Multimedia Information Systems in Open-World Domains

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Abstract

The use of different media types in information systems allows to communicate semantically expressive data of problems encountered in open-world domains. As a consequence, new methodologies have to be developed to cope with the rich semantics of data in such multimedia information systems. We present WERKL, *a system architecture that takes into account the dependency between the semantic and the architectonic spaces as found in real-world problems. Within* WERKL *we give a description of the* exploration *process that supersedes the* search *paradigm of traditional information systems. We further discuss implementation issues and demonstrate the applicability of this architecture by reviewing on-going projects based on* WERKL.

1 Introduction

Computer-based information systems manage digital resources which represent properties of the covered domains. Typically, human decision-makers use these abstractions of the real world as foundations for their decision-making processes. Additionally, the systems may themselves apply algorithms exploiting the available domain knowledge to generate explicit representations of information that is hidden in the mass of data. In either case, information is generated by selecting a certain set of data in respect to a given information need.

Traditionally, these abstract resources were very limited in terms of expressiveness and user interaction capabilities. First approaches settled for file systems that were basically used solely to store alphanumeric data. Further research led to the development of database management systems (used primarily for structured

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data) and information retrieval systems (used for unstructured — mostly textual — data). These systems impose a certain structure and interaction paradigm on data in order to allow the formulation of information processing activities. Theories and models within these technologies are used as guidelines for developing information processing applications.

The rapid development of the information processor's workbench — the computer — in terms of speed and storage capabilities along with its connection to the data highway gave rise to the desire to include more semantically expressive data in information systems that would ease the communication of information. *Multimedia* is the term that nowadays denotes applications that handle pictures, drawings, animations, videos, audio, and other media types. *Multimedia information systems* use these media types to communicate information. They should offer functions to create, store, manage, retrieve, process, and use media objects.

While research on multimedia information systems is still in its infancy, there are obvious signs that this field will become a dominant player in the future. The recent focus of publications on topics such as digital libraries [17] or hypermedia applications [25, 5] is just the tip of the iceberg. The change of the underpinning technologies entailed by the transition from traditional to multimedia information systems raises a vast amount of research issues, some of which we will discuss in more detail in the next section. In our view, one of the most important impacts of this new technology will be related to the novel opportunities for dealing with the problems encountered in open-world domains, including a more comprehensive active involvement of the human user into the information retrieval process. This follows from the assumption that a large proportion of information needs typically occurring in open-world domains can be most adequately satisfied by an *explorative* rather than a *search* approach.

2 Research issues

The use of additional media types besides the standard alphanumeric texts places new demands on the information-processing cycle as given by Wiederhold [52]. Within the data acquisition phase, different media components have to be processed and treated in accordance to their specific needs. This includes in particular the application of standardized formats and techniques to validate and align media data.

After validation the data is *stored* in the system. In addition, an *index* for later selection and retrieval has also to be allocated. There are two alternative approaches for index generation:

- by some kind of automatic media interpretation process generating an abstract representation of the semantic content of the respective media components:

this variant is highly dependent on the quality of the supplied data, but guarantees the generation of "complete" indices with respect to the available data;

- by providing support for the generation of a hand-crafted index structure that uses a set of terms to characterize the semantic content: here a far greater flexibility in the design of the index is gained at the price of increased maintenance work (lack of automatic "synchronization" of the index to changes in the data)

The issues of storing and indexing have direct consequences for the range of supported access and retrieval strategies, as all *queries* use the index structure to locate and retrieve relevant information items in respect to the task at hand. Multimedia information systems offer the novel opportunity to tap into the rich semantic content of media chunks to provide support for the user in the formulation of queries. This goes hand in hand with a shift of focus in the human-computer interaction, away from the usual delegation paradigm and towards a human-computer cooperation.

Once data are selected and retrieved by the system the resulting information has to be communicated to the user. At this point methods are needed to plan the actual presentation of the data. This topic is covered by research in multi-modal user interfaces [38, 50]. Evaluation of the relevance of retrieved data can be used to learn new facts, both about the domain and the user, that can be employed in future interaction cycles. Research issues in multimedia information systems call for a concerted approach that brings together experts on media, knowledge representation and information processing, and domain modelling. The transition towards open-world perspectives challenges the capabilities of applications to cope with unanticipated system states.

Closed-world domains can be modeled with a limited number of features providing a sufficient coverage of the domain: all relevant data are collected and all knowledge needed to process these data independently of the human user is formalized. Within a closed world domain, an information system should always be capable of reaching a meaningful goal state, provided that the end user operates within the limits of the modeled domain. Successful application examples can be found, e.g., in traditional expert systems.

In contrast, for information systems in open-world domains it cannot be assumed that all possible states and aspects of the world are covered. The semantic dimensions of such domains are not limited and thus cannot be fixed *a priori*. This necessarily incomplete coverage of the domain leads to so-called *breakdowns* ([53], or see also e.g. [16]), that signal the transition from the currently covered part of the domain to territory that has not yet been formalized. In the event of a breakdown, processing within the information system cannot be continued without intervention by human users who have to either redefine the query or modify the contents of the knowledge base.

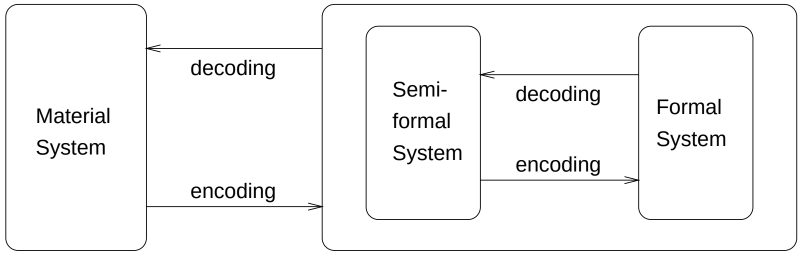

Figure 1: The two stage formalization process

In the following we will advocate the use of multimedia components within information systems to provide guidance in handling such exceptions. We will introduce WERKL, an information system model for open-world domains, and show prospective application areas.

3 System architecture

The basic architecture of WERKL comprises two layers: a semi-formal *data layer* and a formal *index layer*. This distinction between two layers follows the theory of ontological design [53, 32], where the representation of artifacts is divided into a *semantic space* and an *architectonic space*. The architectonic space accounts for explicitly represented properties of the artifacts while the semantic space covers the totality of all potential associations tied to these elements. Figure 1 shows the relations between these two layers and objects of the real world.

The system architecture (Figure 2) can be conceptually represented by a six-tuple $[M, R_m, I, R_i, X, O]$ where:

- M is a set of media data;
- R_m is a set of relations defined on M; } *semi-formal layer*
- I is a set of index layer nodes that are used to qualify M;
- R_i is a set relations defined on members of I; } *formal layer*
- X is a set of relations defined on M and I;
- O is a set of information generating computational operations defined on M, R_m, I, R_i, and X.

} WERKL

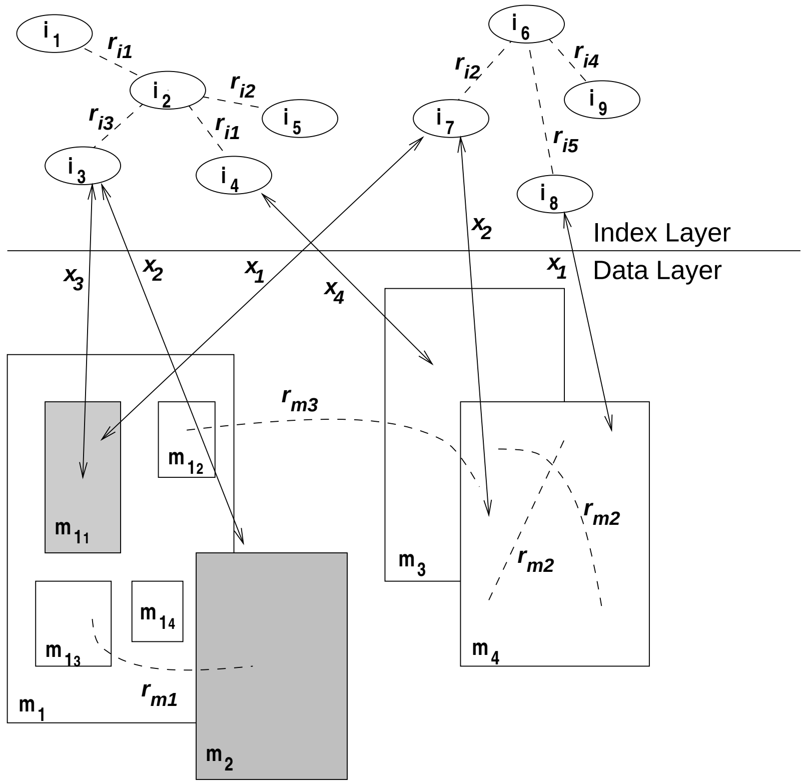

Figure 2: The WERKL system architecture

Candidate techniques to implement these conceptual entities will be discussed in the next section. The design of the system architecture is intended to allow for various approaches in regard to the actual implementation. This is necessary also because of the rapid development in research fields that focus on the supporting technologies. The intention of the system architecture is to provide a framework that can be used to exploit different actual implementations in different domains.

The two-stage acquisition approach — for the data and index layers — alleviates the difficult task of abstracting real world objects. This is especially true for domains where multimedia items can be used to supply a more immediate perceptually accessible computer-based representation of such objects: e.g., a picture can be represented more "comprehensively" by a scanned image than by some verbal description. In contrast to pure data acquisition methodologies this approach combines the simultaneous acquisition of both formal and informal aspects of the domain: e.g., the insertion of a picture along with a formal description of certain aspects of its content in an appropriate formalism. In terms of the example given above, while the picture holds "indefinitely rich" semantic information (i.e., the picture can be interpreted in an unlimited number of ways by humans), the formal description will always just cover a limited amount of the semantic content.

In this case the incomplete coverage accomplished by the domain knowledge encoded in the index layer is more of an advantage than a drawback: the lack of an once-and-for-all commitment for structuring of the data warrants a flexible handling of the system's content. If users feel that the system does not satisfy their needs in terms of expressiveness they can modify the index layer accordingly: the basic attitude is to provide as much freedom as reasonably possible. Finding an appropriate balance is one of the crucial topics for future multimedia information systems (see section 6).

In contrast to classical information systems that were primarily designed to perform retrieval of exactly matching items given characteristics of these items in a formal language, multimedia information systems tend to support a more interactive nature of the retrieval process. This is necessary as users are not assumed to have a clear understanding of the content of the system. Instead of having to learn the structure of the index space, users should be to endorsed in an serendipitous exploration of the semantic space.

In order to meet all these goals, WERKL has to draw extensively on different kinds of knowledge:

- knowledge about the domain;
- knowledge about the task at hand;
- knowledge about the user.

Knowledge will be exploited during different stages of the information processing cycle: during the acquisition process, knowledge about the domain is used to guide the user in the construction process. Knowledge about the user's task eases the human-computer interaction process as the system's responses are tailored to the problem setting. Finally, knowledge about users will tune the performance of the system over time and personalize individual sessions. To enable accumulation of knowledge, formal models are needed that function as generic classes of these knowledge types.

For most of the operations in O there already exist well-established theoretical frameworks empirically proven by implementations. We therefore focus on the exploration process within the retrieval functions of O, of which we provide a description based on a formalization of the design process by Smithers and Troxell [46]. The exploration process can be represented by a six-tuple $[P, T, < S_i \ldots S_f >, H, D, E]$, where

- P is the union of M and I;
- T is a set of heuristics that compute the semantic distance between objects of M using R_i, R_m and X.

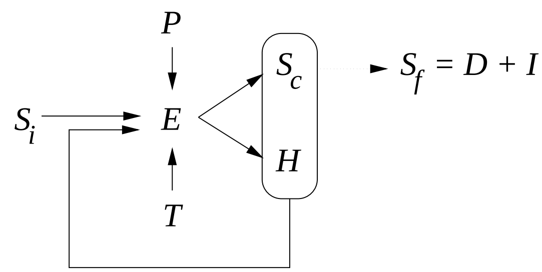

Figure 3: The WERKL exploration cycle

- $< S_i \ldots S_f >$ is a poset of property sets. Property sets are non-empty sets of instances of M and I. These sets are the intermediary results obtained during an exploration process, S_i being the initial set, S_f the final set that fully determines the information need, and the current one being referred to as S_c;
- H is the exploration history: it is a set of sequences of property sets and applied transformations;
- D is an initially empty set of data items meeting the requirements defined by S_c, $(D = S_c - I)$;
- E is the exploration process that extends D by taking P, T, S_c, and H as input and producing a series of transformations on S_c (leading to the next S_c and the corresponding next D).

Figure 3 shows a schema of the exploration cycle.

The heuristics in T are distilled from meta-knowledge about the domain, the actual implementation of the data and index layers, and about the user's task. As such, some of these rules will be applicable to all domains, whereas others are tailored to certain usages.

4 Implementation issues

After having presented a conceptual view of WERKL, a system architecture that copes with problems of open-world domains, we will now discuss the implications of certain technological decisions on the overall approach. As stated before, one of the design objectives of WERKL is to keep the actual implementations open to different techniques that can be employed to solve the various aspects of the problem. As a consequence we cannot give a complete survey of all possible techniques; instead we will discuss those that seem most promising to us.

Within the data layer techniques now found in common multi- and hypermedia applications can be used. The main functionalities to be provided by this layer are the preprocessing (such as cleanup), the storage (formats), and the local integration (such as hypermedia links, media alignment, etc.) of media chunks. The representation of semantic relations between objects of this layer has a semi-formal character, that is, the system does not have a deeper understanding of the meanings of relations that are given by users but can still apply some heuristics.

The implementation issues found at the data layer level are covered mostly by research within the multimedia and hypermedia community. This includes research on multimedia operating systems and network protocols, on hypermedia formats (e.g., MHEG [13, 8], HyTime [14, 41]) and models (e.g., Dexter Reference Model [29, 24], HDM [18, 19]). One of the most inhibiting facts for the development of multimedia information systems is — at least from our point of view — the lack of a standard for the effective reuse of multimedia objects. Building multimedia collections is a costly procedure and requires a lot of effort. Without a standard the threat of losing all acquired data because of the introduction of new formats not compatible to the previous ones is a serious problem.

In contrast to what was said on the data level issues, we cannot identify any single established research community that deals with problems encountered on the index level and, in further consequence, with computational operations within O. Still there are various research fields that can contribute to an overall problem solution. The most closely related fields are of course the research fields of traditional information systems (i.e., database and information retrieval systems), but a lot of work has also been done in areas related to artificial intelligence and human-computer interaction. Thus a main entry in the agenda of research on multimedia information systems will be to bring together those achievements to solve the pending problems.

One approach on this issue is to support the concurrent development of indices that are grounded in a shared set of data objects. Indices represent certain *views* on the domain. We do not expect that the rich semantic content of the multimedia data items can be abstracted in a single, unified index structure. Instead, we support the generation and exploitation of parallel views on the subject area. The separate views can be shared between users and exploited in the interaction process with the system, both during acquisition of data and retrieval of information. The evaluation process of these indices could be then expected to be self-regulating: indices that prove to be of value will prosper whereas others will atrophy. The relationships between indices and documents as well as amongst indices will be exploited in operations within O to support users with their tasks at hand.

We are currently investigating the use of *ontologies* as index structures that qualify objects of the data layer. By using ontologies we can draw on well-established theories along with methodologies and tools developed for this purpose. Ontologies allow for a declarative approach to the formalization of the domain knowledge. Our main research effort lies in establishing a methodology that sees the acquisition and retrieval processes as strongly interlinked activities. For that reason the user has strong influence on both processes, even though parts of these processes can be automated using the knowledge encoded in the system. Among the benefits of opting in favour of description logics, we can only briefly mention the availability of theoretical results on computational tractability and performance; a wide range of algorithms (e.g. analogical reasoning for both maintenance and reasoning; capturing of interrelationships of terms, integrity constraints; discovery of new knowledge validation via induction; organization, "weakening" of queries, "query by refinement", semantic query optimization; dealing with incomplete/generic information, providing intensional answers), or the use as basis for knowledge sharing and mediation [9, 10, 11, 6, 7, 34, 26, 28, 27, 20, 39, 22, 23, 52, 48].

Interaction with the system results in a constant refinement of the system's content. Either via direct user input (e.g., acquisition of data or indexing) or via monitoring of user behaviour. In the following we will briefly step through a typical interaction cycle of an exploration process. Assume that a user has to accomplish a certain task that requires the satisfaction of an information need that cannot be expressed precisely using some query language; this might e.g. be due to the fact that in general the semantic content of the data layer is not sufficiently detailed formalized, given that the system operates within an "indefinitely filled semantic space" [32]. Instead, the user has to resort to an explorative information gathering process to obtain the sought-after information.

The user starts out by selecting a nonempty set of terms of an ontology of the index layer that seems "promising", i.e. is assumed to refer to relevant data items. The system retrieves the corresponding data items. The user then provides feedback by indicating which items are relevant and which are not. The remaining selected set of data items activates more terms within the ontology, which in turn refer to further semantically related data items. As with other *spreading activation* algorithms, the user simultaneously gains an understanding of the domain and of the structure superimposed on the domain space. This knowledge can in turn be utilized to direct the interaction process.

What is unique to multimedia information systems is that the implicit semantic content of media items can be used to overcome breakdown situations, as mentioned in section 2. A breakdown occurs when the heuristics built into the system do not suffice to locate any further relevant data items. In this situation, users can utilize their own world knowledge to intuitively choose another starting point for the exploration task applying the already acquired knowledge about the domain; this might include the shifting of the viewpoint expressed by choosing a different ontology.

5 Applications

In a first empirical evaluation, WERKL is currently being applied in three ongoing projects: HYSAT, BDB, and VENIVA. VENIVA (Venetian Virtual Archive) is a research project on electronic access to records in geographically distributed libraries (Venice, Corfu, Crete, Vienna). The records belong to a collection that for historical reasons happened to become fragmented and decentralized. The framework of WERKL allows the construction of index sturctures and the application of access mechanisms that reflect the diversity of user types and their needs (e.g., students, non-qualified researchers, administrative researchers, foreign researchers).

The BDB project is aimed at building multimedia catalogues of products for the building construction industry. In this project, ontologies are used to represent the different views of experts involved in the building industry. The exploration process allows the discovery of products that users have not been aware of prior to the interaction process. It also supports users in tailoring the system according to their needs.

HYSAT (Hypertext System for Architectural Typology [31]) is a project targeted at developing a design-supporting tool for students of architecture. Within this project, multimedia documents are used to represent design examples. Multiple indices focus on the various aspects found in building design (e.g., construction, form, function, etc.). Using the system, students learn both about the domain and the structure of the domain space in terms of examples and abstract concepts.

In the following we discuss an interaction scenario for the HYSAT application (see Figure 4). In Figure 4 the drawings represent data items while the term hierarchies represent ontologies in the index layer. We used two architectural textbooks [12, 49] to extract two example indices. The numbers (1 to 11) in Figure 4 state the chronological order of the exploration steps.

Let us assume the designer sets out with the question: "How to design a wide-spanned roof sheltering a gymnasium on a rectangular site?". After retrieving some design cases referred to by the term Roof in the ontology Construction (1–3), she gets interested in an example of a dome-shaped roof (4). Because she wants to know the consequences of a dome-shaped roof for the ground plan, she seeks for a corresponding example in the ontology Formative Idea[1]. The descriptor in the ontology Construction for the selected roof is Dome (5). At this point, the user wants to change point of view and asks the system to determine an alternative description[2] of the documents referred to by Dome. The proposed solution combines the concepts Roofs of the current ontology with the concept Concentric of a different ontology. The user follows to this new perspective (6). Additional information items retrieved for

[1]Note the polysemy of the term "Formative Idea" in the example, i.e. its different use in different ontologies.

[2]E.g. by applying the Minimum Description Length principle [40].

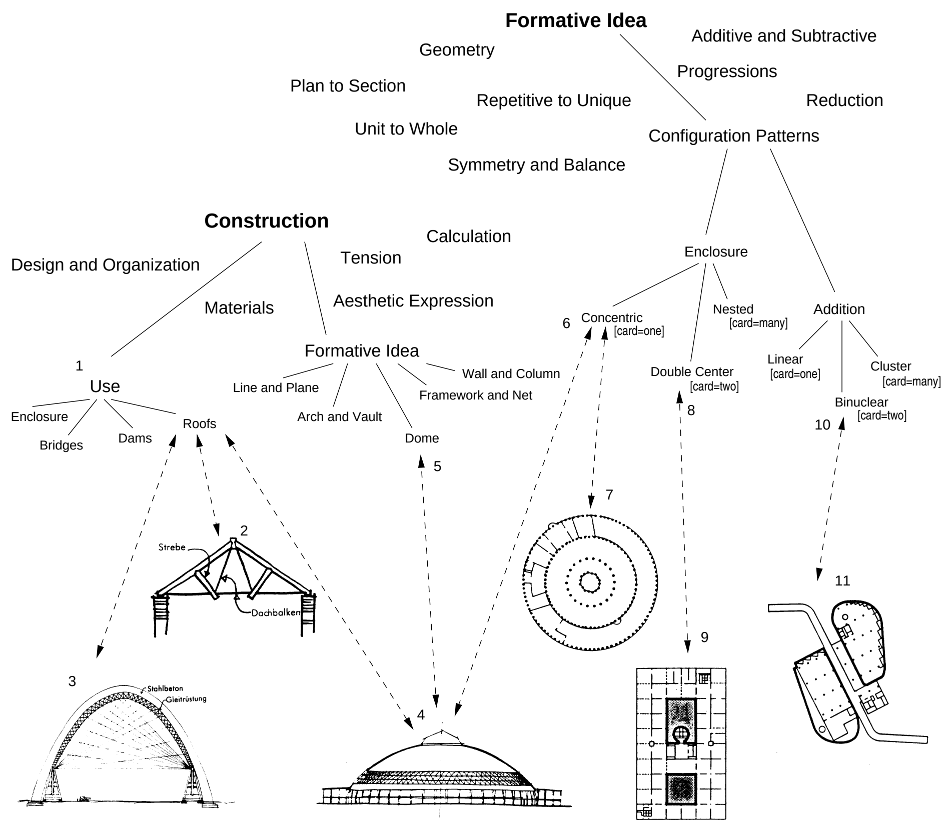

Figure 4: Exploration in HySAT

Concentric (7) turn out to be inconsistent with the rectangular site prescribed in the problem definition.

To find alternative solutions, the user tries to weaken the requirement in the current point of view and discovers Double Center (8) as a closely related term concerning Enclosure. Examples prove to be suitable for a rectangular site (9), e.g. two domes. At this point, the user furthers the search by asking the system for alternatives to the found solution (which supersedes some of the interim assertions, such as the concept Dome). Using the *regularity* identified between the Enclosure and Addition hierarchies of the ontology Formative Idea, the system chooses the concept Binuclear (10) and proposes the documents referenced by it (11). These are finally accepted as solution to the problem. Note how the information retrieval process led to the exploration of regions of the design space — represented by selections of multimedia documents — that the user was previously unaware of.

6 Related research

We feel that placing the emphasis on the *dynamic* aspect of the information processing task by its interpretation as *explorative* process is an essential and distinguishing feature of our approach. The level of assistance a computer system can provide is clearly related to the amount of domain knowledge that is explicitly represented[3]. Early related research which was aimed at developing systems supporting designers' argumentation activities was originated by Rittel [42] whose work in turn drew on the Issue Based Information Systems (IBIS) introduced by Kunz [33]. However, later experiences such as the research projects leading from SEPIA to DOLPHIN [47, 35] or from Aquanet to VIKI [36, 37] pointed out a number of difficulties including the premature commitment to specific knowledge structures, the limitations of covering only the architectonic space, and problems in (re-)use of existing structures by the average end-user.

The acknowledgement of the relevance of an appropriate coverage of the semantic space is further documented in the development history of the ARCHIE project [21, 15]; here, a gradual shift of emphasis towards the semantic space was accompanied by an abandonment of a detailed structuring of the architectonic space. While ARCHIE could be said to suffer from an overly detailed decomposition of the covered design cases, ARCHIE-2 tried to overcome problems by using informal story-based case representations. This group of systems — which also includes the family of ASK systems [44, 45, 1] — has proven very successful for settings with well-defined user information needs, albeit at the cost of the high human resource demands of the question-based indexing method.

An imbalanced coverage of the architectonic and the semantic spaces thus has been proven to limit usability: users are either confronted with a detailed vocabulary placing a high cognitive burden and imposing artificial restrictions on the accessible domain space, or with brittle systems that fail to provide assistance for unprecedented usage patterns. This lesson is reflected in the recent work on DEDAL and DE-KART [2, 3, 4]. While DEDAL's conceptual index is based on a model of the artifact being designed, a growing number of *proximity retrieval heuristics* concurrently tap into the semantic space and thereby ensure that the users can also access parts of the architectonic space that are not already explicitly incorporated in the system's knowledge base. In this interpretation, although currently restricted to the domain of retrieval of technical documentation, DE-KART can be taken as an example of the kind of incremental extension of the index space we discussed earlier.

[3]Statistical approaches (e.g. [43]) notwithstanding.

7 Conclusion

Setting out from the problems posed for multimedia information systems aimed at providing support for open-world domains, we identified the explorative approach for satisfaction of information needs as promising alternative to other established techniques in this particular setting. We then presented WERKL, a multimedia information system architecture built upon this core idea. WERKL is currently undergoing first empirical evaluations in a number of application-oriented projects which we also expect to provide feedback needed for tackling some of the remaining open questions such as the criticality of the size of the collection of multimedia items or habitability issues [51, 30]: Besides all the theoretically appealing and scientifically intriguing facets of the research concerning this class of multimedia information systems, we feel that practical aspects must never be lost out of sight. From personal everyday experience the authors themselves are painfully aware of the demand for and the current utter lack of an ubiquitous tool providing support for the processing and exchange (i.e., the *sharing*) of data and meta-data from real world domains. This is certain to provide all the incitement for further work they could ask for.

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