Towards a Formal Theory for Complex Objects and Content-Based Image Retrieval

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Abstract. Advanced services in digital libraries (DLs) have been developed and are widely used to address the required capabilities of an assortment of systems as DLs expand into diverse application domains. In order to reuse, integrate, unify, manage, and support these heterogeneous resources, the notion of *complex objects (COs)* has emerged as a means to facilitate aggregation of content and to help developers to manage heterogeneous information resources, and their internal components. In particular, complex image objects (along with the most used service - Content-Based Image Retrieval) have the potential to play a key role in information systems, due to the large availability of images and the need to integrate them with other datasets (and metadata), and image manipulation software. However, the lack of consensus on precise theoretical definitions for these concepts usually leads to ad hoc implementation, duplication of efforts, and interoperability problems. In this article we exploit the 5S Framework to propose a formal description for Complex Objects and Content-Based Image Retrieval, defining their fundamental concepts and relationships from a digital library (DL) perspective. These formalized concepts can be used to classify, compare, and highlight the differences among components, technologies, and applications, impacting digital library researchers, designers, and developers. The theoretical extensions of digital library functionality presented here cover complex image objects, within a practical case study, to exemplify the integrative use of services, thus balancing theory and practice.

Categories and Subject Descriptors: H. Information Systems [**H.2 Database Management**]: Miscellaneous

Keywords: Content-Based Image Retrieval, Complex Object, Digital Libraries, 5S Framework

1. INTRODUCTION

Advances in data compression, data storage, and data transmission have facilitated the creation, storage, and distribution of digital resources. These advances led to an exponential increase in the volume and assortment of data deployed and used in many applications. In order to deal with those data, it is necessary to develop appropriate information systems to efficiently manage collections of such data.

Users involved in creation, management, and access to heterogeneous resources are often concerned with improving productivity. For this, it is important to provide developers with effective tools to reuse and aggregate content. This has been the goal of a quickly evolving research area, namely Digital Libraries.

In order to reuse and aggregate different resources, Complex Objects (COs) have been created, motivating solutions for integration and interoperability. Such objects are aggregations of different information combined together into a unique logical object [Nelson and de Sompel 2006; Nelson et al. 2001]. Figure 1 shows the

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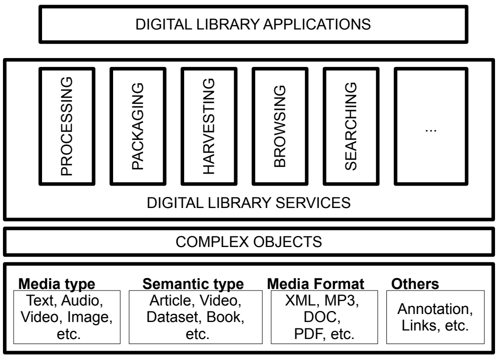


Fig. 1. Architecture for a CO-Based Digital Library.

architecture for a CO-Based Digital Library. The bottom layer has the data sources, accommodating different media types, with different semantic types and formats. The data sources are aggregated in COs, which are later accessed through different services, such as processing, packaging, harvesting, browsing, and searching. These services are later used by digital library applications. Yet, these applications have faced some issues [Ruijgrok and Slabbertje 2009; Awre 2009b]: (i) inadequate support by available DL software for working with COs; (ii) complicated management of COs arising from specific component particularities (such as documents' legal rights); and (iii) inadequate support for multimodal search of complex objects and all components.

Most existing solutions to deal with these issues have focused only on textual data. With the growing demand for visual data, due to the Web, new challenges have emerged. In particular, if we consider image data, significant research efforts have been spent by the Content-Based Image Retrieval (CBIR) [Torres et al. 2006] community in the development of appropriate systems to efficiently manage image collections.

In spite of all the advances, there is a lack of consensus on the precise formalization involved in reusing, integrating, unifying, managing, and supporting of diverse application domains for COs and CBIR related tasks. To tackle this issue, we can take advantage of formal concepts to understand clearly and unambiguously the characteristics, structure, and behavior of complex information systems. The benefits of adopting a formal model include the abstraction of general characteristics and common features, and the definition of structures for organizing components (e.g., aggregations, collections). A precise specification of requirements also strengthens the correctness of an implementation [Gonçalves et al. 2004]. On the other hand, formalized concepts can be used to classify, compare, and highlight the differences among components, technologies, and applications, impacting digital library researchers, designers, and developers.

In this article, we address the formal definitions and descriptions for COs and CBIR by exploiting concepts of the 5S formal framework [Gonçalves et al. 2004]. Later these definitions are explored in a practical case study, to define the complex image object. Our contribution relies on (i) the formalization of complex objects; (ii) the formalization of content-based image retrieval; and (iii) and the discussion on how to combine them to handle complex image objects in applications.

The rest of this article is organized as follows. Section 2 contains an overview and description of related work in digital libraries, complex objects, and content-based image retrieval. The formalization of complex objects and content-based image retrieval using the 5S framework is described in Section 3. Two case studies and the formalization of complex image objects are presented in Section 4. Finally, conclusions and future work are presented in Section 5.

2. RELATED WORK

2.1 5S Framework

The 5S framework aims to provide an underlying foundation for the definition of digital libraries [Gonçalves et al. 2004]. The unified formal theory first specifies an underlying foundation using key fundamental concepts: Streams, Structures, Spaces, Scenarios, and Societies. In turn, these can be employed to describe other DL concepts, such as digital objects, metadata, collections, and services. *Streams* are sequences of elements of particular types (e.g., characters, pixels, bits, etc.). Streams are used to model static and dynamic content, including textual material and multimedia content. *Structures* specify the way in which parts of DLs are organized. Structures are used to represent hypertexts, system organization, and containment. *Spaces* are sets of objects and their operations. Spaces define the logical, representational, and presentational views of many DL components (e.g., probability and vector spaces). *Scenarios* are sequences of events along with a number of parameters. Events may represent changes in computational states through specific parameter values. Behaviors of DL services are described using scenarios. *Societies* are used to describe entities with their relationships to other entities. Societies may include human users and software entities that play a defined role in the digital library's operation.

These five abstractions are useful in providing a foundation for defining and relating digital library concepts. As an example, a digital object may be defined in terms of its *structured* storage *stream* and *structured* metadata specification. The set of 5S descriptions for a digital library may be encompassed in 5SL representations. The 5SL representations may be used to generate and install an implementation of the described digital library [Gonçalves and Fox 2002].

Initial 5S framework efforts focused on defining the minimal set of features belonging to a digital library. The minimal digital library is defined as a quadruple (Repository, Metadata Catalogue, Services, Society) containing the core digital library components. These features include the basic set of structured content and elementary services provided to end-users. In a minimal digital library, the Structures component is only considered in a few ways; digital objects are represented through one or more structured streams and have an associated metadata record with a simple structure. There are no other structures in the minimal DL. The basic digital library services include indexing, searching, browsing, and visualization [Shen et al. 2006]. Minimal digital libraries have been defined with minor context-specific additions to produce existing libraries such as the archaeological ETANA-DL [Ravindranathan et al. 2004]. Further comparisons between 5S and other digital library models can be found in [Kozievitch et al. 2011].

We chose to work with the 5S framework due to wide flexibility for analyzing the internal structure and components of the CO, the description of services through scenarios, the description and use of components organizations (aggregations, collections); and finally, due to its use for implementing applications [Gonçalves and Fox 2002; Zhu et al. 2003].

2.2 Complex Objects (CO)

Some authors name the integration of resources into a single digital object as *Aggregation* [Brogan 2003], a *Component-Based Object* [Santanchè and Medeiros 2007; Santanchè et al. 2007], a *Complex Object* [Nelson et al. 2001], or a *Compound Object* [Awre 2009a]. We adopt the same definition of structuring digital objects present in [Awre 2009a]: atomistic, compound, and complex. The atomistic approach is when the user has a single file (whether made up from a single or multiple text files) from a preferred format. The compound approach is made up from multiple content files, which may have different formats. A complex object is described using a network of digital objects within the repository.

According to Krafft et al., COs are single entities that are composed of multiple digital objects, each of which is an entity in and of itself [Krafft et al. 2008]. Cheung et al. defined CO in the scientific context as the encapsulation of various datasets and resources, generated or utilized during a scientific experiment or discovery process, within a single unit, for publishing and exchange [Cheung et al. 2008]. In other words, a complex object is an aggregation of objects, that can be grouped together and manipulated as a single object.

COs also were defined as aggregations of distinct information units that when combined form a logical whole [1]. Santanchè, on the other hand, used the idea of COs in the field of software reuse and exchange [Santanchè and Medeiros 2007; Santanchè et al. 2007]. Like the script concept [Schank 1995], or the frame concept [Minsky 1974], the components in a CO are supposed to have the same behavior, respect the same rules, or represent the same concept.

Several complex object (CO) formats arise from different communities [Nelson and de Sompel 2006; Nelson et al. 2001; Kozievitch et al. 2011; Lynch et al. 2007] and can be used under different domains [Kozievitch 2009]. In scientific computing, standards arise, such as Network Common Data Form (NetCDF), Hierarchical Data Format (HDF), and Extensible File System (ELFS). HDF and NetCDF, for example, are used in multi-dimensional storage and retrieval, while ELFS is an approach to address the issue of high performance I/O by treating files as typed objects.

COs often are found in persistent database stores. They may be represented using standards from the Moving Picture Experts Group (MPEG) [Burnett et al. 2006] or Metadata Encoding and Transmission Standard (METS)[2]. One example, for including digital object formats, is the Moving Picture Experts Group - 21 Digital Item Declaration Language (MPEG-21 DIDL).

Even though there are a number of standards aiding in the management of COs, there is still incompatibility, motivating solutions for integration and interoperability. As each standard is specialized for a particular domain, it is hard to interoperate across contexts. Yet, it is possible to match some of them, as proposed in [Dourado et al. 2007], in their comparative study of IMS Content Package (IMS CP) and Reusable Asset Specification (RAS).

New standards have emerged, like SQL Multimedia and Application Packages (SQL/MM) [Melton and Eisenberg 2001]. These were defined to describe storage and manipulation support for complex objects. A number of candidate multimedia domains were suggested, including full-text data, spatial data, and image data.

The Open Archival Information System (OAIS) [CCSDS 2002] is an International Organization for Standardization (ISO) reference model, with a particular focus on digital information, both as the primary form of information held and as supporting information for both digitally and physically archived materials. The objects are categorized by their content and function in the operation of an OAIS, into Content Information objects, Preservation Description Information objects, Packaging Information objects, and Descriptive Information objects.

The Open Archives Initiative (OAI) [Lagoze and de Sompel 2001] is a framework for archives (e.g., institutional repositories) containing digital content (i.e., a type of digital library). The OAI technical infrastructure, specified in the Open Archives Initiative Protocol for Metadata Harvesting (OAI-PMH) [Suleman et al. 2003], defines a mechanism for data providers to expose their metadata. This protocol mandates that individual archives map their metadata to the Dublin Core, a simple and common metadata set for this purpose.

OAI also launched the Object Reuse and Exchange (OAI-ORE) project [Lynch et al. 2007] which defines standards for the description and exchange of aggregations of Web resources, and is developing interoperable, and machine-readable mechanisms to express compound object information on the web. OAI-ORE makes it possible to reconstruct the logical boundaries of compound objects, the relationships among their internal components, and their relationships to other resources. The information is encapsulated with named graphs: a set of RDF assertions identified by a URI. Figure 2 [Kozievitch and da Silva Torres 2010] highlights some concepts from the 5S framework and OAI-ORE. Note that concepts such as resource - digital object and complex object can be mutually mapped.

[1] `http://www.openarchives.org/ore/` (As of Aug. 2011)
[2] `http://www.loc.gov/standards/mets/` (As of Aug. 2011)

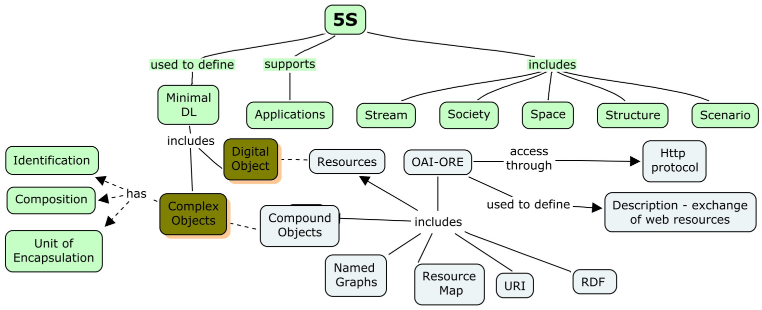


Fig. 2. Matching the main concepts of the 5S framework and OAI-ORE.

A named graph can be described by a resource map. OAI-ORE uses the web architecture, essentially consisting of:

—URIs for identifying objects;
—resources, which are items of interest;
—standard protocols, such as HTTP, that enable access;
—links via URI references;
—named graphs for encapsulating information into a compound object.

METS addresses packaging to collect digital resource metadata for submission to the repository. It is a Digital Library Federation initiative. A METS document consists of the following sections: header, descriptive metadata, administrative metadata, file section, structural map, structural links, and behavior. METS uses a structural map to outline a hierarchical structure for the digital library object, where file elements may be grouped within fileGrp elements, to provide for subdividing the files by object version. A $\langle fileGrp \rangle$ structure is used to comprise a single electronic version of the digital library object. $\langle FContent \rangle$ was created to embed the actual contents of the file within the METS document, but it is rarely used. METS provides an XML Schema designed for the purpose of:

—Creating XML document instances that express the hierarchical structure of digital library objects.
—Recording the names and locations of the files that comprise those objects.
—Recording associated metadata.

METS can, therefore, be used as a tool for modeling real world objects, such as particular document types.

SCORM[3] is a compilation of technical specifications to enable interoperability, accessibility and reusability of web-based learning content. With a Content Aggregation Model, resources described in an XML file named imsmanifest.xml, organized in schema/definition (.xsd and .dtd) files, and placed in a zip file, are used as a content package. SCORM defines a web-based learning Content Aggregation Model and Run-Time Environment for learning objects. In SCORM, a content object is a web-deliverable learning unit. Often, a content object is just an HTML page or document that can be viewed with a web browser. A content object is the lowest level of granularity of learning resources, and can use all the same technologies a web page can use (e.g., Flash, JavaScript, frames, and images).

MPEG-21 [Burnett et al. 2006] aims to define an open framework for multimedia applications, to support, for example, declaration (and identification), digital rights management, and adaptation. MPEG-21 is based on two essential concepts: the definition of a fundamental unit of distribution and transaction, which is the digital item, and the concept of users interacting with them. Within an item, an anchor binds descriptors to a fragment,

[3] `http://scorm.com/` (As of Aug. 2011)

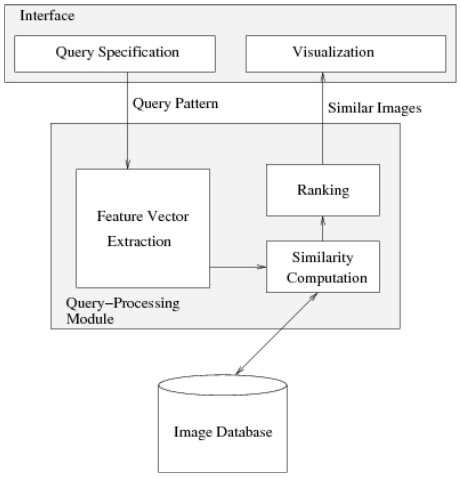


Fig. 3. Typical CBIR system.

which corresponds to a specific location or range within a resource. Items are grouped in a structured container using an XML-based Digital Item Declaration Language (DIDL). In addition, a W3C XML Schema definition of DIDL is provided.

Table I summarizes OAI-ORE, METS, SCORM, and MPEG-21 regarding basic principles available in complex objects: what is the data basic unit, how to relate a part of a document, how to identify it, and how to structure the components.

Name	Unit	Internal Component	Identifier	Structure
OAI-ORE	Resource	Behaves like HTML	URI	Named Graph
METS	Simple object	FContent structure	OBJID	Structural Map
SCORM	Asset	Sequence rules	——	Schema/definition files
MPEG-21	Resource	Anchors and fragments	URI	XML-DIDL

Table I. How standards handle basic CO concepts.

2.3 Content-Based Image Retrieval (CBIR)

A typical *CBIR* solution requires the construction of **image descriptors**, which are characterized by [Torres and Falcão 2006]: (i) an *extraction algorithm* to encode image features into *feature vectors*; and (ii) a *similarity measure* to compare two images based on the distance between their corresponding feature vectors. The similarity measure is a *matching function*, which gives the degree of similarity for a given pair of images represented by their feature vectors, often defined as a function of the distance (e.g., Euclidean), that is, the larger the distance value, the less similar the images.

Figure 3 shows an overview of a content-based image retrieval system. The interface allows a user to specify a query by means of a query pattern (e.g., a query image) and to visualize the retrieved similar images. The query-processing module extracts a feature vector from a query pattern and applies a distance function (such as the Euclidean distance) to evaluate the similarity between the query image and the images. Next, it ranks the database images according to similarity and forwards the most similar images to the interface module. Note that database images are often indexed according to their feature vectors using structures to speed up retrieval and distance computation.

There are several digital libraries that support services based on image content [Bergman et al. 1997; Zhu et al. 2000; Hong et al. 2000; French et al. 2003; Wang and Du 2001; Wang et al. 2004]. One example is the digital museum of butterflies [Hong et al. 2000], aimed at building a digital collection of Taiwanese butterflies. This digital library includes a module responsible for content-based image retrieval based on color, texture, and patterns. In a different image context, Zhu *et al.* [Zhu et al. 2000] present a content-based image retrieval digital library that supports geographical image retrieval. The system manages air photos which can be retrieved through texture descriptors. Place names associated with retrieved images can be displayed by cross-referencing with a Geographical Name Information System (GNIS) gazetter. In this same domain, Bergman *et al.* describe an architecture for storage and retrieval of satellite images and video data from a collection of heterogeneous archives.

There are still other initiatives covering new searching strategies for improving the CBIR systems [French et al. 2003; Wang and Du 2001], and image descriptors [Wang et al. 2004].

Another important initiative for the digital library domain is related to the proposal of the Content-Based Image Search Component (CBISC) [Torres et al. 2006]. CBISC is a recently developed component that provides an easy-to-install search engine to query images by content. It can be readily tailored for a particular collection by a domain expert, who carries out a clearly defined set of pilot experiments.

Several researchers have worked to formalize content-based image retrieval systems [Traina Jr. et al. 2005; Atnafu et al. 2004]. However, these formalisms typically describe these kinds of services under the database perspective (in general, based on the relational or object-relational models). To the best of our knowledge this article constitutes the first formal attempt to describe content-based image retrieval services by using digital library concepts described with the 5S framework. One benefit is that the 5S framework is generic enough to formalize these concepts without relying on implementation decisions.

There are several applications which support services based on image content, allowing integration in distinct domains [Murthy et al. 2010; Achananuparp et al. 2007]. The identification of fish species [Murthy et al. 2011] is an example of a desired capability of a biological research system [Lyons et al. 2006]. These applications require the management of images, text, and annotations. Users may search with keyword descriptions or match a query image with images in the collection of fish images. Digital libraries in this context may be required to provide specialized support such as image processing algorithms for fish contours. In a different context, images are also used as the basis to match fingerprints [Kozievitch et al. 2010]. In this case, algorithms used for processing images are not only related to the implementation of CBIR mechanisms, but also to specific software used to properly represent fingerprint details, such as direction, flow, contrast, and curvature. Along with these parameters, specific details (minutiae) are analyzed on the image, to compare if two different images (from the police records and the crime scene, for example) belong to the same person.

3. PROBLEM FORMALIZATION AND OVERALL APPROACH

Formalizing complex objects and content-based image retrieval facilitates the development, comparison, and evaluation of solutions based on distinct information resource integration; makes clear to users what a solution means; indicates how components are related; and helps users evaluate the applicability of a solution. Furthermore, it allows us to leverage special-purpose techniques for combining, aggregating, and reference the integration process. In this section, we first introduce the basic notations based on the 5S framework, followed by an overall approach for formalizing complex objects and content-based image retrieval.

3.1 Background on the 5S Framework

Gonçalves et al. [Gonçalves et al. 2004] presented a formal framework for DLs (5S Framework). A "minimal digital library" (Def. 24 of [Gonçalves et al. 2004]) was defined as the highest-level concept. Fig. 4 [Gonçalves et al. 2004] illustrates the supporting layers of definitions: mathematical foundations (e.g., graphs, sequences, and functions), the 5S (streams, structures, spaces, scenarios, and societies), and key concepts of a DL (e.g., digital object, collection). Arrows represent dependencies, indicating that a concept is formally defined in terms of previously defined concepts that point to it. We adopt the definitions in [Gonçalves et al. 2004] and extend them in the discussion below.

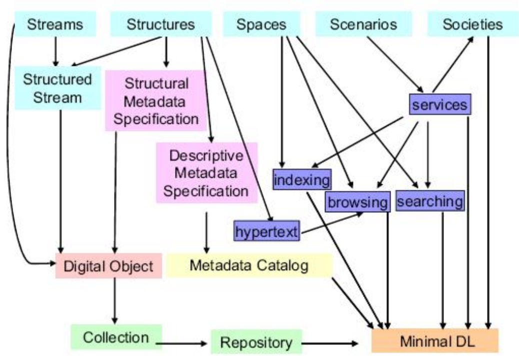


Fig. 4. Main concepts of a Minimal Digital Library at the 5S Framework.

3.2 Notations

Notation: Let DL_1 be a digital library; let $\{do_1, do_2, \ldots, do_n\}$ be the set of digital objects do present in DL_1; let H be a set of universally unique handles (unique identifiers); let SM be a set of streams; and let set ST be a set of structural metadata specifications.

3.3 Complex Objects

From a computational view, a DL, in terms of content, is mainly composed of simple components named digital objects.

A **digital object** is defined as a tuple $do = (h, SM, ST, StructuredStreams)$, where

(1) $h \in H$, where H is a set of universally unique handles (labels);
(2) $SM = \{sm_1, sm_2, \ldots, sm_n\}$ is a set of streams;
(3) $ST = \{st_1, st_2, \ldots, st_m\}$ is a set of structural metadata specifications;
(4) $StructuredStreams = \{stsm_1, stsm_2, \ldots, stsm_p\}$ is a set of StructuredStream functions defined from the streams in the SM set (the second component) of the digital object and from the structures in the ST set (the third component).

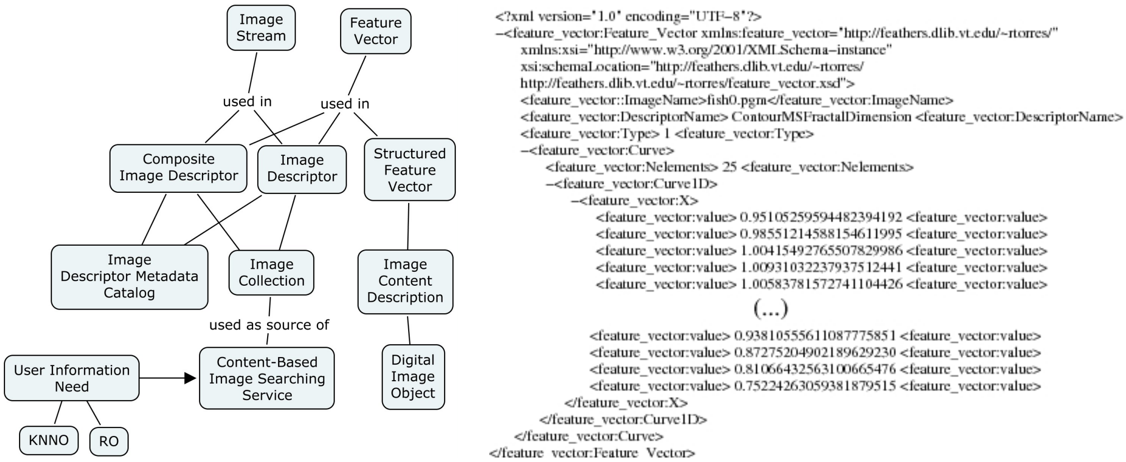
Streams are sequences of elements of an arbitrary type (e.g., bits, characters, images, etc.). *Structural Metadata Specifications* correspond to the relations between the object and its parts (as chapters in a book). *Structured Streams* define the mapping of a structure to streams (how chapters, sections, introduction, etc. are organized to define a book). More details are available in [Gonçalves et al. 2004].

Definition 3.1. We define a **complex object** as a tuple $cdo = (h, SCDO, S)$ where

(1) $h \in H$, where H is a set of universally unique handles (labels);
(2) $SCDO = \{DO \cup SM\}$, having $DO = \{do_1, do_2, \ldots, do_n\}$, and do_i is a digital object or another complex object; and $SM = \{sm_a, sm_b, \ldots, sm_z\}$ is a set of streams;
(3) S is a structure that composes the complex object cdo into its parts in $SCDO$.

Note that the mentioned definitions consider the object's metadata in a separate catalog [Gonçalves et al. 2004]. The DO and SM components are finite sets, therefore the S structure is also finite, defining what belongs to the CO or not (concept referred to as a boundary).

The S structure in the **complex object** is not specified, therefore can be extended to any structure that represents parts of a whole, such as a list, a tree, or even a graph. As a practical example, we can mention the Fedora



(a) (b)

Fig. 5. (a) 5S extensions to support content-based image description and related services. (b) Example of a structured feature vector.

Commons approach [Awre 2009a], where lists represent multiple single files which were packed together, and graphs represent files which are related, creating networks of digital objects. If we consider files arranged in HTML5 [Park et al. 2010], the S structure can be extended to a cyclic graph. Our focus is not to explore these fine-grained concepts, but to consider a high-level approach: aggregate logically and perhaps physically, distinct objects, so they can be represented as a single unit.

3.4 Content-based Image Retrieval

Figure 5-a presents the proposed concepts based on the 5S framework to handle image content descriptions and related digital library services. These concepts are precisely defined below. Some of these concepts were introduced in [Torres and Falcão 2006]. In this article, we extend them by taking into account digital library aspects.

Definition 3.2. An **image *stream*** (or simply **image**) $\hat{I}$ is a pair $(D_I, \vec{I})$, where:

—D_I is a finite set of *pixels* (points in $\mathbb{N}^2$, that is, $D_I \subset \mathbb{N}^2$), and
—$\vec{I} : D_I \rightarrow \mathsf{D}'$ is a function that assigns each pixel p in D_I to a vector $\vec{I}(p)$ of values in some arbitrary space D' (for example, $\mathsf{D}' = \mathbb{R}^3$ when a color in the RGB system is assigned to a pixel).

Definition 3.3. A **feature vector** $\vec{fv}_{\hat{I}}$ of an image $\hat{I}$ is a point in $\mathbb{R}^n$ space: $\vec{fv}_{\hat{I}} = (fv_1, fv_2, ..., fv_n)$, where n is the dimension of the vector.

Examples of possible feature vectors are a color histogram [Swain and Ballard 1991] and a multiscale fractal curve [da S. Torres et al. 2004]. They essentially encode image properties, such as color, shape, and texture. Note that different types of feature vectors may require different similarity functions.

Definition 3.4. A **feature vector digital object** is the digital object $do = (h, SM, ST, StructuredStreams)$ which represents the feature vector.

Definition 3.5. Given a structure $(G, L, \mathscr{F})$, $G = (V, E)$ and a feature vector $\vec{fv}_{\hat{I}}$, a **StructuredFeatureVector** is a function $V \rightarrow \mathbb{R}^n$ that associates each node $v_k \in V$ with $fv_i \in \vec{fv}_{\hat{I}}$.

Figure 5-b presents an example of the use of a **StructuredFeatureVector** function. In this case, an XML structure (structural metadata specification) is mapped to a feature vector obtained by applying the image

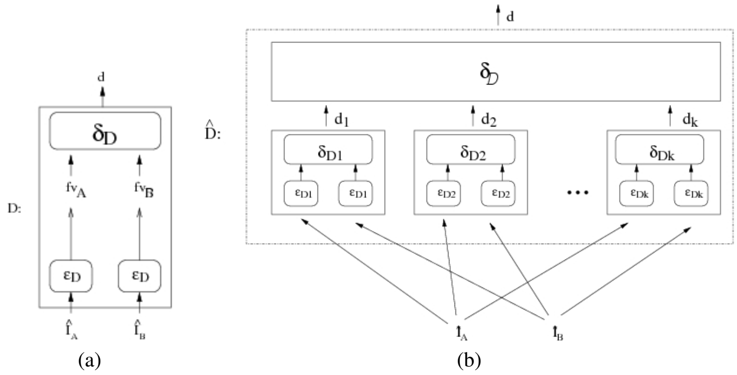


Fig. 6. (a) The use of a simple descriptor D for computing the similarity between images. (b) Composite image descriptor.

descriptor *Contour Multiscale Fractal Dimension* [da S. Torres et al. 2004] to the image stream defined by the file "fish0.pgm".

Definition 3.6. A **simple image content descriptor** (briefly, **image descriptor**) D is defined as a tuple $(h_{desc}, \varepsilon_D, \delta_D)$, where:

—$h_{desc} \in H$, where H is a set of universally unique handles (labels);
—$\varepsilon_D : \{\hat{I}\} \rightarrow \mathbb{R}^n$ is a function, which extracts a *feature vector* $\vec{fv}_{\hat{I}}$ from an *image* $\hat{I}$.
—$\delta_D : \mathbb{R}^n \times \mathbb{R}^n \rightarrow \mathbb{R}$ is a *similarity function* (e.g., based on a distance metric) that computes the similarity between two images as a function of the distance between their corresponding *feature vectors*.

Figure 6(a) illustrates the use of a simple descriptor D to compute the similarity between two images $\hat{I}_A$ and $\hat{I}_B$. First, the extraction algorithm ε_D is used to compute the feature vectors $\vec{fv}_{\hat{I}_A}$ and $\vec{fv}_{\hat{I}_B}$ associated with the images. Next, the similarity function δ_D is used to determine the similarity value d between the images.

Definition 3.7. A **composite image descriptor** $\hat{D}$ is a tuple $(h_{desc}, \mathscr{D}, \delta_{\mathscr{D}})$ (see Figure 6(b)), where:

—$h_{desc} \in H$, where H is a set of universally unique handles (labels);
—$\mathscr{D} = \{D_1, D_2, \ldots, D_k\}$ is a set of k pre-defined simple image descriptors.
—$\delta_{\mathscr{D}}$ is a similarity function which combines the similarity values obtained from each descriptor $D_i \in \mathscr{D}$, $i = 1, 2, \ldots, k$.

Definition 3.8. An **image content description** *ICD* is a tuple $(FV, ST_{FVs}, Structured_{FVs})$, where

—$FV = \{\vec{fv}_1, \vec{fv}_2, \ldots, \vec{fv}_k\}$ is a set of feature vectors;
—$ST_{FVs} = \{stfv_1, stfv_2, \ldots, stfv_m\}$ is a set of structural metadata specifications;
—$Structured_{FVs} = \{strfv_1, strfv_2, \ldots, strfv_m\}$ is a set of StructuredFeatureVector functions defined from the *feature vectors* in the FV set (the first component) of the image content description and from the structures in the ST_{FVs} set (the second component).

Definition 3.9. A **digital image object** *ido* is a digital object with the following extensions and constraints:

—*ido* is a *digital object* $= (h, SM, ST, StrStreams, ICD, StrICDStreams)$, where
(1) $h \in H$, where H is a set of universally unique handles (labels);
(2) $SM_{sd} = \{sm_{sd}[i, j]\} \in SM$, where $sm_{sd}[i, j] =$
$\langle a_i, \ldots, a_j \rangle, 0 \leq i \leq j \leq n$. $sm_{sd}[i, j]$ refers to substreams (regions) of an image stream.

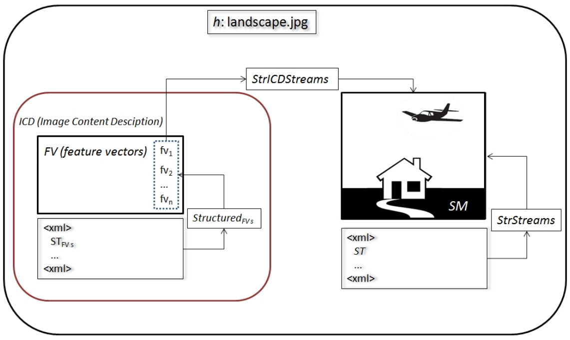


Fig. 7. Digital image object elements.

(3) $ST = \{st_1, st_2, \ldots, st_m\}$ is a set of structural metadata specifications;
(4) $StrStreams = \{stD_1, stD_2, \ldots, stD_m\}$ is a set of StructuredStream functions defined from the image substreams in the *SM* set (the second component) of the digital object and from the structures in the *ST* set (the third component).
(5) *ICD* is an *image content description* (Definition 3.8).
(6) $StrICDStreams = \{stimgD_1, stimgD_2, \ldots, stimgD_m\}$ is a set of StructuredStream functions defined from the *image stream* in the *SM* set (the second component) of the digital image object and from the structures in the $ST_{FVs} \in ICD(2)$ set.

Figure 7 illustrates the relations among the concepts used to define a digital image object. The definition of *StrICDStreams* allows associating feature vectors with parts (objects, regions) of image streams.

Definition 3.10. An **image collection** *ImgC* is a tuple $(C, S_{imgdesc}, FV_{imgdesc})$, where C is a collection (see Def. 17 in [Gonçalves et al. 2004]), $S_{imgdesc}$ is a set of image descriptors, and FV_{desc} is a function $FV_{desc} : \{C \times S_{imgdesc}\} \rightarrow ICD(1)$, where ICD is $ido(5)$ and $ido \in C$.

Function FV_{desc} defines how a feature vector was obtained, given a digital image object $ido \in C$ and an image descriptor $\hat{D} \in S_{imgdesc}$.

Definition 3.11. Let $S_{imgdesc}$ be a set of image descriptors with k handles in H. An **image descriptor metadata catalog** $DM_{S_{imgdesc}}$ for $S_{imgdesc}$ is a set of pairs $\{(h, \{dmdesc_1, \ldots, dmdesc_{k_h}\})\}$, where $h \in H$ and the $dmdesc_i$ are descriptive metadata specifications for image descriptors.

Descriptive metadata specifications of descriptors could include, for example, data about the author (who implemented the extraction and similarity functions), implementation date, and related publications. Recall that, in general, a metadata catalog is used to assign descriptive metadata specifications to digital image objects (see Def. 18 in [Gonçalves et al. 2004]).

4. CASE STUDY

In this section we exemplify how the 5S extensions for complex objects and content-based image retrieval can be explored to define the complex image object concepts in the SuperIDR and CTRnet projects. The services and digital objects of these tools are not unlike those of a digital library (DL) with extended functionality (such as annotations, and multimodal search).

4.1 Superimposed Image Description and Retrieval Tool - SuperIDR

SuperIDR is a superimposed image description and retrieval tool [Murthy et al. 2006; Murthy et al. 2009; Kozievitch et al. 2010; Murthy et al. 2011], developed with the aim of helping users to work with parts of

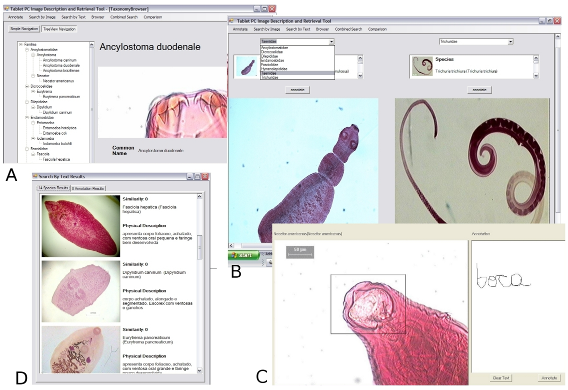


Fig. 8. SuperIDR Tool: A- Treeview navigation, B- Comparison, C- Annotation and D - Text search.

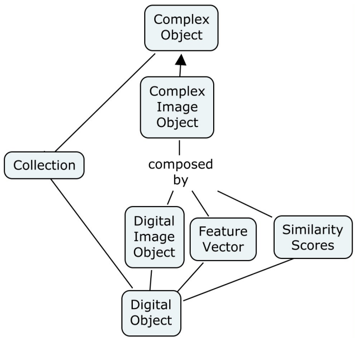


Fig. 9. The Complex Image Object.

images in situ, where they can select, annotate, and retrieve parts of images in the context of the original image.

SuperIDR is seeded with details of 13 species and 49 images of parasites, taken from microscope analysis. In addition to making annotations, SuperIDR allows searching and browsing of species descriptions, images, image marks, and annotations. Figure 8 shows screenshots of the tool. We defined that the aggregation would comprise the complex image object, aggregating the image, feature vector, and similarity distances.

For formalization purposes, we will adopt the CO definition for describing an image and its components. The main difference between a **complex image object** ICO and a **digital image object** IDO is that the CO definition considers the image and the feature vector as atomic digital objects, to facilitate object manipulation and related services (such as referencing, harvesting, etc.).

If we consider the CO definition (in section 3.3), the complex image object (ICO) has the structure $ico = (h, SCDO, S)$, where:

—h is a unique handle that identifies ico;

—$SCDO = \{DO \cup SM\}$, having $DO = \{do_1, do_{21}...do_{2k}, do_{31}, ...do_{3k}\}$, where do_1 is an **image**, k is the number of descriptors, $do_21...do_2k$ is a set of **feature vector digital objects**, and $do_31...do_3k$ is a set of **Structured-FeatureVectors** (with the similarity measures, according to a specific descriptor k); and $SM = \{sm_1, sm_2, \ldots, sm_n\}$ is a set of streams;

—S is a structure that identifies how do_1, $do_{21}...do_{2k}$, and $do_{31}, ...do_{3k}$ are composed.

Figure 9 presents the ICO, and its corresponding components: the digital image object, feature vector and similarity scores. Note that each ICO component is a **digital object**, therefore having also its own handle. This allows users to explore the collection not only by the COs, but also by the individual components (digital objects).

An **complex image object collection** $ImgCO$ is a tuple $(C, S_{imgdesc})$, where C is a collection (see Def. 17 in [Gonçalves et al. 2004]), and $S_{imgdesc}$ is a set of image descriptors. Function FV_{desc} defines how a feature vector was obtained, given a complex image object $ico \in C$ and an image descriptor $\hat{D} \in S_{imgdesc}$.

In our SuperIDR example, each ICO has the structure $ico = (h, SCDO, S)$, where:

—h is a unique handle that identifies ico;

—$SCDO = \{DO \cup SM\}$, having $DO = \{do_1, do_{21}, do_{31}\}$, where do_1 is a **parasite image**, $k = 1$ (BIC descriptor [Stehling et al. 2002]), do_{21} is a **feature vector digital object**, and do_{31} is a **StructuredFeatureVector** (another digital object with the similarity measures, according to a specific descriptor k); and $SM = \{sm_1, sm_2, \ldots, sm_n\}$ is a set of streams;

—S is an XML structure that identifies how do_1, $do_2 1$, and $do_3 1$ are composed.

The **complex image object collection** represented in our SuperIDR example has 43 ICOs and one descriptor. Function FV_{desc} classifies image pixels as either *border* or *interior*, and then later computes two color histograms, one for each type of pixels. A pixel is classified as border if at least one of its 4-neighbors has a different color. If its 4-neighbors have the same color, it is classified as interior.

In summary, our case study explored the main concepts for ICOs (such as identification, components, collection, and StructuredFeatureVector) resulting from the CBIR process in SuperIDR. A straightforward benefit of this work is the use of these definitions to construct applications, including requirements gathering, conceptual modeling, prototyping, and code generation, similar to initiatives presented in [Gonçalves and Fox 2002; Zhu et al. 2003; Moreira et al. 2009; Zhu et al. 2003]. As an example, consider the use of 5S formal theory to integrate an archaeological digital library, using applications such as 5SGraph [Zhu et al. 2003]. The formalization of the concepts can facilitate the development, comparison, and evaluation of solutions; making it clear to users what a solution means; and helping users evaluate the applicability of a solution.

4.2 Evaluating image descriptors in the CTRnet Project

The Crisis, Tragedy, and Recovery Network (CTRnet) [Kozievitch et al. 2010; Yang et al. 2011] objectives include to develop better approaches toward making technology useful for archiving information about such events, and to support analysis of rescue, relief, and recovery, from a digital library perspective. CTRnet has several modules, including crawling, filtering, a Facebook application, user visualization, metadata search, and Content-Based Image Retrieval. The CBIR module builds upon the EVA tool [Penatti and da S. Torres 2010] for evaluating image descriptors for content-based image retrieval. Eva integrates the most common stages of an image retrieval process and provides functionalities to facilitate the comparison of image descriptors in the context of content-based image retrieval.

Compared to the previous case study, CTRnet images can be evaluated by several descriptors, creating more components. Also, a clear description of ICO concepts can be used as a basis to integrate the CBIR module with other CTRnet modules. We defined that the complex image object would be composed of the image, the feature vectors, and similarity distances from each descriptor. Figure 10 shows the image ranking for Cathedral_P_A_P.jpg, using two different descriptors: BIC [Stehling et al. 2002] and SASI [Çarkacioglu and Yarman-Vural 2003].

The ICO presented in Figure 10 can be defined by the structure $ico = (h, SCDO, S)$, where:

—h is a unique handle that identifies ico;

—$SCDO = \{DO \cup SM\}$, having $DO = \{do_1, do_{21}, do_{22}, do_{31}, do_{32}\}$, where do_1 is an **image**, $k = 2$ (BIC and SASI descriptors), do_{21} is a **feature vector digital object** using the BIC descriptor, do_{22} is a **feature vector digital object** using the SASI descriptor, do_{31} is a **StructuredFeatureVector** using the BIC descriptor, and do_{32} is a **StructuredFeatureVector** using the SASI descriptor; and $SM = \{sm_1, sm_2, \ldots, sm_n\}$ is a set of streams;

—S is an XML structure that identifies how do_1, do_{21}, do_{22}, do_{31} and do_{32} are composed.

The **complex image object collection** has 111 ICOs and two descriptors. Function FV_{desc1} (BIC) is based on the color information. Function FV_{desc2} (SASI) is based on second order statistics of clique autocorrelation coefficients, which are the autocorrelation coefficients over a set of directional moving windows.

In summary, the CTRnet case study explored ICOs for aggregating information related to different descriptors, resulting from the CBIR process. These definitions can be used as a basis to aggregate information and define how these concepts relate to other CTRnet modules (such as metadata, and crawling).

(a) (b)

Fig. 10. Image ranking in CTRnet using BIC (a) and SASI (b) descriptors.

5. CONCLUSIONS AND FUTURE WORK

Many digital library implementations and applications demand additional and advanced services to effectively reuse and aggregate different resources. Examples of commonly required services include those related to the support of newer, more complex media types such as images, multimedia objects, and related information. In this article we address the formal definitions and descriptions for Complex Objects and Content-Based Image Retrieval.

The proposed extensions for digital library functionality take advantage of formalization to understand clearly and unambiguously the characteristics, structure, and behavior of the main concepts related to components, technologies, and applications. Later these definitions are explored in two case studies, to exemplify how the CO and CBIR concepts can be explored to define the complex image object. Our contribution relies on (i) the formalization of complex objects; (ii) the formalization of content-based image retrieval; and (iii) the discussion on how to combine them to handle complex image objects in applications. These formalized concepts can be used to classify, compare, and highlight the differences among components, technologies, and applications, impacting digital library researchers, designers, and developers. The set of definitions also may impact future development efforts of a wide range of digital library experts since it can guide the design and implementation of new digital library services based on complex objects, and image content.

A straightforward benefit of this work is the use of these definitions to create applications, like those proposed in [Gonçalves and Fox 2002; Zhu et al. 2003], or the formalization of more complex services that can be created by using the proposed constructs. As future work we can mention the analysis of multimodal search services, recommendation systems for complex objects, image browsing services based on image content similarity, and management of complex simulation-based content.

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