Task-based Wireless Mobile Agents Search and Deployment for Ad hoc Network Establishment in Disaster Environments

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Abstract. In disaster environments, due to the destruction of local communication infrastructures, wireless mobile agents (robots) are employed to search and deploy to establish ad hoc networks. With the guidance of the network, first responders can efficiently perform tasks in disaster environments. However, due to the uncertainties and complexities of disaster environments and the limited capabilities of wireless mobile agents, it is challenging to apply wireless mobile agents to disaster environments in both theory and practice. To this end, a task-based wireless mobile agents search and deployment approach is proposed for ad hoc network establishment in disaster environments. The proposed approach consists of a search module and a deployment module. The search module enables wireless mobile agents to efficiently move and collect information in an unknown and complex disaster environment. The deployment module enables wireless mobile agents to find suitable deployment locations based on the collected information. The ad hoc networks established by the proposed approach can guarantee the communications of wireless mobile agents in ad hoc networks. In addition, it can cover the maximum number of tasks and maximum size of area in the disaster environment. The experimental results demonstrate the advantages of the proposed approach in terms of wireless mobile agents search and deployment for ad hoc network establishment in disaster environments.

Keywords: Wireless mobile agent; Search and deployment; Ad hoc network establishment; Disaster environments

1 Introduction

Nowadays, disasters throughout the world such as the hurricane Katrina, Indian Ocean tsunami, 2008 Sichuan earthquake, etc [Bedford and Faust, 2010] have become an important social and political concern. After a disaster happened, many stationary tasks, such as saving survivors in debris, extinguishing fire of buildings, etc, need first responders to perform. Due to the destructions of local communication infrastructures, a number of mobile wireless agents (WAs) are employed to search and deploy to establish ad hoc networks in the disaster environment [Deshpande et al., 2012], [Jiang et al., 2008], [Ortiz et al., 2004], [Balachandran et al., 2006], [Srinivas et al., 2006]. With the guidance of the established networks, first responders can efficiently perform tasks in the environment. In recent years, ad hoc networks established by WAs play an important role in disaster search and rescue due to their low infrastructure dependency, low expense, quick deployment, quick adaptability and scalability.

When WAs just enter a disaster environment, they lack information about the environment. In addition, the ubiquitous obstacles in the environment hinder their search paths and occupy their deployment locations. Except the difficulties brought by the environment, the limited capabilities (e.g. energy, sensing and communication) of WAs also make the search and deployment in such environments more difficult. In many applications, a large number of stationary tasks are unevenly distributed in the environment and only a small number of WAs can search and deploy to establish ad hoc networks in the environment. In these applications, the search and deployment of WAs is prone to discovering and covering the maximum number of tasks, which is called task-based WAs search and deployment (TBWSD) for ad hoc network establishment in disaster environments.

In order to achieve efficient TBWSD for ad hoc network establishment in uncertain disaster environments, first of all, the approach should enable WAs with limited energy, sensing and communication capabilities to efficiently move and collect information in the environment. Then, the ad hoc network established for TBWSD should achieve three objectives: **1) Communication of WAs:** Since the sensing and communication ranges of WAs are limited, WAs should be able to communicate with other WAs in the network so as to share the information about their covered stationary tasks and first responders. **2) Maximum coverage of tasks:** Since stationary tasks are unevenly distributed in the environment, the established ad hoc network should be able to cover the maximum stationary tasks so as to ensure that most of tasks can be performed by first responders with the guidance of the network; **3) Maximum coverage of area:** Since first responders can move around in a disaster environment, the established ad hoc network should be able to cover the maximum area of the environment so as to increase the opportunities to guide first responders.

In order to achieve the requirement and three objectives of TBWSD, a task-based WAs search and deployment approach is proposed for ad hoc network establishment in disaster environments. The proposed approach consists of a search module and a deployment module. The search module enables WAs with limited energy, sensing and communication capabilities to efficiently move and collect information according to the density of tasks. The deployment module finds suitable deployment locations for WAs to establish ad hoc networks by considering the three objectives of TBWSD according to the information collected by the search module.

The rest of the paper is organized as follows. The problem description and definitions are given in Section 2. The task-based WAs search and deployment approach is introduced in detail in Section 3. The experiments are demonstrated and the results are analyzed in Section 4. The related work is introduced in Section 5. The paper is concluded and the future work is outlined in Section 6.

2 Problem Description and Definitions

Let D be a 2-dimension disaster environment, which are divided into many equivalent size locations $Loc_{(x,y)} \in D$ and the size of each location is S. Based on the occupation, the locations in D can be divided into three types : 1) free locations (i.e., $Loc_{(x,y)} = F_{(x,y)}$), 2) obstacle locations (i.e., $Loc_{(x,y)} = O_{(x,y)}$) and task locations (i.e., $Loc_{(x,y)} = T_{(x,y)}$). After entering D, WAs search to collect information. The definition of a WA and its collected information are described as follows.

Definition 1: A *WA* (WA_j) can be defined as a four-tuple WA_j=<$WA_{(x_j,y_j)}$, Eng_j, Sta_i, $ANet_k$>, where $WA_{(x_j,y_j)}$ is the current location of WA_j, Eng_j is the remaining energy of WA_j, which is represented by the number of locations that WA_j can move, Sta_j is the status of WA_j, which can be either 'searching' or 'deployed'. If Sta_i is 'searching', $ANet_k$ must be '$\varnothing$', otherwise $ANet_k$ is the information of the ad hoc network, to which WA_j belongs.

Definition 2: The *collected information* ($Info_j$) of a WA (e.g. WA_j) can be defined as a two-tuple $Info_j$=<$ASet_j$, $LSet_j$ >, where $ASet_j$ is the information of ad hoc networks, whose information is collected by WA_j and $LSet_j$ is the set of locations in D, whose information is collected by WA_j.
Based on the three types of locations, the set of locations can be further defined as $LSet_j$=<$FSet_j$, $OSet_j$, $TSet_j$>, where $FSet_j$, $OSet_j$ and $TSet_j$ are the set of free locations, obstacle locations, and task locations, respectively.

The ad hoc network ($ANet_k$) is established by WAs, which can share their collected information with each other. Therefore, the information of an ad hoc network is the sum of collected information of WAs establishing the network, which is described as follows.

Definition 3: The *information of an ad hoc network* ($ANet_k$) can be defined as a three-tuple $ANet_k$=<$WASet_k$, $LSet_k^C$, $LSet_k^U$>, where $WASet_k$ are the WAs establishing $ANet_k$, $LSet_k^C$ is the set of locations covered by $ANet_k$, and $LSet_k^U$ is the set of locations uncovered by $ANet_k$, but whose information is collected by WAs in $ANet_k$. Based on the three types of locations, the set of covered locations and uncovered locations can be further defined as $LSet_k^C$=<$FSet_k^C$, $OSet_k^C$, $TSet_k^C$> and $LSet_k^U$=<$FSet_k^U$, $OSet_k^U$, $TSet_k^U$>, respectively.

Since obstacle are considered in the proposed approach, the movements of WAs in the environment need to avoid obstacle locations. Therefore, A* search algorithm [Pokorny and Vincent, 2013] is employed to create the paths between two locations for WAs in the proposed approach. The reason for this choice will be explained later. A path created by A* search algorithm is described as follows

Definition 4: The *path* of WA_j ($Path(WA_{(x_j,y_j)}, Loc_{(x,y)})$) can be defined as a sequence of locations $Path(WA_{(x_j,y_j)}, Loc_{(x,y)})$=($Loc_{(x_1,y_1)}$, $Loc_{(x_2,y_2)}$, ..., $Loc_{(x_n,y_n)}$), where $Loc_{(x_n,y_n)}$ are the n^{th} location that WA_j moves to before arriving $Loc_{(x,y)}$.

Since WAs rely on wireless technologies, the sensing and communication distances of WAs are limited. In this paper, we assume that the sensing and communication distances of all WAs are the same and is r locations. The sensing and communication range of a WA (e.g. WA_j) is a circle with its centre at $WA_{(x_j,y_j)}$ (see Definition 2) and its radius equal to r so that the coverage area of WA_j is πr^2.

In order to guide first responders to efficiently perform tasks, the ad hoc network established for TBWSD should achieve the three objectives, which are the communication of WAs, the maximum coverage of tasks and the maximum coverage of area. First, due to the limited sensing and communication capabilities of WAs, the distance between two WAs that can communicate with each other should be less than r. However, in that situation, there must be an overlap between the coverage areas of the two WAs. In order to maximize the coverage area of the ad hoc network established by them, the optimal distances between WAs that can communicate with each other in the network are r, which is illustrated in Fig.1..

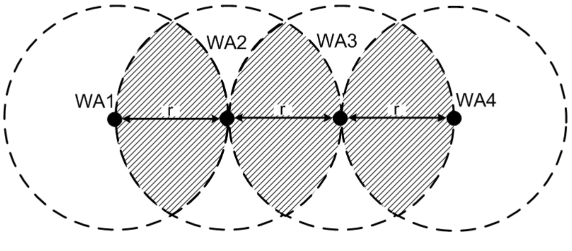


Fig. 1. The optimal distances between WAs in the ad hoc network

In Fig.1., the black circles represent the locations of WAs, the circle areas inside the dash lines represent the coverage areas of WAs and the shadow areas are the overlaps between WAs that can communicate with each other. From Fig.1., it can be seen that when the distances between WAs are r, the size of each shadow area is $(\frac{2}{3}\pi - \frac{\sqrt{3}}{2})r^2$, which is about 39% of the coverage area of a WA (i.e., πr^2). Based on this result, it can be deduced that the maximum coverage area of an ad hoc network that achieves the three objectives of TBWSD and is established by N number of WAs is about $N \cdot \pi r^2 - 39\%(N-1) \cdot \pi r^2$.

Based on the maximum coverage area, the objective value (e.g. $Objval_k$) is proposed to evaluate whether an ad hoc network (e.g. $ANet_k$) achieves the three objectives of TBWSD, which is described as follows.

$$Objval_k = \frac{S \cdot |FSet_k^C| \cdot |TSet_k^C|}{(|WASet_k| \cdot \pi r^2 - 39\%(|WASet_k| - 1) \cdot \pi r^2) \cdot (|TSet_k^C| + |TSet_k^U|)}, \tag{1}$$

where S is the size of each location, $|FSet_k^C|$ is the number of free locations covered by $ANet_k$ (see Definition 3), $|TSet_k^C|$ is the number of task locations covered by $ANet_k$. $|WASet_k|$ is the number of WAs establishing $ANet_k$ and $|TSet_k^C| + |TSet_k^U|$ is number of task locations, whose information is collected by WAs in $ANet_k$. The value of $Objval_k$ is a number in [0, 1], where 0 and 1 represent $ANet_k$ does not and does achieve the three objectives of TBWSD, respectively.

3 A Task-based WAs Search and Deployment Approach

The modules of each WA are illustrated in Fig. 2..

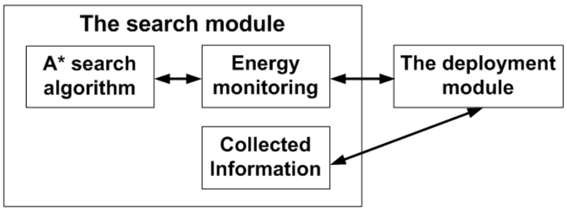


Fig. 2. The modules of each WA

From Fig. 2. it can be seen that each WA in the proposed approach has two modules: a search module and a deployment module. The main objectives of the search module are to help the WA to plan the search path and collect information about the environment. At the same time, the deployment module calculates the most suitable deployment location according to the current collected information. In addition, the search module also monitors the remaining energy of the WA to decide when to finish the search and begin to deploy according to the current and deployment locations of the WA.

3.1 The search module

In this subsection, the search strategy and the energy monitoring of the search module are introduced in detail.

The search strategy Due to the destruction of local communication infrastructures, WAs need to move and collect information in an uncertain and complex environment. In addition, due to the limited energy, sensing and communication capabilities of WAs, it is impossible for a WA to search all locations of the environment. Therefore, the search strategy is proposed, which can help the WA to move to the highest task density locations so as to collect as much information of task locations as possible with the limited energy. The search strategy is described in Algorithm 1.

Algorithm 1: The search strategy employed by WA_j:

```
repeat
    $Temp = \varnothing$
    for each $T_{(x,y)} \in TSet_j$ do
        if $Distance(T_{(x,y)}, WA_{(x_j,y_j)}) \leq r$ then
            $Temp = Temp \cup T_{(x,y)}$
    $(x_{mean}, y_{mean}) = (\frac{\sum_{x \in Temp} x}{|Temp|}, \frac{\sum_{y \in Temp} y}{|Temp|})$
    $dis = Distance(Loc_{(x_{mean},y_{mean})}, WA_{(x_j,y_j)})$
    if The movement check of energy monitoring returns 1 then
        $WA_j$ moves through $Path(WA_{(x_j,y_j)}, Loc_{(x_{mean},y_{mean})})$
        $Eng_j = Eng_j - |Path(WA_{(x_j,y_j)}, Loc_{(x_{mean},y_{mean})}|$
until $dis < one\ location$;
```

Algorithm 1 is explained as follows. At the beginning, the temporal variable $Temp$ is initialised as $\varnothing$ (Line 2). After variable initialisation, the tasks within the sensing and communication range of WA_j are recorded in $Temp$ (Lines 3 to 5). Then, the mean (i.e., the average value) of locations of tasks in $Temp$ is calculated and recorded in $Loc_{(x_{mean},y_{mean})}$ (Line 6). After that, the difference between $WA_{(x_j,y_j)}$ and $Loc_{(x_{mean},y_{mean})}$ is calculated and recorded in dis (Line 7). Finally, if the movement check function of the energy monitoring returns 1, WA_j will move from $WA_{(x_j,y_j)}$ to $Loc_{(x_{mean},y_{mean})}$ through the path created by A* search algorithm and WA_j loses some energy for this movement (Lines 8 to 10). The process is repeated until dis is less than one location, which indicates that WA_j has already moved to the highest task density location (i.e., Loc_{high}) in the area (Line 11).

WA_j records Loc_{high} and the number of covered task locations at Loc_{high}. However, since Loc_{high} might be the local highest task density location, if WA_j decides to continue to search in the environment, it should move far away from Loc_{high} until $Loc_{(x_{mean},y_{mean})}$ does not point to Loc_{high} direction. In addition, during the search, WA_j might move within the communication range of another WA (e.g. WA_u). In this situation, WA_j and WA_u will share their collected information (i.e., $Info_j$ and $Info_u$, see Definition 2) with each other.

From the search strategy, it can be seen that in the proposed approach, the movements of WA_j are many short-distance movements. Since $Loc_{(x_{mean},y_{mean})}$ is within the sensing and communication range of WA_j, the information of locations between $WA_{(x_j,y_j)}$ and $Loc_{(x_{mean},y_{mean})}$ can be known by WA_j. In this situation, A* search algorithm is the best choice for path planning, which can quickly create the path between $WA_{(x_j,y_j)}$ and $Loc_{(x_{mean},y_{mean})}$ and avoid sophisticated calculations.

Energy monitoring The energy monitoring of the search module is to update the deployment location during the search and check the energy for each movement of the WA (e.g. WA_j) so as to decide when the WA must stop its search and begin to move to the deployment location. The energy monitoring includes two functions: 1) The deployment location update and 2) The movement check.

Since the deployment module creates real-time suitable deployment location for WA_j based on the current collected information, with the enlarging views of WA_j, the new deployment location (i.e., Loc^{new}_{deploy}) is more suitable than the old deployment location (i.e., Loc^{old}_{deploy}). The deployment location update function must check whether the remaining energy (i.e., Eng_j, see Definition 1) is enough for WA_j to move from current location to Loc^{new}_{deploy}. In the function, first, A* search algorithm is employed to create the path from current location to the new deployment location (i.e., $Path(WA_{(x_j,y_j)}, Loc^{new}_{deploy})$, see Definition 4). After receiving the path, the update of the deployment location is described in Equation 2.

$$\begin{cases} |Path(WA_{(x_j,y_j)}, Loc^{new}_{deploy})| \leq Eng_i & Loc^{new}_{deploy} \\ |Path(WA_{(x_j,y_j)}, Loc^{new}_{deploy})| > Eng_i & Loc^{old}_{deploy} \end{cases} \tag{2}$$

If Eng_i is enough for WA_j to move to Loc^{new}_{deploy}, Loc^{new}_{deploy} replaces Loc^{old}_{deploy}, otherwise, the deployment location is still Loc^{old}_{deploy}.

When WA_j wants to move to a location (i.e., $Loc_{(x,y)}$) through a path (i.e., $Path(WA_{(x_j,y_j)}, Loc_{(x,y)}))$, the movement check function checks that after this movement, whether Eng_j is enough for WA_j to move to the deployment location (i.e., Loc_{deploy}). The check of the movement is described in Equation 3.

$$\begin{cases} (|Path(WA_{(x_j,y_j)}, Loc_{deploy})| + |Path(WA_{(x_j,y_j)}, Loc_{(x,y)})|) \leq Eng_i & 1 \\ (|Path(WA_{(x_j,y_j)}, Loc_{deploy})| + |Path(WA_{(x_j,y_j)}, Loc_{(x,y)})|) > Eng_i & 0 \end{cases} \tag{3}$$

If Eng_j is enough for WA_j to move to Loc_{deploy}, the function return 1, otherwise, the function return 0 and WA_j begin to move to Loc_{deploy}.

3.2 The deployment module

In this subsection, the theoretical background and the deployment location finding of the deployment module are introduced in detail.

The theoretical background Since the coverage areas of WAs are circles, the problem of deploying WAs to cover task locations is the same as the problem of using circles to cover scattered points. In paper [Guo et al., 2010], [Hochbaum and Maass, 1985], authors pointed out that if a circle can cover the maximum number of scattered points, there are at least two points on the border of the circle. Based on this, Theorem 1 is proposed as follows.

Theorem 1. *Given two locations in a space and the radius r of the circle, if the distance between the two locations is less than $2 \cdot r$, two new locations can be found. If the centre of the circle at one of two locations, two given locations are on the border of the circle.*

Proof. If the two locations are on the border of the circle, the line between the two locations is a chord of the circle. Since, the perpendicular bisector of the chord passes through the centre of a circle, one of two locations, the centre of the circle and the midpoint the chord form a right-angled triangle. According to the pythagorean theorem, the distance between the centre of the circle and the chord is $c = \sqrt{r^2 - (\frac{Distance(two\ points)}{2})^2}$. In addition, the $(\frac{Distance(two\ points)}{2})^2 \leq r^2$ so that $Distance(two\ points) \leq 2 \cdot r$. The centres of the circle are the two new locations, which are symmetric on the both side of the chord.

Theorem 1 is represented by $(Loc_{c_1}, Loc_{c_2}) = CentreLoc(Loc_{(x_1,y_1)}, Loc_{(x_2,y_2)}, r)$ in this paper, where $Loc(x_1, y_1)$ and $Loc(x_1, y_1)$ are two given locations in the environment. If the distance of them less that $2 \cdot r$, Loc_{c_1} and Loc_{c_2} are two new locations found by Theorem 1.

The deployment location finding The deployment module find the most suitable deployment location for a WA (e.g. WA_j) based on the current information collected by the search module (i.e., $Info_j$, see Definition 2). According to whether WA_j has collected information of ad hoc networks in the environment, the deployment location finding process can be divided into two situations: 1) The deployment location finding without information about ad hoc networks and 2) The deployment location finding with information of ad hoc network.

The deployment location finding without information of ad hoc networks: If WA_j has not collected information of ad hoc network in the environment (i.e., $ASet_j = \varnothing$, see Definition 2), it will establish an ad hoc network by itself. Since the coverage area of a WA is fixed, the deployment location of WA_j should be the highest task density location (i.e., Loc_{high}) that can cover the maximum number of task locations.

The deployment location finding with information of ad hoc networks: If WA_j has collected information of ad hoc networks in the environment (i.e., $ASet_j \neq \varnothing$, see Definition 2), it will join the ad hoc network (e.g. $ANet_k$) including the most number of WAs. The three objectives of the ad hoc network established for TBWSD should be achieved after WA_j joining $ANet_k$. Therefore, the deployment location of WA_j should be able to communicate with one WA in $ANet_k$. According to Fig.1., the optimal distance between two WAs in an ad hoc network is r. In order to cover the maximum number of task locations, based on Theorem 1, the deployment location of WA_j can be decided by two locations in the environment. Therefore, the deployment location of WA_j is decided by two locations (i.e., one location of a WA in $ANet_k$ (i.e., $WA_j \in WASet_k$, see Definition 3) and one location of an uncovered task (i.e., $T_{(x,y)} \in TSet_k^U$, see Definition 3)).

The detail deployment location finding process of WA_j with information of ad hoc networks is described in Algorithm 2.

Algorithm 2: The deployment location finding process of WA_j:

```
1  $Temp = \varnothing$
2  for each $T_{(x,y)} \in TSet_k^U$ and $WA_u \in WASet_k$ do
3      if $Distance(T_{(x,y)}, WA_{(x_u,y_u)}) \leq 2 \cdot r$ then
4          $(Loc_{c_1}, Loc_{c_2}) = CentreLoc(T_{(x,y)}, WA_{(x_u,y_u)}, r)$
5          $Temp = Temp \cup Loc_{c_1} \cup Loc_{c_2}$
6  for each $Loc_c \in Temp$ do
7      if $Loc_c \neq O_{(x,y)}$ then
8          for each $T_{(x,y)} \in TSet_k^U$ do
9              if $Distance(T_{(x,y)}, Loc_c) \leq r$ then
10                 $TSet_c = TSet_c \cup T_{(x,y)}$
11 choose the $Loc_c$ with $Max(|TSet_c|)$ as $Loc_{deploy}$
```

Algorithm 2 is explained as follows. At the beginning, the temporary variable $Temp$ is initialised to $\varnothing$ (Line 1). After that, all potential deployment locations decided by one location of a WA in $ANet_k$ and one location of an uncovered task are calculated based on Theorem 1 and recorded in $Temp$ (Lines 2 to 5). If the potential deployment location is not occupied by the obstacle, the task locations covered by WA_j, which are uncovered by $ANet_k$, are recorded in $TSet_c$ (Lines 6 to 10). Finally, the potential location that can cover the maximum number of uncovered task locations are chosen to be the deployment location for WA_j (Lines 11).

4 Experiments

Two experiments are conducted to evaluate the performance of the proposed approach (TBWSD). The first experiment is to evaluate the search module of the proposed approach. The benchmark approach in the first experiment is the robot-sensors deployment approach (RSD) proposed by Reich et al. [Reich and Sklar, 2006a]. The second experiment is to evaluate the deployment module of the proposed approach. The benchmark approach in the second experiment is the dynamic relays deployment approach (DRND) proposed by Guo et al. [Guo et al., 2010].

4.1 Experimental settings

In two experiments, 100 tasks and a number of obstacles are randomly distributed in a 50×50 environment. In the first experiment, a WA without knowledge about the environment collects information in the environment based on RSD and TBWSD, respectively, when the sensing and communication range of the WA is 10 locations and the energy of the WA is 80 locations. RSD is a decentralised robot-sensors search and deployment approach, which employs the blind search mechanism to search tasks in a disaster environment. The number of tasks discovered by the WA is the indicator in the first experiment. In the second experiment, 1 to 10 WAs with global knowledge about the environment establish ad hoc networks according to DRND and TBWSD, respectively, when the sensing and communication range of WAs is 10. DRND is a centralised relays deployment approach, which establishes ad hoc networks by covering the maximum number of tasks in the environment. The coverage of tasks, the coverage of area and the objective values (see Equation 1) of the established ad hoc networks are the three indicators in the second experiment.

4.2 The experimental results of the first experiment

The experimental results of the first experiment are illustrated in Fig.3..

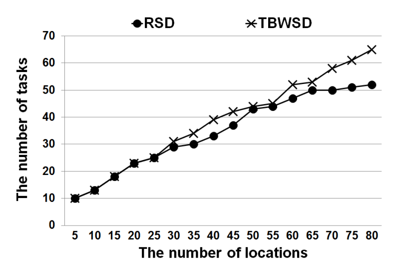
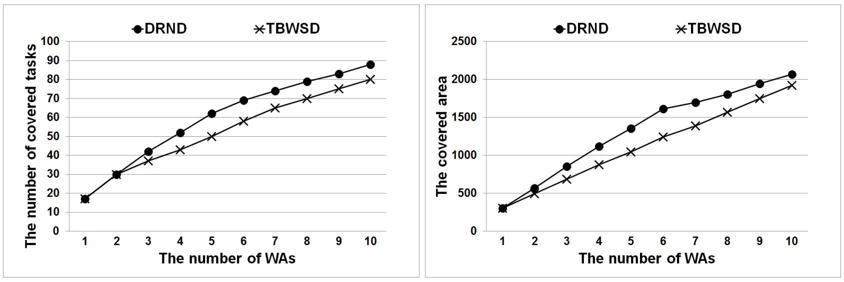


Fig. 3. The experimental results of the first experiment

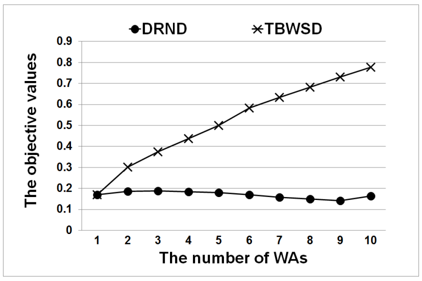
The X-axis of Fig.3. represents the number of locations moved by the WA, while the Y-axis of Fig.3. represents the number of task locations, whose information is collected by the WA. From Fig.3, it can be seen that at the beginning of the experiment, the number of tasks, whose information is collected by the WA based on RSD and TBWSD are the same. This is because that the initial location of the WA in both approaches are the same. After moved a number of locations, the WA based on TBWSD can collect more task locations in the environment than that of RSD. This is because the WA based on TBWSD can move to the locations with highest density of tasks, while the WA based on RSD only randomly moves in the environment.

4.3 The experimental results of the second experiment

The experimental results of the second experiment are illustrated in Fig.4.



(a) The coverage of tasks (b) The coverage of area

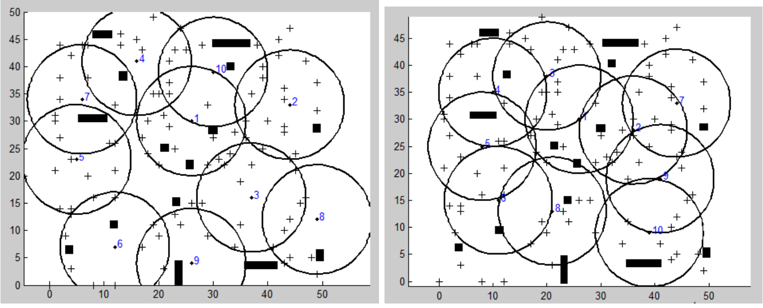


(c) The objective values

Fig. 4. The experimental results of the second experiment

The X-axes of Fig.4 represent the number of WAs, while the Y-axes of Fig.4(a), 4(b) and 4(c) represent the number of covered tasks, the covered area and the objective values of the established ad hoc networks, respectively. From Fig.4(a)., it can be seen that the ad hoc networks established by DRND can cover more tasks in the environment than that of TBWSD. This is because that DRND is a centralised approach without considering the communication of WAs in the established networks so that DRND finds the locations to deploy WAs from the whole environment. While in order to guarantee the communication of WAs in the established networks, TBWSD just finds that kind of locations from the areas around the WAs that have already deployed in the envionment. Therefore, DRND always finds the global maximum tasks covering locations to deploy WAs, while TBWSD just finds the local maximum tasks covering locations to deploy WAs. From Fig.4(b)., it can be seen that the ad hoc networks established by DRND can cover more area in the environment than that of TBWSD. This is because that generally, the global maximum tasks covering locations are far from the coverage areas (communication ranges) of WAs that have already deployed in the environemnt so that the overlaps between the coverage areas of WAs in the ad hoc network established by DRND are small. While in TBWSD, each WA in the ad hoc networks must lose at least 39% of its coverage area (communication range) as the overlap to communicate with another WA, which significantly decreases the coverage area of the established networks. From Fig.4(c)., it can be seen that the objective values of the ad hoc networks established by DRND is less than that of established by TBWSD. This is because that although the ad hoc networks established by DRND can cover more tasks and area in the environment, without the communication of WAs, the objective values of ad hoc networks, which indicate the average work efficiency of each WA, do not increase with the increase number of WAs. While in the ad hoc networks established by TBWSD, although each WA loses at least 39% of its coverage area (communication range) as the overlap to communicate with another WA, the communication of WAs enables information about tasks covered by different WAs to be shared among WAs in the networks so that the objective values of ad hoc networks increase linearly with the increase number of WAs.

The ad hoc networks established by 10 WAs according to DRND and TBWSD are illustrated in Fig.5..



(a) The ad hoc network established by DRND

(b) The ad hoc network established by TBWSD

Fig. 5. The established ad hoc networks

In Fig.5., the crosses represent the locations of stationary tasks, the black rectangles represent the locations of obstacles, the points represent the deployment locations of WAs and the circle areas inside the solid lines represent the communication ranges of WAs. Form Fig.5., it can be seen that the locations of WAs deployed by DRND are scattering and irregular. While the locations of WAs deployed by TBWSD are concentrated and regular, which can communicate one by one and follow the distribution of tasks in the environment.

5 Related Work

Heo et al. proposed a distributed self-spreading approach for deployment of mobile wireless sensors [Heo and Varshney, 2003], which was inspired by the equilibrium of molecules. The strength of interaction forces between two mobile wireless sensors is calculated from the distance between the two sensors. The final location of each sensor is the balance point of interaction forces of its surrounding sensors. The main objective of Heo et al. approach is to minimize the overlaps of coverage areas between sensors so as to maximize the coverage area of the established ad hoc network. Different from Heo et al. approach, our approach not only maximizes the area covered by the network, but also maximizes the number of tasks covered by the network so as to ensure most of tasks in the environment can be performed by the guidance of the established ad hoc network.

Reich et al. proposed an approach for establishing robot-sensor networks for search and rescue [Reich and Sklar, 2006b]. In their approach, a very large number of sensor robots guide a smaller number of mobile robots to perform tasks, which corresponds to WAs and first responders in our approach, respectively. Although Reich et al. approach considers the three objectives of TBWSD, the deployment of sensor robots only relies on a series of hierarchical behaviors, which cannot find the optimal deployment locations that maximize the three objectives of the ad hoc network established for TBWSD. Different from Reich et al. approach, in our approach, the deployment location finding process is based on an enumerating process, which can find the optimal deployment locations for WAs so as to maximize the three objectives of TBWSD.

Guo et al. proposed a dynamic relays deployment approach for wireless networks establishment in disaster environments [Guo and Huang, 2009]. In their approach, the wireless communication devices are taken by the first responders and the relays are deployed to locations where have the highest density of the communication overlaps of first responders. The problem that Guo et al. approach handles is similar with TBWSD. However, Guo et al. assume that the relays are powerful enough to freely communicate with external environments so that the communication of deployed relays is not considered. This assumption limits the application of their approach in disaster environments, when the communication ranges of first responders are limited. In our approach, the objective of the established ad hoc network is to guide first responders to efficiently perform tasks in the disaster environment. The communications of WAs just ensure that the information about covered tasks and first responders can be shared among WAs in the established ad hoc network.

6 Conclusion and Future Work

In this paper, a TBWSD approach is proposed for ad hoc network establishment in disaster environments. The proposed approach enables WAs to efficiently move and collect information in an uncertain environment and establish ad hoc network by considering the communication of WAs, the coverage of tasks and the coverage of area. the experimental results demonstrated that the ad hoc networks established by the proposed approach have better performance than some of current approaches in terms of the three objectives of TBWSD. In the future, we will extend the proposed approach to handle the dynamic changes of disaster environments.

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