal to the calculated direction and goes through the estimated vertex (see Fig. 3). As the higher

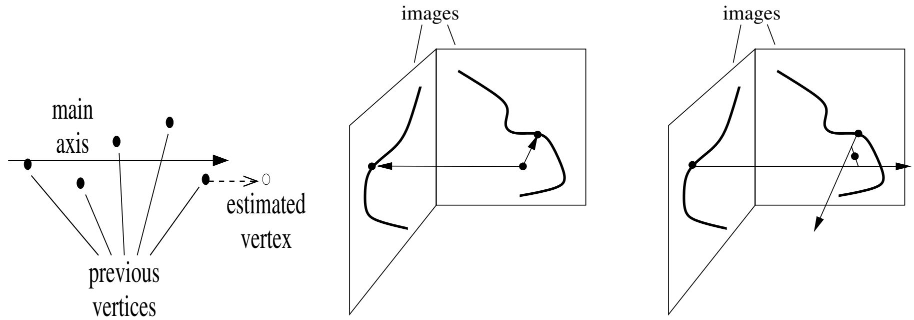

Fig. 2. Left: The first step of each iteration is the estimation of the actual catheter direction and the estimation of a new vertex in 3D. The actual catheter direction is computed using the main axis transformation of the last recently reconstructed catheter path points. Mid: The estimated 3D vertices are projected to the 2D images using a homogeneous coordinate transformation. Right: The backprojection of the corrected 2D vertices to 3D space results in the 3D point with the shortest distance to all projection rays.

greyvalues of the gradient magnitude image correspond to harder edges in the original image, the edges of the catheter are likely to have high greyvalues. To find the catheter edges, the gradient magnitude values along the orthogonal line are evaluated using bilinear interpolation. The interpolated values are weighted with a normal distribution with its expectation value at the estimated position of the edge, which is calculated from the estimated centre and the typical width of the catheter; the standard deviation of the used normal distribution is one of the adjustable parameter of the algorithm. Now the global maximum is searched in the weighted curve. If the maximum value is located in an interval around the expectation value and the value exceeds a lower bound, then the maximum is used as new catheter edge. Otherwise the edge detection process marks the found maximum of the gradient magnitude as invalid. This has the effect that values are ignored which are unlikely to correspond to an edge, because maxima far away from the expected position or soft edges are ignored. If both catheter edges are found by this method, their centre is calculated and saved; if only one edge is found, the most likely centre is calculated from the found edge and the width of the catheter; if no edge is found the original estimated point is taken as probable centre, and no correction of the estimated point in the 2D image occurs.

The catheter centre position correction will be done for each of the images. The corrected 2D positions are used to compute a new three dimensional vertex. A projection ray is casted from each image through the corrected catheter centre position on the images. The vertex having the smallest distance to all of these rays is determined (see Fig. 2). This vertex is taken as the new 3D centre point of the reconstructed catheter.

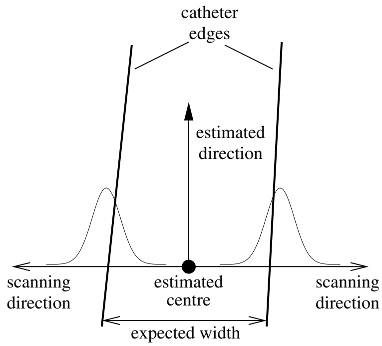

Fig. 3. The estimated catheter centre is corrected by detecting the catheter edges in the 2D images. The edge detection uses a weighted interpolation of the gradient magnitude values, and searches along the "scanning direction", which is orthogonal to the estimated catheter direction.

This whole method is iterated a maximum user definable number of times or until the number of errors exceeds a bound. The error counter is increased when no edge was found on one of the images. Single or only few sequent errors do not have much influence at the reconstruction, because the other images will very likely not show errors at the same time. This approach makes it possible to reconstruct the catheter correctly. This also enables the algorithm to master crossings of the catheter in the projected image.

During the first iterations of the main loop there are not enough preceeding vertices to estimate the actual catheter direction. Therefore, the algorithm uses a starting point and an initial direction, which is used until enough vertices have been calculated. Also the width of the catheter, if not provided externally, has to be determined in the beginning of the reconstruction process. This is done by averaging the distances between the found catheter edges over the first iterations.

4 Results and Discussion

Figure 4 shows a result of the reconstruction process using two test images as input. The algorithm has no problems with the reconstruction of the helix; in particular the circle, as one projection of the helix, will be cycled two times.

As a more realistic example Fig. 5 shows the reconstruction result with X-ray images from the clinical routine. These images show the capability of the algorithm together with its drawbacks. The reconstruction of the pleura drainage tubes is possible because of the good visibility of the strips inside the tubes. The 2D X-ray images contain discontinuities, which have not disturbed the reconstruction process. The central venous catheter is only partially visible in one of the projections and is therefore not reconstructible with the presented algorithm. To allow the reconstruction, the central venous catheter should be marked with the same strips as the pleura drainage contain them.

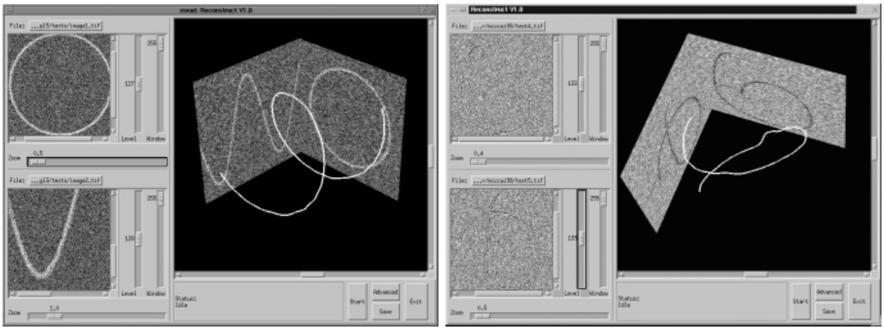

Fig. 4. The left image shows a screenshot of the test application showing two noisy test images for the catheter reconstruction process. The original path (helix) has been reconstructed. The right image shows the reconstruction of two noisy test images with a crossing in one of the images.

We found that the presented algorithm is capable of extracting the 3D path of catheters out of two (or more) X-ray images. But, of course, the algorithm or at least our first implementation is not free of some shortcomings.

First, the algorithm, at least in our implementation, needs a user provided start point and start direction. For the clinical routine, this should be replaced by an automatic process which identifies suitable catheter start points.

In addition, the algorithm has some adjustable parameters which influence the catheter edge detection in the 2D images, and the estimation of a new 3D vertex along the catheter path. The catheter edge detection is controlled by the standard deviation parameter of the Gaussian weighting function, and by the cut-off value which decides if an catheter edge has been found or not. Choosing these parameters badly can reduce the amount and quality of found catheter edge positions, and therefore lead to incorrect reconstruction results. In practice, we found that a certain set of values[2] gives good results, and the parameters are not critical.

The estimation of the new 3D vertex along the catheter path is controlled by the number of known 3D points and the step size. These parameters have much more effect on the quality of the reconstruction process. Since the algorithm extrapolates the linear main axis which approximates a number of vertices, the smoothness of the reconstruction conflicts with the largest possible curvature of the catheter. With increasing number of vertices that are used for extracting the direction, the smoothness improves but the maximum curvature is upper bounded. If the local curvature of the catheter is high, it may happen that the estimated centre vertex is not lying on the catheter anymore. In this case the reconstructed curve will leave the trace of the catheter at this point. A possible solution to this problem is to use second order extrapolation polynomials, which are an option for further improvement.

[2] The Gaussian weighting function should have a width of approx. 0.5 to 1.0 of the estimated catheter thickness. The edge detection cut-off value is set to twice the value of the second maximum of the gradient magnitude image along the scanline.

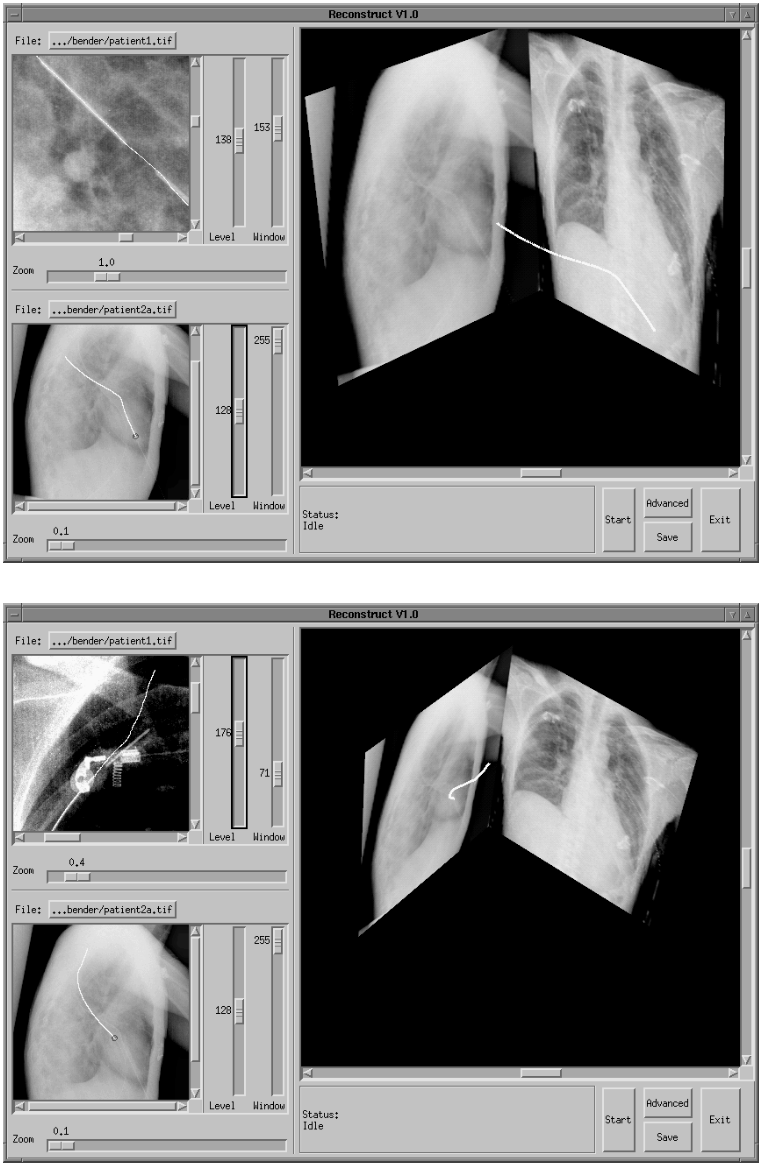

Fig. 5. These two screenshots show reconstruction results with X-ray images from the clinical routine. The upper screenshot shows a situation which has been adapted completely by the algorithm: even the gap in the contrast strip has not disturbed the path reconstruction. The lower screenshot shows the result of the reconstruction of the second pleura drainage of this patient. In this case the gap in the strip could not be crossed because the catheter wire has a non-zero curvature at this place. The linear estimation of new points along the catheter path has the effect that the reconstruction leaves the correct path.

5 Conclusion

We have presented an iterative algorithm for the reconstruction of the 3D path of catheters out of 2D X-ray projections. The algorithm contains some weaknesses that should be improved, which are basically the manual setting of the reconstruction start point and start direction, and the linear extrapolation of new catheter path points, which should be enhanced to second order extrapolation to overcome some problems during the reconstruction process.

On the other hand, the algorithm needs a small set of preconditions, which are fulfilled for typical X-ray images containing visible catheter paths, and it needs only standard X-ray images as input data, which can be produced for patients with catheters very easily. Therefore the algorithm can serve as base for a tool for the doctor in the clinical environment, and should be able to improve the accuracy and quality of the therapy.

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