Available online at www.sciencedirect.com

ScienceDirect

Fuzzy Sets and Systems 279 (2015) 87–100

FUZZY sets and systems

www.elsevier.com/locate/fss

Incorporation of fuzzy spatial relation in temporal mammogram registration

Fei Ma [a,*], Limin Yu [b], Mariusz Bajger [c], Murk J. Bottema [c]

[a] *Mathematical Science, Xi'an Jiaotong-Liverpool University, Suzhou, China*
[b] *Electrical and Electronic Engineering, Xi'an Jiaotong-Liverpool University, Suzhou, China*
[c] *School of Computer Science, Engineering and Mathematics, Flinders University, Australia*

Received 30 June 2014; received in revised form 27 March 2015; accepted 28 March 2015

Available online 2 April 2015

Abstract

This paper presents a method for incorporating fuzzy sets based spatial relations in registering temporal mammogram pairs. In the proposed method, four spatial relations, *to the right of, to the left of, below*, and *above*, are considered. The histogram of all possible angles between all pairs of points in a pair of regions of interest (ROIs) is treated as a fuzzy set and spatial relations between the pair of ROIs are characterized by measuring to what degree this fuzzy set approaches the four spatial relations. Based on the spatial relations, association of ROIs of temporal mammogram pairs is then treated as a graph matching problem and registration of temporal mammogram pairs is realized by finding the common subgraph between two graphs representing a pair of temporal mammograms. 95 pairs of real temporal mammograms are used to test the proposed method. 70.8% of matched ROI pairs are visually identified as "good" matches. When the registration results are incorporated in a cancer detection scheme, the A_z score (area under the ROC curve) is improved from 0.846 to 0.852. The results demonstrated that registration of temporal mammograms based on fuzzy spatial relations improves the overall detection efficiency.

Keywords: Fuzzy spatial relation; Temporal mammogram registration; Breast cancer detection

1. Introduction

Spatial arrangements of objects, such as distance and direction between objects and the topology of an image, are important in many recognition and interpretation tasks. Spatial relations provide structural knowledge of an image and constitute a fundamental part of image analysis along side object recognition and texture analysis. Spatial relations have been employed in various applications, such as aerial imaging, computational linguistics [1], autonomous robotics [2] and medical imaging [3].

* Corresponding author. Tel.: +86 512 8816 1633.
E-mail addresses: fei.ma@xjtlu.edu.cn (F. Ma), limin.yu@xjtlu.edu.cn (L. Yu), mariusz.bajger@flinders.edu.au (M. Bajger), murk.bottema@flinders.edu.au (M.J. Bottema).

http://dx.doi.org/10.1016/j.fss.2015.03.021

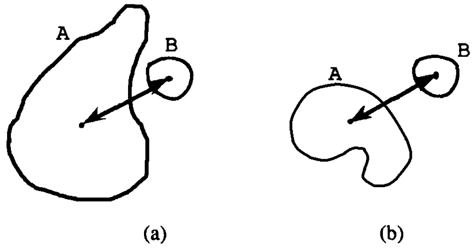

Fig. 1. Ambiguity of spatial representation using centroids of objects. Objects in (a) and (b) have exactly the same spatial relation. However, shape, size and orientation of object A in (a) and (b) are different. The centroid spatial relation representation cannot accurately express the spatial relations between the objects in this example.

Qualitative and precise expression of spatial relation is not a trivial task. Crisp definitions of spatial relations, such as "left of", "right of", "above" and "below", have been found inadequate in expressing complex spatial relations (Fig. 1). As Freeman [4] pointed out, humans have an inherent ability to assess spatial relations based on imprecise reasoning. The "all-or-nothing" approach in interpreting images is inadequate for modelling human judgement. On the other hand, the intrinsically imprecise aspects of spatial relations can be modelled by using fuzzy sets.

Spatial relation expressions based on fuzzy sets have been explored and applied in various applications. Le Ber and Mangelinck [5] used spatial relations to analyze satellite images in order to diagnose agricultural systems and to forecast environmental problems. Barra and Boire [6] incorporated fuzzy set based spatial relations in a fusion framework to aid the segmentation of MR brain images. Colliot et al. [3] also incorporated fuzzy subsets based spatial relations with deformable models in segmenting brain subcortical structures in magnetic resonance images (MRI). They claimed that incorporating such information with deformable models improved the segmentation results. Fuzzy sets based spatial relations have been useful tools in some linguistic scene descriptions or ontology applications. For example, Keller and Wang [7] created a fuzzy logic rule-based system to combine spatial relationships and other important scene properties for linguistic scene description. Hudelot et al. [1] proposed a fuzzy representation based ontology of spatial relations and illustrated the potential contribution of the ontology in the task of image interpretation. Kuipers [2] described multiple representations of spatial semantic hierarchy which is used in intelligent robot control, map-building and navigation.

Breast cancer is the most common cancer among women worldwide. Early detection of breast cancer is believed to be the key to reduce the mortality. As the most effective method for early breast cancer detection, breast cancer screening has been introduced in many countries to provide intensive monitoring of breast cancer. For example, in Australia, women, primarily those between the ages of 50 to 69, are recommended and invited to attend screening every two years. Mammograms taken in different visits form temporal sequences and are kept for future reference.

When reading the mammograms, radiologists usually compare the current mammogram with a previous one to check the changes between the two mammograms. Extracting and utilizing such temporal information by computer programs have not been entirely successful so far. A key stumbling block is image registration; the problem of identifying objects in one image with the matching objects in the other image. The difficulty of registering sequential mammograms lies on the nature of the mammogram itself which is a 2D projection of a 3D object. Natural changes of the breast over time not related to cancer, differences in equipment used for image acquisition over time, differences in the positioning of the breast, and inconsistent distortion of breast morphology at acquisition can all cause the temporal mammograms be very different.

Despite the complexity, there have been many attempts in registering temporal mammograms and analyzing temporal changes. Rigid or affine deformations between temporal mammograms was often assumed and used in many attempts [8,9]. However, these methods were limited by the fact that the map between mammograms of the same breast is usually not smooth and not even well defined. Another approach is based on alignment of images and then searching in one image for mapping regions of another image. Timp and Karssemeijer used the center of breast to register temporal mammograms globally and performed local searching to associate suspicious regions [10]. Marias et al. [11] firstly align breast boundaries of two mammograms, and then match representations of internal structure based on thin plate splines. Engeland et al. [12] compared 4 mammogram registration methods and found that the mutual information (MI) based method outperforms the others. Díez et al. [13] also evaluated 8 intensity based rigid and nonrigid image registration algorithms among which the B-Spline Free-Form Deformations (BSP) method obtained