Human-computer interaction in medial image analysis

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Chapter 1

Introduction

The variety of image acquisition modalities available today is very large, capturing reality with sensors that measure physical properties and store their values as digital images. For medical applications, digital images reveal information about the interior of biological bodies in a non-invasive fashion, opening up possibilities for the study of the human inner body to levels not imagined before. Medical image analysis consists of the study of digital images with the aid of computational tools that facilitate the measurement and visualisation of entities of interest. As a prerequisite for most digital analysis techniques, the object under study must be identified and isolated from the rest of the image in a processing step named image segmentation.

Intuitively, segmentation is "the action of dividing into segments", where a segment is "any of the parts into which something is separated" [6]. In the context of digital image processing, segmentation "subdivides an image into its constituent parts or objects. The level to which this subdivision is carried out depends on the problem being solved" [3]. More specifically, segmentation refers to the recognition (which type and location) and delineation (precise spatial extent) of objects of interest represented in the image [2]. The output of the segmentation step may be a representation of all pixels inside the object (figure 1.1-a) or the image positions of the boundary between the object and the background (figure 1.1-b).

In medical imaging, objects in the image correspond to real entities such as organs, bones, prostheses, and physical probes. See for example figure 1.1, where a cross-section of the aorta and the spine are visible among other structures. Depending on the application, just a few objects in the image are relevant, e.g. a particular organ [9] or a few blood vessels [7]. It also occurs that only part of an object needs to be segmented, e.g. wall segments of the heart ventricle [4], or that the structure of interest is the space between objects, e.g. the ankle joint space [8]. The need for full-image segmentation occurs less often in medical applications, for example in brain mapping [1]. Even when the segmentation goal seems to be relatively modest, however, segmentation is a difficult step in the analysis of medical images.

While it is easy and quick for humans to segment visual information, it is very difficult for computer programs to perform this task automatically. This is particularly
true for medical applications, where the image quality is limited by acquisition and reconstruction to the point that the delineation of an object may not be completely supported by evidence in the image data. For example, note the faint boundary between the aortic thrombus and the spine in figure 1.1-b. Methods that take into account the object's shape, in addition to the image data, usually perform better in such cases, but they have difficulties in the presence of large biological variation and aberrations caused by pathology. An expert human operator, however, can clearly identify the position of an almost invisible boundary, or instantly recognise a heavily deformed entity, although the precise boundary position may vary for different operators. These skills are attributed to sophisticated visual perception mechanisms and contextual knowledge about the segmentation problem, which are difficult to incorporate into automatic methods. As a consequence, still today human operators outperform computers in several segmentation tasks, especially in the presence of abnormalities.

In a scenario where automatic segmentation, with a reliable and generally applicable technique, is not possible using current computer vision technology, there is high motivation to consider interactive methods. The strength of these methods lies in the combination of complementary skills of a human operator and a computational method in the segmentation process, with improved performance as compared to purely manual or purely automatic procedures.

In this thesis we discuss the structured design and implementation of interactive segmentation methods to serve for medical image analysis, stressing the need for reliable, precise and repeatable segmentation results obtained with efficient human-computer interaction.

We start by examining examples of interactive segmentation methods in the survey presented in chapter 2. Existing interactive methods in general fall into one of two broad categories. In the first category, computation is added to a manual segmentation procedure to increase efficiency, to reduce the amount of user intervention, and to reduce intra- and inter-operator variability. In the second category, user par-
ticipation is added to a computational method to efficiently bootstrap the process and to increase the reliability of results. In most situations, however, interaction and computation are combined in an ad-hoc fashion, without full understanding of the impact of such combination in the segmentation results generated by these methods.

The research questions addressed in this thesis naturally arose from the conclusions of this survey, aiming at a structured approach to interaction for image segmentation. In the first place, is it possible to combine the strengths of a computational method with human expertise in such a manner as to produce reliable, precise and repeatable segmentation? If this is true, how should interaction and computation be integrated into a single process, with the guarantee that the desired segmentation outcome can be generated in all circumstances? In the third place, how can intuitive user-interfaces be designed, such that medical users can comfortably and efficiently steer a sophisticated computational method towards the desired result? In the fourth place, how can user interventions be interpreted to support efficient segmentation tools capable of learning from user actions and revising the knowledge contained in the computational method? And finally, can an evaluation procedure be devised to establish objectively the performance of such an interactive method?

As a first attempt to simultaneously address all these issues, in chapter 3 we propose a structured approach for interactive segmentation. In this framework, interaction and computation are combined on the basis of cases where the computational method fails, motivating user intervention. In such cases, the information provided by the user is used to reconfigure parameters for the computational method, allowing for recovery from a failure condition. In the proposed framework, interaction happens at a higher semantic level, opening up the possibility for the design of interactive tools with “intelligent” behaviour.

In the remainder of the thesis we pursue the implementation of an interactive segmentation method based on this framework, which turned out to be less straightforward than expected when seen as an extension of existing computational methods. Many difficulties were encountered to adopt deformable models [5] as the supporting computational method for interactive segmentation. These difficulties motivated the development of a new deformable model method described in chapter 4, called Piecewise DM. In the new method, the parameters for the boundary model can be reconfigured dynamically based on information derived from interaction with the user.

In chapter 5, we apply the framework to design an interactive method where the Piecewise DM is adopted as the backbone for its implementation. A performance analysis of this method was carried out to determine what the method can and cannot do, and under which circumstances. Due to the difficulty in performing a theoretical analysis in this case, an experimental approach was adopted in the experiments, where the limits of functioning of the method are explored on the basis of synthetic data. By understanding the behaviour of this method under limiting conditions, we expect to determine the applicability of the framework for interactive segmentation to a broader range of practical problems.

Finally, in chapter 6 the framework for interactive segmentation is applied to a clinical application, namely the segmentation of the ankle joint space in osteoarthritic
ankles. In this application, the visual evidence of the boundary of interest is very low, requiring an efficient interactive segmentation solution where results are reliable and repeatable. Such a solution was developed using a customisation of the method described in chapter 5.

Bibliography


