How it may feel: Making firefighters experience future support for tactical navigation

In a previous special issue of this magazine on Rapid Prototyping for Ubiquitous Computing [1], the authors of the introduction argue that the design of pervasive computing systems is significantly more difficult than that of traditional systems because of the greater space of possible design options, the higher cost of development, and the more intricate and unpredictable impact on the context of use. While various rapid prototyping techniques have been developed since the arrival of graphical user interfaces early in the 1980s and have been successfully applied for exploring the related design space with comparatively small effort, they argue that adapted tools and techniques are required for prototyping and exploring the design space of ubiquitous computing. They consider this exploration essential for realizing this emerging technology’s potential of “bringing the benefits of rich computational capabilities to dynamic, diverse situations…” because the reactions, performance and acceptance of prospective users are otherwise hard to predict. An explanation for this has been offered in [2] for the case of emergency response work, arguing that the implications of using new technologies are unpredictable because they depend on the corresponding work practice which itself is influenced – often unpredictably even for the users – by the technology. Therefore, the exploration of design options for future work practice requires engaging prospective users in using the technologies in realistic scenarios in order to obtain cues for a possible evolution of their work practice.

An important element of many rapid prototyping approaches is the partial simulation of system functionality to make them available for user testing with minimized effort if the implementation of fully functional prototypes would require substantial efforts or even and in particular if it would still be technically impossible. For instance, a number of the approaches presented in the above special issue propose different adaptations of the traditional and established Wizard of Oz (WOz) technique which consists in simulating selected system functionalities through the actions of human ‘wizards’. As simulations always require making certain abstractions and striking trade-offs between the resulting benefits and limitations, different approaches prove more or less useful for prototyping, depending on the design questions, type of technology and kind of application. For instance, one differentiating feature of WOz techniques for location-based services is given by what tasks are allocated to the wizard and which are automated by the system [3].

The stakes for meeting the above challenge of properly exploring the design space are particularly high when designing pervasive computing systems for hostile environments
because they could help averting damage to people and property but could also increase risks. This can be studied particularly well for the case of structural firefighting, discussed in this paper, where the immediately dangerous environment and the physiological and psychological stress make usable enhanced support both very desirable and very difficult to design and effectively deliver without overloading users and increasing dependencies.

As shown in a recent survey in this magazine on Location and Navigation Support for Emergency Responders [4], numerous studies have explored various technologies and approaches for this particularly useful type of support [5-8]. While some of these studies include empirical investigations of firefighting work practice and to a certain degree system evaluations with firefighters [5-7], most studies address specific technological questions with no or little user involvement. An analysis of the most comprehensive approaches shows that for the case of realistic navigation support, important dimensions of the design space require further exploration [6], including user interfaces, collaboration support and work practice.

As a tool for this exploration, we introduce the FireSim mixed-reality prototyping (MRP) approach which we developed for the design of the LifeNet tactical firefighter navigation support system and successfully applied in a field study.

The following starts with key results from our own ethnography of firefighter navigational work practice, grounding the LifeNet approach of local guidance based on relative positioning which we discuss against related approaches. For studying firefighter navigation we present a grounded reference search and rescue (SAR) scenario exhibiting a dense selection of important navigational challenges and how they are supported by LifeNet.

We explain the challenges of prototyping this kind of system, by putting the MRP approach in the context of our overall design process and discussing related approaches. We then provide a detailed description of applying the MRP approach to study the LifeNet system within the reference SAR scenario at the training site of the Paris Fire Brigade.

The results of this study suggest that the MRP approach is sufficiently accurate for prototyping the comparatively subtle interaction of firefighter locomotion and navigation support, that the MRP prototyping infrastructure is rugged and unobstructive to a degree that allows for rough handling and action in constraint spaces as is typical of firefighter navigation, that firefighters appreciate the experience provided by MRP. Regarding the LifeNet approach the study demonstrated that the principle of relative positioning can indeed provide for effective and accepted navigation support. It also showed differing results regarding specific LifeNet design options and unanticipated implications for work practice as compared to previous studies with other techniques, warranting further research. In conclusion, we argue that the MRP approach constitutes an effective and advantageous instrument for exploring navigational support for structural firefighting.
The Design Space of Firefighter Navigation Support

This section provides background on firefighting work practice and discusses a few related approaches to navigation support in addition to LifeNet.

Current Work Practice

In smoke-filled environments firefighters use protective clothing and breathing apparatuses affording them limited protection for a certain time. Under poor or zero visibility, many fire services use ropes as navigational aids, called lifelines.

Firefighters engage in teams of two, being connected to each other by a short rope. Engaged teams operate under the orders and supervision of a team leader who stays in proximity of their entrance point to the dangerous environment and is responsible for typically not more than 3 teams. The team leader has a security team on standby to send in after teams in need of rescue. The first firefighter of a team attaches himself to one end of a lifeline and the other end gets attached at the entrance point. When sweeping an area the team proceeds in a crouched position along the walls, dragging the lifeline behind them while their colleagues at the entrance point typically hold it under some tension to maintain a sense of connectedness and make entanglements less likely. Eventually, the team may decide to attach their end of the lifeline to some object such as a door knob before starting their retreat in order to enable the team replacing them to more quickly navigate to their last location. Whether following a previously established lifeline or not, firefighters use their hands and feet to carefully check whether it is safe to proceed in a given direction (see Figure 4), which is notoriously questionable under often rapidly deteriorating conditions. Moreover, constant probing of the environment by touch allows firefighters to identify doors, wall corners and other building features that they use as additional clues for finding their way. To inform subsequent teams of locations and search status, firefighters use crayons to label doors of rooms they have already searched and they scribble simple floor plans when returning to their team leaders. In summary, lifelines constitute a navigation support system that provides local guidance and firefighters use this support in combination with all other available information, in particular what they can still acquire through their sense of touch and locomotion. The exploration of an area using lifelines may be a time-consuming gradual process, involving several teams.

Fire services drill their members to reliably execute these practices under stress in order to maximize safety while facing the operational realities of unpredictable environment changes, failing tools and firefighters being pushed to their physiological and psychological limits. The practices introduce considerable redundancy and provide a certain level of resilience.

To protect this system of tools and practices from unforeseen consequences, fire services are extremely cautious about introducing new tools and deviating from established practices.
For the case of lifelines, accident reports and our own observations show numerous limitations: lifelines can get burned by fire, cut or stuck under doors, and entangled with other objects such as furniture and railings. They afford limited operational range, only a single, typically suboptimal retreat path and only limited support for navigating to tagged locations. Once dropped, lifelines can be very hard to recover.

But what is particularly important for this article is that despite the above limitations lifelines provide robust navigational support based on local guidance without absolute localization and firefighters trust their lives to this system because, as they say, it provides them with a physical link to their group leaders.

**Related Approaches to Firefighter Navigation Support**

Among the numerous approaches [4, 6] that have been tried to bring advanced support to the wider localization and navigation requirements of firefighters, two are particularly relevant for our LifeNet approach and design space explorations, namely SIREN [5] and the more recent FIRE [7].

Like LifeNet, both SIREN and FIRE propose the use of sensor networks to support localization, multi-hop messaging and environmental sensing. SIREN puts particular emphasis on customizable alerts and messaging and proposes a PDA-based interface. FIRE instead puts considerable emphasis on the design of an interface for a micro-display integrated with the breathing mask. They mention, without providing details, that an arrow [9] could be displayed for guiding firefighters and warn against the risk that firefighters may misinterpret interfaces that do not show particular hazards as meaning that these hazards are not present. Unlike LifeNet, both SIREN and FIRE propose that objects are shown on floor plans at the absolute positions that the sensor networks are capable of estimating for them. FIRE explicitly mentions the need for calibrating a pre-installed sensor network to obtain satisfactory localization and – like SIREN – mentions that ad-hoc deployment of the sensor nodes could be an option to avoid dependency from such an infrastructure. But neither provide details on how this ad-hoc deployment could be achieved, how satisfactory localization and navigation support could be provided on the basis of such an uncalibrated system, nor how the workflow of an actual SaR mission would be supported.

The FIRE researchers argue that “Successful implementation of an advanced information technology system for emergency response will require gradual enhancements to the currently used system, and careful consideration of how to gain and maintain trust in the system.” They qualify their own research as exploratory and assert that their system is meant to be complimentary to existing firefighting techniques and requires extensive user testing to determine its actual benefit.

**The LifeNet Concept and Design**

Like the above approaches, LifeNet is a system based on a network of sensor nodes, called beacons, for supporting firefighter navigation during structural fires [6, 10].
Frontline firefighters use the system by deploying beacons while moving about, effectively creating an ad-hoc sensor network, capable of environmental sensing, wireless multi-hop communication, and navigation support based on the following components:

i) a beacon ejector capable of automatically deploying beacons
ii) one beacon integrated with each boot
iii) a computing unit exchanging information with the beacons in the boots
iv) a micro-display integrated into the breathing mask showing navigational instructions provided by the computing unit
v) a device allowing the firefighters to input information.

Different from the above approaches, LifeNet features a number of consequential properties, motivated by the work practice of using physical lifelines. Most importantly we adopted the lifeline principle of providing local guidance based on an ad-hoc deployed system without providing absolute positioning. This reduces the technical requirement on the beacons to the capability of estimating their relative location among neighboring beacons, i.e. the angle and distance, with sufficient precision to support navigating from one beacon to the next.

The downside of this simplification is not being able to show objects at their absolute location on a map. We readily accepted this consequence as maps are in fact not available for the vast majority of buildings. Nonetheless, the system does support navigation to tagged locations anywhere in the network of deployed beacons.

Consequently we had to find interface designs that are not based on maps and support navigation based on the information available for the firefighters’ local neighborhood. The design used in this study is given in Figure 4, a radar-like interface showing surrounding beacons in a top-view of the local neighborhood of the user, with the next beacon to navigate to marked with crosshairs. Moreover, the interface shows the estimated duration for up to two available retreat paths (bottom-right), the estimated duration and length to the current navigational target (top-middle), and the estimated time until the firefighters must start their retreat (middle-right). More details on this interface and an arrow-based variant, as discussed for FIRE, are presented in [6, 10].

To support the collaborative workflow of SaR operations as presented above, we added an additional LifeNet client for the group leader, namely a TabletPC offering LifeNet-based command and control functions for registered firefighters (see Figure 3). For both the firefighter and group leader interfaces we included all features required for carrying out realistic scenarios, including in particular navigation to previously tagged locations.

**Design Context and Related Approaches**

To put the MRP approach into context before presenting it in more detail, the following section describes its role in our overall design process and its relation to a number of other approaches.
Our design process started with immersive ethnographic studies of firefighting work practice [cp. 11], creating the grounded domain understanding and the inspiration for defining the original LifeNet concept, as reported in the previous section. Throughout the design process we applied different techniques to foster participatory design, in particular three custom simulation-based prototyping techniques [12].

The first was a low-effort board game simulation with paper prototyping that we mainly used at an early stage to explore scenarios on building maps like the one of Figure 2. In fact, the SaR scenario presented in this article was originally developed and subsequently refined with this simple technique.

To address the limitations of the board game simulation for investigating the highly interactive aspects of indoor navigation support without having to resolve the many technical challenges of implementing a functional physical LifeNet prototype, we then developed a purely virtual but otherwise fully functional game-like multi-player LifeNet simulation. We used this technique by having groups of firefighters play out the same kind of SaR scenarios as before, allowing us to study different navigation interfaces and refine the workflow between collaborating firefighters [6].

While similar virtual simulations have successfully been used to explore certain ubiquitous computing applications, for example with the UbiREAL simulator [13], the spatial and bodily nature of activities such as firefighter navigation limits the extent to which they can be studied satisfactorily with purely virtual simulations.

The first attempt in our design process to address this limitation was to implement a functional physical LifeNet prototype for field testing [10]. While this prototype demonstrated that the LifeNet concept could be implemented, the actual implementation proved very challenging and yet too fragile and insufficiently powerful for infield user testing. In fact, firefighters to whom we presented this system displayed reserve and a certain skepticism on account of the brittle devices.

This experience reflects quite precisely the prototyping challenges for pervasive computing outlined in the introduction and prompted our second attempt which is the mixed-reality approach presented here. This approach combines elements from two existing approaches and adapts them for infield studies of firefighter navigation support.

The first approach consists in providing human players with real counterparts to the simulated systems used by the virtual actors they control. By linking these real and virtual systems into a coherent mixed-reality system, functionality can be implemented more or less flexibly either in the real system or as a virtual simulation. While this approach is of course also commonly used in car and aircraft simulators, an application more related to this article’s domain is presented in [14] for a case of guiding navigation in a virtual environment through tactile cues delivered over real actuators.
The second approach addresses the challenge of prototyping location-aware applications for users that move about in a real environment by having human facilitators track the users’ locations over dedicated systems, a Wizard of Oz technique as discussed in the introduction [3].

While our MRP approach incorporates these two approaches, it does so in a particular fashion that responds to technical requirements of the LifeNet system being prototyped, characteristics of the supported firefighter activities, and to the situation in which usage experiences are provided.

As observed in [11], prototype fidelity can have a significant impact on the enabled user experience and as argued in [15], different levels of fidelity can be combined in a mixed-fidelity prototype to efficiently address the given prototyping challenge.

Our approach results in a particular fidelity-mix and we present results from a field study on the suitability of this mix for the intended design space exploration.

We consider the MRP approach a medium stage design technique and currently explore two ways in which it can instruct further design.

First, it can serve to explore and assess design options such as interface variants, network density and sensor accuracy in the context of realistic, collaborative infield studies in which users exhibit and evolve actual work practice. This affords a strong empirical indication for selecting design options for implementing promising physical prototypes.

Second, it yields precise empirical data on how domain experts would operate the system in realistic settings. This data can be used to define grounded user models for computer-controlled actors using the prototype system. These user models enable simulations of large-scale scenarios with possibly hundreds of actors and studying the corresponding phenomena which would be impractical with the MRP approach. Of course, results of such simulations need to be carefully interpreted within the constraints defined by the user models they are based on.

**The FireSim mixed-reality prototyping approach**

This section explains the FireSim mixed-reality prototyping (MRP) approach. As the virtual LifeNet simulation is an integral part of this approach, we describe this in some more detail first.

**Virtual LifeNet Simulation**

With this game-like multi-player simulation, human players can control virtual firefighters and simulate complete SaR scenarios, including all LifeNet functionality. The right screen in Figure 1 shows the environment from the first-person perspective of a virtual firefighter, with the mask-integrated micro-display providing navigational instructions represented by the interface in the bottom left (cp. Figure 4).
The virtual LifeNet implementation includes beacons that are indestructible but otherwise behave realistically as physical objects during deployment, have reliable communication between them provided they have line of sight, and have virtual sensors capable of determining the distance and relative orientation to beacons within a certain range. While these virtual sensors obtain their data from world knowledge of the virtual environment, the processing of the data and the networking and communication services on the beacons are essentially implemented in the same way as on any standard ad-hoc sensor network. Finally, the wearable and group leader systems within the virtual environment use exactly the same implementation as the real systems.

**Mixed-reality LifeNet Simulation**

The key idea behind the MRP approach is to maintain a synchronized virtual simulation while a real scenario unfolds, connect partially implemented real prototypes with their fully implemented virtual counterparts and share information and services between them as best supports the investigation in terms of efforts, skills and research questions.

To this end we set up a virtual LifeNet simulation on the 2nd floor of the training house of the Paris Fire Brigade (Figure 1, right). This simulation was extended with the possibility to connect actual firefighters (Figure 4) and group leader systems (see Figure 3) on the 1st floor to their virtual counterparts over a wireless network. The real systems then interacted with the virtual simulation, in particular the virtual LifeNet simulation for which
no real counterpart existed. As a result the micro-display of the real firefighter system showed the same information as the virtual one.

In order to synchronize the virtual simulation with the real scenario, we had a facilitator observe the actions of a real firefighter through video feeds on the monitor shown on the left side of Figure 1, sent from cameras we had installed to cover the entire first floor, and control a virtual firefighter to replicate these actions as similarly as possible. To the same degree, the interface perceived by the real firefighter corresponded with his own actions.

**A Mixed-Reality LifeNet Field Study**

In this section we explain how we applied the approach presented above during a two-day field study, conducted in May 2009 at the training site of the Paris Fire Brigade (BSPP). Three teams of five firefighters, recruited for the occasion from different fire stations, participated each in a number of simulation runs with changing roles.

For each simulation run we obtained video feeds covering the firefighters’ actions, log-data from the virtual environment for later reconstruction of paths and interfaces, and video recordings of feedback sessions directly after each simulation run and of one final group discussion.
To illustrate the unfolding of the simulation and the kind of experiences made by the firefighters, we describe one session in more detail.

**Simulation Run of Search and Rescue Scenario**

Figure 2 gives an overview of the SaR scenario. It starts with two crews arriving at the first floor, one at access point AP1 (grid cell E8) and one at AP2 (D19), each including two teams with two firefighters each (1A, 1B and 2A, 2B) and a group leader (1* and 2*).

By assigning reconnaissance missions to their respective teams via the TabletPC, the group leaders send in teams 1A and 2A to conduct a systematic search of the floor while keeping teams 1B and 2B standing by as security. As the search teams start their missions their beacon ejectors automatically deploy an initial beacon because no beacons are present in the vicinity yet, thus effectively starting one separate LifeNet at each access point.

As the teams proceed along the walls they deploy further beacons, the ones from 1A and 2A shown in green and blue respectively. Since these teams are the first on this floor, the LifeNet initially only provides them with directions for their current retreat path.

Eventually 2A finds two victims located in a bathroom (L15). The leader of team 2A taps a button once for each victim, to tag the location as containing two victims. This information is stored in the closest deployed beacon and a ‘Victim found’ message containing the ID of this beacon is sent from beacon to beacon and eventually reaches the device of 2*.
who then tasks 2A to extract the first victim while not having sufficient resources for handling the second.

In the meantime 1A eventually deploys a beacon at location I13, effectively linking both LifeNets such that information propagates across the entire network and both teams acquire an additional retreat path to the respectively other access point (see bottom-right of Figure 4). As a result the as of yet unhandled “Victim found” message from team 2A reaches 1*. Team 1A shortly afterwards finds a third victim at location J11 and quickly completes extraction to AP1, enabling 1* to engage the backup team 1B.

To focus the study on the most interesting part of the scenario we carried out the above steps in the virtual environment and started the mixed-reality simulation at this point.

As shown on the group leader system on the right side of Figure 3, the ‘Victim found’ message from team 2A was received at 17:38 in this particular session and 1* processed it to create a ‘Rescue mission’ for 1B which started at 17:39 and used as destination the beacon indicated in the ‘Victim found’ message.

As shown by the grey line in Figure 2, 1B was guided on the shortest path to the victim, using the shortcut previously established by 1A and using the beacons deployed by 2A for the second part of the way.

Upon reaching the victim, the leader of team 1B tapped a button located on his right trouser leg indicating that they would start extraction of the victim. The button used was actually a sticker and the action was executed by the facilitator watching the tapping on the video feed. As a result their mission changed to “Extraction” with their current access point becoming their new navigation target, and 1* received the corresponding ‘Extraction started’ message at 17:42. About half a minute later, 1B reached the location shown in Figure 4.

Shortly before, the facilitator had created a fire at location G10 resulting in the surrounding beacons registering rising temperatures and eventually failing. While this cut off
communication between 1* and 1B, LifeNet was still able to alert both parties of the cut-off retreat path. Consequently, the alternative retreat path to AP2 became active for 1B.

At the time of Figure 4 the interface of 1B therefore indicated as the next beacon to navigate to the one that is behind and to the right of the team. The firefighters stopped in their progression and waited for a few seconds before slowly turning and starting on the new path. As shown in Figure 2, they then took a direct path of beacons to AP2 and completed the extraction shortly afterwards.

**Results from the Field Study**

This section provides selected results from the design space exploration, concerning the LifeNet system, implications for work practice, and the MRP approach.

**Results for LifeNet System**

As the most obvious result the study showed that the LifeNet concept of only local guidance based on a self-deployed ad-hoc infrastructure yields effective navigation support. More specifically, unanimous feedback from the firefighters indicated that they found the support easy to use and that they appreciated the extended LifeNet capabilities, including the sense of connectedness to their group leader, while suggesting a number of new modifications for the interface, such as connecting beacons belonging to a path.

An interesting, more specific result was obtained for the current LifeNet limitation that connectivity between beacons may be disturbed or interrupted by obstacles such as furniture or wall corners. This effect was actually present in our simulation due to connectivity being defined by line of sight. The firefighters successfully developed and applied an ad-hoc work practice of probing movements to work around this limitation. This indicates that this limitation may be acceptable to some degree in combination with an appropriate work practice. If confirmed by more comprehensive studies this would substantially facilitate a physical LifeNet implementation.

**Results for Work Practice**

As mentioned above, the firefighters spontaneously developed a technique of moving about in a small area around their current location in case they lost connectivity and were thus consistently able to reestablish connectivity by effectively using themselves as relay beacons in the network. This illustrates the simple but often neglected fact that the firefighters’ abilities can be an important factor in effective system performance.

The typically rejected idea of using another team’s path in case one’s own path became unavailable received significantly higher approval, also compared to our previous studies with other techniques [6, 12], after the firefighters had successfully experienced how the LifeNet would support this.

The moment shown in Figure 4 is essential in this respect. Before reaching this location the firefighters had progressed confidently and quickly along the same path they had tak-
en on their way in, relying both on the navigation interface and their trained ability to remember their path. Receiving directions to deviate from this path in the depicted moment constituted an unprecedented experience and resulted in a moment of consternation and initial probing of the situation before embarking with increasing confidence on the new path.

Despite this unprecedented approval and much to our satisfaction the firefighters also went on to further critically explore the concept beyond the scope of what they had directly experienced during the study. For instance, they pointed out the problematic tactical implications regarding accountability and availability of teams being rerouted to different access points and started a discussion on how these could be handled.

Furthermore, they discussed complementing automatic with manual beacon deployment and whether beacons should be integrated with traditional lifelines or not, contrasting opinions voiced after previous virtual simulations.

**Results for MRP Approach**

In the presented case, the approach allows a partition of LifeNet functionality across the real and virtual part of the simulation that enables low-cost exploration of a number of axes of the design space, including sensor performance of the beacons (e.g. accuracy, latency) and deployment strategy (e.g. spatial resolution, redundancy) through virtual simulation. While this virtually simulated LifeNet was in fact invisible to the firefighters, the firefighter system was intentionally rugged which not only allowed comparatively rough handling but also avoided raising skepticism due to brittle devices.

Compared to the related approaches discussed earlier, two important differences with the MRP approach can be identified. First, the firefighters did not have to control an actor in a virtual environment to experience the corresponding behavior of a real system as presented in [14]. Instead they could indirectly control the simulation through their bodily behavior, as is appropriate for the embodied interaction with LifeNet, bringing all the previously explained factors of firefighter navigation into play.

Second, informing the wizards of the firefighters’ locomotion via top-view video feeds not only provided material for later analysis but also left the firefighters virtually unobstructed by any prototyping infrastructure, and providing the wizards with a first-person virtual interface, enabling them to replicate these movements with a comparatively high precision, provided sufficient lighting. This certainly helped the participating firefighters in reappropriating the scenario as their own experimental space which they did by introducing new navigational challenges such as opening and closing certain doors and having one of their colleagues play the victim in need of extraction. Both of these aspects are crucial for dealing with the relatively subtle interaction of the firefighters’ navigational movements with the supporting system, and both aspects would have been problematic to achieve with the approach presented in [16].
In terms of synchronization, the use of human facilitators has also proven a highly flexible option allowing for spontaneous extensions and modifications to be made with minimal effort, as illustrated by the makeshift “Victim found” button. Still, the use of one human facilitator per simulated firefighter makes scaling up this approach relatively expensive.

The most visible effect of being able to use the systems in realistic work settings was that all participants exhibited a very satisfactory level of engagement in the sense of taking the missions seriously, focusing on the assignments and behaving realistically. Evidence for the interest created by this engagement was that they requested and carried out more sessions than originally scheduled, that debriefings showed an atypical balance of perspectives from all participating roles, and that they introduced scenario variations as mentioned above.

The variation of introducing a human victim led to a particular unexpected and instructive exploration. In this configuration the leading firefighter moved backwards during extraction which had not been the case before. While the firefighters completed extraction successfully in both cases, an observing firefighter argued that his colleagues had to interpret the navigation interface differently when moving backwards and his colleagues tried to convince him that this was in fact not the case. While his colleagues were obviously right since the interface is relative to the firefighter’s orientation, it was much to our surprise that they confirmed this by going back to the virtual simulation.

**Conclusions and Future Work**

While absolute indoor localization would of course be a desirable service for firefighters, substantial research in this direction during at least the last 15 years has not resulted in marketed products yet. Maybe and hopefully this will change some day but until then it is worthwhile exploring less challenging alternatives that may sooner result in helpful services. The confirmation of the local guidance principle of LifeNet is an important result in this respect, warranting further explorations.

Of course many questions about the technology and its use remain for LifeNet and similar approaches, requiring, as stated by the authors of FIRE, extensive exploration and user testing to eventually obtain systems usable by firefighters.

Therefore we consider the presented mixed-reality approach the more substantial contribution, as it has proven an effective, efficient and accepted instrument for exploring the design space of indoor navigation support with firefighters.

We know from experience that the most sophisticated reflections can also be triggered with the simplest of techniques, including an engaging discussion, and therefore do not believe that the MRP approach affords any unique predictive powers. But as shown above we do believe that it strikes a particularly good trade-off between effort and obtainable results for exploring the support of embodied experiences such as navigation.

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The reported end-users’ decision to explore a question encountered in the mixed-reality simulation by going back to the virtual simulation shows that different techniques do not exist independently within a design process but actually form a kind of methodological ecosystem. Their motivational effect and their powers as design tools depend on being chosen, adapted, applied and combined based on the context of the design process.

We hope that these results encourage other researchers working on similar systems to explore them in realistic scenarios by using this or similar techniques. This may help comparing approaches on a level that is meaningful for eventual applications [2], reduce risks of costly and potentially dangerous erroneous developments, and finally reduce the understandable skepticism of end-users towards new technologies to the level warranted by direct and realistic experiences.

As explained above, we are continuing this research along two lines. First, by exploring design options for implementing a navigation support system integrated into lifelines (www.project-profitex.eu). Second, by creating grounded user models for computer-driven simulations of technology use in large-scale emergencies (www.socionical.eu).

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Abstract
Designing pervasive computing applications for hostile environments presents a particular challenge because of both the greater stakes in terms of potential benefits and risks and the generally greater space of design options. Thoroughly exploring this design space in realistic usage settings is therefore as difficult as it is important to validate design options early on and understand their implications for future work practice. As a contribution to the ongoing discussion of prototyping techniques for pervasive computing, this article presents the FireSim mixed-reality prototyping approach that we developed for and applied to the exploration of the LifeNet system for tactical firefighter navigation support. Based on this concrete case of pervasive computing for hostile environments we explain the related design challenges and present results from a field study of collaborative search and rescue operations with professional firefighters. Results are related to design options, emerging work practices, and the quality of the presented prototyping approach to facilitate user-driven design space explorations.

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