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# Dealing with Uncertainty

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We have codified our sensor fusion techniques in a project called the Location Stack, a general framework for location-aware pervasive computing with a publicly available implementation.[12] We are applying Bayes filters to more complex scenarios, such as learning a person's activities from long-term sensor logs. More complex estimation problems apply structured versions of Bayes filters, such as dynamic Bayesian networks.[13]

We strongly believe that probabilistic-filter techniques have tremendous potential for inference problems in pervasive computing. Location estimation is just the beginning of connecting Bayesian reasoning systems to raw sensor data. The full power of such techniques lies in their ability to represent uncertainty at different levels of abstractions, thereby enabling truly context-aware pervasive computing systems.

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# Coping with Uncertainty in a Location-Based Game

*With location-based games, how you manage uncertainty can make the difference between fun and fiasco. Game designers should know what uncertainties to hide and what to reveal to create an engaging experience.*

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*Mixed Reality Laboratory*
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*Blast Theory*

Location-based games, a new form of entertainment, take place on the city streets. Players equipped with handheld or wearable interfaces move through the city. Sensors capture information about the players' current context, which the game uses to deliver an experience that changes according to their locations, actions, and, potentially, feelings. In collaborative games, you could transmit this information to other players, on the streets or online. The net result is a game that interleaves a player's everyday experience of the city with the extraordinary experience of a game.

Moreover, location-based games offer exciting commercial prospects. They build directly on current wireless (but usually disconnected and location independent) games for mobile phones. Analysts predict that the market will reach billions of dollars in the next few years and that it represents a potentially significant income stream for third-generation mobile telephony. Early examples of location-based wireless games include Bot Fighters! from Its Alive! and Battlemachine from UnwiredFactory. Such games provide an interesting focus for research, offering an open space in which you can create a wide variety of experiences—both collaborative and competitive. You can also deploy them in public with relative ease and safety. Several research projects use mixed online and mobile players to different extents. These include Pirates! from the Interactive Institute,[1] the ARQuake project,[2] and Border Guards from the Mixed Reality Systems Laboratory.[3]

This article describes our experiences, focusing on uncertainty, in publicly deploying an experimental, mobile mixed-reality game called Can You See Me Now? This involved collaboration between the Mixed Reality Laboratory at the University of Nottingham, a partner in the UK's Equator project, and Blast Theory, an artists' group. We've staged CYSMN as an experimental public performance at two new-media festivals—Shooting Live Artists in Sheffield in 2001 and the Dutch Electronic Arts Festival in Rotterdam, 2003.

## Can You See Me Now?

CYSMN is both a public artwork (in game format) and a research vehicle for location-based applications. As an artwork, we've aimed to create an engaging public experience and to show how you can use location-based wireless technologies to create new kinds of artistic experiences. We've seen evidence for our success in positive responses from the public, press, and commissioning bodies; further European bookings for CYSMN; and receipt of the 2003 Prix Ars Electronica Golden Nica award for interactive art. As a research vehicle, we've hoped to test our technology in the most realistic and stressful situations we can, moving from the lab to the field and giving access to numerous users. This builds on the approach of staging public performances as a research method that we've developed since 1996.[4]

The concept for CYSMN is a chase game. Three runners, who are professional performers, run through actual city streets equipped with handheld computers, wireless network connections (using 802.11b), and Global Positioning System receivers. They chase up to 15 online players through a virtual model of a city.

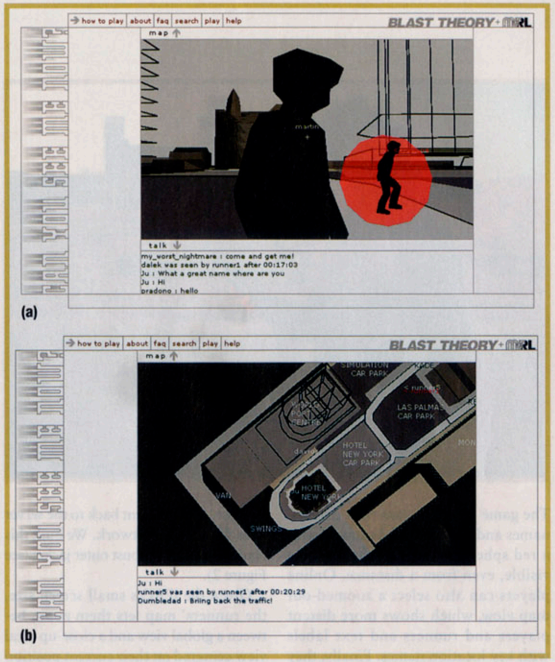
### The online players' experience

Online players can move through the model with a fixed maximum speed, access a city map view, see other players' and runners' positions, and exchange text messages with them.

Online players start at the CYSMN Web page, where they can explore background information about the game, including instructions on how to play. They enter a name for themselves and then join the queue to play (we restricted the number of simultaneous players). When it's their turn, they're dropped into a highly abstract 3D model of the hosting city. The model shows the streets' layout and outline models of key buildings but doesn't feature textures or details of dynamic objects such as cars or, of course, most of the population. Additionally, the Rotterdam map included wire-frame representations of two buildings still under construction. Online players use the arrow keys to run around this model. They cannot enter solid buildings, move out of the game zone, or cross several fences. They must avoid the runners. If a runner gets within five virtual meters of an online player, the player is *seen* and out of the game. Scoring is based on the time elapsed since joining the game.

Online players see themselves represented as running avatars, similar to the other players and the three runners.

Figure 1. Online player's interface: (a) close up view and (b) map view.




## Useful URLs

- Blast Theory: www.blasttheory.co.uk
- CYSMN Rotterdam Archive: www.canyouseemenow.v2.nl
- CYSMN Sheffield Archive: www.canyouseemenow.co.uk
- Its Alive!: www.itsalive.com
- Mixed Reality Laboratory: www.mrl.nott.ac.uk
- Uncle Roy All Around You: www.uncleroyallaroundyou.co.uk
- Unwiredfactory: www.unwiredfactory.com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The game labels avatars with players' names and highlights the runners with a red sphere that makes them highly visible, even from a distance. Online players can also select a zoomed-out map view, which shows more distant players and runners and text labels with key location names. Finally, they can view and enter text messages and hear the runners' audio. Figure 1a shows an example online player's interface, with the player's avatar in the foreground and a runner close by in the background. Figure 1b shows the interface in map mode.

### The runners' experience

The runners move through the streets and can see online players' and other runners' positions on a handheld map, see the players' text messages, and communicate with one another using walkie-talkies.

The game delivers the runners' interface on an HP Jornada handheld computer from a server in a nearby building over an 802.11b wireless local area network. A GPS receiver plugged into the computer's serial port registers a runner's position, which is sent back to the server over the wireless network. We built this equipment into a robust outer jacket (see Figure 2).

Given the iPAQ's small screen size, the runners' map lets them zoom between a global view and a close-up local view centered on their current position (see Figure 3). The runners used walkie-talkies with earpieces and a head-mounted microphone. They carried digital cameras so that they could photograph the physical location where they caught each player. These pictures appeared on CYSMN's archive Web sites after the event.

Deploying CYSMN required support from a behind-the-scenes technical crew, housed in a central building in the game zone (along with six public terminals for local online players). This three-person technical crew in the control room ran and managed the online server and supported the runners. This team used, for example, a game space overview and interfaces for managing queuing players, monitoring the wireless network, displaying the runners' status (including connection status) and GPS status, and playing the game. The control room and runners also used a walkie-talkie channel separate from the 802.11b network for communication.

Figure 2. A runner with game equipment built into his jacket.

## Causes of uncertainty

CYSMN's most significant source of uncertainty was the GPS. In Sheffield, we used standard GPS with Garmin eTrex receivers, and the game zone spanned a mixture of open urban spaces with a few narrow, built-up side streets. Our system log analysis showed that reported GPS error ranged from 4 m to 106 m with a mean of 12.4 m and a standard deviation of 5.8 m. In Rotterdam, we upgraded to differential GPS and used Trimble Lassen LP receivers with Sarantel antennas. The game zone contained a similar mix of open spaces, several of which looked out over open water (with a good view of the sky to one side) and narrower built-up streets toward the game zone's center. Log analysis showed that in this case, reported error ranged from 1 m to 384 m, but with a lower average error of 4.4 m and a standard deviation of 4.9 m. To improve accuracy, we configured the receivers to ignore satellites that were low in the sky (below 15 degrees), although this sometimes made getting a GPS fix more difficult. In both environments, we had *black spots*, where multipath reflections led to particularly high errors and, thus, large jumps in the reported position.

Our second major uncertainty arose from the use of 802.11b networking. We had only partial coverage even though we invested considerable effort in deploying 802.11b in both game zones. (We deployed an 8 m mast on a rooftop supplemented by two omni antennas in Sheffield. In Rotterdam, we deployed a network of seven wireless access points: four on buildings and one each on a lamppost, van, and ship.) Consequently, runners would move in and out of connectivity, frequently leaving and rejoining the game. For Rotterdam, system log analysis revealed three broad categories of packet loss intervals:

- Periods of short loss (less than 5 seconds) that account for 90.6 percent of loss intervals and were probably due to communication errors
- Two-hundred seventy-eight moderate periods of loss (between five seconds and 10 minutes) that were probably due to detours out of connectivity or interference
- Two loss periods of about 15 minutes and one of about 40, probably resulting from major equipment failures

The runners' separate walkie-talkie channel provided broader coverage across the game zone than the 802.11b network, although it sometimes had interference from other walkie-talkie and radio users.

A third source of uncertainty arose from frequent technical failures such as cables working loose and damaged connectors (our runners were really running; consequently, their equipment suffered a battering) and soft failures such as batteries running out of charge. These problems added to GPS and connection problems.

Delay was our fourth source of uncertainty, arising from Internet and 802.11b network delays and game server processing delays. Although variable, we saw a typical delay of six seconds or more between one participant acting and another participant seeing that action.

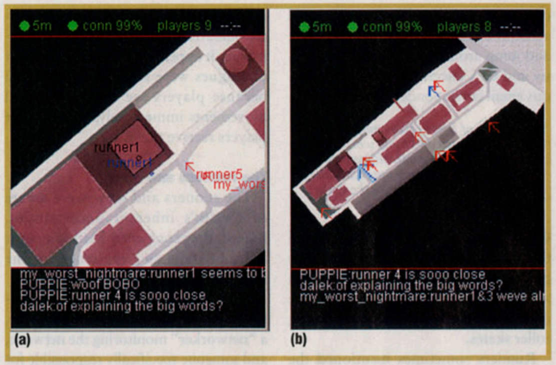


Figure 3. The runner's interface: (a) close up and (b) map view. Blue arrows show runners, red arrows online players, and the bottom of the screen shows the most recent player text messages. The information at the top in green shows the current estimated GPS error as provided by (left) the GPS receiver, (middle) the network connection strength, and (right) the number of online players in the game.

## Experiencing uncertainty in CYSMN

In Sheffield, CYSMN ran for six hours over two days and received over 200 online plays; in Rotterdam, it ran for 20 hours over five days and received over 1,000 online plays. For our analysis, we drew on three data sources: ethnographic observations of players, runners, and technical crew—including video data capture and transcription; system log analysis such as GPS, network traffic, and over 3,000 online player chat messages; and player feedback email. We provide a summary of the highlights here.

### The players

Overall, CYSMN was well received, and the players seemed to feel genuine engagement and even tension, especially when the game was working smoothly. Players would hear their names over the audio channel and then be chased. They had to tune into their environment, including awareness of the runners (hearing them as they negotiated traffic and breathed heavily while running) and other ambient sound (including a mobile disco at one point). In Rotterdam, some players even saw runners pass by a window as they came to get them. As one player put it in an email:

> *The start of me becoming totally engaged was when I met up with my partner who was playing in the same room, and through fits and starts we found each other and then ran "hand in hand" in desperate flight across the city. I then had this real feeling of the need to protect her from being caught, and we could work cooperatively in keeping an eye out for incoming runners.*

However, the game did not always run smoothly, and the uncertainties sometimes had an apparent effect. Players noticed—especially when they were caught as a result—that runners would sometimes suddenly appear, disappear, and jump around (reflecting connectivity and GPS uncertainty). As the previous email correspondent put it,

> *A couple of times I was caught and I just hadn't seen anything, which is a shame because the adrenaline rush when you see a runner approach and you try to escape is part of the draw in the game.*

Online players sometimes attributed these effects to the game's structure, as power ups or runner characteristics such as invisibility, blindness, or laziness. One player even accused a runner of wearing roller skates.

Runners sometimes mentioned the causes of uncertainty, especially GPS, over the public audio channel, and knowledgeable players homed in on this. Some players would speculate that the runners deliberately exploited GPS characteristics by hiding in areas with poor GPS. Other players recognized its tactical advantages for themselves.

Other effects of uncertainty were more hidden from the players. In spite of a few text messages questioning whether runners were actually present, runners' failures to connect were mostly hidden. Players didn't have a global game space overview, so while they could see that no runners were in their local area, they wouldn't know if none were present in the game as a whole. Also, the walkie-talkie channel was separate from the 802.11b data channel, and runners would often talk over the walkie-talkies even when not connected to the game. In fact, they would deliberately talk more, offering richer verbal descriptions of their local environment, to create the illusion that they were still actively participating.

Additionally, the game largely hid network delays, except for when several players' consoles shared the same physical space. In these cases, players could hear audio streams out of synchronization. Or, as one player reported, it appeared to players that their colleagues were lagging behind them because players see their own local movements immediately, before other players receive them.

#### The runners and crew

The runners and crew were aware of CYSMN's inherent uncertainties. Indeed, they constantly battled against them to stage an experience for the online players.

Runners communicated with a controller monitoring the overall game state, a "networker" monitoring the network, and someone specifically responsible for helping the runners. Runners would monitor GPS and connectivity status with their handheld interfaces. The main approach to resolving GPS problems was to move to a new (and hopefully better) location. Our analysis shows that the runners and crew built up an extensive working knowledge of good and bad locations during the 10 or more days of rehearsal and live game play. The control room would also update runners with ongoing condition changes, such as areas with low coverage to avoid.

Different satellite configurations also affected GPS uncertainty. Configurations could change radically throughout a single two-hour session, occasionally worsening to the point where only three or four satellites were potentially available, making GPS very unreliable. In response, the crew printed out charts of satellite availability over the day, particularly highlighting availability during game time. The crew pinned these on the control room wall and discussed them in daily briefing sessions so that they and the runners would know of difficult periods of game play.

Runners also exploited their knowledge of GPS uncertainty tactically, as this excerpt shows:

> *Crew:* So your tactics: slow down, reel them in, and get them?
>
> *Runner:* If they're in a place that I know it's really hard to catch them, I walk around a little bit and wait till they're heading somewhere where I can catch them.
>
> *Crew:* Ambush!
>
> *Runner:* Yeah, ambush.
>
> *Crew:* What defines a good place to catch them?
>
> *Runner:* A big open space, with good GPS coverage, where you can get quick update because then every move you make is updated when you're heading towards them. Because one of the problems is if you're running towards them and you're in a place where it slowly updates, you jump past them and that's really frustrating. So, you've got to worry about the GPS as much as catching them.

So, runners and the technical crew coped with and even exploited CYSMN's uncertainties, but only after building up extensive knowledge of the technologies' behavior in the game zone. Although our interfaces for revealing these uncertainties helped, they clearly contributed only one part of a complex mix of processes and technologies.

### Strategies for dealing with uncertainty

Uncertainty affected participants' experiences in different ways, depending on their role (for example, street or online player), technical knowledge, and currently available information.

One response to uncertainty is to use improved technologies that remove it. Much of the research community focuses on this, trying to develop better positioning and wireless networking technologies. However, we anticipate that, for the foreseeable future, location-based game designers will have to cope with significant uncertainty. So, we've focused on strategies for dealing with uncertainty when it's present.

For example, game designers can remove some uncertainty by carefully choosing the game zone. GPS and network traffic logs from Rotterdam showed that some locations (the narrow built-up streets at the center) offered consistently poor positional accuracy, connectivity, or both. With careful scouting, game designers can focus play on good coverage areas. Furthermore, analysis of CYSMN showed a variation in GPS uncertainty over time, suggesting that designers should be flexible when choosing playing times. This won't always be possible because locations and playing times are determined as much by available access, safety, and sponsors' needs as by suitability to the underlying technologies. These also significantly impact nongaming applications because you can't reasonably ask location-based service providers to move their premises to fit the technology.

Our experience with CYSMN suggests two further strategies:

- Hide the uncertainty so that participants are less aware of it and feel minimally disrupted by its worst effects
- Reveal the uncertainty so that participants can work with it

#### Hiding uncertainty

To hide uncertainty's effects from the online players, we implemented a position validation scheme to filter out situations that would place runners in impossible locations, such as inside buildings or in the water, because of inaccurate GPS measurements. We first input GPS reports into a raw data space in the game server, which would then compare them to a predetermined map of acceptable locations. The server corrected unacceptable positions to the nearest acceptable position in the game space before publishing them via a second validated data space. This technique effectively hid some of the uncertainty's most obviously disruptive effects (we did not observe runners appearing in forbidden locations, and online players did not refer to this in their text messages). However, this mechanism involved a tradeoff because its use sometimes led to sudden jumps in position. For example, a small update in GPS position that moved a runner across the midpoint of a virtual building might instantaneously change the nearest valid location from being on one side of the building to the other. In our case, we felt a sudden jump in position was less problematic than appearing in a building.

We implemented an animated sequence to show online players the moment a street player sees them. Once the system determined that a player had been seen, the virtual camera would smoothly zoom into a close up view of the player over several seconds and show the runner's avatar nearby. Players would at least always end up seeing a runner, even though they might not have seen the runner beforehand because of a significant GPS jump. We also deliberately used *seen* rather than *caught* to introduce fuzziness into how close a runner had to get to a player. In general, we would recommend that game designers consider employing these techniques to smooth out critical moments of game play that uncertainties in the underlying technology might disrupt.

Having online players experience events on the streets through streamed audio also hid some effects of uncertainty.

Online players could see only the city's virtual model. Their live connection to the streets was through audio, which offered a rich source of contextual and atmospheric information but did not lead to a direct comparison of reported and actual positions (as embedded video views might have). Furthermore, even when disconnected, runners continued talking to provide continuity.

Finally, CYSMN's overall structure also hid uncertainty from online players. In an augmented-virtuality-style experience, you explicitly overlay or embed the physical world on or into the virtual world.[5] However, CYSMN creates an *adjacent reality*, where the virtual and physical worlds are separate, often quite divergent, and connected in looser ways. Online and street players have access to different information and can exchange this as part of the game. For example, some buildings in the CYSMN virtual model haven't yet been built in the physical space, and the virtual model lacks many physical world features, such as traffic.

We would recommend that game designers avoid situations in which players will likely perceive a direct mismatch between reality and uncertain position measurements (for example, where the system tries to show them both worlds in a precisely aligned way or where players on the city streets see a clearly erroneous position on an electronic map). Instead, we suggest that designers deliberately give online and street players different and limited game perspectives, providing each with a distinct role and encouraging them to communicate and share information. More generally, we argue that this adjacent-reality structure provides sufficient space for players to weave their own interpretations of technical quirks into the game experience. This lets them maintain a willing suspension of disbelief without breaking their engagement with the game.

#### Revealing uncertainty

For our second strategy, we go the other direction and deliberately reveal uncertainty to participants. Our experience suggests that runners worked better with uncertainty once they had a working knowledge of its presence and characteristics. We enabled this by providing information about estimated GPS error and connectivity on their PDA interface. Mobile phones do this already, by making signal strength information routinely available to users. We took this approach to greater extremes in the control room. There, various interfaces provided detailed information about uncertainty in relation to each runner, so the technical crew could troubleshoot the system and advise the runners how to proceed.

Although this strategy of revealing uncertainty helped some participants work with the technology, we could have gone further. Runners' main concerns when faced with problems were whether they should move to a new location or whether their equipment was somehow malfunctioning (and they needed to call a member of the technical crew for assistance). We should have given the runners a sense of how uncertainty varied across the game zone—for example, by providing dynamic color-coded maps of good and bad areas. This would have let them better judge whether to change location and, if so, where to go. Discussions in debriefing sessions also raised the idea of showing runners other runners' status so they could see if their difficulties were specific to them or shared.

Your strategy—whether to hide or reveal uncertainty—will depend on the participants and their task. Tasks that involve maintaining engagement with a compelling experience—games and art, for example—should seek to hide uncertainty. More work-oriented tasks that involve making important decisions based on uncertain information should seek to reveal it. Tasks that involve both, such as CYSMN, where the runners work to create an experience for the online players, can adopt both strategies simultaneously.

We are carrying these ideas forward into a second game called Uncle Roy All Around You, which differs from CYSMN in several important ways. The game employs public street and online players. The experience is more contemplative and mysterious, involving a journey across the city rather than a frenetic chase. We also use General Packet Radio Service rather than 802.11b and a positioning system based on self-reported and implied location from map usage rather than GPS. We've applied more of our strategies in Uncle Roy, and street and online players must interpret more types of uncertain information. At the same time, we're providing the technical crew with a more sophisticated management interface to let them understand the game's state and intervene where necessary. ■


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