Sensor Network Navigation without Locations

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Outline

• Introduction
• Problem specification
• Design principles
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Introduction

• This work proposes to utilize the sensor network infrastructure as a cyber-physical system for navigating internal users during emergencies.

• The users are equipped with communicating devices like 802.15.4 compatible PDAs that communicate with sensors in the network.

• The design objectives of this work are twofold.
  – First, to release the necessity of utilizing location information.
  – Second, to address emergency dynamics that can lead to variations of dangerous areas.

Figure 1. Sensor network navigation

– 4. Most, if not all, existing approaches assume the availability of locations on each sensor node.
  The location information, however, may not always be available in many realistic situations where emergency guidance are needed, e.g., an underground tunnel or coal mine, a complex indoor area, and etc.

– 5. In addition, existing approaches usually do not specifically consider the impact of variations of dangerous areas.
  The expansion, shrinking, or disappearing of areas which is deemed dangerous.

– 1. There are not necessarily one or more sinks as data processing centers.

– 2. the navigation of human beings is inherently different from routing data packets, e.g., packet reroute, multi-path routing, data redundancy and etc.

– 3. the time factor becomes critical in the context of human navigation other than the data delivery in the network.

– 4. Most, if not all, existing approaches assume the availability of locations on each sensor node.

– 5. In addition, existing approaches usually do not specifically consider the impact of variations of dangerous areas.
Problem specification

Problem specification

• We consider the scenario of navigating human beings on the field under emergencies, where there might be several dangerous areas that threaten the safety of human beings, e.g., excessive heat, poisonous gas, passage obstacles, and etc. People need to be guided out of the field while keeping away from those dangerous areas.

Problem specification

• We characterize the navigation problem as a path planning problem and present its assumptions, objectives and requirements as follows.

Problem specification

• Assumptions

We assume an emergent field containing several areas of dangers, as the red areas shown in Figure 1. The dangerous areas might emerge, disappear, expand or shrink as the time passes and the number of different dangerous areas at any time instance \( t \) is a constant \( L_t \).

A sensor network system is deployed on the field, where each sensor is able to detect the dangers distributed over the field.

The sensor node triggers a “yes” alarm if it resides in the dangerous area and triggers “no” if outside. Thus the boundary of a dangerous area can be outlined by the pairs of neighboring sensors with different outcomes.

Each user carries a communicating device like 802.15.4 compatible PDA that can talk with sensors.

By measuring the strength and direction of wireless signals, the user is able to track any targeted sensor node. Thus the navigating route can be interpreted as a sequence of nodes.

Problem specification

• Objectives

The objective of a successful navigation is to plan a path for each user to one or more pre-known exits on the field which lead to safe departure, bypassing all the dangerous areas.

The navigation process is carried out in a fully distributed manner without any dedicated central agents like sinks.

Each user is hand-off guided by sensors along the route.

Problem specification

• Requirements

– We require that the selected navigation route is safe, i.e., the route should be apart from the dangerous areas with guaranteed safety.
– We require that the selected navigation route is efficient, i.e., the route should not be excessively long. A shorter route results in a rapider departure from dangers.
– We require that the navigation protocol is scalable, i.e., the building and updating of the navigation routes should be local and lightweight.
Design principles

The main idea is that we embed a distributed safety road map system in the sensor network.

The navigation system maintains the road map as a public infrastructure across the network and guide different users across the field through the same road map, saving unnecessary overhead of individually planning routes for different users.

The road map is updated in an event-driven manner when the dangerous areas vary.

A. Building the Road Map

- We denote the entire emergent field as region \( E \) and the combination of dangerous areas as region \( D \). Thus the road map is built in the remainder region \( R = E \setminus D \), since human beings can only move outside dangerous areas for ensuring their safety.

- We build the basic framework of the road map by concatenating the medial axis of region \( R \). The medial axis is a set of points, each of which is closest to at least two different points on the boundaries of dangerous areas.

B. Guiding Navigation on the Road Map

We utilize the road map framework as a backbone for navigating different users inside the field.

The road map divides region \( R \) into different cells. Each cell is separated by road segments from others and contains a dangerous area inside it.

![Figure 2. The basic road map framework](image)

As proven in [3], the medial axis of region \( R \) is a finite set of continuous curves and it retains the topological features of this region.

1) Connecting the exit to the road map backbone

- We find the exit in one of the cells and build a route connecting the exit and the road map backbone.

- We assign a virtual power field around the dangerous area in the cell, where the power \( p \) of each point is inversely proportional to its distance \( d \) from the dangerous area, e.g., \( p = 1/d \).

![Figure 4. The finally obtained directional road backbone](image)
Design principles

• **Lemma 3.1.** The local minimum points of the virtual power field in each cell only reside on the medial axis.

\[ \text{(a) } \quad \text{(b) } \]

Design principles

• Lemma 3.1 guarantees that we can successfully build a route connecting the exit and the road backbone without halted at an intermediate point of local minimum.
• Such a route ensures that any point on the route is not any closer to the dangerous area than the destination exit.
• The route connecting the destination exit intersects the road backbone at a point we call gateway, which can be treated as exit on the road backbone.

\[ \text{Figure 4. The finally obtained directional road backbone} \]

Design principles

2) Assigning directions on the road map

This can be achieved by flooding from the gateway throughout the road backbone.

The flooded information includes:
the closest distance to the dangerous areas, \( d_c \),
the distance along the road to the gateway, \( d_r \),
the direction \( D \) along the road.

Each point receives the flooded information from different directions.

Design principles

• Each point first compares \( d_c \) and maintains the path with the largest \( d_c \).
• Among the paths with the same value of \( d_c \), the point keeps the shortest path with the smallest \( d_r \).
• It records the direction \( D \) of such a path. Finally, each point knows a path towards the gateway and maintains the direction of this path.

\[ \text{Figure 4. The finally obtained directional road backbone} \]

Design principles

3) Exploring the routes for users

Navigating each user to the destination exit includes three stages.

A: the inside of the cell to the road backbone,
moves along the most descending direction of the virtual field until he reaches the road map backbone.
B: Along the road backbone, The route is selected simply according to the directions assigned on the road map, i.e.,
C: along the route that connects the exit and the gateway on the road map.

\[ \text{Figure 4. The finally obtained directional road backbone} \]
4) The safety of the navigation route
We show by following theorems that the selected navigation route provides global safety as well as local safety.

- **Theorem 3.3.** The selected navigation route maximizes the minimum distance of all possible routes to the dangerous areas.

\[
\text{Figure 4. The finally obtained directional road backbone}
\]

- **Theorem 3.4.** For any given path segment on the selected navigation route, any substitute path will not be farther to the dangerous areas.

\[
\text{Figure 4. The finally obtained directional road backbone}
\]

C. Reacting to Emergency Dynamics
- Due to the emergency dynamics, the dangerous areas might vary during the navigation process.
  - expanding, shrinking, emerging, diminishing.
- A straightforward but highly inefficient mechanism is to entirely reconstruct the new road backbone whenever the variation of dangerous areas is detected.
- we describe an updating principle which additively rebuilds the road map according to the emergency dynamics and affects only a local district.

\[
\text{Figure 4. The finally obtained directional road backbone}
\]

- **Lemma 3.5.** When the dangerous area in a cell expands or shrinks continuously, only the points within c are affected.

\[
\text{Figure 4. The finally obtained directional road backbone}
\]

- **Lemma 3.6.** The emerging of a new dangerous point affects the points within the newly constructed cell and the diminishing of a dangerous point affects the points within the original cell.

\[
\text{Figure 4. The finally obtained directional road backbone}
\]

- **Theorem 3.7.** The impact of the emergency dynamics in the field is local.

\[
\text{Figure 4. The finally obtained directional road backbone}
\]

(b) expanding and (c) shrinking
when the dangerous area varies on point p (expands or shrinks), it only floods and updates the statuses of the points within the sector-like region in the cell.
Design principles

- **Lemma 3.8.** Assume the sizes of a dangerous area $A$ and its surrounding cell $c$ are $s$ and $s'$ respectively. After expanding or shrinking one point on $A$, the average sector-like region affected is of size $O(s'/s^{1/2})$.

\[ \text{Design principles} \]

\[ \text{Implementation experience} \]

Implementation experience

- Protocol Implementation
- not any location information
- the number of hops ->
  distance measurement

\[ \text{Implementation experience} \]

Implementation experience

- Each sensor node maintains a list of variables,

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
variable & type & size (bits) \\
\hline
s.danger & danger ID & 8 \\
\hline
s.border & Y/N & 8 \\
\hline
s.mDist & hops & 8 \\
\hline
s.mSet & node IDs & 80 \\
\hline
s.road & Y/N & 8 \\
\hline
s.nextHop & node ID & 8 \\
\hline
s.rDist & hops & 8 \\
\hline
s.potential & Value & 8 \\
\hline
\end{tabular}
\end{table}

s.danger marks whether the current node resides within or outside (0) a dangerous area, and s.danger is set to the ID of the dangerous area if the current node resides in such a dangerous area.

\[ \text{Implementation experience} \]

Implementation experience

- s.border Y/N 8
  s.border is a boolean variable that indicates whether the current node is on the boundary of the dangerous area.

- s.mDist hops 8
  s.mDist records the distance from the current node to the nearest dangerous area.

- s.mSet node IDs 80
  s.mSet records the set of nodes on the boundaries of dangerous areas that are of s.mDist to the current node.

- s.road Y/N
  s.road is a boolean variable that indicates whether the current node is on the road map backbone.

- s.nextHop node ID
  s.nextHop stores the ID of the next hop node along the path direction on the road.

- s.rDist hops
  s.rDist records the minimum distance to the dangerous areas on the path from the current node to the exit.

- s.potential Value
  s.potential records the potential value of ordinary nodes.
Implementation experience

- When emergency happens, each sensor node first senses.

- Each node inside a dangerous area generates a random number as the ID of the dangerous area and floods it across the area. The ID of smaller value suppresses other IDs and the smallest ID dominates the entire area. Finally, different dangerous areas are set to different IDs.

- The nodes inside a dangerous area set $s_{\text{danger}}$ to the ID value and those outside dangerous areas set $s_{\text{danger}}$ to 0.

- The node on the boundary of the dangerous area easily detects its position from its neighborhood information and sets $s_{\text{border}}$ to Y.

Implementation experience

In practical usage, however, when sensor nodes are sparsely deployed over the field, the nodes on the road backbone may not be connected into one component.

To solve this problem, we compromise the accuracy of the medial axis, letting $s_{m\text{Set}}$ of each node stores the boundary nodes of both $s_m\text{Dist}$ and $s_m\text{Dist} + 1$.

By such means, the medial axis is indeed broadened and more nodes are dedicated on the road backbone, largely increasing the connectivity of the road backbone.

Implementation experience

- The gateway node then floods the exit information throughout the road backbone.

- The flooded message contains two items, $dc$, which records the minimum number of hops to the dangerous areas along the road from the current node to the gateway, $dr$, which records the number of hops along the road from the current node to the gateway.

Implementation experience

- Each node initially sets its $s_{\text{nextHop}}$ to be null, and $s_r\text{Dist}$ to be 0. On receiving the flooded message, each node first compares its $s_r\text{Dist}$ with $dc$ in the message. If $s_r\text{Dist} < dc$ ($s_m\text{Dist} < dc???$), this node switches its $s_{\text{nextHop}}$ to be the ID of the node that forwards the message and sets its $s_r\text{Dist}$ to be $dc$. Then this node alters $dc$ in the message to be $\min(dc, s_m\text{Dist})$ and resends this message. Otherwise this node simply discards the message.

*Figure 4. The finally obtained directional road backbone*

Implementation experience

- When the dangerous area varies, nodes in its cell react to update the road backbone.

- Each time a sensor node is switched into or out of the dangerous area, it generates a report and floods it within those nodes that record it in their $s_m\text{Set}$. Those nodes accordingly update their $s_m\text{Dist}$ and $s_m\text{Set}$. The potential values $s_{\text{potential}}$ of those nodes are also updated. The road map backbone is then updated, and the corresponding nodes update their $s_{\text{road}}$.

- Such an operation only affects the nodes within a local sector-like district. The gateway node initiates a flood on the road backbone to reassign the path directions.
Implementation experience

B. Prototype Experiment

- We implement a prototype system including 36 TelosB motes deployed into 6 × 6 grids in the atrium in the university campus, with 10 meter space in-between neighboring nodes. The system provides navigation for a person carrying a laptop computer or PDA that can talk with sensors.

- Figure 6 (b) showcases an instance of the interactive experiment.

- Figure 6 (c) shows the traffic cost of each node.

Performance evaluation

- We conduct large-scale simulations to further evaluate the effectiveness and scalability of our approach.

- We compare the performance of this design with the skeleton graph based approach proposed by Buragohain et al. (SG for short) [4] as well as the potential field based approach proposed by Li et al. (PF for short), [10].
Performance evaluation
(a) Performance ratio of the minimum distance to the danger;

(b) Performance ratio to the shortest path;

(c) Performance ratio to the minimum exposure(1/dist²)path;

(d) Average network overhead for updating the network in the event of changes in dangerous areas.

Related work and conclusions
• We propose a road map based approach that provides human navigation in the distributed sensor networks.
• Primarily different from existing works, we validate our design without relying on location information, which surprisingly overcomes natural intuitions.
• We further discuss the situation in the event of emergency dynamics, which has not yet been explored by previous studies.
• We also introduce an updating scheme that locally updates the road map system in the network when the dangerous areas vary, which largely reduces the network overhead.

Related work and conclusions
• We implement a prototype system consisting of 36 sensor nodes. Through a black box challenging game, we validate the effectiveness of our design.
• We further evaluate the performance of our approach through large scale simulations as well as compare it with two existing approaches.
• The simulation results show that although with much relaxed assumptions, our approach achieves comparable performance with significantly reduced communicational overhead.
Thank you very much!