Wrists in space: deformable models for segmentation and matching techniques for registration of 3-D MR and CT images of the wrist

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Discussion and Concluding Remarks
Figure 53: Image segmentation and registration of 3-D CT images of the wrist. The segmented surfaces of the bones are shown in the neutral position of the wrist (top) and transparent in other postures during ulnar-radial deviation (middle) and flexion-extension (bottom) after registration.
MEDICAL IMAGING plays an increasingly prominent role in many disciplines in medicine. A variety of imaging devices produce images for diagnosis and treatment of disease, for monitoring the effects of therapies as well as for the planning of surgery, and radiotherapy. The analysis of these images is often complicated as the visualization techniques that are commonly used generally do not present the true three-dimensional (3-D) anatomical structure contained in volumetric data. Moreover, quantitative information is often needed, and this information is not directly available. This has led to a growing interest in medical image processing techniques to improve the analysis of medical imagery. An important class of these techniques involve segmentation and registration of images (Fig. 53). In the segmentation process the relevant anatomical structures are extracted. The segmented data are very suitable for quantification since image measurements, such as the estimations of the diameter of aneurysms, do not have to be carried out manually, but can be performed efficiently and reproducibly by computer means. Moreover the anatomical morphology can be visualized by surface rendering and does not have to be imagined by showing cross-sections through the anatomical tissues or by projecting the 3-D information onto planes. The true 3-D geometric visualization has many advantages. Improved views of the extent of pathological tissues can be obtained. Surgery planning can be performed carefully by simulation. In case when more modalities are involved or when time sequences are obtained, image registration can be applied to bring the anatomical structures into spatial alignment. After alignment a fusion step may be performed to integrate multiple image data, for instance to track the process of disease or to observe the perfusion of contrast agents in order to obtain functional information about organs.

In this study new segmentation and registration techniques were developed for the morphological and kinematical analysis of joints. The techniques were applied to 3-D MR and CT images of the wrist joint.

Deformable models were chosen for image segmentation because they offer some attractive features. They provide continuous geometrical representations of structures which can be detected in spite of incomplete boundaries, often due to a lack of image contrast. By adjustment of the mechanical properties of the models, curvature parameters for instance, smoothness constraints can be imposed in order to acquire anatomical realistic shapes. Due to the physics-based nature of the models this adjustment is intuitive, although the number of parameters to be tuned can be quite large. Deformable models offer a combined solution to the requirements of edge detection, continuity, and smoothness constraints.
2-D Deformable Contour Model

The two-dimensional (2-D) contour model due to Kass et al. [19] was modified for the tracking of the carpal bone contours in stacks of 2-D MR images. This new contour model is described in Chapter 2. In order to improve the performance of the original snake model 1-D radial scale-space relaxation and contrast equalization were used. In the relaxation stage the image intensity is filtered with a series of 1-D second order Gaussian filters. Moreover, the resampling method proposed by Lobregt and Viergever [37] was adopted to reduce the shrinking of the snake. Since the coherence of the snaxels – the elements or points of the (discrete) snake – is maintained by resampling, the dependency on elasticity could be diminished. This improved snake model is less sensitive to initialization and has no tendency to cut off contour sections of high curvature. A surface description for each bone was obtained by connecting the stacked contours by triangle strips.

Although the snake model generally produced satisfactory results, some problems remained unsolved due to the 2-D approach. The main limitations were that a snake was not suitable to provide a good contour detection in the upper and lower image slices through the carpal bones, and that no solution was provided for topology changes of the contour which may take place between successive image slices. These problems are absent in a true 3-D model. The 2-D model may still be the model of choice for the segmentation of anisotropic image data or in situations where more user interactivity is required, since interactive steering methods are easier performed in 2-D than in 3-D space.

3-D Deformable Surface Model

The two-dimensional (2-D) contour model due to The new 3-D triangulated deformable surface model (DSM) as explained in Chapter 3, was developed to extract the surfaces of the bones in 3-D MR and CT images of the wrist (Fig. 53 top, p. 114). This surface model is robust to initialization, provides wide geometrical coverage and quantitative power. By applying 1-D radial Lagrangian mechanics, vertex resampling, and surface regularization, an accurate and fast surface extraction is obtained. The shrinking of the surface is eliminated by applying special curvature forces and by omitting elastic forces [37]. The initialization is facilitated by the placement of a geometric primitive (tetrahedron) within each bone to be segmented. This initial surface is inflated to a binary approximation of the boundary derived from the image. During inflation, the surface is refined by the addition of vertices. After the surface is fully
inflated, a detailed, accurate boundary detection is obtained by the application of radial scale-space relaxation. The coherence of the vertices is retained by applying vertex resampling based on edge collapsing and splitting. By application of a connectivity controlled and volume preserving edge collapsing strategy the occurrence of highly connected vertices is prevented and grid distortion is reduced. Moreover, the occurrence of mesh folding [55] is prevented. By using Rivara’s edge splitting principles [56] the shape and regularity of all triangles is maintained and the transition between small and large triangles is smooth in a natural way. Surface regularization is applied to obtain a locally equidistant spacing of the vertices.

The DSM was applied for the surface segmentation in eight MR and sixteen CT scans of the wrist of different volunteers. After surface extraction the morphology and the architecture of the wrist joint was studied by surface rendering (Fig. 53 top, p. 114). This 3-D visualization technique aids the radiologist in the diagnostic interpretation of the images and may help to investigate for example carpal luxation. A quantitative characterization of the architecture may also be applied to classify instabilities of the wrist, and also of other joints, such as the ankle. Stindel et al. [91] derived architectural parameters for the classification of foot type from MRI data obtained from the tarsal bones (tarsalia) in the foot. Their architectural parameters were based on normalized distances between the centroids of the tarsalia and on angles between the principle bone axes and lines connecting the centroids.

An inherent 3-D approach is always beneficial when detecting a 3-D phenomenon. By using information on 3-D image gradients and geometry in the calculation of image and curvature forces, respectively, the quality of the surface extraction is improved compared to the prementioned 2-D approach in which the surface was reconstructed from contour stacks obtained by snakes.

The modified snake model of Chapter 2 is an example of a globally parameterized model, in contrast with the newly developed triangulated deformable surface model of Chapter 3, which is based on an unstructured triangular mesh taking into account necessarily locally defined physical properties. Globally parameterized deformable contour and surface models have the advantage of being less sensitive to initialization, since local deformations influence the entire contour or surface, whereas in a local model the shape of the model is only influenced locally. In a local model the coupling between the vertices over a larger distance of the model is absent and the model may even intersect itself when stronger smoothness constraints are imposed.

An important advantage of local surface models is that the coherence between the vertices can be established by vertex resampling. Elastic forces that give rise to shrinking and generally degrade the quality of the boundary de-
tection, can be eliminated as a consequence. The local addition and removal of vertices as used in the local resampling algorithm, however cannot be applied in a global deformable surface model, since it breaks up the symmetry of the corresponding structural mesh.

Globally parameterized models can also be advantageous when a priori model information about shape and expected grey value intensity is used [68–70]. Local models provide wide geometric coverage in contrast with parameterized models that offer the greatest parsimony [9]. In order to improve the compactness of the triangulated DSM an adaptive mechanism may be considered that controls the density of model points on the basis of vertex curvature in combination with image curvature.

In the 3-D segmentation algorithm the possibility for the user to interact with the surface extraction process is limited since it takes too much time to extract the surface of a bone in a 3-D MR or CT image (0.5-2.5 min on a Sun SPARC 20 at 66 MHz). Therefore, user defined steering forces, such as spring or repulsion forces, were not applied for interactive steering. User interactivity to a certain extent is required, however, since the quality of the surface segmentation was sometimes locally counteracted, for example due to blood vessels surrounding the bones in MR images or internal bone structures of very high contrast in CT images. In these cases some effort had to be put in editing the images in order to obtain an anatomical realistic shape.

Quantification of 4-D Joint Kinematics

The two-dimensional (2-D) contour model due to the fully automatic 3-D matching technique as explained in Chapter 4, was developed for the registration of bones of the wrist joint in a sequence of CT images corresponding to different postures of the wrist during radial-ulnar deviation or flexion-extension of the hand (Fig. 53 middle and bottom, p. 114). Of the wrists of eleven volunteers axial helical CT scans were made. The wrists were imaged in the neutral position with a conventional CT-technique, and in 15 to 20 other postures with a low-dose technique. The registration procedure consists of two steps. First, a segmentation of the bones in the wrist joint is obtained by application of the DSM to the scan of the wrist in neutral position. Second, the movements of the bones between successive postures are calculated by registering the bones with their counterparts in the other scans. The registration is performed by application of a 3-D matching algorithm based on chamfer matching [71] and grey value correlation.

Accurate estimates of the relative positions and orientations of the carpal bones during flexion and deviation were obtained in a large number of differ-
ent postures. An error analysis in which the influence of the x-ray dose and the size of the reconstruction matrix was determined, demonstrated that the accuracy of the registration procedure is at least 0.5 mm for translation and 0.4° for rotation.

Since information of the entire volume of the bones was used in the matching algorithm, the translation and rotation parameters could be estimated much more accurately than could have been the case when algorithms had been used based on information of the surface only, such as anatomical landmark techniques [14, 92] or surface registration [15, 16, 41]. In addition, these last approaches require repeated landmark or surface detection which may include large amounts of operator intervention. Moreover, due to the increased accuracy in the volumetric registration a low-dose scan technique could be used to reduce the exposure to x-rays. As a result, the wrist could be imaged in a large number of different postures during radial-ulnar deviation and flexion-extension, using a modest amount of x-rays.

Both normal and pathological wrist motion can be studied by viewing the bones using a visual animation tool that was developed specially for “carpal navigation.” The geometric information served as a basis to display four-dimensional (4-D) joint kinematics. The animation is of vital importance in the understanding of the complex movements of the bones during different motions of the wrist and can also aid to the recognition of pathological wrist motion.

Once a database of normal in vivo carpal kinematics has been established, the kinematics of an injured wrist can be compared to these reference data. It is expected that in this way a possible ligament lesion can be detected with high specificity and sensitivity, and that no other diagnostic modality will be needed.

In the near future the introduction of volumetric CT-imaging using cone beam geometry and 2-D detector arrays, can be expected in the clinic. With this technique it will be possible to acquire transmission data of a complete volume within a very short time period. Therefore, this new CT imaging technique will be promising for motional analysis of joints, which is still demanding on currently available CT and MR scanning systems.

**Future Research**

The two-dimensional (2-D) contour model due to The use of a triangulated deformable surface with a flexible topology would provide a solution to the problem of self-intersection of the surface. McInerney and Terzopoulos have developed (local) topologically adaptive contour and surface models [58, 59]
in which self-intersection will be detected using interior information or so-called ‘burned vertices’. Whenever a self-intersection is detected the topology of the contour or surface is adapted. Extending the topological flexibility in a suchlike way would expand the segmentation capabilities of the triangulated DSM, since it allows for a topologically consistent description of complex geometrical, multi-part shapes such as arterial or bronchial ‘tree’ or brain structures.

A deformable surface model based on neural networks due to Crzeszczuk et al. [93], which stems from the area of computer graphics, may also be promising for the segmentation of medical images. Their NEUROANIMATOR exploits neural networks for model deformation instead of Lagrangian dynamics, which has some important advantages such as numerical stability and speed. Moreover, the “learning” capabilities of neural networks can improve the automation and quality of the segmentation. Neural networks can be incorporated for geometric reasoning strategies to allow for shape recognition or correction. Neural feedback can also be applied for local parameter adjustments or conditional in- and deflation of the surface.

The performance of computer hardware has increased substantially during the past years. On a state of the art computer or parallel system the DSM as described in Chapter 3 has the potential to run in real-time. In this setting the editing of images, which is needed to prevent locally erroneous boundary detection, can be replaced by user interactive steering of the surface model. To that end a 3-D toolbox must be developed for the distribution of different physical properties over the mesh, such as masses and curvature parameters. For the local attraction or repulsion of the surface 3-D cursors are required for the placement of attractors and repulsors. Additional volume visualization may be needed to facilitate 3-D navigation through the yet unsegmented space. An example of such application is the physics-based framework for geometric design due to Qin and Terzopoulos [94]. In this framework dynamical non-uniform rational B-splines (D-NURBS) are exploited for interactive sculpting of complex shapes.

In the future the registration method may be an effective tool to study changes in dynamics of the wrist before and after operative interventions. For that purpose more volunteers will have to be examined in order to enlarge the database of the wrist movements. These data have to be statistically analyzed for the development of a kinematic model of the normal wrist for diagnostic purposes. Such model may be used for automatic detection of pathological motion patterns. Additionally, architectural parameters could be derived to investigate the spatial relationship between the bones. This may aid to the classification of wrist instabilities. Also, the relationship between the architec-
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Figure 54: Principal axes and centroids (crossings of the axes) of the segmented surfaces of the wrist joint, which are suitable for derivation of architectural parameters.

tural and kinematic parameters may be considered.

The registration method may also be applied for the kinematic analysis of other joints (ankle or knee) or the cortical spine. A beautiful example how kinematic parameters can be used to quantify neck mobility – necessary to diagnose whiplash patients before and after medical treatment – has been developed by Woltering [81]. The kinematic data in conjunction with the geometric bone description may also aid to the design of prostheses or external fixators [76] or can be used for educational purposes and for simulation of joint locomotion in virtual reality.

Conclusion

The two-dimensional (2-D) contour model due to In this study segmentation and registration techniques were developed for 3-D MR and CT images of the wrist. With the aid of these techniques an important step forward is made in the morphological and kinematic in vivo analysis of the wrist joint.

The segmentation algorithms – based on deformable models – that were developed in this study offer a realistic geometric representation of the carpal bones, which were acquired with only limited user interaction. This surface representation offers excellent views of carpal morphology and joint architecture.

By application of the full automatic registration algorithm described in this thesis, the carpal kinematics could be accurately estimated in a large number of different postures of the wrist. Due to this large number of postures the motion of the carpal bones could be visualized (semi-)continuously by animating the bones in an interactive movie loop. This visualization turned out to be very effective to present in vivo wrist motion. Both geometric and kinematic data obtained in this study form a basis for quantitative image analysis. Architectural parameters derived from the segmented surfaces (Fig. 54, preceding page) and the kinematic parameters calculated by application of the
registration algorithm can be used for computer aided diagnosis (CAD) of wrist instabilities. In the future this analysis could provide valuable information on the long term results of operative interventions and possibly predict results of new techniques in the fast evolving field of wrist surgery.