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CONTEXT-AWARE WORKFLOW MANAGEMENT FOR INTELLIGENT NAVIGATION APPLICATIONS IN PERVASIVE ENVIRONMENTS♠

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ABSTRACT—Pervasive computing is a user-centric distributed computing paradigm, allowing users to access their preferred services even while moving around. To make this vision a reality, context-aware workflow management is one of key issues because the context of pervasive applications is changing instantly. In this paper, we propose a context model for intelligent navigation applications and then present a context-aware workflow management algorithm (CAWM) which can dynamically adjust workflow execution behaviours based on current context information. The correctness of the CAWM algorithm has been also verified theoretically by formulating it as a Petri-net model. Furthermore, the proposed context model and workflow management algorithm can apply to other applications by simply revising the corresponding context structures only.

Key Words: Intelligent computing, pervasive computing, workflow, context awareness, Petri nets

1. INTRODUCTION

PERVASIVE computing is a new distributed computing paradigm that provides mobile users their preferred services while moving around. Due to the high mobility of users, pervasive software runs in an extremely heterogeneous and dynamic environment, where many kinds of network nodes and communication protocols co-exit, and network topology and bandwidth change frequently. As a result, context awareness and context-driven self-adaptation are key

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characteristics distinguishing pervasive environments from traditional distributed systems. Pervasive software has to be aware of the context changes for dynamically adjusting execution behaviors and supporting seamless roaming to make the user-centric vision a reality. Along with this direction, there have been many active application-driven researches [1-5].

Context-aware workflow management is an important enabling technology to achieve the desired goals of pervasive computing. It should consider the characteristics of both static and dynamic topologies, wired and wireless subnets, mobile and disconnected users, etc. However, none of existing workflow management proposals can sufficiently address the combined and new requirements for pervasive applications.

Context-aware navigation service is one of significant pervasive applications. In this paper, we consider a context-aware workflow management for pervasive navigation in a campus, in which there are many libraries, restaurants and bus stops, each of them in a different location. Alex plans to first visit a library for borrowing some books (A_1), then have a lunch in a restaurant (A_2), and finally take a bus to go home (A_3). Figure 1 illustrates such a tour, where A_1, A_2 and A_3 are these three sub-activities in Alex's campus tour. We assume he is not familiar with the campus environment and just holds a PDA (personal digital assistant) with GPS (global positioning system) function. To make the tour convenient and efficient, the pervasive campus should provide him an intelligent navigation based on current context. When Alex wants to take a bus, for example, a campus navigation system should find the shortest bus stop from his current location and send the navigation information (e.g., routing path) to his PDA. Furthermore, the navigation system should automatically transmit requests and responses via qualified network links that have stable connection and sufficient communication bandwidth. From the above scenario, we find that navigation applications are highly context-dependent, especially in the following dimensions:

- *current location*. When Alex hopes to have a lunch, for example, the navigation system should find a restaurant closest to his current location.
- *connected network*. The navigation system has to select a qualified network to transmit requests and responses for Alex, based on current network topology and bandwidth.

Workflow management aims at providing the process transparency for a group of activities. As a result, workflow management for intelligent navigation applications in wireless network environments has to be aware of current context, e.g. network connectivity, bandwidth and user location, for reliable and intelligent navigation services. So, context-aware workflow management is a valuable and important service for mobile and pervasive environments.

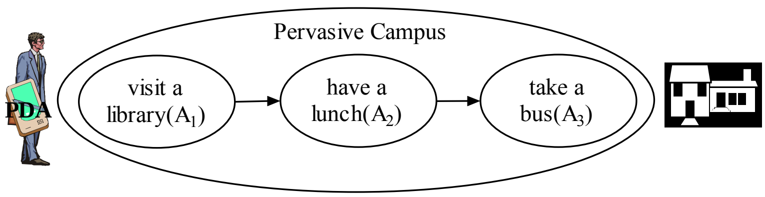


Figure1. A tour in a pervasive campus.

This paper is motivated to solve such an issue for providing a context-aware management service characteristic to navigation applications in pervasive campuses. We propose a context model for the campus navigation and then present a context-aware workflow management algorithm (CAWM). The correctness of the CAWM algorithm is also verified theoretically by formulating it as a Petri-net model.

The remainder of this paper is organized as follows. Section 2 provides an overview of related work. Section 3 proposes a context model for campus navigation applications. Section 4 presents a context-aware workflow management algorithm CAWM. Section 5 validates the correctness of CAWM through Petri nets. The implementation and case study are presented in Section 6. Finally, Section 7 concludes this paper with a discussion on our future work.

2. RELATED WORK

Workflow management technologies have been extensively researched in recent years. From the perspective of adaptation to execution environments, existing workflow models fall into two categories: non-context-aware workflow management [6-10] and context-aware workflow management [11-13] (see Table I).

Non-context-aware workflow management models are not adaptive to the context of workflow execution. DISCOBOLE [6] is a service architecture for interconnecting workflow processes. This model supports heterogeneous workflow process interconnection for inter-enterprise cooperation, where several heterogeneous workflow management systems co-exist. McRunjob [8] is a grid workflow manager used to generate large number of production processing jobs in high energy physics. It converts core metadata into jobs submitted in a variety of environments. Krishnan et al. [9] presented a workflow framework for Grid services (GSFL) to manage workflows within the Open Grid Services Architecture (OGSA) framework. The GSFL focuses on the definition of an XML-based workflow language and the description of an implementation of a workflow engine. Nichols et al.[10] proposed a model for autonomic workflow management (AWM) in Grids. The model integrated dynamic fault tolerance mechanism with Grid-based workflow management architecture, providing awareness and resilience to failures. Task net (TN) [7] is transactional workflow model based on colored Petri net. It defined a workflow specification language that can express the dependency relationship of task states and enable users to express both the transaction- and application-oriented requirements.

Table I. Some related workflow models

Models	*Main function*	*Context-aware*	*Applicable environments*
DISCOBOLE	Process cooperation	No	Heterogeneous systems
McRunjob	Job generation	No	High energy physics
GSFL	Grid workflow management	No	Grids
AWM	Fault tolerance	No	Grids
TN	Transactional workflow	No	Distributed systems
CAWE	Web services workflow	Yes	Web services environments
CAWDRA	Automatic resource allocation	Yes	Distributed healthcare systems
ACAS	Autonomous context-aware service	Yes	Mobile computing

There also have been reports on context-aware workflow management. CAWE (Context-Aware Workflow Execution) [11] is a framework for management of context-aware Web Services-based workflow systems. The CAWE framework introduced a hierarchical workflow representation, specifying context-dependent actions and a declarative specification of the conditions determining how to select the appropriate context-dependent workflow part at runtime. The context in CAWE proposal is based on Web Services systems, with no consideration of the features of wireless and mobile environments. In CAWDRA (Context-aware Workflow Driven

Resource Allocation) [12], Hsieh presented a workflow model to describe the medical service processes in healthcare systems, with the goal of automatic resource allocation. ACAS (Autonomous Context-Aware Services) [13] is a model for the discovery and execution of services on connected and partially autonomous mobile devices. Discovery and execution procedures are sensitive to context changes, by running a service registry on the mobile device itself. However, this framework did not use workflow technologies to manage the discovery and execution of services. In conclusion, the above workflow systems have not yet included sufficient functions to support context-aware services for pervasive computing. Distinguishing from these proposals, this paper investigates, by the first time, how to automatically manage workflows for navigation applications in a context-aware way in pervasive environments.

3. CONTEXT MODEL FOR CAMPUS NAVIGATION

Context awareness enables systems automatic configurations and adjustments to provide better services for users. Context is the representation of the information that is relevant to the individuals and devices within the activity space [18]. A context adaptive system typically enables the user to maintain a certain application (in different forms) while roaming between different wireless access technologies, locations, devices and even simultaneously executing everyday tasks. Context-aware campus navigation systems focus on providing navigation information (e.g., text, photo) of targets for users with mobile devices (e.g., PDA). As a result, the following context dimensions have to be considered for campus navigation applications (see Table II).

- *Person*: profile, preferences and requirements of a user,
- *Location*: longitude and latitude (or relative position) of the user,
- *Network*: connection and performance of networks, and
- *Mobile device*: computing and storage capacity of devices

Table II. Context of pervasive campus

Entity	*Attribute*	*Value*
Person	Name	Name description
	Sex	Male, female
	Age	Value of age
	Identity	Teacher, student, guest etc.
	Requirement	Requirement description
	Preference	Behaviour preference
Network	Connectivity	Connected, disconnected
	Bandwidth	High, medium, low
	Cost	Expensive, cheap, free
	Stability	Good, medium, bad
Device	Available_battery	Full, half, low
	Available_data	Available, unavailable
	Computing_capacity	High, medium, low
	Available_memory	Full, half, low
	Available_cache	Full, half, low
Location	Longitude	Value of longitude
	Latitude	Value of latitude

We abstract the context information using *entities*, *attributes* and *relationships* among entities, and model them in a Entity Relationship (ER) diagram. Note that some attributes (e.g., preference) can not be directly abstracted from entity profiles and data mining-like technologies will be used for this purpose. The graphic context model for pervasive campus navigation is shown in Figure 2, where we only illustrate attributes of the entity Person. Attributes of other entities can be easily included in the same way according to Table II. An entity is fully captured by means of its attributes. For example, a user Alex can be described like Person.Name = "Alex," Person.Identity = "student," Person.Age = "20," Person.Sex = "male," Person.Requirement = "he needs to visit a library, a restaurant and a bus stop," and Person.Preference = "he likes computer books."

On the other hand, there are relationships between two entities. For example, the relationship denoted as "Person $\overset{m \quad n}{\text{——}}$ Location" in Figure 2 means that a person may appear at many locations while a location can be visited by many persons.

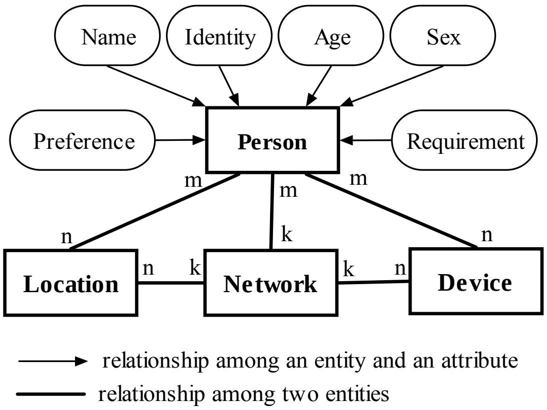


Figure 2. Context model for pervasive campus navigation.

4. CONTEXT-AWARE WORKFLOW MANAGEMENT

In this section, we define Petri net model for a context-aware workflow, and then present the context-aware workflow management algorithm CAWM.

4.1 Context-aware workflow based on Petri nets

A Petri net is an effective modeling tool applicable to many systems, especially to distributed and parallel systems. It can model systems' events, conditions and relationships, expressing control flow as well as data flow in a set of activities. The occurrence of these events may change the state of the system, causing some of the previous conditions to cease holding and other conditions to begin to hold [14-17]. We model a context-adaptive pervasive workflow in Petri nets as follows.

Definition 1. A context-adaptive workflow (CAW) is a 7-tuple CAW=(P,T,I,O,IT,CO, M_0), where

$P=\{p_1,p_2,\ldots,p_m\}$ is a finite set of places,

$T=\{t_1,t_2,\ldots,t_n\}$ is a finite set of transitions such that $P\cap T=\varnothing$ and $T\cap P=\varnothing$,

$I\subseteq P\times T$ is a finite set of input arcs from p_i to t_j ($1\leq i\leq m, 1\leq j\leq n$)

$O\subseteq T\times P$ is a finite set of output arcs from t_j to p_i ($1\leq i\leq m, 1\leq j\leq n$)

$IT=\{IT_1, IT_2,\ldots,IT_k\}$ is a finite set of user's interested targets,

Table III. Workflow composite operators

Operator	*Priority*	*Expression*	*Description*
ANY	1	$ANY(m,E_1, E_2,\ldots, E_n)$	M out of n events $E_i(1\le i\le n)$ occur(s)
EXC	1	$EXC(E_1, E_2,\ldots, E_n)$	Only 1 out of n events $E_i(1\le i\le n)$ occurs
NOT	2	NOT E_1	E_1 does not occur
AND	3	E_1 AND E_2	Both E_1 and E_2 occur
ALL	3	$ALL(E_1, E_2,\ldots, E_n)$	All events $E_i(1\le i\le n)$ occur
OR	4	E_1 OR E_2	At least one of E_1 and E_2 occur(s)
REP	5	REP E_1 n	E_1 occurs n times
PRE	6	E_1 PRE E_2	E_1 occurs before E_2
SEQ	6	$SEQ(E_1, E_2,\ldots, E_n)$	E_1 PRE E_2 PRE …PRE E_n

CO is a finite set of context information, and

M_0 is the initial marking.

CAWM manages workflows in the event-driven way, including atomic and composite events. We defined five types of atomic events: context change event, method call event, state transition event, (absolute and relative) time event and user-defined event. The composite events are composed of the atomic events or lower-level composite events, using the composite operators with specified priorities listed in Table III, where E_i ($1\le i\le n$) indicates an atomic or a composite event. The highest priority is 1.

```
Context-Aware Workflow Management Algorithm
Input: a set of expected targets (IT);
Output: navigation information of IT;
{   i=1;
    while (IT ≠ ∅ ) do
        Ci= candidates corresponding to ITi;
        j=1;
        suc=true;
        while  (Ci ≠ ∅ ) and (suc) do
            k=1;
            repeat
                η =bandwidth of network Nk;
                if (η is low) k++;
            until (k>K) or (η is high or medium);
            send request for Ci,j to server via network Nk;
            wait for navigation information of ITi,j;
            if (the user does not satisfy) {
                Ci=Ci-{Ci,j};
                j++;  }
            else
                suc=false;
        endwhile
        IT=IT-{ITi};
        i++;
    endwhile  }
```

Figure 3. Context-aware workflow management algorithm for campus navigation (CAWM).

4.2 Context-aware workflow management algorithm

Context-aware campus navigation targets on providing expected navigation information based on current context information. Let $IT=\{IT_i \mid IT_i$ is one of expected targets, $1 \le i \le n\}$ be the set of a user's interested targets (e.g., library, restaurant) in a campus. IT is an ordered set with the dependence $IT_i \prec IT_{i+1}$, i.e., specifically, IT_{i+1} is not executed until IT_i finishes. C_i is a set of candidates corresponding to an interested target IT_i such that $C_i = \{C_{i,j} \mid C_{i,j}$ is a candidate of IT_i, $1 \le j \le m\}$. C_i is also an ordered set, for example, $C_{i,j}$ is closer to a user's *current location* than $C_{i,j+1}$. Note that *current location* is the latest position where the user is located when last sub-activity finishes. At the beginning of a campus navigation workflow, for example, current location means the place where Alex initiates a request just after Alex arrives at a library. In other words, current location refers to that library. Moreover, we assume a request can be sent to servers via K different network links $N = \{N_k \mid N_k$ is a network link between the request node and the server, $1 \le k \le K\}$.

Our context-aware workflow management algorithm (CAWM) adopts an event-context-action (ECoA) mechanism. As illustrated in Figure 3, the algorithm can dynamically adjust workflow execution policies based on current context information. Attributes of each entity can take the values given in Table II. The algorithm requires that the value of a network bandwidth for transmitting workflow requests and results must be high or medium. Figure 4 illustrates the execution flow of the algorithm CAWM.

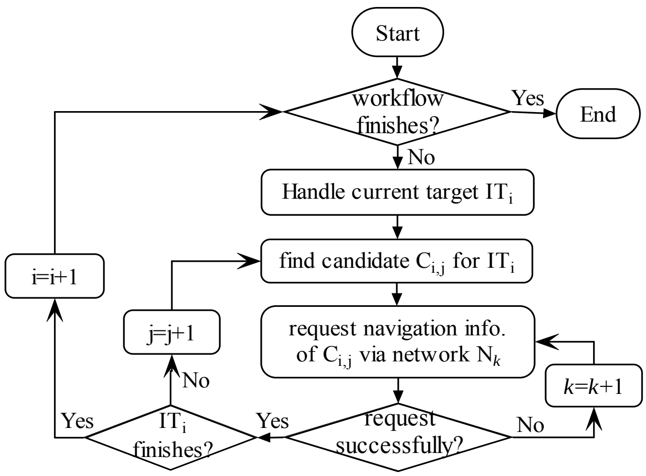


Figure 4. Flow diagram of the CAWM.

5. CORRECTNESS VALIDATION OF THE ALGORITHM CAWM

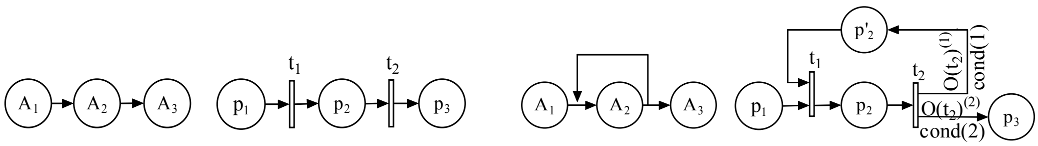
In this section, we formulate the CAWM algorithm as a graphic Petri net model and then validate its correctness using the reachability tree analysis technology of Petri nets.

5.1 Activity diagram and graphic Petri net

Compared with other validation tools, Petri net can model systems or protocols with instinctive graphics. Before illustrating graphic Petri nets of the CAWM, we introduce possible workflow execution sub-structures, as shown in Figure 5, where A_i denotes a sub-activity in a workflow, and p_i and $t_i/t_i(j)$ mean corresponding system states and actions, respectively. In each sub-figure, the left is the diagram of a sub-activity and the right is corresponding Petri nets. To express selective executions, in particular, we introduce a *selective transition* concept. Let O(t) be the set of output arcs of a transition t such that $O(t)=\{O(t)^{(i)} \mid O(t)^{(i)}$ is one of output arcs, $1 \leq i \leq n\}$, where n is the number of t's output arcs.

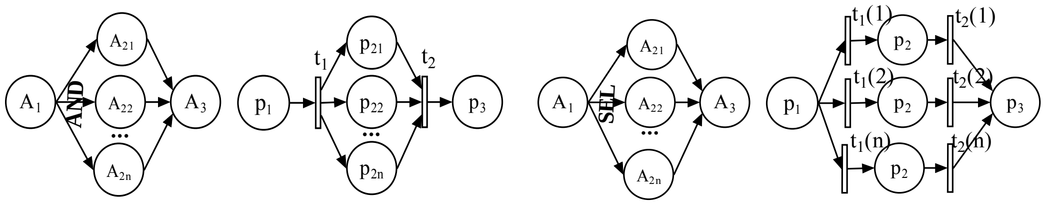
Definition 2. A transition t is *selective* if (1) any $O(t)^{(i)} \in O(t)$ associates with a condition $O(t)^{(i)}.cond(i)$, and (2) when a firing occurs, only $O(t)^{(i)}$ with $O(t)^{(i)}.cond(i)=true$ $(1 \leq i \leq n)$ is fired.

The *selective transition* concept extends modeling ability of Petri nets by introducing firing conditions for each output arc. Let a selective transition t_2 in Figure 5(2) denote the data transmission via a network link N_k, and the corresponding conditions be network performance. When t_2 is fired, $O(t)^{(2)}$ is actually fired only if the network link N_k is qualified, i.e., $O(t)^{(2)}.cond(2)=true$. Otherwise, only $O(t)^{(1)}$ is fired when the network link N_k is not qualified.



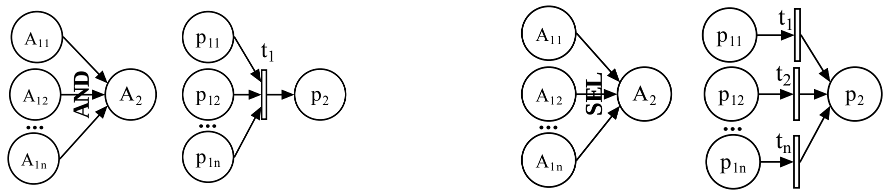
(1) sequential execution: sub-activities A_1,A_2,A_3 are executed one by one

(2) iterative execution: A_2 is repeatedly executed



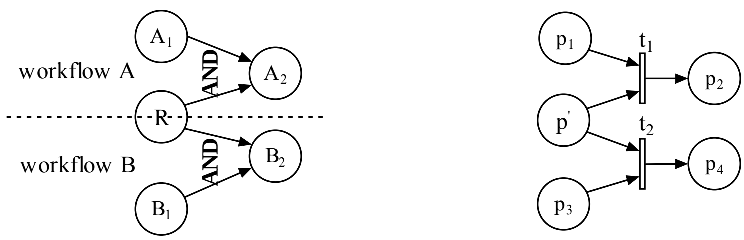
(3) AND-Split: all successors A_{21},A_{22},…A_{2n} are executed

(4) Selective(SEL)-Split: one of successors A_{21},A_{22},…A_{2n} is executed



(5) AND-Join: A_2 is executed if and only if all predecessors A_{11},A_{12},…A_{1n} finish

(6) Selective(SEL)-Join: A_2 is executed if one of predecessors A_{11},A_{12},…A_{1n} finishes



(7) Exclusive resource: workflows A and B exclusively use the resource R

Figure 5. Workflow execution structures and corresponding Petri nets.

5.2 Petri nets of CAWM

Our workflow management CAWM is responsible for finding the navigation information of targets, requested by a user, based on his/her current context. Generally, there are multiple candidates for a requested target. As a result, CAWM first selects a qualified network link between the user and a server, then finds a candidate for a requested target IT_i, and finally gets the navigation information of IT_i. Figure 6 illustrates such an activity diagram of CAWM, where each activity respectively denotes: (1) A_1- CAWM initiates IT_i; (2) A_2- CAWM finds a candidate; (3) A_3 - CAWM finds a qualified network link; (4) A_4 - CAWM gets navigation information of the candidate; (5) A_5 - CAWM judges whether the candidate is satisfied; and (6) A_6- CAWM judges whether the workflow is finished.

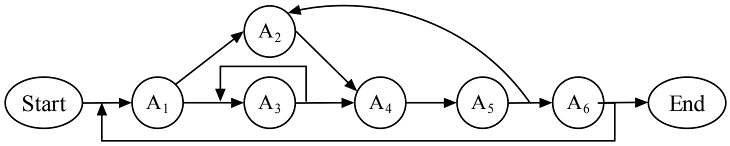


Figure 6. Activity diagram of CAWM.

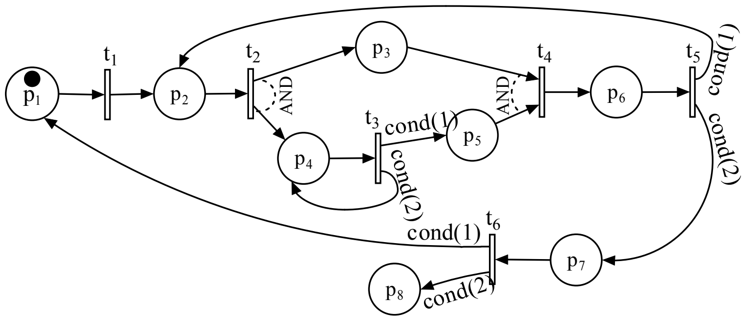


Figure 7. Graphic Petri net of the CAWM (PN-CAWM).

Figure 7 depicts the graphic Petri net of the CAWM, a simplified PN-CAWM, where places refer to states of sub-activities while transitions mean the execution of corresponding actions (see Table IV). Three selective transitions t_3, t_5 and t_6 denote inspecting network status, checking the navigation information for a target IT_i and judging whether a workflow finishes, respectively. More specifically, $O(t_3)$.cond(1) denotes that network N_k has good performance (e.g., enough bandwidth), $O(t_5)$.cond(1) denotes that a user does not accept the candidate $C_{i,j}$, and $O(t_6)$.cond(1) denotes a workflow does not finish. Similarly, $O(t_i)$.cond(2), i = 3, 5 and 6, denote otherwise, respectively.

According to Figure 7, we have the Petri net PN-CAWN=(P,T,I,O,IT,CO,M_0), where $P=\{p_1, p_2,\ldots,p_8\}$; $T=\{t_1,t_2,\ldots,t_6\}$; $I=\{I(t_1),I(t_2),I(t_3),I(t_4),I(t_5),I(t_6)\}$; $O=\{O(t_1),O(t_2),O(t_3),O(t_4),O(t_5),O(t_6)\}$. Note that for a selective transaction t, only qualified output arcs are actually fired when t is fired;

M_0={1,0,0,0,0,0,0,0}. Finally, IT is the set of visiting targets in a workflow, for example, IT={library, restaurant, bus stop} in Alex's tour; and CO is the set of context during the execution of a workflow.

Table IV. Places and transitions of PN-CAWM

Elements	*Status*	*Meaning*
p_1	Active(IT_i),	Sub-activity IT_i is initiated
p_2	Executing(IT_i)	IT_i is executing
p_3	Found($C_{i,j}$);	Candidate $C_{i,j}$ is found
p_4	Checking(N_k);	N_k is been checking
p_5	Qualified(N_k);	N_k is qualified
p_6	Finished(IT_i);	A user gets navigation information of IT_i
p_7	Satisfied(IT_i);	A user satisfies the navigation information
p_8	End	A workflow finishes
t_1		IT_i is initiated
t_2		CAWM finds $C_{i,j}$ for IT_i
t_3		CAWM inspects whether N_k is qualified
t_4		CAWM requests navigation information of $C_{i,j}$ via N_k
t_5		A user satisfies navigation information for IT_i or not
t_6		CAWM checks whether a workflow finishes

5.3 Correctness validation of the CAWM

Petri nets can analyze the behavioral properties, which depend on the initial marking, including reachability, boundedness, liveness, coverability, reversibility, persistence and so on. For a bounded Petri net, the coverability tree is called the reachability tree and all above problems can be solved by the reachability tree [15]. Peterson [14] also pointed out that in Petri nets, many questions can often be reduced to the reachability problem.

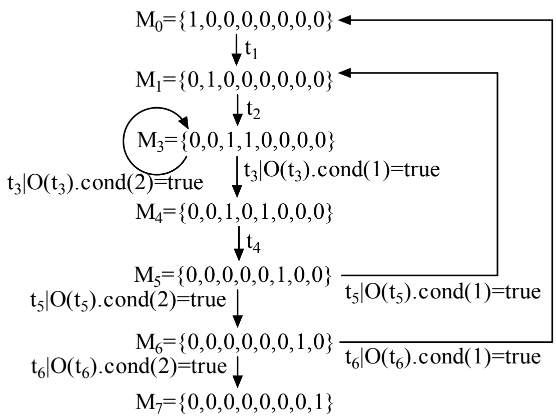


Figure 8. Reachability tree of the PN-CAWM.

A marking M in a Petri net is an assignment of tokens to each place. The movement of tokens expresses the status conversion of workflow systems. M is reachable from another marking M' if M' may be transformed to M through a sequence of firings. The set of all possible markings reachable from a initial marking M_0 in a Petri net (N, M_0) is expressed by R(M_0). For the PN-CAWM, M=(m_1, m_2,…, m_8) is a marking and m_i indicates the number of tokens in place p_i (i=1,2,…,8).

The boundedness and liveness of a Petri net are often used as correctness criteria in protocol validation. This paper mainly discusses these two properties by analyzing the reachability tree of the PN-CAWM. Reachability tree intuitively describes all the states from the initial state M_0, where nodes denote M_0 and its successors. In a reability tree, the M_0 is the root and leaf nodes correspond to final states. A path from the M_0 to a leaf node means an execution sequence. Figure 8 is the reachability tree of the PN-CAWM. In the following, we prove the PN-CAWN is bounded and L1-live.

Theorem 1. PN-CAWM is bounded.
Proof: A Petri net (N, M_0) is said to be k-bounded (or simply bounded) if the number of tokens in each place does not exceed a finite number k for any marking reachable from the initial marking M_0, i.e., $m_i \leq k$ for every place p_i and every marking $M \in R(M_0)$ [15]. By examination of the reachability tree of the PN-CAWM, ω (a symbol to represent an arbitrarily large value) does not occur anywhere, and the number of tokens in each place is never more than 1. Therefore, the PN-CAWM is bounded and k equals to 1.

Theorem 2. PN-CAWM is L1-live.
Proof: A transition t is L1-live if t can be fired at least once in some firing sequences. Furthermore, a Petri net (N, M_0) is said to be L1-live if each transition in the Petri net is L1-live [15]. For a bounded Petri net, the reachability tree contains all possible reachable markings. By examining the reachability tree of the bounded Petri net PN-CAWM, each marking is reachable and each transition can be fired at least once from M_0. Thus, PN-CAWM is L1-live.

Theorem 2 indicates that PN-CAWM can be deadlock-free as long as the firing starts from M_0. According to theorem 1 and theorem 2, we can conclude that the workflow management algorithm CAWM is correct.

6. INTELLIGENT CAMPUS NAVIGATION SYSTEM

We have developed an intelligent pervasive campus system (iCampus) with the architecture shown in Figure 9, which integrates various heterogeneous networks (wired and wireless networks, sensor network, self-organized network, Bluetooth etc.), and covers libraries, restaurants, meeting rooms, offices and sports fields. iCampus provides users intelligent personalized services and software migration and roaming in the campus.

Intelligent campus navigation is the major function of our iCampus system, which can provide navigation information for users in the graphical and textual way based on user's current locations, network states and device capacity. Our workflow management algorithm CAWM is at the centre of the intelligent campus navigation subsystem. When a user enters the campus, he needs to input his interested targets only and the navigation subsystem will automatically connect an appropriate server and show the path information and brief introduction of targets on his PDA. For example as illustrated in Figure 10, the navigation information of a library is shown in a PDA. Moreover, we have implemented a Petri-net-based automatic verification tool in our campus navigation system.

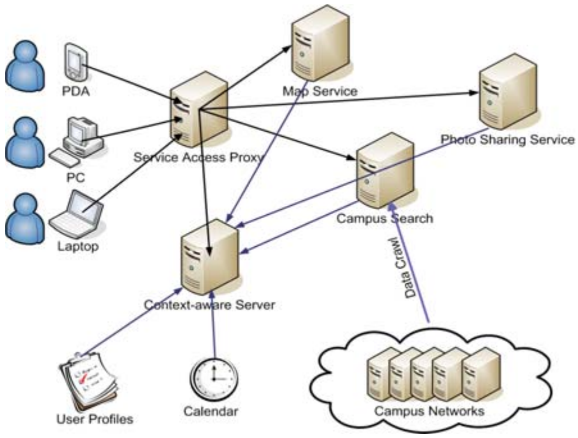


Figure 9. System architecture of intelligent pervasive campus

Figure 10. Navigation information for a library.

We present a case study to explain how CAWM provides navigation information for the campus tour mentioned in Section 1. The set of interested targets is $IT=\{IT_1, IT_2, IT_3\}$, where IT_1, IT_2 and IT_3 mean to visit a library, have a lunch and finally take a bus, respectively. IT is an ordered set such that $IT_1 \prec IT_2 \prec IT_3$. In the pervasive campus shown in Figure 11, each interested target IT_i has two candidates, i.e., C_1 ={library A, library B}, C_2 ={restaurant A, restaurant B} and C_3 ={bus stop A, bus stop B}. In addition, let there be K wireless links between Alex's PDA and the server. CAWM automatically discovers navigation information of the three interested targets in the following steps (see Figure 11):

(1) Alex requests the navigation information of IT_1, IT_2 and IT_3 through his PDA.

(2) PDA selects a qualified wireless link that can be used to communicate with a server and then connects with the server.

(3) The server returns the navigation information of both libraries A and B. Alex selects library B that has his preferred books.

(4) CAWM returns the navigation information of restaurant B and bus stop B that are closer to the library B than their counterparts.

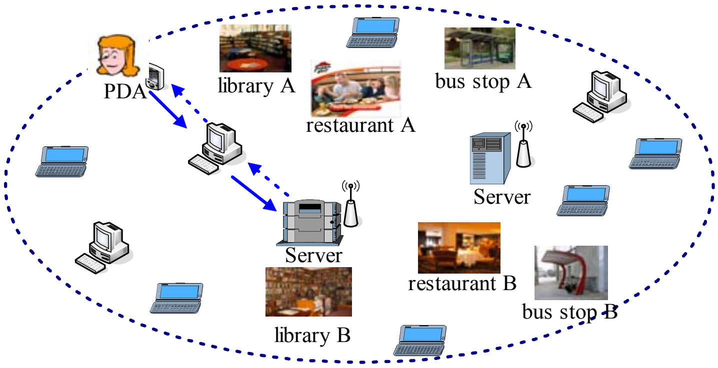


Figure 11. A CAWM-based navigation for a campus tour

7. CONCLUSIONS AND FUTURE WORK

We have presented a context model and a context-aware workflow management algorithm CAWM for pervasive campus navigation. Advantageous to the existing workflow management technologies, our algorithm can adjust workflow execution behaviors based on current context information. We also modeled the workflow management algorithm and analyzed its correctness through Petri nets. We implemented CAWM in our intelligent pervasive campus system. Experimental testing has demonstrated that CAWM is able to guide campus users intelligently and transparently. Although we currently focus on navigation applications, the CAWM can be extended to other pervasive applications, for example, traffic information and traveling guidance, by enriching context entities and attributes.

As part of the future work, we shall investigate how to model users' behavior, using data mining and reasoning, and further predict the users' actions based on the their profiles and history data. These results shall be integrated to our system and extend it into a context knowledge based intelligent navigation system for many application areas.

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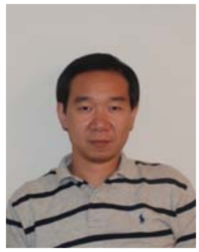

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