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Abstract

In this paper, we review 300 references on video retrieval, indicating when text-only solutions are unsatisfactory and showing the promising alternatives which are in majority concept-based. Therefore, central to our discussion is the notion of a semantic concept: an objective linguistic description of an observable entity. Specifically, we present our view on how its automated detection, selection under uncertainty, and interactive usage might solve the major scientific problem for video retrieval: the semantic gap. To bridge the gap, we lay down the anatomy of a concept-based video search engine. We present a component-wise decomposition of such an interdisciplinary multimedia system, covering influences from information retrieval, computer vision, machine learning, and human–computer interaction. For each of the components we review state-of-the-art solutions in the literature, each having different characteristics and merits. Because of these differences, we cannot understand the progress in video retrieval without serious evaluation efforts such as carried out in the NIST TRECVID benchmark. We discuss its data, tasks, results, and the many derived community initiatives in creating annotations and baselines for repeatable experiments. We conclude with our perspective on future challenges and opportunities.

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1

Introduction

1.1 How to Retrieve Video Content?

This question is highly relevant in a world that is adapting swiftly to visual communication. Online services like YouTube and Tudou show that video is no longer the domain of broadcast television only. Video has become the medium of choice for many people communicating via Internet and their mobile phones. Digital video is leading to an abundance of narrowcast repositories, with content as diverse as Al Jazeera news, concerts of the Royal Philharmonic Orchestra, and the baby panda at your local zoo, to name just three examples. A nation's broadcast archive can be expected to contain petabytes of video data, requiring careful treatment for future preservation and disclosure. Personal video archives are likely to be much smaller, but due to the amount of effort involved, the willingness to archive for the purpose of future retrieval will be lower. At all stages and for all target groups, effective and efficient video retrieval facilities will be necessary, not only for the public broadcasters, but also for any private broadcaster and narrowcaster-to-be.

User needs determine both the effectiveness and efficiency of video search engines. To understand what are the user needs for video retrieval, we draw inspiration from the video production process. According to Jain and Hampapur [106], the purpose for which a video is created is either entertainment, information, communication, or data analysis. For all these purposes, the user needs and demands vary substantially. A consumer who wants to be entertained, for example, will be satisfied if a complete movie is accessible from an archive through a mobile phone. In contrast, a cultural anthropologist studying fashion trends of the eighties, a lawyer evaluating copyright infringement, or an athlete assessing her performance during training sessions might be more interested in retrieving specific video segments, without going through an entire video collection. For accessing complete video documents, reasonable effective commercial applications exist, YouTube and Netflix being good examples. Video search applications for consumers and professionals targeting at retrieval of specific segments, however, are still in a nascent stage [112]. Users requiring access to video segments are hardly served by present-day video retrieval applications.

In this paper, we review video search solutions that target at retrieval of specific segments. Since humans perceive video as a complex interplay of cognitive concepts, the all-important step forward in such video retrieval approaches will be to provide access at the semantic level. This is achievable by labeling all combinations of people, objects, settings, and events appearing in the audiovisual content. Labeling things has been the topic of scientific endeavor since Aristotle revealed his "Categories." Following in this tradition are Linnaeus (biology), Werner (geology), Mendeleev (chemistry), and the Human Genome Project (genetics) [263]. In our information age, Google labels the world's textual information. Labeling video content is a grand challenge of our time as humans use approximately half of their cognitive capacity to achieve such tasks [177]. Two types of semantic labeling solutions have emerged: (i) the first approach relies on human labor, where labels are assigned manually after audiovisual inspection; (ii) the second approach is machine-driven with automatic assignment of labels to video segments.

1.2 Human-Driven Labeling

Manual labeling of (broadcast) video has traditionally been the realm of professionals. In cultural heritage institutions, for example, library experts label archival videos for future disclosure using controlled vocabularies [56, 148]. Because expert labeling [50, 155] is tedious and costly, it typically results in a brief description of a complete video only. In contrast to expert labor, Web 2.0 [172] has launched social tagging, a recent trend to let amateur consumers label, mostly personal, visual content on web sites like YouTube, Flickr, and Facebook. Alternatively, the manual concept-based labeling process can be transformed into a computer game [253] or a tool facilitating volunteer-based labeling [198]. Since the labels were never meant to meet professional standards, amateur labels are known to be ambiguous, overly personalized, and limited [69, 73, 149]. Moreover, unlabeled video segments remain notoriously difficult to find. Manual labeling, whether by experts or amateurs, is geared toward one specific type of use and, therefore, inadequate to cater for alternative video retrieval needs, especially those user needs targeting at retrieval of video segments [204].

1.3 Machine-Driven Labeling

Machine-driven labeling aims to derive meaningful descriptors from video data. These descriptors are the basis for searching large video collections. Many academic prototypes, such as Medusa [22], Informedia classic [255], and Olive [51], and most commercial video search engines such as Baidu, Blinkx, and Truveo, provide access to video based on text, as this is still the easiest way for a user to describe an information need. The labels of these search engines are based on the filename, surrounding text, social tags, closed captions, or a speech transcript. Text-based video search using speech transcripts has proven itself especially effective for segment-level retrieval from (English) broadcast news, interviews, political speeches, and video blogs featuring talking heads. However, a video search method based on just speech transcripts results in disappointing retrieval performance, when the audiovisual content is neither mentioned, nor properly reflected in the associated text. In addition, when the videos originate from non-English speaking countries, such as China, and the Netherlands, querying the content becomes much harder as robust automatic speech recognition results and their accurate machine translations are difficult to achieve.

It might seem that video retrieval is the trivial extension of text retrieval, but it is in fact often more complex. Most of the data is of sensory origin (image, sound, video) and hence techniques from digital signal processing and computer vision are required to extract relevant descriptions. In addition to the important and valuable text data derived from audio analysis, much information is captured in the visual stream. Hence, a vast body of research in machine-driven video labeling has investigated the role of visual content, with or without text. Analyzing the content of visual data using computers has a long history [195], dating back to the 1960s. Some initial successes prompted researchers in the 1970s to predict that the problem of understanding visual material would soon be solved completely. However, the research in the 1980s showed that these predictions were far too optimistic. Even now, understanding visual data is a major challenge. In the 1990s a new field emerged, namely content-based image retrieval, where the aim is to develop methods for searching in large image archives.

Research in content-based retrieval has resulted in a wide variety of image and video search systems [17, 32, 34, 61, 67, 72, 114, 143, 180, 197, 207, 214, 258, 266]. A common denominator in these prototypes is their dependence on low-level visual labels such as color, texture, shape, and spatiotemporal features. Most of those early systems are based on query-by-example, where users query an archive based on images rather than the visual feature values. They do so by sketches, or by providing example images using a browser interface. Query-by-example can be fruitful when users search for the same object under slightly varying circumstances and when the target images are available indeed. If proper example images are unavailable, content-based image retrieval techniques are not effective at all. Moreover, users often do not understand similarity expressed in low-level visual features. They expect semantic similarity. This expected semantic similarity, is exactly the major problem video retrieval is facing.

The source of the problem lies in the *semantic gap*. We slightly adapt the definition by Smeulders et al. [213] and define it as: “The lack of correspondence between the low-level features that machines extract from video and the high-level conceptual interpretations a human gives to the data in a given situation." The existence of the gap has various causes. One reason is that different users interpret the same video data in a different way. This is especially true when the user is making subjective interpretations of the video data related to feelings or emotions, for example, by describing a scene as *romantic* or *hilarious* [76]. In this paper, those subjective interpretations are not considered. However, also for objective interpretations, like whether a *windmill* is present in a video, developing automatic methods is still difficult. The main difficulties are due to the large variations in appearance of visual data corresponding to one semantic concept. Windmills, for example, come in different models, shapes, and colors. These causes are inherent to the problem. Hence, the aim of video retrieval must be to bridge the semantic gap.

1.4 Aims, Scope, and Organization

In this paper, we review state-of-the-art video retrieval methods that challenge the semantic gap. In addition, we also address the important issue of evaluation. In particular, we emphasize *concept-based video retrieval*. A recent breakthrough in the field, which facilitates searching in video at a segment-level by means of large sets of automatically detected (visual) concepts, like a *telephone*, a *flamingo*, a *kitchen*, or one of the concepts in Figure 1.1. Evidence is accumulating that when large sets of concept detectors are available at retrieval time, such an approach to video search is effective [36, 219, 227]. In fact, by using a simulation study, Hauptmann et al. [85] show that even when the individual detectors have modest performance, several thousand detectors are likely to be sufficient for video search in the broadcast news domain to approach standard WWW search quality. Hence, when using concept detectors for video retrieval, we might be able to reduce the semantic gap for the user.

In contrast to other reviews on video retrieval, which emphasize either content-based analysis [221], machine learning [158], text and image retrieval [283], search strategies [118], interactive browsing

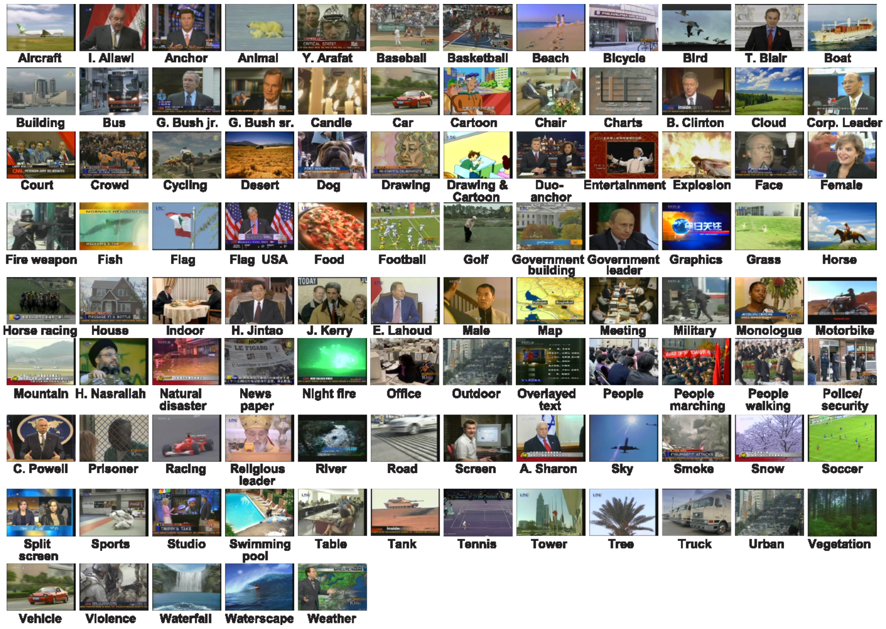

Fig. 1.1 Visual impression of 101 typical semantic concepts [230] for which automatic detection, retrieval, and evaluation results on video data are described in this paper.

models [86], or challenges for the future [129], the aim of this paper is to cover the semantic gap completely: from low-level features that can be extracted from the video content to high-level interpretation of video segments by an interacting user. Although these concepts have a visual nature, concept-based video retrieval is different from still-image concept detection as the concepts are often detected and retrieved using an interdisciplinary approach combining text, audio, and visual information derived from a temporal video sequence. Our review on concept-based video retrieval, therefore, covers influences from information retrieval, computer vision, machine learning, and human–computer interaction. Because of this interdisciplinary nature, it is impossible for us to provide a complete list of references. In particular, we have not attempted to provide an accurate historical attribution of ideas. Instead, we give preference to peer-reviewed journal papers, over earlier published conference papers, and workshop papers, where possible. Throughout the review we assume a basic familiarity with computer science and information retrieval, but not necessarily the specific topic of (visual) video retrieval. For in depth, technical details on the fundamentals underlying many concept-based video retrieval methods, the interested reader is referred to recent books [16, 18, 19, 74, 128, 147, 199], review papers [48, 103, 140, 213, 241, 261], special issues [75, 270], and online proceedings [171], that provide further entry points into the literature on specific topics.

We organize the paper by laying down the anatomy of a concept-based video search engine. We present a component-wise decomposition of such an interdisciplinary multimedia system in our aim to bridge the semantic gap. The components exploit a common architecture, with a standardized input–output model, to allow for semantic integration.

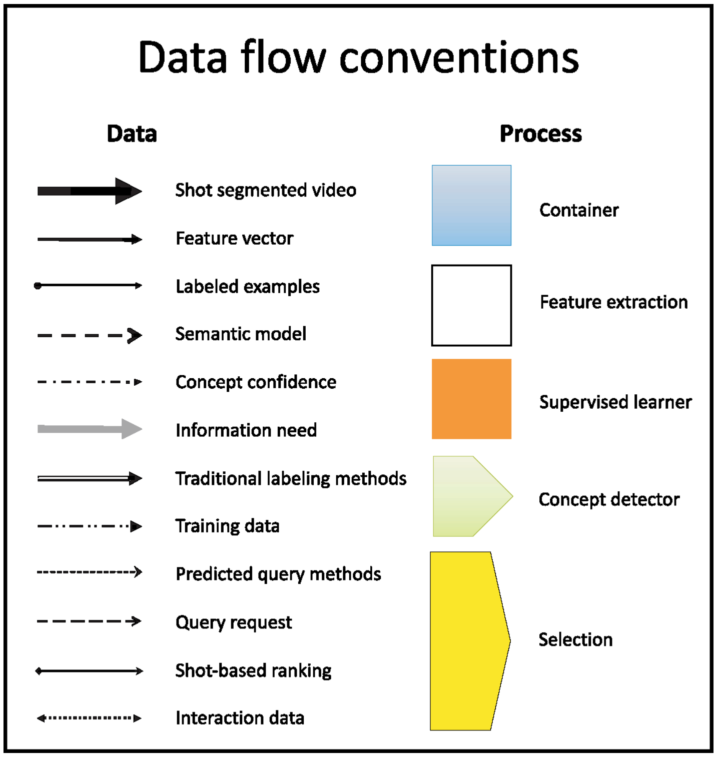

Fig. 1.2 Data flow conventions as used in this paper. Different arrows indicate difference in data flows.

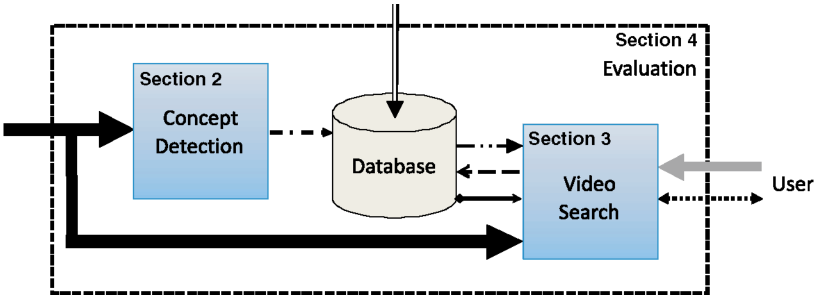

Fig. 1.3 We organize our review by laying down the anatomy of a concept-based video search engine, building upon the conventions introduced in Figure 1.2. First, we detail generic concept detection in Section 2. Then, we highlight how concept detectors can be leveraged for video search in combination with traditional labeling methods and an interacting user in Section 3. We present an in depth discussion on evaluating concept-based video retrieval systems and components in Section 4.

The graphical conventions to describe the system architecture are indicated in Figure 1.2. We will use the graphical conventions throughout this paper. Based on these conventions, we follow the video data as they flow through the computational process, as sketched in Figure 1.3. We start in Section 2, where we present a general scheme for generic concept detection. We cover the common concept detection solutions from the literature and discuss how they interconnect for large-scale detection of semantic concepts. The availability of a large set of concept detectors opens up novel opportunities for video retrieval. In Section 3, we detail how uncertain concept detectors can be leveraged for video retrieval at query time and how concept detectors can be combined with more traditional labeling methods. Moreover, we discuss novel visualizations for video retrieval and we highlight how to improve concept-based video retrieval results further by relying on interacting users. In Section 4, we turn our attention to evaluation of concept-based video search engines and their most important components. We introduce the de facto benchmark standard, its most important tasks, and evaluation protocols. In addition, we highlight the many community efforts in providing manual annotations and concept-based video retrieval baselines against which scientific progress in the field is measured. We conclude the review with our perspective on the challenges and opportunities for concept-based video search engines of the future.

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