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Research Article

Multi-robot Exploration of Unknown Environment Using 2D Laser Scanner

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Abstract: In this study, exploration of unknown environments using LMS 200 Laser scanners with a team of multiple mobile robots is investigated. The aim is to investigate the ability of the cheap LMS 200 laser scanners to scan the environment and build its map. Furthermore, this study proposes two exploration algorithms to reduce the time required to explore a given environment using this type of laser scanners. Each robot is equipped with a single 2D LMS 200 laser scanner which is very cheap compared with 3D rotating laser scanner to explore its surroundings. The proposed exploration algorithms are intensively assessed with this laser scanner. The results of these tests showed that this laser scanner is able to effectively explore unknown environments. Furthermore, the results showed that the proposed exploration algorithms have increased the exploration efficiency by reducing the exploration time. A comparison among different exploration algorithms has showed the effectiveness of the proposed ones compared with the already exist ones.

Keywords: Algorithm, map, robot cooperation, simulation

INTRODUCTION

Range sensing is an important element of any exploration system for mobile robots. There is wide range of sensors suitable for exploration and mapping tasks such as: Infrared sensors, Ultrasonic sensors, Radar, 2D Laser scanners and 3D laser scanners (Ye and Borenstein, 2002). A detailed discussion on the state-of-the-art with some of these sensors is presented in Hebert (2000).

Infrared sensors provide low range coverage, less than 1 m in most cases, this is due to the fact that the emitted energy is not intensively concentrated. The main drawback for this type of sensors is that their readings are affected by the type of the materials that the energy is reflecting from. On the other hand, Infrared sensors are very cheap and reliable for many applications. For instance, they can be successfully employed to detect obstacles very close to the robot. Vision sensors are another important kind of sensors that are capable of collecting rich information about the robots environment. For instance, a camera installed on-board the robot can provide much more detail than other sensors. However, using such sensors is very slow and computationally expensive. In addition, these sensors need complex and robust algorithms to perform well. Moreover, sonar sensors can be used for exploration tasks. However, with this type of sensor, it is not possible to measure object distance by one reading. More than one reading is always required. This is due to the fact that these sensors are of wide beam perception (Hebert, 2000).

The most suitable sensors for exploration tasks are Radar and Laser sensors (scanners). Radar sensors depend on the time-of-flight and frequency to measure the distance to an object. They are suitable for long distance measurements such as air traffic control. However, Radar sensors are sensitive to atmosphere conditions and their angular resolution is low. Similarly, laser scanners also depend on the same time-of-flight concept but they are very accurate sensors with an accurate angular resolution and can measure objects from a relatively long distance. However, laser scanners are much more expensive than other sensors.

Given the current state-of-the art it is expected that a 3D laser scanner would be the best choice for building 3D maps and also it can be used to build a 2D map. However, 3D scanners are very expensive compared to 2D laser. Moreover, 3D laser scanners are not fast enough for exploration and map building in real time on a fast-moving vehicle, due to the slow vertical scan (Hebert, 2000; Amigoni and Caglioti, 2010).

In this study, instead of expensive 3D laser scanner, a 2D Sick laser scanner LMS 200, shown in Fig. 1a, is employed by a team of mobile robots to explore and model unknown environments based on advanced exploration algorithms. As the 2D laser scanners provide less information about the environment than 3D laser scanners, the environment is to be modelled as a simple 2D grid-based map. The performance of the 2D LMS 200 sick sensor will be evaluated with some of the well-known exploration algorithms available in the literature and also it will be assessed with newly proposed exploration algorithms.

(a)

(b)

Fig. 1: (a) sick laser scanner LMS 200, (b) direction of transmission for; LMS 200 (www.sick- automation.ru)

LITERATURE REVIEW

In this section, a number of most related articles to the work presented in this study are summarized and investigated. Most of the published multi-robot exploration algorithms have relied on the use of "frontier cells" e.g., (Wurm *et al*., 2008; Yamauchi, 1997, 1998; Burgard *et al*., 2005; Sheng *et al*., 2006; Ziparo *et al*., 2007; Fox *et al*., 2006; Rocha *et al*., 2005). The concept of frontier-based exploration was initially introduced by Yamauchi (1997). He stated that "To gain the most new information about the world, move to the boundary between open space and uncharted territory". He presented a technique to build grid maps by which the environment is represented by evenly-spaced grids (2D map). Each grid cell has a numeric value that indicates the presence of an obstacle in the corresponding region of the environment. Yamauchi (1998) argued that to discover the environment, each robot moves towards the closest frontier cell. A frontier cell is a free (not occupied) cell for which at least one of its neighboring cells is unexplored. When a robot is directed to such a cell, it is expected that it will gain information about the unexplored area when it arrives. Because a map may contain more than one unexplored areas, the challenge arises of how to plan the exploration mission by choosing the most appropriate frontier cell. When more than one robot is involved in the exploration, it is important to avoid more than one of them moving to the same cell. However, Yamauchi (1998) did not consider this problem and in his technique more than robot may go to explore the same frontier cell and then more time is required to accomplish the exploration task.

Burgard *et al*. (2005) proposed a more advanced technique in which 2D occupancy grid maps were employed to represent the environment to be explored. The exploring robots start at known initial positions. The aim is to minimize the overall exploration time by choosing suitable target points (frontier cells) for individual robots so that they explore different sections of the environment and the overlapping between them is reduced. In this technique, each robot chooses its next target cell by calculating a bidding value for each target cell. The bidding value of a frontier cell depends on the utility of the frontier cell (the area of environment that is expected be explored if the robot visits the frontier cell) in addition to the distance from the robot to the frontier cell. The bidding value of a frontier cell is the difference between the frontier utility and cost. The robot chooses the frontier cell which has maximum bidding value and then it plans a path to this target cell.

A relatively different technique from Burgard's was presented by Sheng *et al*. (2006). He considered the limited communication range between the robots. A nearness measure was introduced in the bidding algorithm which keeps the robots together within the communication range. Robots start from initial positions which are close to each other and the relative positions are known to all for each robot. The 2D occupancy grid was again used to represent the environment. The bidding function selects the cell with the maximum exploration information and the minimum cost with respect to each robot.

Ziparo *et al*. (2007) presented a nontraditional technique in which the goal is to reduce the size of the search area by using Radio Frequency Identification (RFID) tags as coordination points. Robots, in this technique, deploy tags in the environment to form a network of reachable locations. In this approach, a two-layered algorithm is used. At the first layer, there is a local part, where robots are coordinated by RFID chips and perform a local search. And at the second layer, based on the local part, there is a global part which is responsible for monitoring the local exploration.

In summary, in frontier-based exploration technique robots are directed to the front lines of the so-far explored area which are the edges between explored and non-explored regions. But how each robot finds its next target or future cell? The general solution is based on a bidding value calculated for each frontier cell. The bidding value mainly depends on the distance and on the utility of the frontier cell. The robot then chooses the frontier cell that has the maximum bidding value as a next target. A path to the target is then panned and the robot start moving towards it target cell.

In all of the above mentioned research works, the exploring robot senses the neighboring cells using range sensors such as sonar or laser rang-finder. Its sensing range is denoted by a circle of a certain radius centered on the robot. Alternatively, in the proposed technique, each robot is equipped with a sick laser scanner of which a sensing configuration is shown in

Fig. 1b. As shown, in each scan measurement, it scans only 180° instead of 360°. Furthermore, two new exploration algorithms are proposed to increase the laser scanner efficiency in exploring unknown environments.

EXPLORATION WITH LASER SCANNER

The aim of the exploration task is to build a model (map) for the environment with minimum time. The map is an m-by-n grid of square cells, each cell of which is allocated a code to represent its occupancy status, free, occupied or unknown. Each robot is equipped with a LMS 200 Sick laser scanner which can detect the occupancy status of cells which lie in its field of view (180°) and with a distance up to 20 cells (Fig. 1b).

Each robot scans 180° in front of its body as shown in Fig. 1b and then it publishes the collected information to its partners. The published information includes the coordinates of the scanned cells and the result of scanning (either zero if the cell is free or one if it is occupied). The partners instantly include this information into their local maps. After that the robot selects its next target cell. The selection procedure depends on the exploration algorithm used. The details of these algorithms are given later. Then each robot plans its optimal path to the target cell selected and starts moving towards its target cell. The path planning algorithm employed is A* algorithm which is explained in Digor *et al*. (2010). The A* path planning algorithm is chosen as it requires relatively low computations. Once reached, the robot makes another 180° scan starting from where the last scan finished. In other words, it completes 360° for each two scans.

The performance of the LMS 200 Sick laser scanner is to be assessed with the following exploration algorithms:

- **Algorithm 1 (random selection algorithm):** In this algorithm, the robot randomly selects one of the frontier cells available in its local map to be its next target cell. This technique is presented in (Sheng *et al*., 2006) and is introduced here for comparison purposes.
- **Algorithm 2 (Yamauchi's algorithm):** This algorithm is presented by Yamauchi (1998). In this algorithm each robot selects the closest frontier cell available in its local map to be its next target cell. Clearly, the main disadvantage of this technique is that the robots are not spread in the environment and more than one robot is expected to explore the same area. Such a behavior leads to a significant increase in the exploration time.
- **Algorithm 3 (Sheng's algorithm):** This algorithm is presented by Sheng *et al*. (2006). In this algorithm, to reduce the potential overlap, the robot chooses the closest frontier cell but not within a sensor range of any other robots. To save time, it is very important to avoid that more than one robot go to explore the same area or the same cell. Sheng did not effectively solve this problem. For example, it is noticed that when more than one robot are close to each other, according to sheng's technique, each robot chooses a target cell that is away from its neighboring colleague. As they close to each other they may chose two target cells which are close to each other. In such a case, they go to explore the same area or even they may choose the same target cell. This behavior significantly increases the time required to explore the environment.
- **Algorithm 4 (newly proposed):** This algorithm is proposed to in this research work to solve the above mentioned problem of sheng. It is an extension for Sheng's algorithm. In this algorithm the robot chooses the closest frontier cell that is not in a sensor range of any target cells for any other robots. Choosing a target cell that is relatively far away from the target cells of other robots seems to be better than choosing a target cell far away from other robots.

The environment E can be represented as:

$$E = C \cup O \cup U \tag{1}$$

where,

- E : Set of all environment cells
- C : Set of environment cells that are explored by any robot and found to be free
- U : Set of environment cells that are not yet explored by any robot
- O : Set of environment cells that are explored by any robot and found to be occupied

This algorithm (Algorithm 4) can be formulated as follows:

- Make 180° scan, integrate sensor measurement and update the map. Publish the new information collected by this scan to other robots.
- Determine the set of frontier cells F by checking for every cell in the candidate set C if it is adjacent to, at least, one unknown cell:

$$F = \left\{ E_{[xy]} \middle| E_{[xy]} \in C, \exists E_{[(x+i)(y+j)]} \in U, i \in [-1,1], j \in [-1,1] \right\} \tag{2}$$

If $F = \phi$, the exploration is completed.

- Build the subset F_g of frontier cells which are not within sensor range distance from any other target cell g of any other robot.
- If $F_g \neq \phi$, Choose the closet $C_{[xy]} \in F_g$ to be the next target cell, otherwise, If $F_g \neq \phi$, choose the closest frontier cell $C_{[xy]} \in F$ to be the next target cell.

- Plan the path to the target cell g with A* path planning algorithm (Ziparo *et al*., 2007). Follow the path to the target cell.
- Go to step 1.

- **Algorithm 5 (newly proposed):** In this algorithm the robot chooses the closest frontier cell that is not within sensor range of any target cell for any other robots as in algorithm 4. But, if a target cell for a given robot has been scanned by any other robot before it is reached by the robot in question, the robot stops moving towards it and instantly finds another target cell. Such a case happens when, for example, robot (a) is approaching its target cell and before reaching it, it is scanned by robot (b). Now robot (a) finds another target cell and ignores its current one as the benefit of visiting it is much less now.

  This algorithm (Algorithm 5) can be formulated as follows:

- Make 180° scan, integrate sensor measurement and update the map. Publish the new information collected by this scan to other robots.
- Determine the set of frontier cells F by checking for every cell in the candidate set C if it is adjacent to, at least, one unknown cell (see (2)).
- If $F = \phi$, exploration is completed.
- Build the subset F_g of frontier cells that are not within sensor range distance from any other target cell g of any other robot.
- If $F_g \neq \phi$, Choose the closet frontier cell $C_{[xy]} \in F_g$ to be the next target cell *g*. Otherwise, if $F_g = \phi$, choose the closest frontier cell $C_{[xy]} \in F$ to be the next target cell *g*.
- Plan the path to the target cell *g* with A* path planning algorithm.
- As long as the goal target cell is still a frontier cell: $g \in F$, keep on moving towards the target cell g. Otherwise, stop moving and go to step 2, if you reach the cell *g* go to step 1.

All of these algorithms are proposed to enhance the coordination among robots in exploration tasks with more than one robot. Their main aim is to reduce the exploration time to complete the exploration. These algorithms are not designed to enhance the exploration tasks with single robot.

RESULTS AND DISCUSSION

The exploration algorithms are simulated in simulation software Wilensky (1999), Netlog is built with Java and enables the computer-based investigation of the exploration process by a number of robots in an occupancy-grid-based environment. The environment is simulated as an m-by-n grid of square cells. Each cell has information about itself stored in variables.

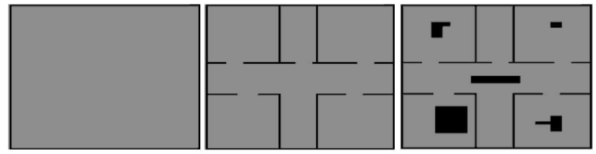

Fig. 2: The environments used to test the exploration algorithms, (a) 50-by-50 square free-of-obstacles environment, (b) 100-by-100 office-like free-of-obstacles environment and (c) 100-by-100 office-like environment with some arbitrary obstacles

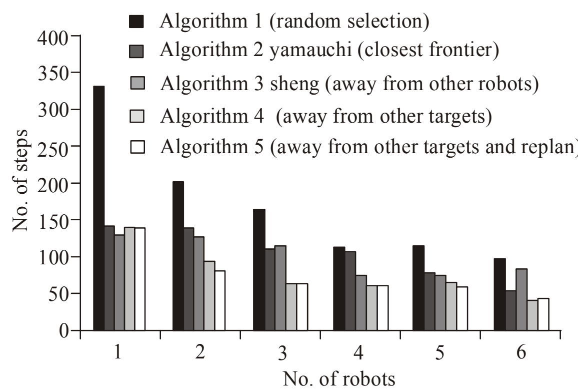

Fig. 3: Exploration time (time steps) versus number of robots for the environment the square-shape environment shown in Fig. 2a

The experimentations started with the above mentioned known exploration algorithms from the literature (Algorithm 1, 2 and 3, see above section). These approaches are introduced here just for comparison purposes. This comparison will show the effectiveness of the proposed algorithms. Then the experimentation proceeds with the newly proposed exploration algorithms (Algorithm 4 and 5). Fig. 2 shows the environments that used to test the algorithms. The five algorithms are tested as follows.

Free-of-obstacles environment: The experimentation started with a 50-by-50 square-shape environment without obstacles shown in Fig. 2a to assess the performance of the exploration algorithms in free space. Each algorithm is tested with different numbers of robots (1 to 6). For instance, Algorithm1 (Random selection) was tested with one robot and time to complete the exploration is recorded. Then it is tested with two robots and time is recorded. This procedure is repeated until the number of robots is six. Same procedure is repeated for the other algorithms. The results are shown in Fig. 3.

Figure 3 shows that the two proposed exploration algorithms: algorithm 4 and 5 has significantly reduced the exploration time compared with other algorithms. The results show that the efficiency of the proposed algorithms increases when more robots are used. Their results are close to each other. Generally speaking, in

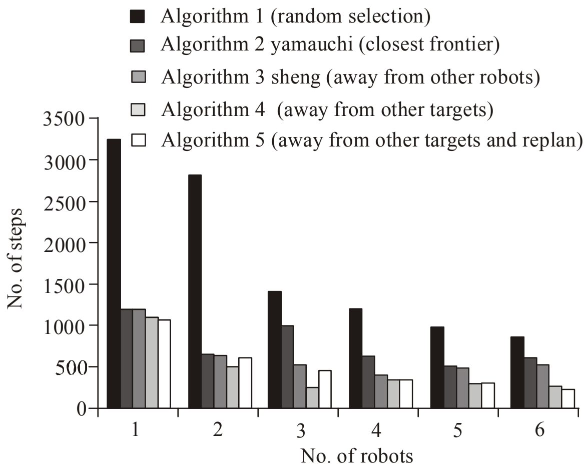

Fig. 4: Exploration time (time steps) versus number of robots for the environment the office-like environment shown in Fig. 2b

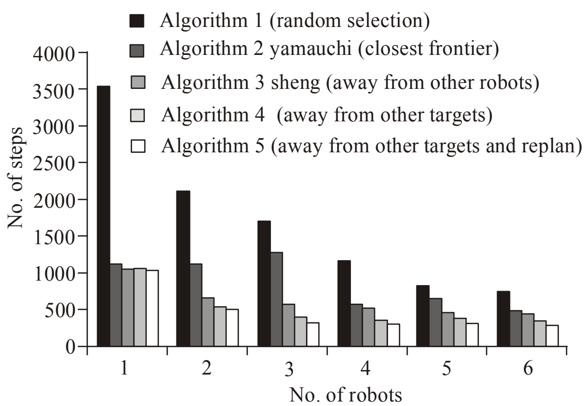

Fig. 5: Exploration time (time steps) versus number of robots for the environment the office-like environment shown in Fig. 2c

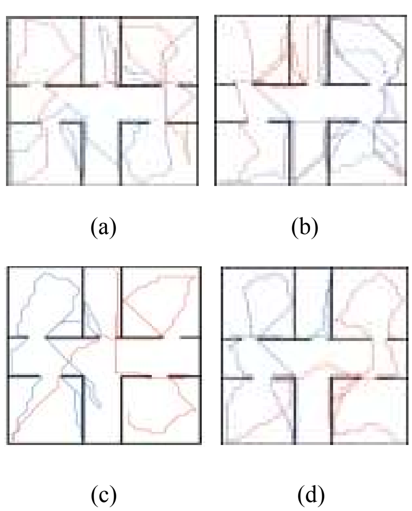

Fig. 6: The trajectories of two robots for the exploration algorithms after exploring the environment shown in Fig. 2b, (a) with algorithm 2, (b) with algorithm 3, (c) with algorithm 4, (d) with algorithm 5

open areas, Algorithm 4 and 5 are more efficient than others.

Office-like environment without obstacles: The experimentation proceeded with the 100-by-100 office-like environment without obstacles shown in Fig. 2b to assess the performance of the exploration algorithms in an office-like environment. As before, each algorithm is tested with different numbers of robots (1 to 6). The results are shown in Fig. 4. Figure 4 shows that the two proposed exploration algorithms: algorithm 4 and 5 have also reduced the exploration time compared with other algorithms.

Office-like environment with some arbitrary obstacles: The experimentation proceeded with the 100-by-100 office-like environment with some obstacles shown in Fig. 2c to assess the performance of the exploration algorithms in an office-like environment when some arbitrary obstacles are added. As before, each algorithm is tested with different numbers of robots (1 to 6). The results are shown in Fig. 5. Figure 5 shows that, as before, the two proposed exploration algorithms: algorithm 4 and 5, as before, have also reduced the exploration time compared with other algorithms.

Figure 6 shows samples of the exploration experiments trajectories of two robots, (a): with Algorithm 2, (b): with Algorithm 3, (c): with Algorithm 4 and (d): with Algorithm 5. The trajectories show that in the proposed algorithms 4 and 5 the trajectories are less nervous than others. This is due to the fact that theses algorithms spread the robots over the environment and each robot go to explore certain part (room) of the environment. While in Algorithm 2 (Yamauchi, 1998)) and Algorithm 3 (Sheng *et al*., 2006) more than one robot go to explore the same room and as a result, more time is required to finish the environment exploration.

CONCLUSION

In this study, 2D Laser Scanner is used to explore unknown environment with a team of mobile robots. This type of laser scanners is used as it is much cheaper than the 3D laser scanners. The experiments showed that this type of laser scanners is efficient to do the task of exploration with different exploration algorithms. More importantly, two new algorithms are proposed to decrease the exploration time. The main idea of the first algorithm (algorithm 4) is that each robot chooses a target cell that is with a certain distance from other target cells of the other robots. This technique has been very successful and more efficient than other ones from the literature in spreading the robots over the environments and avoid that more than one robot go to explore the same area. In the second proposed technique (Algorithm 5) same procedure of Algorithm

4 is used with one adjustment. But in Algorithm 5, while a robot is approaching a given goal cell and this goal cell is scanned by any other colleague before the robot reaches it, the robot stops moving and selects another new target cell. Generally, Algorithm 5 is slightly bitter and more efficient than Algorithm 4. However, these algorithms need to be tested with more real world restrictions such as communication loss and robot localization problems.

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