Location and Navigation Support for Emergency Responders: A Survey

As this overview of products and projects shows, preinstalled location systems, wireless sensor networks, and inertial sensing all have benefits and drawbacks when considering emergency response requirements.

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Although localization is becoming available to the general public and businesses via widespread use of GPS receivers and commercial indoor location systems (see www.ubisense.net, www.sonitor.com, and www.ekahau.com for examples), many solutions aren't yet suitable for use by emergency responders such as firefighters. The conditions they work in are significantly more demanding than nonemergency environments. Darkness, smoke, fire, power outages, water, and noise can all prevent a location system from working, and heavy protective clothing, gloves, and facemasks make using a standard mobile computer impossible.

In the past decade, researchers have put much effort into this challenging problem and have developed a wide variety of ideas to address it. However, previous surveys address localization methods in general and don't take into account specific emergency response requirements.[1] In this article, we look at different localization technologies and techniques that could assist responders in the challenging conditions they face. Although the interface is an essential part of a complete system, we focus here on the underlying localization techniques.

Requirements Analysis

Location and navigation support is useful in many everyday situations but essential in emergency response scenarios. Teams must be able to reach safety quickly if conditions become too dangerous, and incident commanders must be able to keep track of their locations. The simple task of getting out of a building becomes a challenge with little or no visibility due to smoke and power failure. High levels of mental and physical stress add to the difficulty: getting lost in a burning or collapsing building can have fatal consequences for both the rescue personnel and the building's occupants as oxygen supplies run out and medical attention is delayed.

Concrete Problems

The US National Fire Protection Association (NFPA) has identified "lost inside" as a major cause of traumatic injuries to firefighters.[2] The US National Institute for Occupational Safety and Health (NIOSH) has also reported that disorientation and failure to locate victims are contributing factors to firefighter deaths (www.cdc.gov/niosh/fire).

In some instances, firefighters might have only a few seconds to reach safety. They must find the exit as quickly as possible and might not be able to retreat along the same path they used to enter the building owing to a collapsed

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Figure 1. Traditional techniques. Two French firefighters practice using a lifeline with their facemasks blacked out to simulate dark or smoky conditions. (Photo courtesy of Markus Klann, Fraunhofer-Institut für Angewandte Informationstechnik [FIT], used with permission.)

ceiling or floor. Alternative exits might be available but won't be clearly visible. When a firefighter radios a distress call, the rescue team must be able to find that person. Even when situations aren't immediately life-threatening, precious time can be wasted by searching the same room twice or failing to search another. The incident commander also needs to know elements of the building layout, team members' locations, and the parts of the building that have already been searched.

Several recommendations from the NIOSH reports explicitly highlight the need for a navigation and tracking system, and suggest some solutions (see, for instance, www.cdc.gov/niosh/fire/pdfs/face200718.pdf, and www.cdc.gov/niosh/fire/pdfs/face200619.pdf):

> *Train fire fighters on actions to take if they become trapped or disoriented inside a burning structure.*
>
> *Consider using exit locators such as high intensity floodlights, flashing strobe lights, hose markings, or safety ropes to guide lost or disoriented fire fighters to the exit.*
>
> *Ensure that the Incident Commander receives pertinent information (i.e., location of stairs, number of occupants in the structure, etc.) from occupants on scene and information is relayed to crews during size-up.*
>
> *Working in large structures (high rise buildings, warehouses, and supermarkets) requires that fire fighters be cognizant of the distance traveled and the time required to reach the point of suppression activity from the point of entry.*
>
> *Conduct research into refining existing and developing new technology to track the movement of fire fighters inside structures.*

In addition to location and navigation requirements, other reports (such as www.cdc.gov/niosh/fire/pdfs/face200716.pdf) have emphasized the need for reliable communication of interior conditions to the incident commander and for monitoring building stability. Temperature, smoke, sounds, and vibrations are all indicators of a fire's progression and the building's stability.

Current Practices

Firefighters have developed navigation practices for use in poor visibility. Details vary, but overall, they use the same ideas worldwide. These methods tend to be simple and practical, and the equipment is seemingly low-tech and very robust.

Techniques. Following a hose is a simple method for finding the exit in a dark or smoky building. If no hose is available, firefighters can use dedicated ropes called lifelines that connect them to a point outside the dangerous area (see Figure 1). The other end can remain attached if a new team comes in to continue the search,[3] or firefighters can attach additional lines to the main lifeline and branch off in different directions while remaining physically linked to the rest of the team. A series of knots on the main lifeline helps firefighters determine the direction and distance to the exit and can serve as reference points when radioing positions to a commander.[4] Likewise, a flashlight left in a room's doorway helps locate the exit and indicates to colleagues that the room is being searched; a chalk mark on the door indicates that a room has already been searched.[3,4] Teams returning from a search mission can sketch the building's layout to assist the commander and any further teams.

All firefighters entering hazardous areas wear a Personal Alert Safety System (PASS) device attached to their breathing apparatus that sounds an alarm if they haven't moved for a specific amount of time.[5,6] By following the sound, the rescue team can locate that firefighter. Although not strictly a navigation tool, a thermal-imaging camera can also help find people and visualize walls, doorways, and windows when vision is obscured.

High temperatures, thick smoke, noise, gusts of air, obstacles, and falling debris hinder the propagation of the radio, ultrasound, and laser signals typically used for location.

Low-tech methods are quite effective as well. Many firefighters are trained to search a dark room while keeping either their left or right hand in contact with the wall, which helps with orientation and provides a strategy for systematically exploring an unknown space.[7] Human contact and accountability are also essential. Firefighters always perform searches in teams of at least two.[8] During a lifeline search, one team member might stay at a fixed position to help with orientation and provide progress reports to the commander while other colleagues are engaged in a deeper search. Team members report their locations as accurately as possible over the radio to a commander posted outside the building; this person often keeps track of team locations on a whiteboard.

Limitations of traditional methods. Although these simple, practical methods become more effective with training, they sometimes fail. A lifeline might become tangled in furniture, a flashlight buried under debris, or a thermal imaging camera rendered unusable due to rising temperatures. The left- or right-hand method for finding an exit can be misleading to the point where the person using it ends up walking in circles around a large pillar or repeatedly visiting two or three rooms connected by several doors.

None of these traditional methods is a fixed way of operating—they're supposed to aid and support navigation rather than impose an inflexible method. Human error can occur, especially during complex and prolonged incidents. Simple techniques such as taking notes (for the commander) or following a rope (for the search teams) are designed to reduce the mental load. As the NIOSH reports pointed out, there's room for improvements and training. But localization, sensing, and communication are all areas in which embedded computers, body-worn sensors, and wireless sensor nodes could play a role if we can adapt them to harsh conditions.

Constraints on High-Tech Location Systems

Navigation by sight is impossible when darkness, smoke, or dust limit visibility to less than an arm's length. Out-of-reach people or objects can be passed unnoticed. Moreover, the environment can change as ceilings, floors, or shelves collapse, furniture moves, and people searching for an exit open or close different doors. The fire's noise can mask PASS alarms, interfere with radio conversations, and make cries for help difficult to locate.

High-tech systems generally aren't adaptable to these conditions. High temperatures, thick smoke, noise, gusts of air, obstacles, and falling debris hinder the propagation of the radio, ultrasound, and laser signals typically used for location. The City of Phoenix Fire Department analyzed problems with radio communications inside buildings and identified unreliable radio links as the cause of several injuries.[9] Firefighters sometimes must crawl or walk in unusual patterns, so body-worn sensors can end up at odd angles. In addition, there's the issue of presenting the right amount of information to firefighters in an accessible way and ensuring that they can use certain devices in the dark with gloves. Moreover, the devices themselves must be made as robust as possible to withstand rough handling and very high temperatures.[6]

The Fire Information and Rescue Equipment (FIRE) project at the University of California, Berkeley, detailed some of the major difficulties in designing high-tech location systems for emergency services.[10] Researchers found that consistent room-level location updates were more useful than finer-resolution updates, with their higher probability of error. Reliability is key to gaining the trust of the users.

Localization Principles

Researchers have built location systems around a variety of technologies. We can't list all the different methods here, so we offer instead an overview of the most common methods and their potential application to emergency response.

Infrastructure-Based Localization

Many location systems, including GPS and some commercial indoor location systems, use distance and angle measurements to determine a target's coordinates. Typically, this target is a tag that transmits a radio, ultrasound, or infrared signal detectable by sensors installed at known locations in the building. The sensors measure the signal's distance or direction, and a central computer estimates the tag's position via trilateration or triangulation. The sensors and central computer must be connected to each other, the sensor locations surveyed, and the whole system calibrated. The estimated positions are typically detailed and accurate enough for the software to display them on a floor plan.

A different method called *fingerprinting* uses existing Wi-Fi access points to locate a device.[11] Visible access points and their respective signal strengths are different throughout a building, so a wireless client can use them to estimate its location. The level of detail and reliability depend on the number of locations for which fingerprints have been prerecorded.

A position estimate's detail, reliability, and update rate can be very good, but infrastructure-based methods fail when the conditions in the building change (temperature rises, furniture moves, floors collapse), power is lost, or cables are cut.

Localization with Wireless Sensor Networks

In the field of wireless sensor networks, researchers have developed algorithms to determine each sensor's position relative to others. The sensors share individual range or connectivity measurements, and each sensor contributes to the calculation of their locations instead of relying on a central device.[12] If a few sensors are anchor nodes with known absolute positions, the estimates improve and the distributed algorithms can compute absolute locations for all the sensors and place them on a floor plan.

These methods require no calibration except for the anchor nodes' positions—all the other nodes can just be dropped or scattered. Computation is distributed and communication is wireless, which means no infrastructure is required. Individual nodes can fail without compromising the whole system. However, some algorithms might provide incorrect position estimates if sensors are moved from their initial position. Such systems typically consist of nodes distributed quite densely in an open space. Although this might not be a realistic assumption for a search-and-rescue mission in a family home, it could apply to an underground parking lot or an airport terminal.

Sensor nodes can also serve as radio repeaters to ensure reliable communication when standard radios fail due to thick reinforced walls or underground levels. Because nodes are deployed throughout the building, they can also monitor temperature, the presence of toxic gases, or vibrations signaling that the structure is unstable.[10]

Ad Hoc Relative Positioning

Determining a target's direction is the key to many basic navigation techniques, including following a sound, walking toward a light, or even following a rope. By physically rotating the receiver or transmitter or using an array of receivers or transmitters, we can obtain angular measurements between devices.[13,14] For example, sonar arrays and laser range finders on robots and autonomous vehicles help detect obstacles' distance and direction.[15]

This method's principle is particularly simple because we can use the measurements without any complex processing. This limits the added value the system provides but makes it robust because the user understands what's happening. Responders can place ultrasound, radio, or light beacons at strategic locations when they arrive at the scene of a disaster. The main issue is measurement reliability: single measurements can be unreliable because signals are reflected off surfaces or blocked by obstacles.

Proximity Sensing

Precise measurements aren't the only solution—an RFID reader, for example, can detect and identify RFID tags within a certain range. If a tag's position is known, it can help estimate the reader's approximate position. A shorter detection range gives finer locations but requires more tags. And, although RFID tags are cheap and small, don't require a power source, and can even be embedded under carpet tiles,[16] they require calibration to identify each tag's position.

Alternatively, responders can deploy tags in strategic locations such as doorways or corners during an intervention.[17] No preinstallation is necessary, and only a few tags are required—the trade-off is occasional, coarse location estimates.

Dead Reckoning

Dead reckoning consists of adding an object's small movements to build its trajectory from a given starting point. Pedestrian dead reckoning (PDR) involves estimating step lengths and directions using a pedometer and a compass, but more recent techniques use foot-mounted inertial sensors (accelerometers and gyroscopes) to track every detail of the foot's movement.[18] Dead reckoning only requires sensors to be carried or worn by the person being tracked, making it particularly attractive for localization in unprepared environments. Inertial sensors can also provide the incident commander with information about the wearer's posture, such as whether he or she is standing, crouching, or lying down.[19]

Some algorithms might provide incorrect position estimates if sensors are moved from their initial position.

PDR based on inertial sensors gives a detailed account of a person's movements, but the small errors in each measurement accumulate, and the error in the estimated position increases without limit (see Figure 2). Resetting the estimated foot speed to zero at every step makes the position error increase more slowly but can't prevent it completely. Eric Foxlin reported

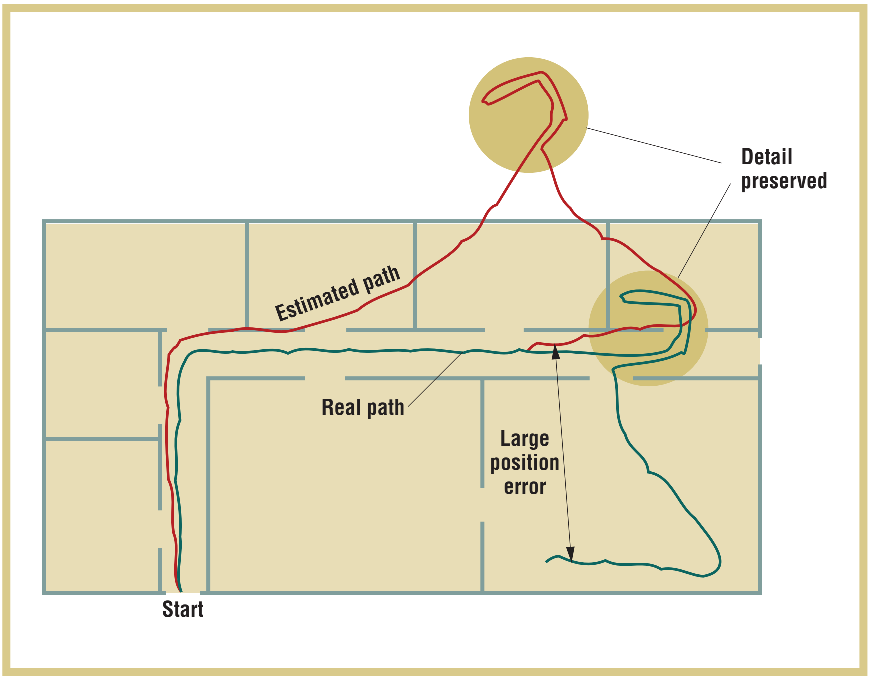

Figure 2. Pedestrian dead reckoning. This technique captures detail, but position error continually increases.

very accurate tracking;[20] Lauro Ojeda and Johann Borenstein also achieved good accuracy in challenging environments.[21] However, other researchers reported much larger errors.[22,23] Sensors' quality, the way they're attached to the foot, and the walking pattern affect results and make predicting uncertainty in a PDR position estimate very difficult. We expect current PDR systems to be unusable in scenarios in which the wearer crawls, climbs, or walks with an irregular pattern (while transporting a victim, for instance). The challenge for researchers is therefore to couple dead reckoning with other localization techniques, without substantially increasing the deployment effort.

Classification Criteria

We've identified the following criteria as particularly relevant for designing and comparing different localization and navigation systems for emergency response.

Primary Function

Tracking determines team locations within a structure, and *navigation* shows the teams how to reach a target location without necessarily knowing exactly its members' location. For instance, a flashing beacon provides navigation support without localization, whereas a number displayed on a door provides location only. Location combined with a correctly oriented floor plan can provide navigation support.

Information Quality

Localization systems are typically characterized by the quality of information they provide. Researchers often compare accuracy, precision, and update rate for different algorithms or systems because they reflect a system's level of detail and reliability. Some systems provide reliable location estimates with a lot of detail, whereas others only give coarse locations. The estimated locations can be consistent with each other over time or can vary to some degree between measurements. Navigation systems are more difficult to evaluate than location systems without a full trial because of the influence of the display and user behavior.

Amount of Information and Flexibility

A system's usability is heavily affected by how much information it provides and how well it can be adapted to different situations. Providing as much information as possible to the user lets that person make his or her own decisions, but this flexibility sometimes comes at the cost of increased mental workload. On the other hand, a system that filters information or even makes decisions for the user most likely won't adapt to unexpected circumstances.

Technology

Much of the electronic equipment that firefighters use is relatively low-tech; high-tech systems tend to be more fragile and more complex, and require training, although in some cases, an intuitive interface masks the complexity. The danger is that if the system's internal workings aren't properly understood, failure can go unnoticed. Devices containing sensitive electronics, for example, are vulnerable to high temperatures and moisture, and thus must be designed to withstand such conditions.[6]

Components

We can also class systems according to their number of separate parts, size, and weight. This is particularly relevant when someone needs to carry a system into a building or deploy it at the scene. Several indoor location systems consist of a network of tens or hundreds of sensor nodes combined with several body-worn sensors and a small computer. This contrasts with a single self-contained thermal-imaging camera, for instance.

Deployment and Prior Knowledge

Some systems must be preinstalled in a building in the same way as smoke detectors or sprinklers. Others can be installed rapidly in strategic locations upon arrival at the scene, either outside the building or inside by a dedicated team. Still others are deployed implicitly by search teams as they perform their mission. Finally, self-contained systems such as PASS devices require no special deployment.

Limitations

All these systems will likely fail under certain conditions. Some devices simply cease working, others work in a degraded mode, and the rest might fail silently and continue to provide incorrect information. One cause of failure is coverage, which can be limited by a particular signal's range or the number of devices deployed.

Additional Features

In some cases, a system will provide extra information in addition to location or navigation—for instance, reliable radio communication or a view of the building's internal environment in real time. These features don't directly provide location or navigation support but are nevertheless valuable to emergency responders. Because these additional features are available at no extra cost, they should be considered when comparing systems.

System Discussion

Each localization approach has its strengths and weaknesses for emergency response. Researchers have built systems that combine the techniques we've described. Table 1 summarizes the different system characteristics.

Pathfinder

SummitSafety's Pathfinder system consists of a handheld tracker and beacons that transmit powerful ultrasound pulses (see www.summitsafetyinc.com). Firefighters can use the tracker to locate a beacon placed at the exit, and rescue teams can use it to find a beacon with a different frequency worn by a firefighter in distress. Walls block ultrasound waves, but the waves will find a path around corners and under doors that firefighters can follow. Smoke, heat, humidity, and audible sounds from the fire don't interfere with the ultrasonic waves, and a directional receiver for ultrasound is a lot smaller than for audible sound, making ultrasound a good choice for this guidance system. The tracker displays the detected signal's amplitude on a bar graph so that firefighters can locate a beacon's direction by scanning a 360-degree circle.

Precision Personnel Location

The Precision Personnel Location (PPL) system developed at Worcester Polytechnic Institute uses RF receivers at fixed locations on emergency response vehicles to track the 3D position of personnel carrying a transmitter inside the building.[24] PPL can use the RF signals alone to estimate location or to correct drift in dead-reckoned positions. The dead reckoning is particularly useful in larger buildings, where RF position estimates are less accurate.

SmokeNet

University of California, Berkeley, researchers developed SmokeNet, a preinstalled sensor network that tracks firefighters in a multistory building.[10] Sensor nodes in each room and approximately every 10 meters along the building's corridors provide room-scale location accuracy, with additional sensor nodes monitoring smoke and temperature and relaying data back to the command post. Color-coded LEDs show occupants which escape routes are safe. The FireEye display mounted inside each firefighter's face mask displays a floor plan and short text messages from the command post. The incident commander uses the electronic Incident Command System to see firefighter locations and health status, as well as smoke detector status.

LifeNet

Markus Klann designed LifeNet to provide the functionality of a traditional lifeline.[3] It consists of beacons and a wearable device that senses nearby beacons and shows navigational guidance on a head-mounted display. The beacons are dropped automatically at appropriate intervals from a device attached to the firefighter's breathing apparatus and form a trail of electronic breadcrumbs. Each beacon acts as a waypoint to guide the firefighter in either direction. Trails deployed by different firefighters combine to offer alternative escape routes, and loops create shortcuts instead of becoming traps. The challenge is to present concise, clear information to the firefighters despite the inaccuracies in detecting beacon direction.

> One cause of failure is coverage, which can be limited by a particular signal's range or the number of devices deployed.

Map Matching with Particle Filter

Researchers from the WearIT@Work project use floor plans to ensure that successive PDR position estimates don't pass through walls.[22] A particle filter keeps track of thousands of different position and orientation estimates (the particles), weighting each one according to how well it fits with inertial measurements. The filter eliminates particles that pass through walls and replaces them with plausible ones. The map-filtering method works with building outlines but benefits from more detailed floor plans. Oliver Woodman and Robert Harle at the University of Cambridge use maps that include vertical positions to represent stairs.[25] Their particle filter uses 2.5-dimensional maps to track locations over several floors and further improve estimates.

TABLE 1
A summary of location support systems for emergency response.

Name	Function		Technology	Deployment	Floor plan	Components	Limitations	Added features
	Tracking	Navigation						
Currently Available								
Lifeline	Distance	Yes	Rope, knots	Implicit	No	Rope, clips	Limited length, can get tangled/trapped	No
Torch	No	Yes	Light	Strategic	No	Torch	Obstacles, thick smoke	No
PASS	No	Yes	Alarm	No	No	PASS device	Sound can get masked, direction difficult to determine	No
PathFinder	No	Yes	Relative ultrasound direction	Strategic	No	Wearable beacon, exit beacon, handheld tracker	Limited functionality, approximate direction of beacon only	No
Commercial indoor localization	Yes	No	UWB or ultrasound	Pre-installed	Optional	Sensors in building, wearable tag	Sensitive calibration, loss of connectivity and power	No
Prototypes								
PPL	Yes	No	RF ranging, inertial sensors	Strategic	Optional	Multiple receivers outside, mobile transmitter	Performs poorly in metal structure or large buildings	No
SmokeNet	Yes	No	RF fingerprints	Pre-installed	Required	One beacon per room, wearable receiver	Sensitive to changes in the environment	Environment monitoring, communication
LifeNet	Distance	Yes	Relative ultrasound direction	Implicit	No	Beacons every few meters, wearable sensor	Beacons can be moved or destroyed	Environment monitoring, communication
PDR alone	No	Yes	Inertial sensors	No	Optional	Shoe-mounted sensor	Drift, unpredictable error	No
Map matching with particle filter	Yes	No	Inertial sensors	No	Required	Shoe-mounted sensor	PDR drift	No
Map matching with RFID	Yes	No	Inertial sensors, RFID	Strategic	Required	Multiple inertial sensors	PDR drift	Posture monitoring
Flipside RFID	Yes	No	Inertial sensors, RFID	Pre-installed	Required	Shoe-mounted sensor, wearable RFID reader, RFID tags	PDR drift	No
Relate Trails	No	Yes	Inertial sensors, relative ultrasound direction	Implicit	No	Shoe-mounted sensor, beacons, wearable sensor	Beacons can be moved, PDR drift	Environment monitoring, communication
HeadSLAM	Yes	Yes	Inertial sensors, laser range scanner	No	No	Head-mounted inertial sensors and scanner	Scanner fails in low visibility, PDR drift	Environment monitoring, communication

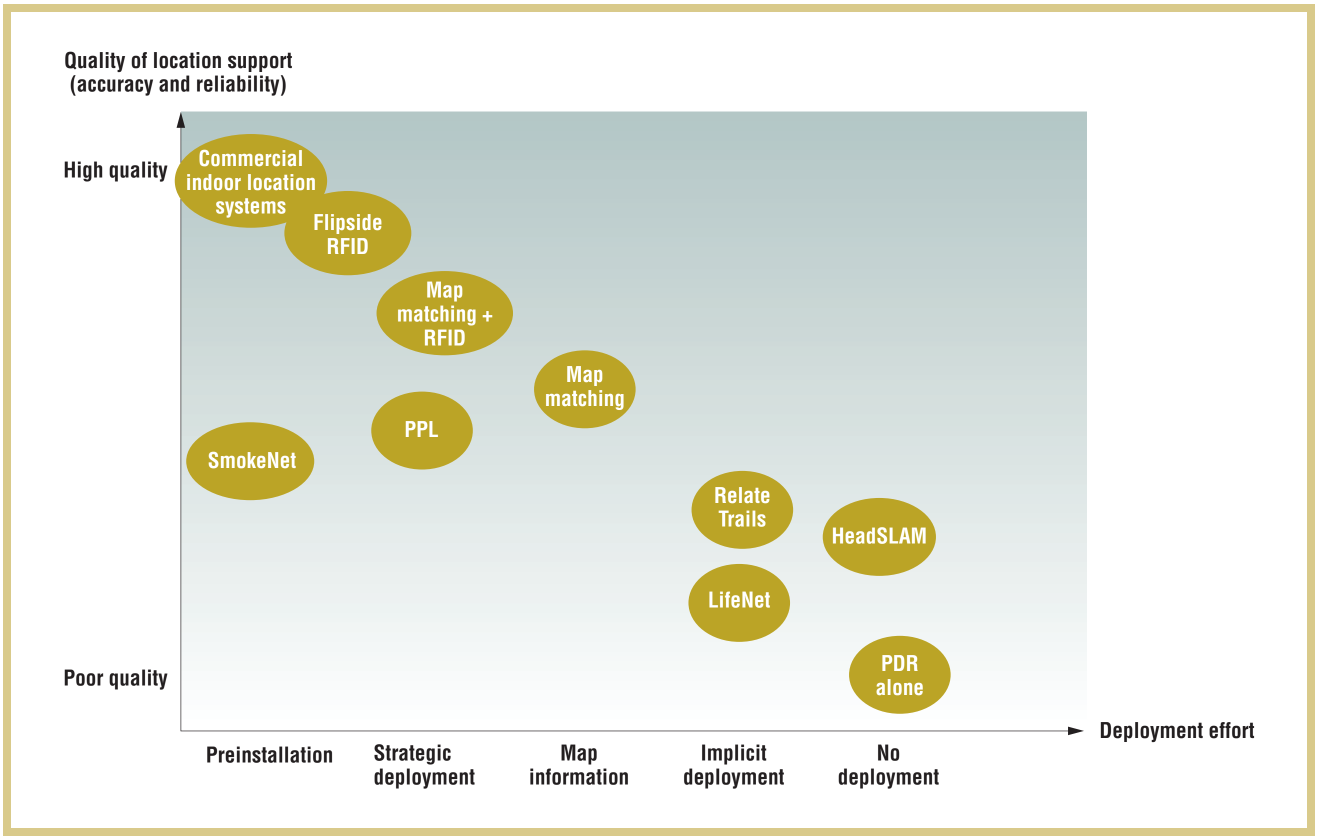

Figure 3. Different location systems. Increased reliability and accuracy comes at the cost of more deployment or prior knowledge of the environment.

Map Matching with RFID

A team from the École Polytechnique Fédérale de Lausanne (EPFL) also found that it could correct the drift in PDR position estimates by using information from floor plans.[26] The first team of firefighters identifies doorways by placing an RFID tag on the frame as it passes through. As the firefighters place each tag, the location system adjusts the PDR position estimate based on the position of the nearest doorway on the floor plan. The system corrects the orientation estimate based on the direction in which the doorway must be crossed. Following teams wear an RFID reader that detects the tags the first team deployed; the system corrects position and orientation estimates in the same way.

Flipside RFID

A US National Institute of Standards and Technology (NIST) team investigated how firefighters could use predeployed RFID tags embedded in a building to correct PDR.[27] The researchers call this the *flipside* of RFID because unlike typical RFID systems, the tags are static and firefighters wear the mobile reader. The reader's range and the distance between tags are the key parameters: a long range will give only approximate locations, but a short range will miss tags.

Relate Trails

The Relate Trails project[21] provides navigation assistance by displaying an arrow on a head-mounted display to help a person retrace his or her path. Ultrasound beacons are dropped on the way in, and then used to correct PDR position and direction estimates on the way out. Absolute positions might be inaccurate due to PDR drift over long distances, but navigation only relies on the position of the user relative to the closest beacons. The use of PDR in addition to beacons allows the system to function to some extent even if beacons are destroyed or out of range.

HeadSLAM

HeadSLAM combines PDR with readings from a laser scanner mounted on a helmet to produce a map.[28] The scanner detects the direction and distance of obstacles such as walls and produces a map resembling an actual floor plan, showing corridors, rooms, and doorways. This idea is based on Simultaneous Localization and Mapping (SLAM) from robotics, in which a robot gradually builds a map of its environment and keeps track of its current position on the incomplete map.[29] SLAM can be very effective when a robot can repeatedly scan the environment, but it's unclear whether it will perform well enough for a pedestrian in an emergency.

In general, we see a trade-off between systems that provide high-quality location information and those that are easy to deploy. Figure 3 shows the dependency of good location information on a preinstalled infrastructure and prior knowledge of the environment. Systems such as PDR that require little deployment or prior knowledge of the area tend to be either unreliable or inaccurate. However, even though preinstalled systems work well under favorable conditions, they're unreliable in a disaster and might not even exist in many locations.

We found two limitations in work to date that warrant attention in future research and development. The first is a lack of accounting for uncertainty in location and navigation support. Inaccuracies are inherent in sensing systems and must be tracked and suitably exposed—to alert first responders to potential heading errors and to inform the central command post's decision-making. The second is a need for benchmarks for system evaluation. System characterization in terms of positional accuracy and error rate is important but not sufficient for understanding how well a system meets tracking requirements in unknown environments. Ultimately, there is no silver bullet for location and navigation support for emergency response, but as we have shown, research is making important strides toward systems that can improve the efficiency and safety of first responders.

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