Ontology and qualitative medical images analysis

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ABSTRACT. We describe a methodology for the analysis of radiographic images which is based on two major techniques: (1) qualitative geometric abstraction and (2) ontological analysis of anatomical structures. The first technique is a bottom-up approach to extract qualitative spatial relations from medical radiographic images and the second technique is a top-down approach to determine which qualitative relations can possibly hold between the parts of (normal and pathological) anatomical structures. The process of image analysis is both a process of feature extraction, and the extraction of qualitative relations among features. These qualitative relations are then used to classify the images within the 'space' of ontological possibilities.

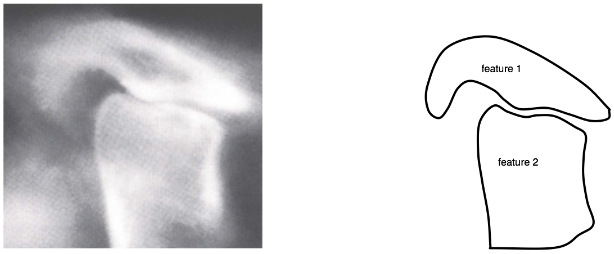
1 Introduction

A medical image is more than a array of pixels. We can distinguish at least three major distinct components of a medical image: (I) The particular anatomical structure from which the image is taken; (II) The array of pixels of measured radiation, hydrogen density, etc.; (III) The collection of features each of which is a cluster of pixels with similar pixel values in the pixel array.

Consider Figure 1(a). This is a tomogram taken of Joe Doe's right TMJ at time t. The anatomical structure (Component I) from which the image is taken is Joe Doe's TMJ. The pixel array (Component II) is the tiff-file that is included in this document. The image (Component III) consists of the features you can distinguish when looking at the image, e.g., the somewhat rectangular shaped feature that takes up large parts of the image and which you know from prior experience and education is a depiction of Joe's condyle.

Given the three components of a medical image, medical image analysis (the process which allowed you to identify Joe's condyle) is a process that has at least four stages: Four Stages of Medical Image Analysis (1) Clustering pixels into features; (2) Analyzing the shape of features and spatial relations between them as they are depicted in the pixel array; (3) Mapping features to anatomical structures and relations between features to relations between (parts of) anatomical structures; (4) Evaluating the depicted anatomical structure (and parts thereof) as normal or pathological in the sense of canonical anatomy.

Consider, again, Figure 1. Stage 1 of the process of analyzing the image shown in Figure 1(a), is to cluster pixels into features like 'feature 1' and 'feature 2' as depicted in the drawing



(a) (b)

Fig. 1. (a) tomogram of Joe Doe's right TMJ taken at time t; (b) two features of the image on the left.

shown in Figure 1(b). This process is complex and must deal with the fact that, a) it is often difficult to extract crisp boundaries from the pixel array and b) that the pixels that are to be clustered into a single feature may be quite heterogeneous. (See, for example, [1] for pointers to the literature of how to deal with those issues.) In Stage 2 of the process of image analysis, characteristics of the shape of the extracted features and spatial relations among the features are determined. For example, (a) the lower boundary of 'feature 1' has a certain characteristic sequence of convex and concave boundary parts (again, see [1].), (b) 'feature 2' is to a certain degree shaped like a rectangle the height of which is larger than its width, (c) both features are disconnected, i.e., they are disjoint and do not touch, (d) 'feature 1' is above 'feature 2', and (e) both features are very close. Obviously it is not easy to specify what is meant by 'very close'. In first approximation one could say that 'very close' means that the smallest distance between is 'feature 1' and 'feature 2' is less than one tenth of the width of 'feature 2'. This number can be determined relatively easily by counting pixels in the underlying pixel array.

In Stage 3, the information about the shapes and the relations between the extracted features is used to map features to anatomical structures (or parts thereof). After having mapped 'feature 1' to Joe Doe's temporal bone and 'feature 2' to Joe's condyle, we can derive from the spatial relations between 'feature 1' and 'feature 2' that Joe Doe's temporal bone and condyle are disconnected but very close.

Finally, in Stage 4, the extracted relations between Joe Doe's temporal bone and condyle are compared to the relations between temporal bone and condyle according to *canonical anatomy*. This then will reveal that the disjointness of Joe Doe's temporal bone and condyle is *normal* but the fact that Joe Doe's temporal bone and condyle are very close is *not normal*. This is because very close as defined above means *too close* for an average articular disc to fit between temporal bone and condyle, since an average articular disc has a thickness of roughly one fifth of the width of the head of the condyle.

We propose a methodology which we call *qualitative geometric abstraction and ontological analysis of anatomical structures*. The aim of this methodology is to provide a conceptual framework that can guide the formalization and implementation of our Stages 2 - 4 of medical image analysis. The term qualitative abstraction as used in this paper was originally introduced in [2]. We also draw from existing work on qualitative spatial representation and reasoning in Artificial Intelligence [3, 4] and Geographic Information Science [5, 6] as well as from existing work on formal ontology in philosophy [7–9].

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The presented methodology can be considered as a *qualitative* alternative to the commonly used *quantitative* techniques based on image registration [1, 10, 11]. Image registration seeks to determinate numerical transformations between image spaces, which map each point of an image onto corresponding points of another image. We argue in this paper that in order to analyze a medical image in the sense of our Stages 1-4, it is often NOT necessary to find a numerical transformation between a given image and a corresponding image in an atlas to identify depictions of anatomical and pathological structures.

2 Qualitative geometric abstraction

In an image, the location of a feature is the set of locations of all pixels that form the feature, i.e., the set of coordinates of all pixels belonging to the feature. It is critical in the process of image analysis to abstract identified features from their location in specific pixel arrays. To abstract here means to consider equivalence classes of features rather than the features themselves.

The difficult problem is to define the equivalence classes in such a way that the *important structural properties* of the individual features are preserved while unimportant/non-relevant details are omitted. To achieve this we distinguish two major techniques of abstraction: (I) Geometric abstraction: based on defining equivalence classes with respect to properties of features and relations between them that remain invariant under certain classes of transformations of the underlying pixels. (II) Selective landmark-based qualitative abstraction: based on defining equivalence classes with respect to location in frames of references defined by landmarks of features and relations between those landmarks.

Geometric abstraction yields equivalence classes of features whose locations can be made identical by certain *transformations*. There are several kinds of transformations (including rotation, translation, scaling, etc.) that correspond to different *degrees* of geometric abstraction. Some of them are listed in Table 1. Particularly relevant in our context are mereologies, topologies, and isotropies.

geometry	group of transformation	invariant properties
direct-isometry	rotation, translation, reflection	distance, volume, congruence, similarity
affine geom.	linear transformations	co-liniarity, neighborhood
isotropies	homomorphisms without reflection	neighborhood, embedding in the plane, clockwise order of figure vertices
topology	homomorphisms	neighborhood, connectedness
mereology	operations that do not create or destroy parts	parthood

Table 1. Classes of geometric abstraction [12]

Depending on the given degree of geometric abstraction (topological/isotropic/affine,...), certain (topological, isotropic, affine,...) properties and relations are preserved while others are traced over. An important aspect of geometric abstraction is that it applies equally to all parts of the image and thus for all features represented in the pixel array.[5] This is desirable for isotropic properties and in particular for topological and mereological relations such as part-of, connected-to, disjoint-from, etc. This is because topological and isotropic properties and relations are fundamental to the function of any given anatomical structure. For example, a broken bone (in topological terms a bone consisting of two disconnected pieces) is fundamentally different from a non-broken bone (in topological terms a bone consisting of one single piece). Similarly, a detached muscle (a muscle topologically disconnected from the bone) is a serious medical problem. Thus it is critical to preserve *all* topological properties and relations in the process of geometric abstraction in image analysis. Similarly, it is important to distinguish an image of a left TMJ from the image of a right TMJ. Hence it is important to completely preserve not only topological properties but also isotropic properties.

The situation is different for properties and relations like shape and distance. Consider Figure 1. Critical for the function of the joint is the minimal distance between the condyle and the temporal bone. On the other hand the diameter of the condyle below the head is, as long as it remains within certain limits, unimportant for the function of the joint. Similarly, the shape of those parts of the boundary of the temporal bone facing the condyle is critical for the function of the joint while the shape of other parts of the boundary is not (so) relevant for the function of the joint.

Since certain shape properties and distance relations are important to the analysis of a medical image, using the technique of *geometric abstraction* to abstract from all but isotropic properties of the features in the image, i.e., topological properties and relations and the embedding of features into the plane, preserves *too few* properties of geometric features. For this reason in image registration one usually works with transformations which do not only preserve isometric properties but which do preserve for example direct isometries (or rigid body movements) which also preserve properties such as distance, volume, angles, etc. However those techniques are *quantitative* and preserve *too many* unimportant properties. As pointed out above there are many normal variations in shape and size between anatomical structures. Moreover, by means of geometrical abstraction it is impossible to abstract *selectively* from shape properties and distances in some parts of the image and not to abstract from those properties in others.

Selective landmark-based qualitative abstraction. When analyzing and classifying medical images *all* isotropic properties need to be taken into account but only *selective* shape and distance properties and relations are important. To deal with shapes and distances selectively we introduced *landmarks* and the notion of *selective landmark-based qualitative abstraction*. Anatomical landmarks are *ontologically salient (often point-like) parts* of anatomical structures [1]. The selective landmark-based qualitative abstraction has two major components: (1) characterize relations between landmarks in terms of qualitative distances (as-far-apart-as, less-far-apart-than, further-apart-than, etc; (2) use landmarks to define frames of reference and specify the location of features in these frames of reference using topological and ordering relations. We briefly discuss both in sequence. For details see also [13].

Consider Figure 2(b) which shows an idealized x-ray image of Joe's TMJ. Salient points on the inferior surface of the depicted temporal bone are local minima (LM3, LM7), local maxima (LM1, LM5) as well as points at which changes from convexity to concavity occur

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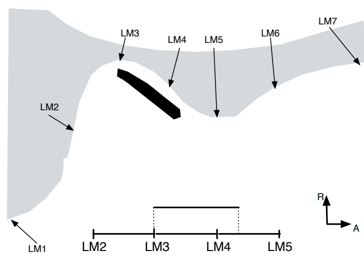
[5] We ignore at this point that also several transformations can be used, each of which is local to a certain part of the image. (E.g., image registration techniques with local transformation domain in according to the classification of [1, 11].)

(LM2, LM4, LM6). Consider the landmarks LM1 and LM3. Existing coordinate differences between LM1 and LM3 along the anterior axis (δa_3^1) and along the rostral axis (δr_3^1) can be used to distinguish the following cases: $\delta a_3^1 = \delta r_3^1$, $\delta a_3^1 < \delta r_3^1$, and $\delta a_3^1 > \delta r_3^1$. In Table 2(a) we consider all combinatorial possibilities for the landmarks LM1, LM3, and LM5.

Notice that the classification in Table 2(a) is *jointly exhaustive and pairwise disjoint*. That is, for any possible constellation of the anatomical landmarks LM1, LM3, and LM5 there is exactly one column in the table. Moreover, since all TMJ images will have the same landmarks on their temporal bones (assuming standardized ways if taking the images and a certain degree of anatomical normality of the depicted bone), we can use Table 2(a) to classify all TMJ images according to qualitative coordinate differences between their landmarks.

$R \in \{=,<,>\}$	1	2	3	4	5	6	7	8	9
$\delta a_3^1 \ R \ \delta r_3^1$	$=$	$=$	$=$	$<$	$<$	$<$	$>$	$>$	$>$
$\delta a_5^3 \ R \ \delta r_5^3$	$<$	$>$	$=$	$<$	$>$	$=$	$<$	$>$	$=$

(a)



(b)

Fig. 2. (a) Nine combinatorially possible patterns comparing the distances between the landmarks LM1 and LM3 and the landmarks LM3 and LM5; (b) location of Joe's articular disc (black) in front of the frame of reference induced by the landmarks LM1-LM7. [13]

Consider the landmarks LM1-LM7 in Figure 2(b). Since the landmarks are points on a one-dimensional line (the boundary of the feature representing Joe's temporal bone), neighboring landmarks define/demarcate one-dimensional intervals on the feature boundary. In the remainder we use the boundaries of an interval in order to refer to that interval, i.e., we write $\overline{\text{L1L2}}$ to refer to the interval bound by LM1 and LM2, and so on. One can see in Figure 2(b), that Joe's articular disc (black) is in front of the intervals $\overline{\text{L3L4}}$ and $\overline{\text{L4L5}}$ on the boundary of the temporal bone. This can be translated into topological relations between intervals as follows: The projection of Joe's articular disc onto the boundary of his TMJ completely covers the interval $\overline{\text{L3L4}}$, partially overlaps $\overline{\text{L4L5}}$, and is disjoint to all other intervals. Here we use the intervals on the boundary of the temporal bone as a *frame of reference* and we can specify the location of the articular disc with respect to the this frame of reference by specifying topological relations between the intervals on the boundary of the temporal bone and projections of the articular disc onto the boundary.

Notice that by using the six intervals created by the landmarks and by distinguishing the relations covers, partially overlaps, and disjoint we can exhaustively distinguish finitely many possible locations of the disk in front of the temporal bone. Moreover, since all (comparable) TMJ images will have the same landmarks on their temporal bone representations, we classify all possible relations between disc and TMJ for all possible TMJs and their images.

3 Qualitative relations and ontological possibilities

The methodology of analyzing medical images by means of extracting qualitative spatial relations between features from raster arrays is *bottom-up*. We start from pixel arrays, extract features, qualitative shapes, and qualitative relations between features, and then derive properties and relations between the depicted anatomical structures and landmarks thereof. The result are equivalence classes which are such that important structural properties of the depicted features are preserved while unimportant/non-relevant details are omitted.

However, the proposed methodology of analyzing medical images has also an important *top-down* component. This component enabled us to distinguish important from unimportant properties. In our present example we always talked about ‘the image of Joe Doe’s TMJ’. That is, we had certain *assumptions* and *expectations* about of what kind of structure is depicted in the image and we *expected* to see certain features in certain parts of the image:

– We expected to see a TMJ in the image shown in Figure 1(a). A TMJ is an anatomical structure that is constituted by certain major parts (temporal bone, condyle,...). Each of these parts has a certain *basic qualitative shape* (temporal bone-like, condyle-like,...). Between those parts certain *qualitative relations* normally hold (temporal bone and condyle are normally disconnected, the temporal bone is above the condyle, temporal bone and condyle are close,...).
– We assumed that in the imaging process the basic properties and relations between the major parts of the depicted anatomical structure are *preserved* in the image in the sense that the features in the images that have certain shapes and that stand in certain relations to each other correspond to properties and relations between the depicted anatomical structures.

These assumptions and expectations allowed us to map ‘feature 1’ in Figure 1(b) to Joe Doe’s temporal bone. The temporal bone-shaped feature in the image had to be a representation of Joe’s temporal bone and the condyle-shaped feature in the image had to be a representation of Joe’s condyle. Moreover, the landmarks LM1-LM7 in Figure 2(b) had to correspond to landmarks in the (hypothetical) sagittal section through Joe’s temporal bone at the level of the middle of the condyle. Similarly, the fact that the average diameter of an articular disc in a normal TMJ is, as rough approximation, larger than one tenth of the width of the condyle allowed us to classify the distance between temporal bone and condyle in Figure 1(a) as too close and thus as abnormal.

Ontological analysis is a critical first step implicitly presupposed in image analysis. Radiologist acquire knowledge about the ontology of anatomical structures (including names of body parts, landmarks, and qualitative properties and relations) as a part of their training. Computer based image analysis requires *computational ontologies* such as the FMA [14] which are formal representations of facts about the major parts of anatomical structures, the qualitative shapes of those parts, and qualitative relations between them [15–18].

4 Conclusions

We described a methodology for the analysis of radiographic images which is based on two major techniques: (1) qualitative geometric abstraction – a bottom-up approach to extract qualitative spatial relations from medical radiographic images – and (2) ontological analysis of anatomical structures – a top-down approach to determine which qualitative relations hold between the parts of (normal and pathological) anatomical structures. Image analysis is a process of feature extraction, the identification of landmarks on those features, and the extraction of qualitative relation among features and among landmarks. These qualitative relations are then used to classify the images within the ‘space’ of ontological possibilities.

It is important to emphasize the qualitative nature of this approach. As pointed out in [15, 13], it is impossible to quantitatively describe canonical anatomy. There is too much variation between the actual shapes and metric arrangements of particular structures in particular human beings. However in all canonical anatomical structures certain parts need to be present. These parts need to have certain qualitative shape properties, and certain qualitative relations need to hold between those parts. Moreover, as indicated in the example, pathological cases can also be characterized and distinguished from non-pathological cases in terms of qualitative relations.

References

1. Brown, L.: A survey of image registration techniques. ACM Comput. Surv. **24**(4) (1992) 325–376
2. Schlieder, C.: Qualitative shape representation. In Burrough, P., Frank, A.U., eds.: Geographic Objects with Indeterminate Boundaries. GISDATA Series II. Taylor and Francis, London (1996) 123–140
3. Weld, D., de Kleer, J., eds.: Readings in Qualitative Reasoning about Physical Systems. Morgan Kaufmann Publishers, INC, San Mateo, Calefornia (1990)
4. Cohn, A., Bennett, B., Goodday, J., Gotts, N.: Qualitative spatial representation and reasoning with the region connection calculus. geoinformatica **1**(3) (1997) 1–44
5. Bittner, T., Frank, A.: On the design of theories of geographic space. Geographical Systems **1** (1999) 237–275
6. Egenhofer, M., Mark, D.: Naive geography. In Frank, A., Kuhn, W., eds.: Spatial Information Theory, A Theoretical Basis for GIS. Lecture Notes in Computer Science, Springer-Verlag (1995)
7. Simons, P.: Parts, A Study in Ontology. Clarendon Press, Oxford (1987)
8. Varzi, A.: Parts, wholes, and part-whole relations: The prospects of mereotopology. Data and Knowledge Engineering **20**(3) (1996) 259–86
9. Smith, B.: Ontology: An introduction. In Floridi, L., ed.: Blackwell Guide to the Philosophy of Computing and Information Blackwell Guide to the Philosophy of Computing and Information, 2003, 155–166,, Oxford: Blackwell, (2003) 155–166
10. Ramirez, L., Durdle, N.G., Raso, V.J.: Medical image registration in computational intelligence framework: a review. Volume 2. (2003) 1021–1024 vol.2
11. Maintz, J.B.A., Viergever, M.A.: A survey of medical image registration. Medical Image Analysis **2**(1) (1998) 1–36
12. Yaglom, I.: Geometric Transformations. Volume 1,2,3. Random House (1962)
13. Bittner, T., Goldberg, L.J.: The qualitative and time-dependent character of spatial relations in biomedical ontologies. Bioinformatics **doi: 10.1093/bioinformatics/btm155** (2007)
14. Rosse, C., Mejino, J.L.V.: A reference ontology for bioinformatics: The Foundational Model of Anatomy. Journal of Biomedical Informatics **36** (2003) 478–500
15. Mejino, J.L.V., Noy, N.F., Musen, M.A., Brinkley, J.F., Rosse, C.: Representation of structural relationships in the foundational model of anatomy. In: Proceedings, American Medical Informatics Association Fall Symposium. (2001) 973–78
16. Donnelly, M., Bittner, T., Rosse, C.: A formal theory for spatial representation and reasoning in bio-medical ontologies. Artificial Intelligence in Medicine **36**(1) (2006) 1–27
17. Smith, B., Ceusters, W., Klagges, B., Köhler, J., Kumar, A., Lomax, J., Mungall, C., Neuhaus, F., Rector, A., Rosse, C.: Relations in biomedical ontologies. Genome Biology **6**(5) (2005) r46

18. Smith, B., Ashburner, M., Rosse, C., Bard, J., Bug, W., Ceusters, W., Goldberg, L.J., Eilbeck, K., Ireland, A., Mungall, C.J., Consortium, T.O., Leontis, N., Rocca-Serra, P., Ruttenberg, A., Sansone, S.A., Scheuermann, R.H., Shah, N., Whetzel, P.L., Lewis, S.: The OBO Foundry: Coordinated evolution of ontologies to support biomedical data integration. Nature Biotechnology **25**(11) (2007) doi:10.1038/nbt1346