

Framework of a Real-Time Adaptive Hypermedia System *

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ABSTRACT

In this paper, we describe a framework for the design and development of a real-time adaptive hypermedia system. The framework leverages on the integration of conventional adaptive hypermedia techniques and ACT-R architecture which serves as the theoretical background for the cognitive model that monitors the interaction process between users and the system. The users' information seeking skills in the hyperspace specified by their viewing patterns within the web pages and access patterns between the web pages are extracted from user tracing data. The user's viewing patterns are discovered by analyzing their fixation sequences with eyePatterns. The user's navigation strategies in the hyperspace are evaluated in terms of information foraging theory to serve as their access patterns. Both of these patterns are transformed into the knowledge stored in the cognitive model. Based on these interaction experiences between the user and the system, the cognitive model will re-arrange the presented information and the structure of the hyperspace in real time in order to facilitate the user to acquire valuable information as they perform information seeking tasks. Besides the flexible adaptability, this integration leads to the immediate feedback to assist the users' cognitive process to accomplish their information seeking tasks. The effectiveness of a conventional adaptive hypermedia system has been enhanced to a great extent.

Categories and Subject Descriptors

H.5.4 [Information Interface and Presentation]: Hypertext/Hypermedia—*architecture, navigation, user issues*;
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General Terms

Design, Human Factors

Keywords

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Adaptation, Cognitive Model, ACT-R Architecture, Information Foraging, Eye Tracking, Web Services

1. INTRODUCTION

Nowadays, both the amount and complexity of information are increasing exponentially, while the limited capability of information processing severely hampers humans to seek, gather and consume valuable information efficiently [10]. From this perspective, one of the most important studies in the information technology research field is how to maximize the allocation of human's attention to useful information rather than to simply provide people with access to the continuously-changing, chaotic, and overwhelming amount of information. Increasingly, massive amounts of information have been available to the average users in the form of hypermedia through the World Wide Web leading to the need for more adaptive and personalized websites. Adaptive hypermedia systems, as an alternative to the conventional "one-size-fits-all" websites [6], aim to augment web users' information processing capability. The basic idea of adaptive hypermedia systems is that by modeling individual user's particular goals, interests and preference, the system can tailor the content and format of the presented information to meet the user's special need in order to maximize their rate of gaining valuable information. Adaptive hypermedia systems can be widely adopted in many application fields, such as education [15] [13], e-commerce [9], and virtual environments [11]. The essential commonality is that users in these application fields have to explore reasonably large amounts of information with diverse goals and background knowledge.

The information structure of adaptive hypermedia systems consists of two interconnected spaces which are knowledge space and hyperspace. Knowledge space is a network model of the knowledge in a specific domain. The set of nodes in this structured domain model refer to a set of domain knowledge elements which can represent bigger or smaller pieces of domain knowledge depending on the particular application. The links among these nodes refer to their semantic relationships [4]. The hyperspace refers to the conventional web pages and page fragments connected by hyperlinks. The connections between these two spaces should be specified by the designers in order to assign web resources to the knowledge. As a crucial component, one of the most important functions of the domain model is to provide a framework to model users' domain knowledge and their goals. The majority of the adaptive hypermedia systems adopt overlay model

to simulate user's knowledge. The overlay model keeps a variable with each domain knowledge element to represent the estimation of user's knowledge level about this element. The user's goal is represented by a subset of domain knowledge elements to be learned. Currently, there is a trend in the research on adaptive hypermedia systems, especially in the online learning application field, tries to combine intelligent tutoring system with educational adaptive hypermedia by introducing "cognitive tutors" which are computational process models into adaptive hypermedia systems [5]. In the representative studies [15] [8], researchers integrated simple production systems with their adaptive hypermedia systems to guide the users' interaction with the systems. Besides the student model and goal model, these production systems can be considered as an adaptation model. Although just in its premature state, these adaptation models' effectiveness is relatively significant. This research trend partially inspired our study.

There are two major problems in the state-of-the-art adaptive hypermedia relating to user modeling and adaptation technologies. From the cognitive psychology point of view, the commercial platforms only provide a simple way of personalization and adaptation. Since the user model of the current adaptive hypermedia systems is no more than a record of a particular user's accumulative history visits, it fails to include some vital cognitive components that have a great effect on users' task performing process, particularly short-term memory, visual attention and misconception. As long as all these cognitive factors are treated appropriately, the adaptive hypermedia system can facilitate users' information seeking behaviors more efficiently.

Another problem hindering the further development of adaptive hypermedia systems is the lack of people with different expertise involved into the process of arranging personalized adaptive experiences to collaborate to achieve a good quality solution. Many adaptive hypermedia systems only serve as prototypes or research experiments without practical value. Consequently, how to integrate users' experiences into the hypermedia to direct the systems' adaptation and personalization is still a challenge. As the production systems were combined into the adaptive hypermedia systems, the system's effectiveness has been enhanced by providing real time feedback. However, these production systems are essentially committed to a particular use. This feature severely constrains the system's ability to acquire users' knowledge in a flexible form.

To solve these problems, we propose a computational process model built on ACT-R cognitive architecture as an embedded assistant to help users perform their tasks by adapting the hyperspace dynamically and providing real-time feedback. ACT-R cognitive architecture [2] aims to provide specification about human cognition. As an integration of various components of human cognition, ACT-R serves as a theoretical foundation to constructing cognitive models in order to produce coherent human behaviors in different environments. As the basic components of ACT-R architecture, the interaction between declarative knowledge and procedural knowledge enables our ACT-R model not only extends the conventional adaptation systems by providing a mechanism to acquire users' knowledge and skills in a more rapid and

flexible manner, but also maintains trails of the users' information seeking process and cognitive states. These performances enable the adaptive hypermedia system to tailor the displayed contents and the structure of hyperspace in ways that improve the efficiency of the users' information seeking behaviors. Furthermore, information foraging theory [12] provides a new point of view to consider the interaction between users and adaptive hypermedia systems. According to this theory, humans can be viewed as informavores who actively seek, gather, and consume information in the culture environment in the same way as creatures like carnivores or herbivorous seek, gather, and consume food in the physical environment. In this sense, how to adapt the presented information to augment users' specific interests and needs can be converted into an optimization problem. We can evaluate and make sense of the user's information seeking behaviors by extracting their viewing patterns within web pages and navigation strategies between web pages in order to transform these patterns into the knowledge needed by the ACT-R model. It should be emphasized that compared to some previous attempts that focused on the learning field, our system aims at more general applications.

2. SYSTEM OVERVIEW

The overall structure of our real time dynamically adaptive hypermedia system is shown in Figure 1. In this structure, both the adaptive hyperspace and the domain knowledge space are components of the conventional adaptive hypermedia system. The user tracing model is responsible for observing and recording the interaction between users and the system to do further analysis. Eye tracking equipment and web logging software are used in this model to collect the eye movement data and the log record data respectively. Subsequently, the users' viewing patterns extracted from their fixation sequences within each web page will be analyzed by eyePatterns [16], and their access patterns are also compiled from the log records to serve as their navigation strategies between these web pages. ACT-R Model is used to learn and store the users' information seeking skills in order to direct the adaptation of the system to facilitate the users to acquire valuable information.

The user tracing model is responsible for evaluating the observed data from the users. These evaluations serve as the users' skills to be learned by ACT-R model in the form of declarative knowledge and procedural knowledge. Based on the observation data from user tracing model, the procedural rules stored in ACT-R model are activated to adapt the content and form of presented information dynamically to users' behaviors and provide necessary feedback in real time. The advantage of the ACT-R cognitive model is that it provides means of applying the psychological rules known from the users' cognitive behaviors to the adaptation of the interface, thereby improving the system's quality and usability.

Our system's adaptive behavior consists of two levels: adaptive presentation and adaptive navigation support. Adaptive presentation refers to adapting the content of a web page to the user's goals and knowledge background. In our system, the information fragments presented within a web page correspond to several Areas of Interest (AOI). Each of the AOIs contains a piece of information corresponding to the domain knowledge elements in the domain knowledge

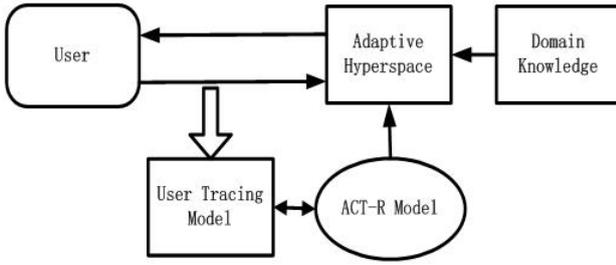


Figure 1: Overall System Structure.

space. The adaptive behaviors at the adaptive presentation level refer to hiding the AOIs which are assessed to be irrelevant to the tasks from the users and using an alternative way to present the displayed AOIs to emphasize their different priorities to the user’s task. The adaptive navigation support is done in two ways: direct guidance which means the system highlights one of the links on the web page to indicate that this is the best link to follow, and web page sorting which means that the system sorts all the web pages according to the relevance evaluation stored as knowledge in our cognitive model: the more relevant the link is to the user’s goal, the closer to the top in the hierarchical structure of hyperspace.

3. METHODOLOGY

3.1 User Tracing Model

The user tracing model consists of two operational modules: monitoring module and pattern extraction module. The monitoring module plays a role as a visual sensor to percept the users’ interactive actions on the interface with eye tracking equipment and web log software. Pattern extraction module is capable of evaluating and recording the observed user’s information seeking behaviors specified by two patterns which are the users’ viewing patterns within a particular web page and the users’ access patterns between the web pages.

The patterns will be mapped into the set of production rules which actively detect these inputs in ACT-R model. These rules update the declarative memory to contain chunks that represent the perceived behaviors which allow the system to adapt its displayed contents and structure of hyperspace. These observations of data enable the ACT-R model to adapt the information presented on the websites to users’ cognitive process to pursue specific goals or interests as well as provide necessary instructions in real time to guide the users’ navigation.

3.1.1 User Access Patterns

The users’ access patterns between web pages refer to the users’ navigation strategies in the website. These access patterns are specified by the data recorded in web server log. Since it records the user access behaviors of the website, web server log is still considered to be the most important source of data for the adaptive navigation support. Based on information foraging theory, we come up with a novel incremental optimization algorithm to evaluate the users’ access patterns dynamically in order to enable ACT-R model to

reorganize the structure of the website in real time. This algorithm not only identifies the set of web pages that are evaluated to be the most valuable to the user’s task, but also provides criteria to re-organize the structure of hyperspace.

In [7], the log data shows that users spend shorter time on an index page choosing a link or topic and much longer time on a content page that they desire to read more thoroughly. We will extend this approach to distinguish index pages from content pages dynamically. In our model, the distinction between index pages and content pages is meaningful as long as it is defined for a specific user’s navigation to perform a specific task in the website. Moreover, besides the time spent between content pages, the time spent within a content page is considered to evaluate the efficiency of the user access pattern.

According to information foraging theory, information presented in the culture environment is clustered into a set of patches, and each patch diffuse unique information scent. In our hierarchical structure hyperspace, the information displayed in each content page is viewed as one information patch. Consequently, the time taken by the users in a specific navigation to view the content page corresponds to the time spent within the patch, and the total time taken by the users in a specific navigation to get to the content page is defined as the time spent between information patches. Essentially, the time spent between content pages is defined as the sum of two parts. The first part is the time spent to choose links within index pages. The second part is defined as the total time taken by the user to download a series of web pages at different depths in the hierarchical structure of the hyperspace. Accordingly, the information scent for each of the links in the web page is specified by the activation level of the related chunks in the ACT-R model. Information diet refers to the user’s selection of links to follow in order to gather valuable information efficiently [12]. The importance of information scent is that it is used by the users to assess the value of information gained per unit cost of processing the source. Based on these scent-based evaluations, the users are able to decide which links to follow so as to maximize the information diet. According to this, the rate of gain of valuable information per unit cost equals to the ratio of the total amount of valuable information that is necessary to be accessed for a particular task and the total amount of time cost within the content pages and between the content pages.

According to information diet model, the users assumed to be bounded rational always attempt to find relevant web pages in response to a goal or interest that are expected to contain most profitable information. The user’s diet in the hyperspace refers to the rate-maximizing subset of the web pages that should be selected. The profitability of a content page is defined as the ratio of value gained from the content page to the cost of time within the page. Then the basic idea of our incremental optimized algorithm is that the users should continue to access content pages in the order of increasing rank of the pages’ profitabilities as long as the profitability of the $k+1$ page is not less than the rate of gain for a diet of the top k pages. The algorithm outputs an optimized set of content web pages that should be accessed by the users to perform a specific task. The cumulative

gain function can be specified by the number of AOIs in the content web page and their mutual relevance with the user's goal which can be quantified by the spreading activation mechanism [1] in the declarative knowledge of the ACT-R model. The time spent in the process is recorded by web log software in the user tracing model. These optimized set of content web pages for a specific task will be transformed into declarative knowledge in ACT-R model.

3.1.2 User Viewing Patterns

The user's viewing patterns refer to the user's fixation sequences in the content pages and their efficiency of information seeking. According to [3], fixation sequence analysis can reveal the users' cognitive strategies to task completion that drive their attention to move around in the web page. A new tool used to discover the similarities in fixation sequences and identify the experimental variables that may affect their characteristics was described. This tool provides a solid practical foundation for constructing our user tracing model. Based on Yarbus' research work [17] that revealed that the order of fixations on regions of a stimulus is influenced by the relative importance of the regions to the viewer, and that viewers exhibited repeated cycles, or patterns, of fixations on the most interesting features of a stimulus, we assume that the users' eye fixations in a web page determine the efficiency of their information seeking behaviors in that page.

eyePatterns [16] will be adopted to extract the users' viewing patterns under a specific task in the pattern extraction module. A web page can be parsed into several sub-regions based on its layout and contents. These sub-regions are defined as area of interest (AOI) normally labeled with different characters. Therefore, the string representation of the fixation sequence corresponds to a concatenation of the AOI codes in the order of fixations occurred within the AOIs. eyePatterns is a software tool that provides several approach to discover the patterns in fixation sequences, moreover unknown and specified patterns can be found through discovery and pattern matching. these fixation sequences are integrated with the semantic meanings of each AOI [14].

3.2 ACT-R Model

To integrate cognitive models into the adaptive hypermedia system we need to keep track of the users' information seeking process and a series of cognitive states to adapt the layout and the structure of the hyperspace in a way to facilitate the effectiveness of information seeking. The key idea is that the cognitive model should incorporate the underlying information seeking skills that allow the users to pursue their goals or interests in an expected most efficient way. Based on the user tracing model, our system can monitor the users' information seeking behaviors and infer their intentions by mapping the behaviors to the components of the model. Subsequently, immediate adaptation of the hyperspace and real-time instructions can be generated to facilitate the users' information seeking behaviors.

3.2.1 ACT-R Architecture

The basic assumption in the ACT-R theory is that human cognition emerges through an interaction between a procedural memory and a declarative memory. Based on this,

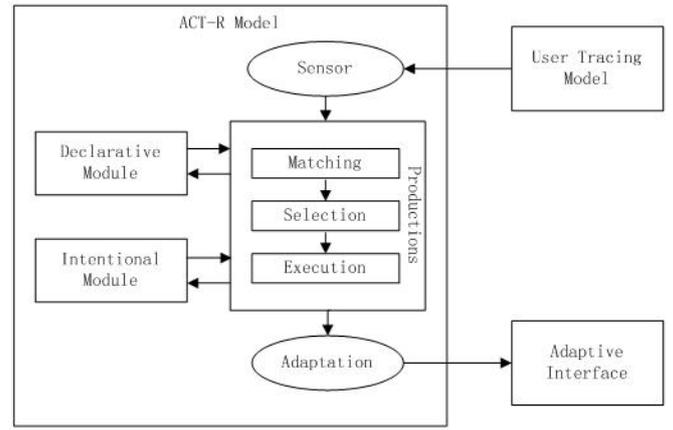


Figure 2: Architecture of the ACT-R Model.

there are several modules within the architecture of ACT-R. The declarative module retrieves information from long term memory, and the intentional module is used for keeping track of current goals and intentions of the users. A central production system is responsible for coordinating the behaviors of these modules. A production is a condition-action pair stored in the procedural memory. At a particular production cycle, once the condition parts of some productions are matched with the patterns from external world and internal modules, they will be gathered into the conflicting set. The conflict resolution will select only one production in each cycle to execute its action based on their utility. These actions make changes to the internal states of the modules and adaptive interface.

3.2.2 Declarative Knowledge

Declarative knowledge represents the various facts that people are aware they know and can explain them in an understandable way, such as the contents of a web page, the function of a certain button. Spreading activation mechanism is applied in the declarative memory to simulate the information retrieval process of human cognition. The declarative knowledge is grouped into a set of chunks, each of which contains a bigger or smaller piece of information depending on the applications. Parts of these pieces of information are corresponding to the contents displayed on the web pages of the hyperspace. An important feature of a chunk is its activation. The activation of a chunk represents to what extent this piece of information is needed at a particular time. The chunks connect to each other through associations which represent the co-occurrence between the pieces of information contained in the linked chunks. The associations have specific strengths to determine the amount of activation flow from one chunk to the related chunk. The users' goals or behaviors activate a group of chunks in this spreading activation network, meanwhile the contents displayed on the web page of the hyperspace activate some other chunks. These activations spreading via the associations through the network reflect the mutual relevance of the users' goals or behaviors and the contents displayed on the web page. All the associated chunks have been activated to a certain higher level.

3.2.3 Procedural Knowledge

The procedural knowledge which specifies how the declarative knowledge is transformed into active behaviors is represented by a set of production rules stored in the procedural memory system. These production rules detect activated declarative knowledge and input patterns from the sensor. At any point of time, multiple rules might be fired, but only one can be selected based on its utility to be executed. Since the user's information seeking behavior is specified by two kinds of patterns, the production rules should be designed accordingly such as:

IF the current page is included in the optimized set of content web pages and it is a leaf, THEN it should be moved up in the hierarchical structure of the hyperspace and linked to an index page.

IF the AOI is with high relevance level in the current page and it is not included in the user's viewing pattern and the current page is included in the optimized set of content web pages, THEN the AOI should be highlighted.

These are the English equivalent forms of the production rules that should be designed in our system.

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