Context-Aware Trails

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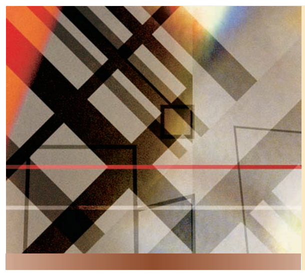
The emergence of converged mobile devices with a wide range of computing, communications, entertainment, and sensing capabilities represents a major step in the evolution of wireless computing. Such devices increasingly shift the decision-making power from the user to the machine, which has the capacity to be better informed about the current environment and can respond more quickly.

People spend much of their time planning where they're going, what to do along the way, and recalling where they've been. Trinity College Dublin's Hermes project (http://hermes.dsg.cs.tcd.ie) is exploring innovative ways to enhance these activities with proactive, context-aware mobile applications.

Drawing on previous work with the EU-funded Global Smart Spaces project (www.gloss.cs.strath.ac.uk), we use the notion of a *trail* to capture a mobile user's daily activities. At the most general level, a trail is a collection of locations, together with associated information about these locations and a recommended order for visiting them.

The trails metaphor makes it possible to explore adaptive characteristics common to all mobile, context-aware applications. Adaptation in this context involves altering the set of interest points on a trail and their visiting order with timeliness, accuracy, and relevance while remaining in tune with user expectations.



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PROPERTIES

The most common and obvious characteristic of an adaptive trails-based application is providing support for planning an appropriate route. This involves processing a rich set of contextual information such as current traffic congestion along different roadways, mode of transport, weather, route characteristics such as scenic or fastest, crowd density, time of day, and so on.

Activities at different locations along the trail also influence the aggressiveness of application adaptation. If the tasks are deemed mandatory or high priority, the application should make it difficult for the user to ignore them. If the tasks are optional, more subtle adaptation is appropriate.

Reliable and timely dissemination of contextual information and services is another key property of adaptable applications. A mobile device with sensing capabilities can determine the information and services available in the current environment and disseminate what is appropriate for the user's activity.

Trails-based applications can also incorporate an element of team-based communication or cooperative work. To this end, models that support ad hoc communication between mobile users provide a useful feature.

APPLICATIONS

Mobile, context-aware trails-based applications range from single-user systems that focus on individual daily activities to multimedia groupware that supports a wide collection of user requirements.

For example, a simple route planner can help a business traveler in an unfamiliar city get from the airport to a meeting location. The application, deployed on a PDA, calculates the best route based on factors including the user's current location, personal transportation preferences, real-time road traffic data, and bus and train schedules. It also presents a digital map of the area, overlaid with currently feasible routes and their estimated traversal time. Dynamic route adaptation may occur if traffic conditions make a different mode of transport or route more appropriate.

Other applications can manage the activities of multiple users. For example, a delivery company can equip operatives on bicycles or motorcycles with PDAs running a trails-based information system administered by staff in a traditional office. Administrators receive client requests and assign them to mobile couriers based on their current location, mode of transport, workload, schedule, and shift end time.

The application notifies couriers of new jobs via vibrotactile alerts and displays a trail on their PDA showing the

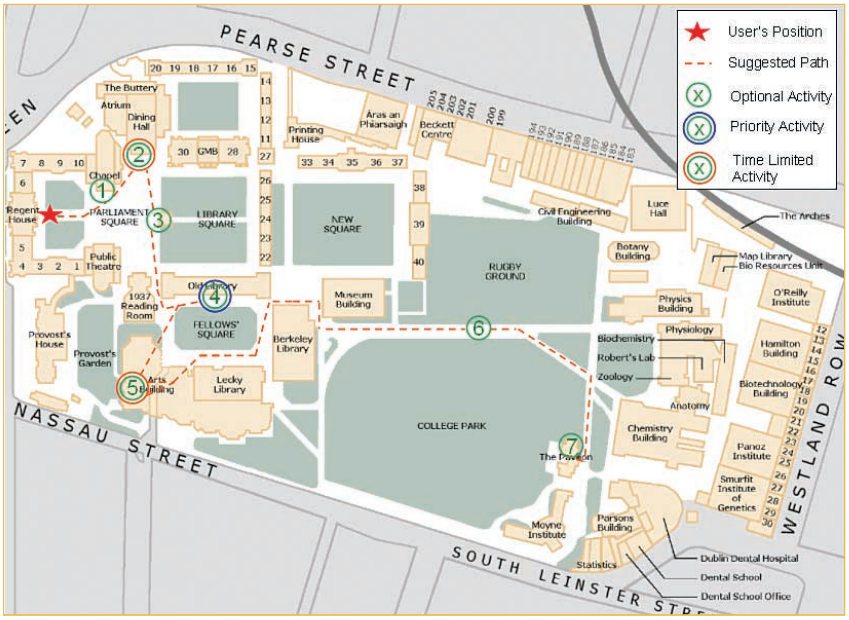

Figure 1. Context-aware trail application for mobile users. A recommended tourist trail through the Trinity Dublin Campus includes optional high-priority and time-constrained activities.

optimal route from their current location to the package pickup point and on to the drop-off point, as well as textual and audio information about the job. Dynamic route adaptation may occur based on factors such as assignment urgency and traffic conditions, and courier monitoring is also possible.

A more relaxed trail, such as that shown in Figure 1, is appropriate to support tourists' interests. For example, we are currently developing a context-based application that disseminates multimedia-based "stories" about previous inhabitants of an old part of Dublin to mobile users.

Finally, trails-based applications can be used to support multiplayer games. For example, consider a treasure-hunt game involving teams of PDA-equipped mobile players dispersed throughout a city or other large ubiquitous computing space. The game's objective is to arrive at an initially unknown destination as fast as possible by solving a set of cryptic riddles. Each clue hints at a location, which contains the next clue. Clues are tailored to team members' interests and vary in difficulty, delivery format (video, audio, or text), language, and topic.

The game uses trails to determine optimal routes between clue locations in real time, based on mode of transport, street congestion, team progress (very successful teams may be hindered slightly to keep the game interesting), and the location of other team members (if, say, two or more team members are required to reveal the clue), as well as more typical contexts such as location, weather, and time.

CHALLENGES

There have been significant advances in the understanding of human-computer interaction as users perform tasks of greater variety and complexity (J.M. Carroll, *Human-Computer Interaction in the New Millennium,* Addison-Wesley, 2002). However, the form factor and limited interface capabilities of mobile devices such as PDAs inhibit the representation of the dynamic adaptation of trails-based applications.

In addition, poor data quality complicates context acquisition. Contextual information may be stale or uncertain in terms of fuzziness and trust, while power and signal strength limitations, together with frequent user mobility, also contribute to its unreliability. Frequent re-adaptation to undo previous bad decisions is unacceptable. Sensor data fusion, a large research field, addresses these and related issues.

Further, mobile networks require new protocols for reliable and consistent sharing of information among groups of users who come together in an ad hoc fashion (J. Wu and I. Stojmenovic, "Ad Hoc Networks," *Computer*, Feb. 2004, pp. 29-31).

Moreover, the limited processing and power capabilities of PDAs challenge algorithm design for dynamic adaptation. A balance must be found between the time it takes to reconfigure the current trail and application responsiveness. The Lancaster GUIDE project (www.guide.lancs.ac.uk) provides a good example of a mobile, context-sensitive system experiencing this problem.

Determining whether the user is following a similar or previous path can enhance trail reconfiguration. Pattern recognition may be used to discover such situations, though the inevitable inexactness of repeated user behavior presents challenges for recognition and matching algorithms. The journal *IEEE Transactions on Pattern Analysis and Machine Intelligence* explores these and related issues.

Finally, a recent Invisible Computing column (B. Schilit et al., "Wireless Location Privacy Protection," *Computer*, Dec. 2003, pp. 135-137) outlined several privacy protection challenges that apply to trails-based applications.

TECHNOLOGY

In collaboration with Intel Research, we are developing a generic software framework that addresses these challenges and provides a configurable platform for developers of mobile, context-aware applications. Building such a framework involves both exploring and creating appropriate technologies.

Sensor fusion

Consider, for example, classical sensor fusion technology, which has difficulty satisfying context-sensing requirements because

- source configuration is highly dynamic,
- inexpensive sensors are inferior to human perceptual capabilities, and
- sensor numerical parameters must be converted to meaningful semantics.

Among the proposed solutions to this problem include those based on Dempster-Schafer theory, a generalized form of Bayesian theory. In addition, many projects have addressed how to fuse the output of numerous, low-cost, multimodal sensors for context awareness, including Technology Enabling Awareness (www.teco.edu/tea), MediaCup (http://mediacup.teco.edu), and Smart-Its (www.smart-its.org).

Trail generation

The trail-generation process involves two conflicting requirements:

- generating a highly customized optimal trail, and
- application responsiveness.

The first requirement negates the usefulness of classic route-generation techniques, such as shortest-path hill climbing, which do not consider users' personal route-planning preferences. Current best practices in route planning are knowledge- and experience-based. These approaches generate routes most likely to conform to the user's current preference.

For unfamiliar situations, proposed collaborative case-based approaches generate a route based on similar users' experiences. Notwithstanding the semantic difficulty of identifying similarities among different users, these algorithms' recursive nature further strains system resources and thereby slows application responsiveness.

Trail reconfiguration quality can be enhanced by pattern matching recent contextual data—for example, location, user activity, and time—against a database of previous trails. This is similar to established pattern-matching techniques such as Lemple-Ziv compression as well as memory reference string prediction. A solution based on the later technology would require a probabilistic model of which trails are most likely.

Mobile, context-aware applications have far to go to realize their potential. Progress will remain slow if developers must confront the full set of technical challenges for each individual application. An application framework that provides a reusable, configurable set of solutions to such challenges will give developers a head start. ■

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