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MSEND: Modified Situation-Aware Emergency Navigation Algorithm in Wireless Sensor Networks

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Abstract:
When emergencies happen, navigation services that guide people to exits while keeping them away from emergencies are critical in saving lives. To achieve timely emergency navigation, early and automatic detection of potential dangers and quick response with safe paths to exits are the core requirements, both of which rely on continuous environment monitoring and reliable data transmission. Wireless sensor networks (WSNs) are a natural choice of the infrastructure to support emergency navigation services, given their relatively easy deployment and affordable costs, and the ability of ubiquitous sensing and communication. In this paper, we propose SEND, a situation-aware emergency navigation algorithm, which takes the hazard levels of emergencies and the evacuation capabilities of exits into account and provides the mobile users the safest navigation paths accordingly. By guiding users following the descend gradient of the hazard potential field, SEND can thereby achieve guaranteed success of navigation and provide optimal safety.

I. INTRODUCTION:

Recently there is a trend to incorporate WSNs into emergency navigation systems aiming at providing early and automatic detection of potential dangers, such as geologic disasters, wildfire hazards and oil/gas leakages, and navigating people to safe exits while keeping them away from emergencies. In a mobile scenario, people are equipped with communicating devices like mobile phones that can talk to the sensors. When emergencies happen and mobile users are trapped in the field, the sensor network explores the emergencies and provides necessary guidance information to the mobile users, so that the users can be eventually guided to safe exits through ubiquitous interactions with sensors. Almost all existing approaches equally regard the hazard levels of different emergencies. In existing method, the evacuation capabilities of exits are generally assumed to be equal. When there are more than one safe exit, the existing methods simply guide people to the nearest one for the sake of timeliness which causes extreme congestions at the exit and significantly prolongs the emergency navigation time while leaving other exits of low usages. So we should take into consideration both the hazard levels of concurrent emergencies and the evacuation capabilities of exits. However, the main challenge here is how to define the safety properly, incorporating the impacts of both different hazard levels of emergencies and different capabilities of the exits at the same time. SEND is the first situation-aware emergency navigation scheme, considering the impacts of both the hazard levels of emergencies and the evacuation capabilities of exits. It is fully distributed and does not require any location information. It is more robust to emergency dynamics since the constructed hazard potential field reflects more global properties of the underlying connectivity. Both small-scale test bed experiments and extensive simulations on large-scale WSNs, in 2D validate the effectiveness and efficiency of SEND.

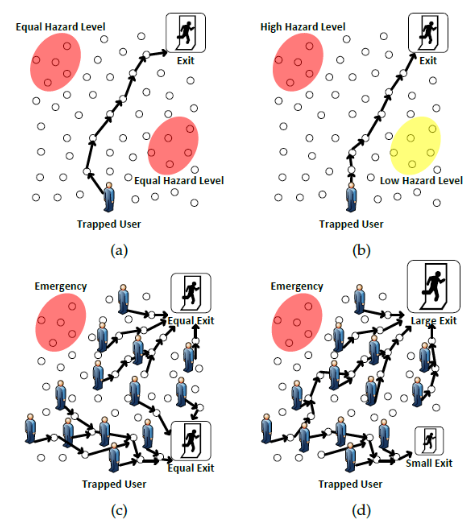


Fig. 1. Illustration of situation-aware emergency navigation with a 2D WSN. The emergency navigation paths when (a) there are equal hazard levels of emergencies, (b) the hazard level is higher at the red marked area and lower at the yellow marked area, (c) the two exits have equal evacuation capabilities, and (d) one exit has higher evacuation capability than the other.

Theoretical Foundation:

In this section, we propose a model to quantify the safety in 2D continuous domains and to clarify, we may use hazard instead of safety to describe emergencies.

Network model:

Consider a field where there may be different emergency events and multiple exits with different evacuation capabilities. People inside the field are anticipated to be immediately navigated to appropriate exits while being far away from emergencies in proportion to corresponding hazard levels. Specifically, the emergency navigation paths are expected to be farther away from areas with higher hazard levels, and more people should be guided to exits with higher evacuation capabilities. Based on these observations, we formulate the navigation problem as a path planning problem. Let R denote a 2D continuous space, which represents the field of interest. Inside R , there exist n safe exits, which are located at points Pe={pie|i=1,2,…,n}. Each exit is assigned a weight based on its evacuation capability. Suppose that in R, there are m emergencies occurring at points Pd={pjd|j=1,2,…,m}. Each emergency is also assigned with a weight based on its hazard level. We denote the set of weights of exits and emergencies

We={wie|i=1,2,…,n} and Wd={wjd|j=1,2,…,m}, respectively. The table below summarizes the notations used in our model.

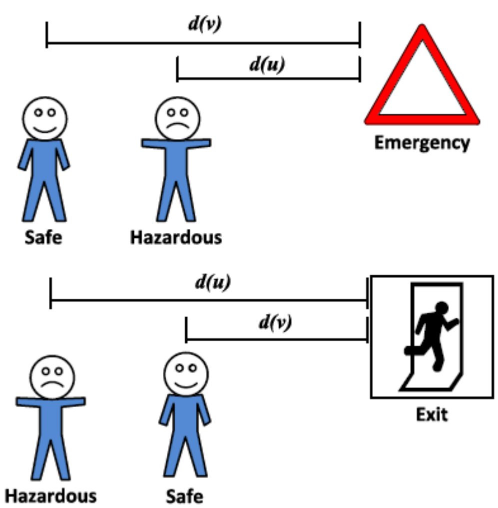
Notation Summary

Symbol	Definition
$\mathcal{R}$	a continuous open space in 2D or 3D
P_d	the set of points where emergencies occur
P_e	the set of points where safe exits locate
$\lvert pq \rvert$	the Euclidean distance between points p and q
$\overrightarrow{pq}$	the vector connecting the points p and q
W_d	the set of weights of safe exits
W_e	the set of weights of emergencies
$G(V, E)$	a sensor network as an undirected graph
V	the set of sensor nodes
E	the set of the links between neighbor sensors
V_d	the set of sensors with hazardous readings
V_e	the set of sensors located at exits
V_n	the set of sensors with normal readings
$F(v)$	the hazard potential function of sensor node v

Single Point Hazard

An emergency navigation problem is essentially to find the optimal emergency navigation paths in terms of safety. In the following, we first focus on the hazard of an arbitrary point in the field of interest, which is the basis of finding the safest navigation path.

Hazard Intensity: To quantify the hazard of a location, we use a metric called hazard intensity, which is based on the observation that for an internal user, one may feel more hazardous threat when getting closer to emergencies, and would feel safer when getting closer to exits. The figure below shows an illustration of this simple observation. It is indicated that, the emergencies with higher hazard levels have higher probability to jeopardize the users and the exits with higher evacuation capabilities yield higher probability for users to get evacuated.



Hazard Potential: The hazard intensity reflects only an instant feeling of the user, which is not enough to quantify the hazard of a single point. So in order to avoid this, we introduce a function called hazardous potential, which represents the total hazardous intensity one user has starting from infinity and ending at point p. We select infinity as a common reference point to evaluate the hazard potential in different spaces. Therefore, we define the hazard potential of
point p as follows:

$$\Phi(p) = \int_{\infty}^{p} \overrightarrow{I}(l)\,\mathrm{d}l$$

The hazard potential describes the cumulative hazard intensity that the user should take when moving from p to infinity. A positive value of the hazard potential indicates a higher chance of the user to be harmed .Therefore, the hazard potential can be used as a tool to quantitatively measure the amount of hazard of a single point.

SEND Algorithm:

In discrete sensor networks we first define hazard potential field in the network, which is the discrete counterpart of hazard potential field in continuous domains. Then we propose an iterative method to establish the hazard potential field by sensor readings in a fully distributed manner. Based on the established hazard potential field, we next propose a path selection method and theoretically prove that the selected paths guarantee successful navigation and are optimal in terms of safety. We also propose a scheme to accelerate the establishment of the hazard potential field, in order to achieve timely emergency navigation.

Hazard Potential Field in Sensor Networks:

Consider a relatively dense sensor network can be viewed as a discrete approximation of a continuous space R. The sensor network is then modelled as an undirected graph G(V,E), where V is the set of vertices that represent the sensor nodes, and E denotes the set of edges that represent the communication links between sensor nodes. Let Vd denote the sensors with hazardous readings, Ve the sensors at the exits, and Vn the remaining sensors with normal readings. We first define the hazard potential field in discrete WSNs. The hazard potential function F(v) of a sensor node v is the following equation,

$$F(v) = \frac{1}{|N(v)|} \sum_{u \in N(v)} F(v),\ v \in V_n$$

N(v) --> set of neighbor nodes of node v and
|N(v)| --> cardinality of N(v)

When emergencies occur across the sensor field, only the sensor nodes near the emergencies and exits have abnormal readings. It is not easy for the hazard potential functions of all sensors to satisfy the above equation. Therefore, we need to distribute these readings to the whole network and establish the hazard potential field. We propose an iterative method to distribute abnormal readings to the network and establish the hazard potential field in a fully distributed manner. To be more concrete, when there is no emergency, each node v ϵVn is assigned a hazard potential value as 0, while each sensor v ϵVe is assigned a negative hazard potential value reversely proportional to its capability. When the emergency happens, each sensor v ϵVd will set its hazard potential value with a positive value proportional to the hazard level of its reading. Theoretically, the hazard potential of the sensor v ϵ Vdcould be any positive number, and a larger potential represents a larger hazardous reading; likewise, the potential of the sensor v ϵVe could be any negative number, and alarger potential represents a smaller capability. In our implementation, the potential of the sensor with a hazardous reading is set in [0, 1], while the potential of the exit is set in [-1, 0]. For example, we set the potential of the sensor with a small hazardous reading with 0.5 and the potential of the small exit with -0.5 .At first, every sensor v ϵVnUVe has set its hazard potential value. When the emergency happens, every sensorv ϵVd begins to set its hazard potential value. At this time, the potentials of the sensors with hazardous readings, the exits and other sensors with normal readings are positive, negative and zero, respectively. When the hazard potential functionF(v) of v ϵVd U Ve is fixed, every sensor v ϵVn conducts the iteration as follows:

$$F^{(k+1)}(v) \leftarrow \frac{1}{|N(v)|} \sum_{u \in N(v)} F^k(v), \; v \in V_n$$

According to Dirichlet boundary condition, this iterative process will finally converge if the hazard potential F(v) at the position of v ϵVd U Ve is set to be constant. Once the hazard potentials of all nodes in the network are stable, the final F(v) is the hazard potential of node v.

Safest Paths Identification:

With the established hazard potential field in the sensor network, it is straightforward to select the safest paths among all possible paths that link the internal users and safe exits. In particular, every user initiates the path selection by communicating to a nearby sensor node v ϵVn with a normal reading, which then selects a neighbor node u ϵN(v) with the smallest hazardous potential F(u) among its neighbors and sets it as the next destination node. By repeating this process, the emergency navigation path comes into being and is guaranteed to reach the sensor at the location of one exit. This process can then be expressed as

$$S(v) = \arg \min_{u \in N(v)} F(u)$$

where S(v) denotes the next destination node of the current sensor v. There are two salient properties for the paths selected in this manner as follows: The emergency navigation paths selected by the proposed method guarantee successful navigation. The navigation paths selected by the proposed method are optimal in terms of safety.

Accelerated Hazard Potential Field Establishment:

As emergency navigation is a time critical application, we need to pay special attention to the time consumed on path planning. Centralized methods such as Gauss Seidel method are able to speed up the convergence; however, they can not work in a distributed manner and require a relatively long time to collect all the sensor data to a sink. Based on the local information of each sensor node, we consider to utilize the multi-step forward prediction technique to boost the hazard potential field establishing process. In order to estimate the multi-step forward prediction value of each sensor based on a small amount of preceding iterative hazard potential function values. By extrapolation, we can then predict the multi-step forward hazard potential function value of each sensor. As a result, the iteration process can skip over a number of iterations, with the help of the estimated value, and jump directly to multiple steps forward. So, we can significantly reduce the number of iterations and thus boost up the convergence speed of the hazard potential field establishing process. To this end, we propose to utilize cubic extrapolation . Cubic extrapolation works by using only local and incomplete information to reduce the redundancy of the iteration. Second, the memory of each sensor in the network is limited due to the hardware constrains of the sensors. Cubic extrapolation uses only a constant number of the past time series to estimate multi-step forward values of the hazard potential. Last but not least, considering the dynamics of sensing environment, cubic extrapolation is an input-adaptive method, which is robust in dynamic environments. In the hazard potential field establishing phase, each sensor node v memorizes a time series F1(v), F2(v),....., Fk(v). Let time k be the independent variable and Fk(v) be the dependent variable representing the hazard potential value in the k-th round of iteration. We assume that the iterative value Fk(v) can be expressed as a point on the third-order curves that traverse at least four preceding iterative values Fk-i(v), i = 1, 2, 3, 4. This assumption allows us to estimate a k-step forward value of F(v) using at least four known values. The formulation of the process thus can be expressed as follows:

$$F^{k-i}(v) = \lambda_1(k-i)^3 + \lambda_2(k-i)^2 + \lambda_3(k-i) + \lambda_4$$

wherei = 1, 2, 3, 4, indicating that we have four unknown variables along with four equations. Thus the hazard potential field establishment of the whole network can be accelerated. The number of rerouting procedures due to the impact is high that decrease the reliability of the network. This method fails to control the impact with less time due to frequent path selection and switch over. Due to interruptions in communications, the observed communications if an impact occurs is high.

Prevention of packet loss:

The proposed path planning algorithm for mobile anchor node presented in this section is termed as Z-curve. The trajectory of the basic curve is shown in below Figure (a) which is based on shape Z. The key motivation in the Z-curve designing is, a trajectory must have shorter jumps to avoid the co linearity problem and must create a path for mobile anchor node to transmit three consecutive non-collinear location information messages in order to reduce the localization time. If the mobile anchor node moves on the Z-curve path, unknown sensor nodes can be localized more accurately while the trajectory passes through whole network region and even considering the border of the deployment area. We use the level of the curve concept as follows. The basic curve is said to be of level (1) where l=1. To derive level (l), a 2-dimensional network region must be divided into 4l sub-squares and the mobile anchor node moves in the Z-curve path by connecting the centers of the cells. Each vertex of the basic curve is termed as C1,C2,C3,C4 as shown in below Figure 6(a) with level (l-1), which is appropriately reflected and/or rotated to fit into the new level curve. I illustrate level (2) and level (3) of Z-Curve in below Figure (b) and (c), respectively.

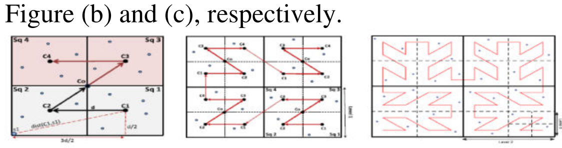


Figure.2. Z-curve traversing path

Path Planning

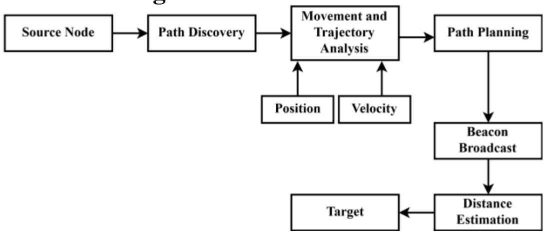


Figure.3. Path Planning Process

Step 1: In the first step the relation between the communication range and localizability of unknown sensor nodes is analyzed. Hence all unknown sensor nodes are localizable by *Z-curve* path, if:

$$\forall s_{i\,(i=1,\ldots,n)} \exists \{b_{j\,(j=1,2,3)} \mid dist\,(b_j, s_i) \leq R_c\}$$

where s_i denotes unknown sensor nodes and b_j denotes the anchor messages transmitted from three different anchor positions (e.g. *C*1). *dist* (b_j, s_i) and R_c are distance between sensor node and anchor, and communication range, respectively. ***Step 2:*** In the second step the communication range of the mobile anchor node traversed by the *Z curve* is adjusted as all sensor nodes must cover fully for localization. As mentioned in first step, the network region in level (1) is divided into four sub-square, namely sq_k, (k = 1, . . . ,4) and the centroid of each sub-square is named as C_k. *Co* indicates the center of the basic *Z-curve*. The side length of each sub square is defined as the resolution of the proposed trajectory and it is denoted by *d*. To achieve the full coverage by the *Z-curve*, the main requirement is that the anchor message transmitted at C_k position would be received by sensor nodes located at the same *sq* and in addition with two more adjacent *sq*. So that, each unknown sensor node can receive three anchor messages. Let s_1 indicates the most distant sensor node located at the adjacent *sq* from *C*1. Hence, if s_1 can receive the anchor message from C_1, then we can guarantee that the message would be heard by all sensor nodes located inside sq_1, sq_2, sq_3.

From above figure (a), by applying the Pythagoras theorem we obtain:

$$(dist\,(C_1, s_1))^2 = (d/2)^2 + (3d/2)^2$$

$$\Rightarrow dist\,(C_1, s_1) = \sqrt{(5/2)}d$$

where *(dist* (C_1, s_1)*)* indicates the distance between sensor node s_1 and anchor position C_1. And, from equation (1) we can obtain that $dist\,(b_j, s_i) \leq R_c$. *So*, $Rc \geq \sqrt{(5/2)}d$. It is also valid for C_2, C_3 and $C_{4\ \text{anchor}}$ positions. Hence from this, all the unknown sensor nodes are able to receive three anchor messages and can cover fully for localization when the mobile anchor node traverses based on the *Zcurve* with $Rc \geq \sqrt{(5/2)}d$.

Step 3: In this step a shortest path for mobile anchor node is selected to traverse the network region and to broadcast three anchor messages to unknown sensor nodes in the region traversed by the *Z-curve* path planning algorithm. As shown in above figure (a), *Zcurve* path is started by connecting the centers of two adjacent *sq*. The mobile anchor node at anchor position C_1 provides location information for s_i *located* in $sq_{1,2,3}$. Similarly, unknown sensor nodes located in $sq_{1,2,4}$ receive the message from C_2. The anchor message from *Co* is collectable by s_i in $sq_{1,2,3,4}$. Hence, from this all the sensor nodes located in the below half region are localizable and the same process is repeated to achieve localizable for sensor nodes located in above half region. Hence mobile anchor node by moving on the *Zcurve* path provides the chance to achieve three anchor messages through the shortest path.

Step 4: In this step the received anchor messages are verified for non-collinearity. The *Z-curve* path provides three consecutive non-collinear anchor messages via the shortest path length. Let us consider, MSG represents a matrix which is formed by the coordinates of the three consecutive received anchor messages (x_c1 , y_c1), (x_c2 , y_c2), (x_co , y_co) in positions $C_{1,2,0}$.

$$MSG = \begin{pmatrix} x_{C2} - x_{C1} & y_{C2} - y_{C1} \\ x_{Co} - x_{C1} & y_{Co} - y_{C1} \end{pmatrix}$$

Hence, we can prove that the three received anchor messages are non-collinear, when

$$|MSG| = (x_{C2} - x_{C1})(y_{Co} - y_{C1}) - (y_{C2} - y_{C1})(x_{Co} - x_{C1}) \neq 0$$

where, $|MSG|$ indicates the determinant of MSG matrix. The last step demonstrates that the received three anchor messages via the shortest possible path dictated by the *Z-curve* are non-collinear. The total distance travelled by the mobile anchor node based on the *Z-curve* trajectory at level (l) and resolution *d* is given by:

$$length_{(Z-curve)} = [(5/8\times 4^l) - 1]\,d + [(3/8\times 4^l)]\sqrt{2}d$$

Above Figure (a) also implies that total length travelled in level (l) is equal to $2d + \sqrt{2}d$.

Step5: In this step unknown sensor nodes estimate their positions by using trilateration calculation method as shown in below figure. After receiving three consecutive non-collinear messages from mobile anchor node, it will estimate its position according to,

$$pos_{si}(x,y) = [(x_1+x_2+x_3)/3, (y_1+y_2+y_3)/3]$$

where, $pos_{si}(x,y)$ is position of unknown sensor node s_i, (x_1, y_1), (x_2, y_2), (x_3, y_3) are coordinates of mobile anchor node at 1, 2, 3 positions respectively.

ADVANTAGES

- Less rerouting procedures and chances that avoids the impacts due to dynamic path planning.
- Communication is retained in a stable manner to curtail loss and hence the number of routing instances is minimum compared to the existing method.
- The routing adversary impacts are avoided by selecting optimal neighbors with the awareness of their path formation structure such that maximum path distribution is utilized.

II. CONCLUSION:

This paper conducts the first work on situation-aware emergency navigation by considering a more general and practical problem, where emergencies of different hazard levels and exits with different evacuation capabilities may coexist. We first model the situation-aware emergency navigation problem and formally define the safety of a navigation path. We then propose a fully distributed algorithm to provide users the safest navigation paths, as well as an accelerated version that can significantly boost up the speed of the navigation. Both experiments and extensive simulations in 2D scenarios validate the effectiveness of SEND. We are currently devoting to conducting a small-scale system prototype under more complex scenarios. In the future, we would like to explore modeling the hazard speed in the context of emergency navigation. We also plan to cooperate with the local Fire Department to test our prototype, e.g., in the fire-fighting exercises, to provide more evidences on the real effects on user safety in real scenarios.

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