Medical Imaging on the Semantic Web: Annotation and Image Markup

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Abstract

Medical images are proliferating at an explosive pace, similar to other types of data in e-Science. Technological solutions are needed to enable machines to help researchers and physicians access and use these images optimally. While Semantic Web technologies are showing promise in tackling the information challenges in biomedicine, less attention is focused on leveraging similar technologies in imaging. We are developing methods and tools to enable the transparent discovery and use of large distributed collections of medical images in cyberspace as well as within hospital information systems. Our approach is to make the human and machine descriptions of image pixel content machine-accessible through annotation using ontologies. We created an ontology of image annotation and markup, specifying the entities and relations necessary to represent the semantics of medical image pixel content. We are creating a toolkit to collect the annotations directly from researchers and physicians as they view the images on medical imaging workstations. Image annotations, represented as instances in the ontology can be serialized to a variety of formats, enabling interoperability among a variety of systems that contain images: medical records systems, image archives in hospitals, and the Semantic Web. The ontology-based annotations will enable images to be related to non-image data having related semantics and relevance. Our ultimate goal is to enable semantic integration of images and all the related scientific data pertaining to their content so that researchers and physicians can have the best understanding of the biological and physiological significance of image content.

Introduction

There is an accelerating growth in the knowledge about biomedicine—most of it on the Web—and a rapidly rising need for computational methods to enable researchers and physicians to exploit that knowledge to understand and cure disease. This "e-Science" paradigm is gaining traction; the biomedical community has begun to embrace informatics technologies enabling semantic scientific knowledge integration, such as ontologies (Bodenreider and Stevens 2006; Cimino and Zhu 2006), standard syntaxes and semantics to make biomedical knowledge explicit (Saadawi and Harrison 2006; Stoeckert et al. 2002; Whetzel et al. 2006), and the Semantic Web (Ruttenberg et al. 2007). These technologies are enabling the community to access large amounts of data, and to interoperate among diverse data archives.

The medical imaging community, specifically the Radiology domain, faces similar difficulties and has similar needs as the rest of the e-Science community, namely to manage, find, and use the voluminous amounts of imaging data accruing at an explosive pace. However, imaging poses unique challenges hindering direct translation of the informatics methods that are currently being applied to non-imaging biomedical data. The first challenge is that images contain *rich content that is not explicit* and not accessible to machines. Images contain implicit knowledge about anatomy and abnormal structure that is deduced by the viewer of the pixel data, but this knowledge is generally not recorded in a structured manner nor directly linked to the image. Thus images cannot be easily searched for their semantic content (e.g., find all images containing particular anatomy or representing particular abnormalities).

A second challenge for medical imaging is that the *terminology* and *syntax* for describing images and what they contain varies, with no widely-adopted standards, resulting in limited interoperability. The contents of medical images are most frequently described and stored in free-text in an unstructured manner, limiting the ability of computers to analyze and access this information. There are no standard terminologies specifically for describing medical image contents—the imaging observations, the anatomy, and the pathology. Schemes for annotating images have been proposed in non-medical domains (Halaschek-Wiener et al. 2006; Khan 2007; Petridis et al. 2006; Troncy et al. 2007); however, no comprehensive standard appropriate to medical imaging has yet been developed.

The syntax used to encode image data and metadata also varies; current standards in use include the following:

- **Digital Imaging and Communications in Medicine (DICOM)**(Mildenberger et al. 2002), applicable to images acquired from imaging devices.
- **Health Level Seven (HL7)**(Quinn 1999), applicable to information in electronic medical record systems.
- **World Wide Web**, where images are labeled with HTML or RDF, though not with consistent semantics across the Web.

A final challenge for medical imaging is that the particular information one wants to describe and annotate in medical images depends on the ***context***—different types of images can be obtained for different purposes, and the types of annotations that should be created (the "annotation requirements" for images) depends on that context. For example, in images of the abdomen of a cancer patient (the context is "cancer" and "abdominal region"), we would want annotations to describe the liver (an organ in the abdominal region), and if there is a cancer in the liver, then there should be a description of the margins of the cancer (the appearance of the cancer on the image). Such context dependencies must be encoded somehow so that an annotation tool can prompt the user to collect the proper information in different imaging contexts.

We describe our approach to tackling the above challenges to achieve semantic integration of images across hospital information systems and the Web, as well as a method to represent the annotation contexts and image annotation requirements to ensure the proper information is collected in the different contexts. Our project is called the Annotation and Image Markup (AIM) Project of the National Cancer Institute's cancer Biomedical Informatics Grid (caBIG; https://cabig.nci.nih.gov/workspaces/Imaging).

Methods

Our approach to making the semantics of image content explicit is to: (1) **create an ontology** to provide controlled terminology for *describing the contents of medical images*, and a standard *information model for semantic annotations*, (2) **develop an image annotation tool** to collect user annotations as instances of the ontology, using the ontology to inform the user about the types of information that needs to be collected given the annotation context, and (3) **serialize the annotation instance data** to DICOM, HL7 CDA (XML), and OWL representation languages to enable semantic integration and to permit agents to access the image annotations across hospital systems and the Web.

Ontology and Schema for Image Annotation

We created an ontology in OWL-DL to represent the entities associated with medical images and that are required when creating annotations on images (AIM ontology). The ontology includes *anatomic structures* visualized in images, the *observations* made by radiologists about images (such as "opacity" and "density"), the *spatial regions* that can be visualized in images, as well as other image metadata (Figure 1). The anatomic structures and observations are obtained from RadLex (Langlotz 2006; Rubin 2007), an ontology that is made accessible to the AIM ontology by importing this portion of the ontology.

We also created an information model ("AIM schema") in UML to describe the *minimal information* necessary to record an image annotation (Figure 2),† inspired in concept by the MIAME project to describe minimal information for microarray experiments (Brazma et al. 2001). The AIM schema distinguishes image "annotation" and "markup." *Annotations* describe the meaning in images, while *markup* is the visual presentation of the annotations. In the AIM

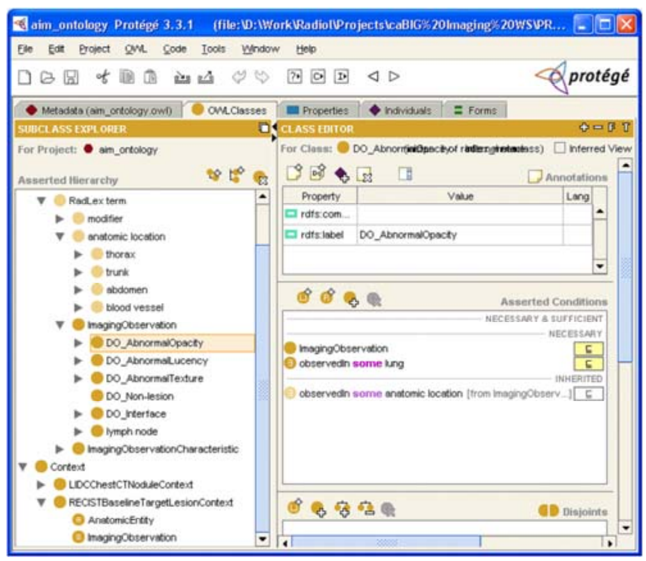

Figure 1. Ontology of Imaging Anatomy and Observations. Screenshot shows the ontology in Protégé. The ontology (left) includes anatomy and imaging observations. Assertions on classes (right) provide knowledge about the anatomic regions that will be visible in particular types of images (for example, the screenshot shows an assertion that abnormal opacity in images may be observed in the lungs), as well as the imaging observations that will occur in those anatomic regions. Specific "contexts" are asserted at run-time to capture common types of scenarios for annotation, where particular combinations of anatomy and imaging observations are appropriate (e.g., "LIDCChestCTNoduleContext"), and automatic classification is used to determine the anatomic entities and image observations that will apply (see Figure 3).

†The AIM information model is available at http://gforge.nci.nih.gov/

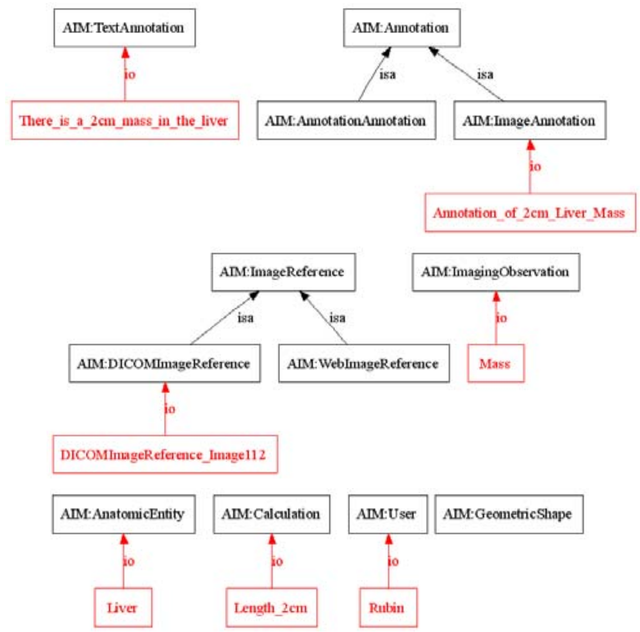

Figure 2. AIM Schema and Annotation Instance. A portion of the AIM schema (black) and example instance of ImageAnnotation (red) are shown. Only *is-a* and *instance-of* relations are depicted. The figure shows that the annotation describes an image (Image 112), which visualizes the liver, and is seen to contain a mass in the liver measuring 2cm in size.

schema, all annotations are either an ImageAnnotation (annotation on an image) or an AnnotationofAnnotation (annotation on an annotation). Image annotations include information about the image as well as their semantic contents (anatomy, imaging observations, etc).

To enable interoperability of AIM between hospital and Web environments, the AIM UML information model was converted to OWL using CIMTool (http://cimtool.org/). The AIM schema was also converted to XML schema (XSD file) to enable validation of instances of AIM XML files.

To tackle the challenge that the content of annotations depends on context, we encoded contextual knowledge in the ontology by adding OWL assertions to the appropriate classes (Figure 1). For example, “abnormal opacity” is an imaging observation that is seen in lungs, so an existential restriction is added to the AbnormalOpacity class (Figure 1). Restrictions were also created to describe anatomic composition; such as the fact that the lungs are in the thorax. A context is encoded by creating a defined class, specifying all necessary and sufficient conditions for the context. For example, a computed tomography (CT) image of the chest obtained to assess a nodule (LIDCChestCTNoduleContext) should have annotations describing anatomic entities that are located in the thorax and any imaging findings that are observed in the lung:

$$\text{AnatomicEntity} \sqsubseteq [\text{LIDCChestCTNoduleContext} \sqcap (\exists\ \text{hasAnatomicRegion.Thorax})]$$

$$\text{ImagingObservation} \sqsubseteq [\text{LIDCChestCTNoduleContext} \sqcap (\exists\ \text{observedIn.Lung})]$$

We implemented the AIM ontology in Protégé-OWL (Knublauch et al. 2004). We used Pellet (http://pellet.owldl.com) to classify the ontology and to infer the requirements for annotation given an imaging context which was asserted at the time of creating an annotation, as described below.

Collecting Image Annotations

We are creating an image annotation tool to collect annotations from users as they review images. A user first provides the tool with the context for annotation (specified using a drop-down box). The annotation tool then asserts the user-specified context in the AIM ontology as a set of defined classes, and it executes the classifier to infer the data fields from the AIM schema that the user should collect for that annotation context (Figure 3).

The contexts are represented as a set of defined classes, specifying the various aspects of annotation appropriate for that context (Figure 1). Following classification, the annotation tool determines the information requirements for annotation by querying the ontology for the subclasses of the annotation context class (Figure 3). The annotation tool uses the names of the classes in the ontology to determine the corresponding data fields in the AIM schema to

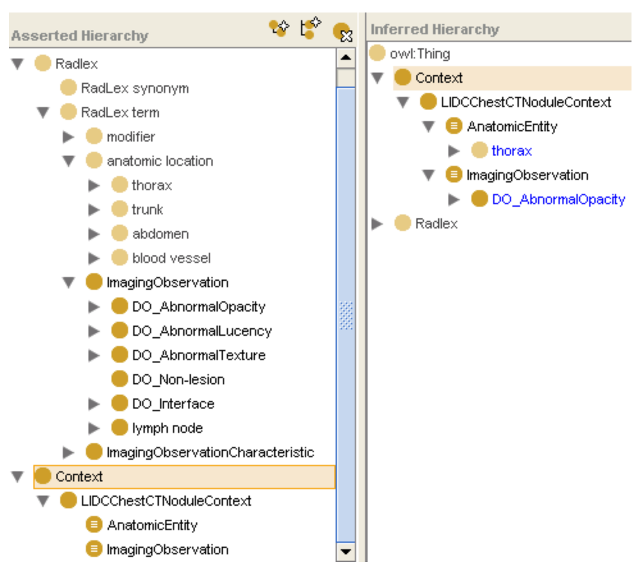

Figure 3. Classification of Ontology to determine entities appropriate for annotation. At run-time, when the user selects a context for annotating an image, that context is asserted in the ontology, and the appropriate entities to be annotated in that context are determined by applying automatic classification to the ontology. In this example, the user selected the LIDC Chest CT Nodule context, and after classification, the system determines that anatomy in the thorax and abnormal opacities are the relevant entities to be annotated.

use for collecting annotation information for that context.

Serializing Annotations to Diverse Formats

Our image annotation tool enables users to capture the information users wish to associate with images or regions of images, storing the annotations as XML ("AIM XML"). All images, regardless of whether they exist on hospital systems or the Web have annotations initially stored as AIM XML, providing a uniform syntax for representing the metadata of all images in a common information model. The AIM XML is subsequently transformed to other formats depending on the type of environment (hospital or Web) in which the image is stored. In addition, AIM XML documents can be validated against the AIM XSD. Since the XSD directly encodes the semantics of image annotations, this validation approach ensures interoperability of the semantic content of images regardless of whether the images are located within hospital information systems or in cyberspace.

To provide interoperability and semantic integration across diverse hospital systems and the Web, we created applications to transform the AIM XML into DICOM-SR and HL7-CDA XML. We also adapted an application previously developed that maps between XML and OWL (Shankar et al. 2007 (in press)) to transform our AIM XML files into OWL. The application reads XML documents and automatically transforms them to an OWL ontology representing the document. The OWL-encoded AIM annotations can be directly published on the Web and their content referenced by semantic Web agents.

We have begun evaluating our work by annotating radiological images using the AIM ontology and AIM schema. A radiologist selected several radiological images and used the AIM schema to create annotations to describe the major abnormalities in the images. We assessed completeness of the AIM schema to capture the annotation information that the radiologist sought to record. We also assessed the completeness of the AIM ontology with respect to its ability to provide the knowledge needed to define the annotation contexts required by the radiologist.

Results

The medical image annotation contexts require users to record different types of information in their annotations depending on the context. Specifically, users need to annotate images with the qualities of abnormal structures (e.g., size, shape, margins, and density), and these qualities vary in different regions of the body. Thus, our image annotation tool requires knowledge about the types of anatomic entities encountered in images and the types of visual observations it needs to prompt the user to collect for the given context. For example, in particular regions in the body, such as the thorax, only certain anatomic structures would be appropriate to mention in an annotation (heart, lungs, and ribs, for example). Likewise, some observations on images are observed only in particular anatomic structures (for example, nodules may be seen in the lung, but not in the ribs; fractures may be seen in ribs, but not in the lung).

The annotation contexts were successfully represented in OWL in the AIM ontology by specifying assertions and defined classes (Figure 1). For example, the context LIDCChestCTNoduleContext representing a CT image of the chest for assessing a nodule was defined using two defined classes, one specifying that the anatomic entities appropriate for annotation are located in the thorax, and the other specifying that the imaging observations appropriate for annotation are those that are seen in the lung. At run-time, when users indicate they are annotating an image in the context "LIDC Chest CT Nodule," the annotation application asserts the class LIDCChestCTNoduleContext in the AIM ontology, then calls Pellet to re-classify the ontology, and finally it queries the ontology to infer the portions of the AIM ontology that are subclasses of the asserted LIDCChestCTNoduleContext class, indicating the portions of the AIM schema needed for annotation in this annotation context (Figure 3). That knowledge is used by the annotation tool to prompt the user as to the annotation information to be collected for that image.

An image annotation comprises a set of instances of the AIM schema (Figure 2). When the user creates an annotation using the AIM image annotation tool, the annotation information is initially stored in XML, compliant with the AIM XML schema. The XML was successfully transformed to OWL using the tool mapping between XML and OWL (Shankar et al. 2007 (in press)), and the annotation could be viewed in Protégé-OWL

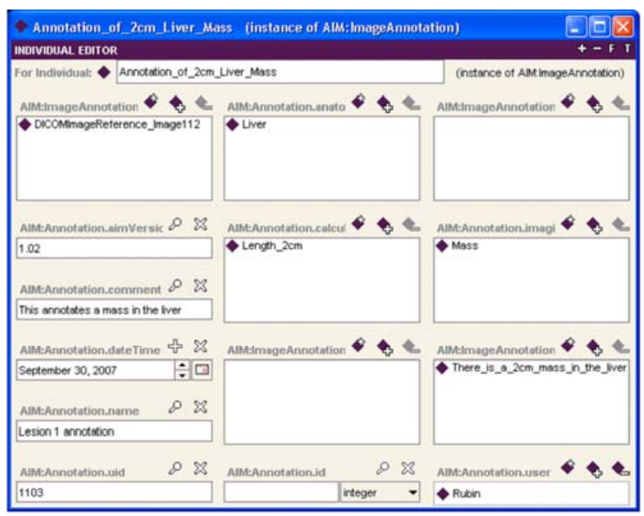

Figure 4. Example Image Annotation instance. An instance of the AIM:ImageAnnotation from Figure 2 is shown, containing the key metadata associated with annotations on images. This annotation captures the fact that the image linked to the annotation visualizes the liver, and that the liver is seen to contain a mass that is 2 cm in size.

(Figure 4). With the image annotation in OWL, the semantic contents were accessible on the Semantic Web. In addition, the AIM XML schema was successfully transformed to DICOM-SR by the application developed for this purpose. The DICOM-SR could be stored in hospital image information systems, and their contents was semantically interoperable with AIM annotations published in cyberspace. The AIM schema contains a unique identifier to the image which is available in all the representation languages, so the image is linked to the annotation regardless of whether the annotation is serialized to DICOM-SR, HL7 CDA XML, or OWL.

Based on our preliminary experience annotating radiological images with AIM schema, the information model was sufficient to capture the semantic contents that the radiologist sought to describe. The AIM ontology also contained sufficient knowledge needed to define the annotation contexts required by the radiologist.

Discussion

Images are a critical type of data in biomedicine. They convey a tremendous amount of information, and radiologists who interpret them make many important distinctions in the images that are needed to relate to other knowledge available within hospitals as well as in cyberspace. However, images on the Web generally have no semantic markup, nor do images residing within hospital information systems. Within hospital information systems, DICOM is a ubiquitous standard for the interchange of images, but even DICOM lacks a formalism for specifying the semantic contents of images. DICOM-SR provides a framework that enables encoding of imaging results in a structured format, but it lacks specification of particular image annotation information requirements.

If semantic information within images were made explicit and associated with images on the Web and in DICOM, many types of Semantic Web applications could be created that access image data, ranging from simple image query programs and image classification (Carneiro et al. 2007; Mueen et al. 2007) to computer reasoning applications (Rubin et al. 2005). In addition, explicit semantic image contents would enable images to be related to the non-image data of e-Science that is pervasive on the Web. For example, images could be mined to discover image patterns that predict biological characteristics of the structures they contain.

There is ongoing work to define methods to describe images on the Semantic Web (Troncy et al. 2007); however, the efforts to date focus on describing the image as a whole, rather than particular regions within the image. In radiology, it is important to describe the semantics of individual regions within images; some regions in biomedical images may contain abnormalities, while other parts could be normal. An image annotation standard should permit users to describe regions in images and to annotate the semantic content of those regions, in addition to the entire image.

Our work addresses the challenges for making the semantic contents of images explicit and accessible both within hospital systems and in cyberspace. First, we have created an information model that specifies the information requirements for image annotation and markup. Our ontology provides controlled terminology needed to describe image contents when users create annotations on images: anatomic structures visualized in images, the observations made about images by radiologists, spatial regions in images, and other metadata (Figure 1), while the AIM schema describes the minimal information necessary to record an image annotation (Figure 2). The AIM ontology and schema enable users to describe the semantic content of images and image regions in a structured and machine-accessible manner. These annotations permit useful queries that would not be possible without such explicit representation, such as “find all images that contain the liver.”

A second challenge our work addresses is that biomedical images are stored in disparate systems, in hospitals and the Web, thwarting interoperability. We have created applications to transform the AIM XML image annotations to DICOM-SR and OWL, enabling applications to access and consume AIM annotations in these diverse settings.

A third challenge our work addresses is recording context-dependent image annotation requirements (minimal information requirements for annotation). The information requirement for image annotation depends on the context (the region of the body imaged and structures contained in the image). Most existing data annotation schemas (such as MIAME mentioned earlier) specify a fixed set of information requirements. There are different minimal information requirements for describing image content depending on the context—the region of the body from which the image was obtained. Our work enables an image annotation tool to acquire context-specific knowledge about the required annotation content. The tool acquires this contextual knowledge from the AIM ontology, leveraging OWL-DL semantics to infer the annotation requirements through automatic classification (Figure 3). The AIM ontology provides knowledge to the image annotation tool that guides the user to supply the appropriate information about images given the imaging context.

A limitation of our approach is that semantic interoperability between Web and hospital systems requires transformation of syntaxes (DICOM-SR, HL7 CDA, and OWL). It would clearly be preferable if all image annotation information were stored in a single format (e.g., OWL); however, data standards in medicine predate the Web and are firmly entrenched and slow to change. Integration can be facilitated with application interfaces for DICOM-SR and HL7 systems to enable them to access the necessary components of the AIM information model to interoperate more easily with data on the Web.

An additional limitation of our work is that we have not yet performed a formal evaluation of AIM with a large collection of images to ensure it is comprehensively applicable, and we have not yet evaluated image annotation tools that are AIM-enabled. In order for AIM annotations to be successful, users must be able to create annotations on images simply and quickly. We are developing the image annotation tool with the goal of fulfilling these desiderata. We will be evaluating it and AIM with a larger group of radiologists and images.

While our work focuses on making semantic contents of medical images explicit, our methods may be more broadly applicable to all types of images on the Web. Ultimately, many new Semantic Web applications could be created that exploit the rich information content latent in images once their semantic content is made explicit and accessible to agents.

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