Towards Cross-Media Information Spaces and Architectures

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***Abstract*—The efficient management and retrieval of information via dedicated devices and data structures has been investigated since the early days of Vannevar Bush's seminal article *As We May Think* introducing the Memex. However, nowadays information is usually fragmented across different media types, devices as well as digital and physical environments, and we are often struggling to retrieve specific information. We discuss three main issues to be addressed when developing solutions for managing information in these co-called cross-media information spaces. First, we have a look at an extensible cross-media linking solution based on the resource-selector-link (RSL) hypermedia metamodel where information can be integrated across applications, devices as well as digital and physical information environments. We then outline some of the limitations of existing digital document formats which are often just a simulation of paper documents and their affordances on desktop computers, and discuss more flexible document representations for cross-media information spaces. Further, new forms of human-information interaction and cross-media user interfaces—including some recent work on dynamic data physicalisation—are discussed. A number of research artefacts are used to illustrate different aspects of the presented data-centric approach for cross-media information spaces and architectures. Last but not least, we provide an outlook on how the embedding of the presented concepts at the level of an operating system might ultimately lead to new possibilities for cross-media information management and innovative forms of human-information interaction.**

***Index Terms*—Cross-media technology, hypermedia, document engineering, human-information interaction, distributed user interfaces, personal information management, future file system**

I. Introduction

The efficient management and retrieval of information has been an issue since the early days of the printing press and the resulting increase of information in the form of paper documents. In his 1945 seminal article *As We May Think* [1], Vannevar Bush discussed the problem of managing and retrieving information from paper documents via hierarchical filing and classification techniques as used in offices and libraries at that time. The issue of getting lost in information space by the sheer amount of available information and the lack of tools for managing this information has later been coined as the problem of *information overload*.

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In his visionary article, Bush described the *mem*ory *ex*tender (Memex), a device that could be used to augment the human memory and intellect by storing and managing paper documents on microfilm. Rather than only using a hierarchical classification of information, he highlighted that the human mind works by association and proposed the use of *associative trails*, *"whereby any item may be caused at the will to select immediately and automatically another. This is the essential feature of the Memex. The process of tying two items together is the important thing."* [1] These associative trails (links) would be stored as separate metadata which could be as important as the information itself. Bush further proposed the new profession of *trail blazers* who would establish new useful trails to navigate through the massive amount of information.

Early hypertext pioneers such as Douglas Engelbart [2] or Ted Nelson [3] were inspired by Bush's vision and brought the idea of defining associations (links) between pieces of information to the digital age. Ultimately, also the World Wide Web, that most of us use for navigating information, is heavily based on the concept of hyperlinks between web pages. Note that hyperlinks as we know them from the Web show some limitations compared to the associative trails proposed by the Memex, given that they are embedded and form part of a document (web page). This implies that only the "owner" of a web page (a person with editing rights) can also add new links—it is not possible to have trail blazers who can add

Fig. 1: Cross-media information spaces

links between arbitrary web pages. Links can further not be easily shared in the form of separate metadata as envisioned in Bush's Memex.

While the Memex would help in managing and retrieving information from microfilm on a single device, today's information environments are more complex. Information is *fragmented across different media types, applications, devices as well as digital and physical environments* as illustrated in Figure 1. In these so-called *cross-media information spaces* we are facing three major challenges:

- *Cross-media linking*: How can we ensure that information that is managed by different applications or published to different devices can be linked in order that users can easily navigate across application and device boundaries? How can we further enable links between various media types, including digital as well as physical information? For example, if we print a web page, it should be possible to still follow any embedded links from the physical printout to the corresponding linked information.
- *Flexible document representation*: How can we represent documents in a flexible way in order that they can adapt to different media types, user needs or the devices they are accessed from? For example, a PDF document that is viewed on a desktop computer might change to an alternative graph visualisation of its text and images when moved to a tabletop computer. Note that different parts of a document may also be distributed over different devices and be concurrently accessed by multiple users.
- *Cross-media user interfaces*: How can we build more flexible user interfaces enabling richer interactions in cross-media information spaces? If we come back to our example of moving a document to a tabletop computer, parts of the cross-media interface to interact with the document might be offered by the tabletop while some user interface components could be provided by our smartphone that we have placed on the tabletop.

In order to address these challenges, we need a more *data-centric approach* where data is central and different metadata (e.g. navigational or structural metadata) can be defined on top of the underlying data. *Data as well as navigational and structural metadata should no longer be owned by individual applications* but be accessible to any application built on top of a cross-media information space. A simple example to illustrate the power of such a data-centric approach is the storage of an email attachment in our file system. While existing solutions do not keep track about the relationship between the stored attachment and the corresponding email, this metadata could be managed as an external link between the two resources and made available to any application. If we later access the stored attachment in our file system, we could easily get access to the original email content.

The ultimate goal when building architectures and solutions for cross-media information spaces is to provide the "glue" between different devices as shown in Figure 1, enabling the flow of flexible document structures between devices, the integration of documents across device boundaries via cross-media linking and the dynamic composition of distributed cross-media user interfaces for these documents. In the following sections we address each of the three major challenges mentioned above and discuss a data-centric approach for cross-media information solutions based on a hypermedia metamodel.

II. Cross-Media Linking

The resource-selector-link (RSL) hypermedia metamodel has been introduced by Signer and Norrie [4] for managing navigational as well as structural links across different media types. An overview of the main components of the RSL hypermedia metamodel is provided in Figure 2, but for the full metamodel the reader should refer to the original article on *As We May Link* [4].

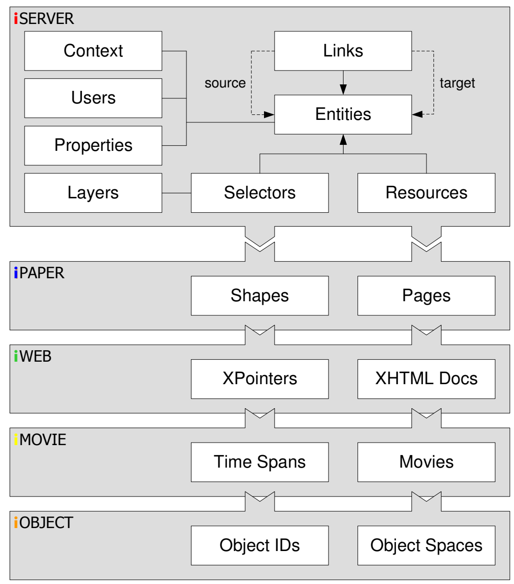

Fig. 2: RSL hypermedia metamodel overview

The three core RSL concepts are the `Resource`, the `Selector` and the `Link` which are all specialisations of an `Entity`. More general than in most existing hypermedia solutions, a link is treated as a first class object and can have multiple sources as well as multiple targets (entities). Further, links are always bidirectional which is different from what we, for example, know from the Web with its embedded unidirectional links. A `Resource` is an abstract representation of a piece of information and concrete implementations (plug-ins) have to be provided for different media types (e.g. HTML documents or movies). It is important to note that as soon as a media type is supported via a new plug-in, it can be linked with any of the already existing media types. Often we do not want to link an entire resource and therefore a `Selector` allows us to address parts of a resource. Each selector is further associated with a layer, which enables multiple overlapping selectors with some well-defined semantics. Given that links are entities, we can, for instance, also define a link that has one or multiple other links as source or target.

Another important feature of the RSL hypermedia metamodel is its integrated user management where each entity (i.e. resource, selector or link) has exactly one creator and where access rights can be defined for other users at the level of an entity. Not only these access rights might determine whether and entity is accessible or not, but the RSL metamodel also offers the concept of *context resolvers* which can be attached to entities in order to support context-dependent adaptation. Last but not least, properties represent some general metadata in the form of key/value pairs that can be attached to entities. While it is out of the scope of this paper to describe all the features of the RSL hypermedia model, more details can be found in [4].

Over the past 15 years, a number of plug-ins for different media types have been realised for the RSL hypermedia metamodel and the corresponding iServer link service implementation by Signer and Norrie [4]. This includes the iPaper plug-in [5], [6] for interactive paper solutions [7], the iWeb plug-in [4] for enhanced linking on the Web, the iMovie plug-in [5] for linking parts of movies or the iObject plug-in [8] for linking physical objects in Internet of Things (IoT) environments.

The tight integration of information across the digital and physical space via cross-media linking has been illustrated in various applications, in particular in the domain of interactive paper solutions and the mapping of paper and digital documents [9]. The EdFest paper-digital festival guide by Signer et al. [10], [11] highlights various aspects of cross-media publishing and linking. While the festival data is stored in a content management system, it can be published as a website, an automatically generated PDF booklet for later printing or as voice output. It is further not only possible to link from paper to digital information but also from paper to paper or from digital information to paper. In addition, information can flow between different media types. For example, a comment written in the paper booklet gets digitised via some handwriting recognition software and is stored in a database. Later, when another user is asking for comments about an event, text-to-speech technology is applied to the stored text in order to present the captured information via voice output.

Another domain where the RSL hypermedia metamodel has been applied is personal information management (PIM) and in particular cross-media personal information management [12], [13] where information is organised and retrieved in digital as well as physical space. While working on a desktop or tabletop computer, users can define explicit links between documents. However, documents can not only be associated via these explicit links but our cross-media PIM solution is also creating implicit links between documents that are used at the same time or in the same context, in order to improve the later retrieval process. Digital documents are further linked to their physical printouts which are tracked by an augmented filing cabinet. While working with a digital document, a user can ask for its digital counterpart and if it has been filed in the augmented filing cabinet, some LEDs will highlight its position. Note that, based on metadata managed by RSL, the filling cabinet can not only highlight a single document but also multiple folders containing documents that are relevant for a given context (e.g. a specific project). In the future some augmented reality solutions such as the Microsoft HoloLens might further be used for bridging the digital and physical space based on cross-media personal information management.

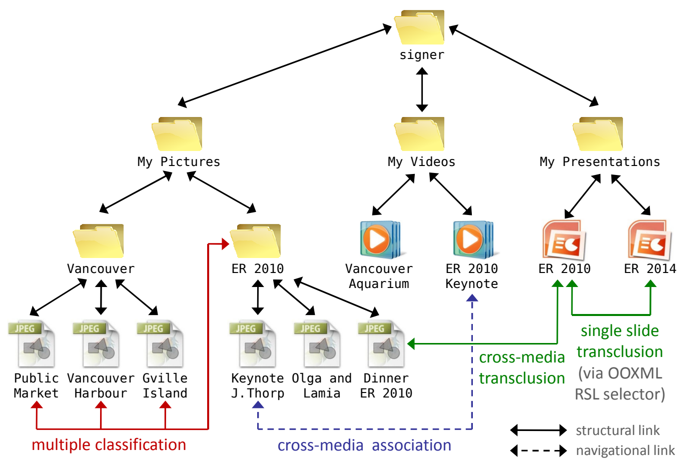

Fig. 3: RSL-based associative file system prototype

In the past, we have also investigated how the RSL hypermedia metamodel might be used for a file management solution that goes beyond the features offered by hierarchical file systems, and developed an RSL-based associative file system [14]. The idea is that we no longer use the folder structure offered by most file systems to organise our documents, but define some structural metadata on top of existing files as illustrated in the example shown in Figure 3. While the example looks like a classical hierarchical file system, the folders are no file system folders but rather just some RSL resources that can be associated with multiple files or other folders via structural links. This implies that the presented RSL-based associative file system allows *multiple classification* where a file can easily be added to multiple folders via different structural links. For example, the file `Vancouver Harbour` belongs to the folder `Vancouver` as well as to the folder `ER 2010`. Note that the same holds for a folder which can be a subfolder of multiple parent folders (not shown in the example). When storing a file, it is sometimes not easy to choose between different potential folders where a file might be put, in which case the later retrieval process may lead to the selection of the wrong path in a hierarchical structure. By using multiple classification, a user can add a single file—without making use of any copies—to multiple folders if they think it belongs to different folders, and thereby simplify the later retrieval process via alternative forms of file management [15]. A main feature of the RSL-based associative file system is that links can be defined between arbitrary files in order to simplify the retrieval and navigation of related files. For instance, in our example the jpeg file `Keynote J. Thorp` has been linked to the movie file `ER 2010 Keynote` of the very same keynote which has been stored in another folder. Finally, we experimented with some forms of transclusion where a single PowerPoint slide can be used in multiple PowerPoint presentations without replication. In order to select a single slide of a PowerPoint presentation, we only had to define a new selector allowing us to address parts of a presentation stored in Office Open XML (OOXML) [16] format.

The extensibility of the RSL hypermedia metamodel via different media plug-ins makes it challenging to provide a general cross-media link browser and editor since for every newly supported media type, we also need the corresponding visualisation as well as the necessary functionality to define selectors. While the Memex vision only included a single media type (microfilm), we have to deal with a potentially unlimited number of media types. In order to support *open cross-media linking*, Signer and Norrie [17] proposed an architecture with visual media plug-ins and we have recently realised a solution for open cross-media linking in the form of an extensible cross-document link service [18]. For each document format or media type to be rendered in the link browser, a visual plug-in must be implemented. The visual plug-in has two main responsibilities. First it has to render a specific document format and visualise any selectors that have been defined. Second, it should provide the necessary functionality for the basic create, read, update and delete (CRUD) operations for a given media type. Note that our dynamically extensible cross-document link service can also be integrated with existing third-party applications and currently serves as a research platform for investigating different types of linking in cross-media information spaces.

III. Flexible Document Representation

Existing digital document formats are often based on monolithic containers of linear content and simply represent a *simulation of paper affordances* on desktop computers [14]. The *What You See Is What You Get* (WYSIWYG) document representation does not exploit the possibilities that digital document formats could offer as criticised by Ted Nelson: *"Most people don't understand the logic of the concept: "What You See Is What You Get" is based on printing the document out ("get" means "get WHEN YOU PRINT IT OUT"). And that means a metaphysical shift: a document can only consist of what can be printed! This re-froze the computer document into a closed rectangular object which cannot be penetrated by outside markings (curtailing what you could do with paper). No marginal notes, no sticky notes, no crossouts, no insertions, no overlays, no highlighting—PAPER UNDER GLASS."* [19]

A major problem is the fact that the *within document structure* describing different parts of a document (e.g. sections or images) is often fixed and only accessible to the application that was used to create the document. Signer and Norrie [4] describe how the RSL hypermedia metamodel can not only be used for defining navigational links between resources but also to define some structure over resources via structural links. Given that structural links are a specialisation of the more general RSL link concept, they offer the same features as a link (e.g. context awareness or access rights). This allows us define different *context-dependent adaptive overlay structures* on top of (parts of) content. The document structure might therefore change based on contextual information such as the device a document is accessed from. The clear *separation between content and structure* further enables cross-media content reuse via *transclusion* [20].

In the following, we would like to illustrate how the RSL hypermedia metamodel has been applied to achieve more flexible document representations in the domain of presentation software or slideware. Our research on next generation presentation solutions all started with the question *"What is wrong with slideware?"*. Many people do not know that the PowerPoint presentation software was originally used to create 35mm slides for slide projectors as well as transparencies for overhead projectors and that this is from where the term *slideware* comes from. It was only later that the output to physical media disappeared and was replaced by the use of digital projectors. Nevertheless, even the latest version of PowerPoint can be mainly seen as a *simulation of physical slides* with their *limited space*, provides mainly *linear navigation* and treats presentations as *monolithic documents*. It is further *difficult to reuse parts of content* (except for copying entire slides) and to embed rich media types.

In order to experiment with more flexible representations of presentations and innovative forms of presentation delivery, we developed the MindXpres[1] presentation platform [21]. MindXpres follows a *content-based approach* where a presenter focusses on creating the content, while the MindXpres platform offers some automatic presentation visualisation with a zoomable user interface. By making use of the RSL hypermedia metamodel and its structural links, MindXpres enables cross-media content reuse via transclusion and without the need to copy content between presentations. The use of RSL's navigational link further supports new forms of non-linear presentation navigation where a presenter can either predefine alternative paths through a presentation or the presentation tool might automatically propose some alternative paths based on the presented content. Note that the content of all MindXpres presentations is stored in a single data store managed by an RSL software library. This implies that presentations no longer have to be seen as monolithic containers but rather as alternative overlay structures on top of the shared underlying content, making it easy to navigate between the content of different presentations. It is also not necessary that the RSL-enabled data store deals with presentation content only, but it could also contain any other information as, for instance, managed by the cross-media personal information management solution presented earlier.

Last but not least, MindXpres blurs the boundaries between documents and applications by offering support for various rich media types via a plug-in mechanism. For example, by making use of our interactive source code visualisation MindXpres plug-in [22], a presenter can simply refer to some

[1] https://mindxpres.com

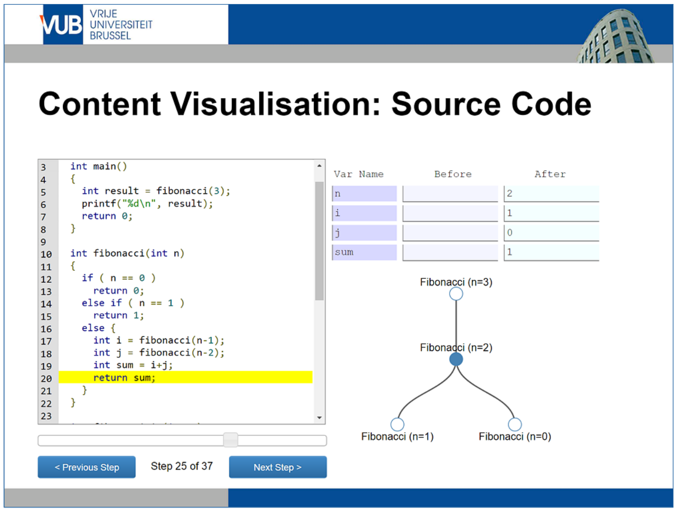

Fig. 4: Interactive source code visualisation in MindXpres

of their source code and the MindXpres plug-in will offer an interactive visualisation of the source code on a slide as shown in Figure 4. In this automatically generated visualisation, the presenter can then step through the code and see changes in the values of variables as well as other visualisations of the executed code such as the call stack. For more details about the flexible MindXpres presentation document format and some of its additional features we refer to [23]. While our work on the MindXpres presentation platform revealed various advantages of using RSL's structural links for realising more flexible document representations, these findings are of course not limited to presentations only and can be applied to other domains in order to address the problems of some existing document formats [14].

IV. Cross-Media User Interfaces

As mentioned earlier, nowadays information is often distributed across different devices as well as the digital and physical space. When interacting with information in these cross-media information spaces, we might therefore want to work with user interfaces that are distributed across different devices as well as the digital and physical space (hybrid user interfaces). We first provide some examples of our work on distributed and tangible user interfaces and then report on some of our more recent work on supporting the development of these kind of user interfaces.

A first cross-media user interface has been realised for our cross-media personal information management solution introduced earlier [13]. While users can interact with an RSL-enabled personal information store via their desktop computer, a tabletop interface or their smartphone, there is also the possibility to use a combination of physical and digital interface components. The augmented filing cabinet offers a number of physical sliders and other tangible interface elements for retrieving paper documents. If a paper document is placed on the tabletop computer, it is tracked by a camera and thereby forms part of the user interface. Our cross-media PIM system identifies the paper document and searches for digital documents that are linked to the physical document. These digital documents are then visualised around the physical document on the tabletop as part of a hybrid user interface.

Another form of hybrid user interface has been investigated in our ArtVis prototype for the exploration of artwork collections [24]. Various tangible objects (e.g. painting tubes) have been equipped with RFID tags and trigger some queries for retrieving specific types of artworks when they are placed close to a painters palette with an integrated RFID reader. While the ArtVis user interface offers some innovative forms of real-time cross-media data exploration, the interaction is unidirectional in the sense that the interaction with a tangible object might trigger some actions in digital space but not vice versa.

Recently some vision-driven research on radical atoms and programmable matter has been proposed by Ishii et al. [25] in order that interactions with tangible objects might not only lead to changes in digital space, but updates in digital space can result in a transformation of physical artefacts. They are currently investigating different shape changing physical interfaces in order to simulate interactions that might later be possible via programmable matter. We have chosen a different approach by physically augmenting the digital space based on our tangible hologram (TangHo) [26] platform in order to enable different forms of dynamic data physicalisation. We are further investigating a framework for dynamic data physicalisation [27] to support new forms of cross-media user interfaces where different physical variables and multiple modalities can be used for the exploration of multi-dimensional datasets.

In order to support the development of cross-media user interfaces and adaptive distributed hybrid user interfaces in particular, we are currently developing the eSPACE reference framework and conceptual model [28]. The conceptual model is again based on the RSL hypermedia metamodel, but this time the structural and navigational links are used to define the bindings between user interface components and the corresponding actions as well as to build more complex user interfaces out of simple UI elements. The adaptation of the resulting cross-media user interfaces is achieved via RSL's context resolvers and the loose coupling of UI elements and the corresponding actions supports reusability and extensibility. Further, the eSPACE conceptual model introduces a specialisation of RSL's structural links for realising distributed user interfaces. An advantage of the fine granularity of UI elements offered by eSPACE is that end users might reconfigure and adapt parts of their user interfaces to better fit their needs. The flexibility in defining cross-media user interfaces might ultimately lead to innovative forms of human-information interaction for cross-media information spaces.

V. Outlook

We have shown how to address the issues of *cross-media linking*, *flexible document representation* and *cross-media user interfaces* in cross-media information spaces, all based on the same RSL hypermedia metamodel. However, different cross-media applications such as the cross-media personal information management framework or the MindXpres presentation platform are based on separate instances of RSL-enabled data stores. Further, these applications have been built on top of an existing file system that does not support any of the discussed hypermedia functionality, and therefore cannot offer access to the navigational and structural metadata to any third-party application. We have outlined how a file management system might profit from additional navigational and structural metadata when discussing the RSL-based associative file system prototype. In order to enable the integration of information across application boundaries and to support the sharing of navigational as well as structural metadata, we therefore propose the embedding of an RSL-based hypermedia engine at the level of an operating system as illustrated in Figure 5.

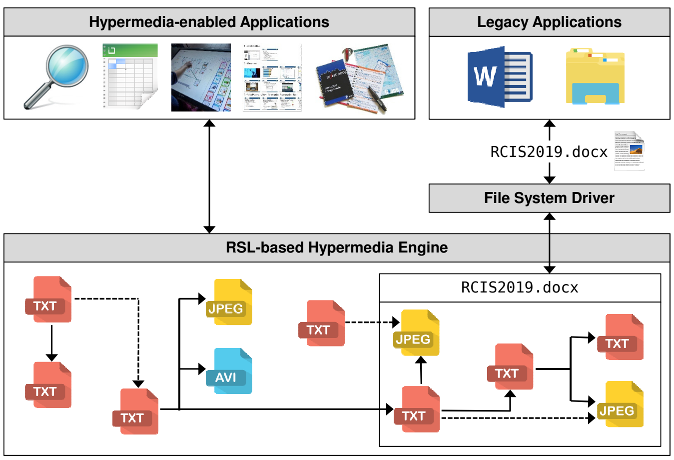

Fig. 5: Next generation cross-media storage platform

The proposed RSL-based hypermedia engine would treat documents or "files" as *placeless documents* [29] and organise them via navigational and structural metadata. Documents would further no longer have to be stored as monolithic containers but the hypermedia engine could provide access to the internal document structure as shown for the document `RCIS2019.docx` in Figure 5, consisting of multiple content fragments (RSL resources) such as text fragments or jpeg images that are combined via structural links (represented by solid arrows). Further, navigational links (represented by dashed arrows) could be used for navigating between documents as well as within documents. The same content fragment could not only be used in a single document but transcluded from other documents, as shown for a part of document `RCIS2019.docx` being integrated into another document via a structural link. Of course the RSL-based hypermedia engine might also support the multiple classification of documents via virtual folder structures as discussed earlier for the RSL-based associative file system prototype.

We cannot expect existing applications that are currently using a classical file system to be adapted in order to make use of the proposed RSL-based hypermedia engine. Therefore, in order to provide some compatibility with these "legacy" applications, a classical file system interface might be offered on top of the RSL-based hypermedia engine. In its simplest form, this file system interface would just store any file as a resource in the underlying cross-media information space managed by the hypermedia engine. However, for some existing document formats, such as the Office Open XML document format with the `docx` extension in our example, specific file system drivers might be deployed which no longer store a file as a single resource but rather as a composition of its content fragments, providing access to the internal document structure. This has the advantage that—without any modifications—legacy applications could store their content via the RSL-based hypermedia engine and make the content and structure of a document available to any newly developed hypermedia-enabled application. In addition, a classical hierarchical file browser could be provided to users who do not immediately want to switch to some next generation file browsers realised on top of the RSL-based hypermedia engine.

By offering an RSL-based hypermedia engine at the level of an operating system, future hypermedia-enabled applications may profit from any of the RSL features (e.g. context awareness or access rights) discussed earlier, and we enable a system-wide application interoperability via the shared content and RSL metadata. Note that content might not only be shared within a system but also between different systems with their own embedded RSL-based hypermedia engine.

Our envisioned cross-media storage platform represents an ideal environment for investigating innovative forms of cross-media information management and human-information interaction. Users gain a lot of freedom in organising their digital and physical content by making use of navigational and structural links or via simple tagging enabled by RSL properties. Further, the findings of different research domains (e.g. personal information management or information retrieval) can be applied on top of the RSL-based hypermedia engine in order to provide some advanced services for dealing with our daily digital as well physical information. By offering new tools for managing content in general cross-media information spaces, we might have to reflect on the role of a document which just becomes a specific view of parts of the underlying shared content fragments as well as to reconsider the file and folder paradigms. The proposal for a next generation cross-media storage platform and the rich features offered by the presented cross-media applications will hopefully stimulate some discussion on innovative solutions for managing and retrieving information in cross-media information environments.

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