

Multi-Robot Cooperation for Efficient Exploration

DOI 10.7305/automatika.2014.12.648
UDK 004.932'1
IFAC 5.9.3; 2.5

Original scientific paper

This paper addresses the problem of exploration of an unknown environment by developing effective exploration strategies for a team of mobile robots equipped with continuously rotating 3D scanners. The main aim of the new strategies is to reduce the exploration time of unknown environment. Unlike most of other published works, to save time, the laser scanners rotate and scan the environment while robots are in motion. Furthermore, the new strategies are able to explore large outdoor environments as a considerable reduction of the required computations, especially those required for path planning, have been achieved. Moreover, another new exploration strategy has been developed so that robots continuously replan the order to visit the remaining unexplored areas according to the new data (i.e. updated map) collected by the robot in question or by the other team members. This new extension led to further enhancements over the above mentioned ones, but with slightly higher computational costs. Finally, to assess our new exploration strategies with different levels of environment complexity, new set of experiments were conducted in environments where obstacles are distributed according to the Hilbert curve. The results of these experiments show the effectiveness of the proposed technique to effectively distribute the robots over the environment. More importantly, we show how the optimal number of robots is related to the environment complexity.

Key words: Multiple robots, Rotating scanner, Robotic mapping

Koordinacija više robota za učinkovite pretraživanje prostora. Ovaj članak istražuje problem pretraživanja nepoznatog prostora razvijanjem učinkovite strategije za tim mobilnih robota s rotirajućim 3D laserskim senzorom. Glavni cilj ove nove strategije je smanjenje vremena pretraživanja nepoznatog prostora. Za razliku od većine objavljenih radova, u ovome članku, radi smanjenja vremena, laserski senzori rotiraju i snimaju prostor dok su roboti još u pokretu. Predložene strategije, pošto se njima znatno smanjuje računaska složenost, pogotovo za planiranje gibanja, omogućuju pretraživanje i vanjskih prostora prostora velikih dimenzija. Nadalje, razvijena je još jedna strategija pretraživanja koja omogućuje robotima da kontinuirano replaniraju poredak kojim će posjetiti ostatak neistraženog prostora, prema novim podacima (ažuriranoj karti) prikupljenim od njih samih ili drugih članova tima. Ovo novo proširenje nadalje unaprjeđuje performanse algoritma, ali uz nešto veću računsku složenost. Kako bi se u konačnici testirale nove strategije pretraživanja na prostorima različite složenosti, provedeni su eksperimenti s preprekama raspoređenim po Hilbertovoj krivulji. Rezultati eksperimenata pokazuju učinkovitost predložene metode u prostornom raspoređivanju robota. Od posebne je važnosti istaknuti da se u članku također istražuje odnos između broja robota i kompleksnosti prostora.

Ključne riječi: tim robota, rotirajući laserski senzor, robotsko mapiranje prostora

1 INTRODUCTION

Exploration is the “act of moving through an unknown environment while building a map that can be used for subsequent navigation” [1]. Exploration and map-building of an unknown environment is one of the main issues in autonomous mobile robotics due to its wide range of real world applications. Such applications may include search and rescue, hazardous material handling, military actions, planetary exploration, path planning, and devastated area exploration [2].

Mobile robots need a map to effectively navigate in their environment. The ability of mobile robots to autonomously move in an unknown environment to gather the sensory information required to build a map for navigation is called autonomous exploration. Generally, an autonomous robot is able to incrementally construct a model (map) for its environment based on the sensory information gathered in an online fashion, i.e., while navigating through the environment. This process requires choosing the best next place for the robot to visit, planning the short-

est paths to reach this next place and controlling the robot's motion during its movement.

Simultaneous localization and mapping (SLAM) technique is often used to construct a map for the environment and localize the robots on it [1]. As the robots move to unexplored new areas, these areas are then included in the map. The main challenge in autonomous exploration is how robots plan the order to visit the remaining unexplored areas while minimizing the total traveled distance [3]. The problem of SLAM is out of the scope of this paper as the aim is to improve the exploration strategy.

The use of cooperative multi-robot systems for exploration of unknown environment has several advantages over single robot systems. Mainly, cooperating robots have the ability to perform a single task quicker than a single robot because the exploration is performed simultaneously [4]. Moreover, using several robots introduces redundancy which makes teams of robots more fault-tolerant than only one robot. One more advantage of robot teams is due to the merging of overlapping information that can help compensate for sensor uncertainty. For instance, a team of robots has been shown to localize themselves more efficiently and precisely, especially when they have different sensor capabilities. On other hand, when robots operate in teams or groups there is the risk of possible interferences between them. "For example, if the robots have the same type of active sensors such as ultrasound sensors, the overall performance can be reduced due to cross-talk between the sensors. Also, the more robots are used the longer detours may be necessary in order to avoid collisions with other members of the team [5].

This research work seeks to extend existing exploration and mapping techniques of single robot to multi-robot in order to increase the exploration efficiency (i.e. to reduce the environment exploration time to accomplish the exploration task). The goal of the proposed method is to have multiple mobile robots exploring a given unknown environment as fast as possible, while coordinating their actions and sharing their local maps in certain time instances in order to save time and robot motor energy. In the suggested technique, each robot is equipped with a laser scanner that is continuously rotating to scan the environment, and is employing a frontier-based exploration algorithm which is important to guide the robots during the exploration. New and improved strategies are proposed to allow the individual robots in the team to efficiently select their next goal target cells. The new strategies were intensively tested. The results show that the new technique is robust and led to promising results. However, more real world constrains (such as localization problem) are to be involved in the next stage of this research work. More importantly, the new technique led to a dramatic reduction of the required computation for the exploration task.

Figure 1 shows the mobile robot Irma3D with its rotating laser scanner, a RIEGL VZ-400 (see [7]) which continuously rotates around the vertical axis and is therefore capable of acquiring 3D scans while in motion. A model of the robot and the laser scanner is built in [7] to implement the new proposed multi-robot exploration strategies.

In this paper, we continue to use the same robot and scanner models used in the work of [7] and the preliminary study [6]. The work in [7] is restricted to one robot. In [6] we extended the work in [7] to more than one robot. To reduce the overlap among robots, we used a bidding function that is calculated for each frontier cell. Each robot calculates the bidding value for each frontier cell in its map and then it selects the frontier cell with maximum bidding value to be the next target. In this research work, to further reduce the exploration time, we propose a new exploration technique that spreads the robots over the environment in a more effective way. Further more, we employ continuously replanning strategy in which robots don't have to reach the recently explored target cells. Instead, they find a new target cell. Moreover, according to the proposed algorithm, there is no need to calculate a bidding value for each frontier cell. This allows for exploration of outdoor large environment.

We consider a robot with a constantly spinning laser scanner, where we look at different revolution speeds, which correspond to our hardware the Riegl VZ400 (cf. Fig. 1), which originates from geodetic surveying. The Riegl VZ400 scanner is a 3D scanner that produces high-precise 3D point clouds. Faster scanning than acquiring a 3D scan in 6 seconds is not supported by the hardware, while the rotation speed can be reduced to yield higher-density range values. Typical coarse, i.e., 6 second scans, yield 300.000 points, while 22.500.000 points are obtained when the scan time is adjusted to 3 minutes.

Spinning the scanner while moving imposes several challenges for the underlying SLAM problem. In [8,9] the odometry/IMU was used to create a 3D scan while moving. [10] provided a rotating scanner and matched a start and end of a rotation for point cloud optimization. [11] considered also spinning SICK laser scanners. Their point cloud optimization algorithm considers planar patches extracted from a sweep and deforms the trajectory using a spline. Recently, we provide in [12] a full 6 degree of freedom solution for trajectory optimization for constantly spinning laser scanners without relying on feature extraction. With these emerging results from the SLAM community, this paper focuses on exploration strategies. The overall goal is to build a complete SPLAM (simultaneous planning localization and mapping) system.

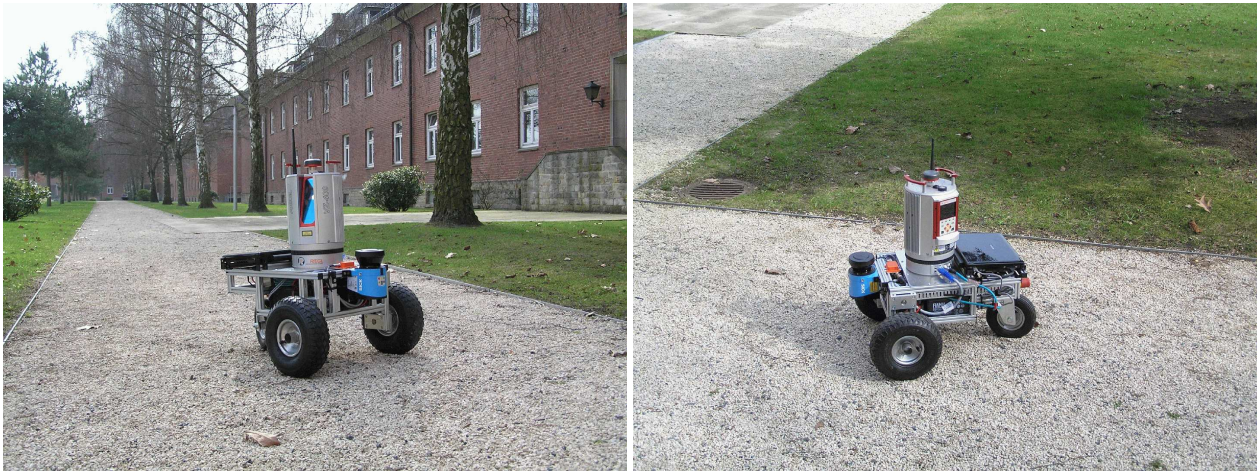


Fig. 1. The mobile robot Irma3D with its sensor: RIEGL VZ400, SICK LMS100, xsens gyro and wheel encoders. The VZ400 needs at least 6 seconds for one revolution [6].

2 RELATED WORK ON EXPLORATION TECHNIQUES

Most of recently published works in the field of robot exploration are based on Yamauchi's technique [13] in which the robots are directed to the edges between the explored and unexplored areas (i.e. frontier cells). The frontier-based exploration concept is still intensively used as a movement strategy [14–18]. All of these research works use a stop-scan-plan-go exploration strategy in which the robot is in a cycle starts with stopping in its target or starting position and makes a complete 360°, then it plans where to go in its next step. Then it starts moving toward its target, when reached, it stops again and the procedure repeats. In the above mentioned works, the decision where to go in the next step is based on computing of a bidding value for each frontier cell. The cell with maximum bidding value wins the bid and the robot starts moving toward it after planning the optimal path. The bidding value mainly depends on the length of the free-obstacles path from the robot to the target frontier cell in question. Utility, which represents the size of the area which is expected to be explored when the robot visits the frontier cell, is another parameter that is included in the bidding function when quick exploration of a relatively big portion of the environment is desired. Finally, in multi-robot systems, a third parameter is introduced in the bidding function to spread the robots in the environment in order to reduce the overlap among them.

For example Sheng et al. proposes a technique in which the robots choose their next frontier target cell according to the bidding function described in Eq. (1) [16].

$$g_i = w_1 I_i - w_2 D_i + w_3 \lambda_i, \quad (1)$$

where g_i is the bidding value for the frontier cell i , I_i the information gain (same as utility) for the frontier cell i (the number of unexplored cells within the robot sensor range but, at the same time, not in the range of other robots or target cells for other robots), D_i the shortest travelling distance to the frontier cell i , λ_i is the nearness measure, and w_1 , w_2 , and w_3 are the weights for these three parameters. The nearness measure is included in this equation to keep the robots close to each other to guarantee the communication amongst them.

In this technique, each robot has to calculate the bidding function represented by equation (1) for each reachable frontier cell in its map. It is clear that this procedure requires huge computation capabilities especially when a large environment is to be explored. This is due to the fact that in large environments, larger number of frontier cells is expected to appear during the exploration progression. Most of other techniques use bidding functions which are slightly different from the one used in [18]. Therefore, they also need to calculate the bidding value for every frontier cell.

Zipparo et al. presented [19] 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.

Burgard et. al. proposed [5] a technique with a slightly different bidding function. In this technique, the environ-

ment to be explored is represented as a 2D occupancy grid map. 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.

3D exploration technique with multiple robots is proposed by R. Roucha et. al [20]. They proposed a grid-based probabilistic model of a 3D map, which stores for each cubic cell a coverage information. The approach employs frontier-based exploration in which robots explore (move) according to bidding function depends on the frontier cells' utility and travel cost. At the beginning of the exploration process an initial map is given to the robot. After that it gets a new set of measurements, updates the map, and shares useful information with other robots. Then it might receive information from other robots and the map is updated according to this information. After getting the new map, a new viewpoint for the sensor is chosen and the robot starts moving accordingly. The robot continues updating the map whenever new data is received from other robots during their navigation. Once the robot reaches the new target position, the process is repeated with a new batch of measurements provided by the sensor from its new pose.

In the further research of Grabowski et al. an exploration algorithm for a team of mobile robots is proposed that exchange mapping and sensor information [21]. In this system, one robot plays the role of team leader that integrates the information gathered by the other individual robots. This team leader controls the movement of other robots to unknown areas.

In this paper, we propose a more effective procedure to select a suitable target cells without using a bidding function. This procedure leads to a significant reduction in the computation complexity required. Moreover, unlike other techniques, robots scan and collect data while moving in the environment during the exploration. Finally, the proposed technique spreads the robots over the environment in a way so that the overlap among robots is minimized.

3 THE PROPOSED TECHNIQUE: EXPLORATION STRATEGIES

The proposed technique aims to improve the way in which robots select their target cells in order to reduce the exploration time and to reduce the computation complexity. In the proposed strategies, the laser scanner of each robot rotates, i.e., scans the environment, all the time and not only when the robot reaches its target. Also, the utility factor is ignored as the proposed technique is designed for full exploration of the environment and not for a quick exploration for a relatively big portion of it. In some applications, the aim is to explore a certain portion, for example 90%, of the environment quickly and not to fully explore the environment. In such applications the parameter utility seems to be important.

The following subsections give a detailed explanation of the newly proposed exploration strategies.

3.1 Stop-scan-replanning-go strategy

In this strategy, we use the known path planing algorithm "Breath-First" as an exploration method. Breath-First is a computational method that can find the optimal path and the distance between two points taking into account the presence of obstacles if any. The robot processes the closer cells before farther ones. As a result, when the robot detects the first frontier cell with Breath-First, it must be the closest frontier cell. More information about the Breath-First Algorithm can be found in [7]. Once found, the selection step is finished and no need to continue with Breath-First algorithm except if the found frontier cell is close to any other target cells for other robot. In particular, no need to find all of the frontier cells and no need to compute the free-obstacles path for them all as in other techniques in the literature. Just the first detected frontier cell is considered, because it is the closest cell.

As the proposed technique is designed for multiple cooperating robots, the problem of overlap among robots needs to be considered. Therefore, when the robot finds its closest reachable frontier cell as described above, it checks if this frontier cell is close to a target cell of other robot, i.e., within the sensor range of target cell of other robot. If so, this frontier cell is temporarily ignored and the robot continues with Breath-First algorithm to find the next closest reachable frontier cell. The process continues until the robot finds a frontier cell that is not within the sensor range of another target cell of other robot. In case that there is no any frontier cell fulfills this condition; the robot selects the closest frontier cell which was initially ignored.

The performance of the exploration strategies is evaluated over the required time (in time steps) to completely explore the environment. One time step is the time required for the robot to scan 72 degree, it is same as the



Fig. 2. The office-like environment used for testing the proposed exploration strategies without obstacles (left) and with some arbitrary obstacles (right) and a simulation snapshot for exploration with two robots (below).

time required for the robot to move from its current location (cell) to an adjacent cell. This scanning data are then published to other robots. Robots are encouraged to spread in the environment to reduce overlap. In particular, each robot is encouraged to go to areas that other robots are not travelling to. It would not be beneficial to direct a robot to explore an area close to a target cell of other robot. It would be more efficient to make only one robot explore that part of the environment. Once a target cell is assigned, the coordinates of this target cell is published to other robots. Some robots might receive this coordinates while travelling or standing on another target cell. Finally, the new information the robot collected during its journey and during standing on the goal frontier cell is broadcasted to the other robots. This information includes the coordinates and the results of the scanning (zero if the cell is free and one if the cell is occupied) of each of the scanned cells. The new information is only available to other robots after the robot sends these data to them, this takes place only after robot finishes its complete 360° scan on its target cell. After broadcasting its new information to other robots, robot starts a new cycle.

The environment E can be represented as $E = C \cup O \cup U$ where E is the set of all environment cells, C is the set of environment cells that are explored by any robot and found to be free, O is the set of environment cells that are explored by any robot and found to be occupied and U is the set of environment cells that have not been explored yet. This strategy can be formulated as given in Algorithm 1.

3.2 Scan-replanning-go strategy

This strategy is similar to the previous one but the robot does not stop to perform a 360° scan when it reaches its target cell. Alternatively, when the robot reaches its target cell, it instantly computes the new target cell and starts travelling toward it. The new information is only available to other robots after the robot sends these data to them, this takes place only after the robot reaches its target cell.

3.3 Continuously-replanning strategy

This strategy is similar to the previous one and also takes advantage of the continuously rotating scanner. But the main difference from other strategies is that if the frontier target cell is opened (scanned), either by the robot in question or by any other robot, while the robot is following a path towards it, the robot instantly publishes its new sensory data and searches for another target cell and changes its path towards the new one. Even if the target cell is not opened while the robot is traveling toward it and the robot reach its target, it does not perform a complete 360° . Instead, it instantly computes the new target cell and starts travelling toward it. Same as before, the new information is only available to other robots after the robot sends these data to them. As in the previous strategy, in this strategy, robots don't implement full 360° scan to save time.

3.4 Classical stop-scan-plan-go strategy

This is a well-known strategy in robot exploration literature. In this strategy, robot stops on its frontier target cell and stay there until it performs a complete 360° scan. Then, it computes the bidding value for each of the frontier cells. The robot starts moving toward its target cell. The main difference between this strategy and the above mentioned ones is that while in motion, robot does not perform scanning.

4 SIMULATION EXPERIMENTATION

The experimentations started with the well-known approach classical stop-scan-plan-go method (see subsection 3.4), which is an extension of art gallery problem. This Fourth approach does not employ the continuous rotating scanner while the robot in motion. Alternatively, the scanner rotates (scans) only when the robot reaches its target cell. This strategy is introduced in this paper just for comparison purposes. Then the experimentation proceeds with the other proposed strategies. The experimentation proceeded as follows:

4.1 Indoor office-like environment

The environments used for testing the exploration strategy are shown in Fig. 2. Each one of the three methods: Stop-scan-replanning-go, Scan-replanning-go and Continuously-replanning in addition to the classical Stop-scan-plan-go, are tested as presented next.

Algorithm 1 Exploration strategy.

- 1: Make 360° scan, integrate sensor measurement and update the map.
- 2: 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:

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

- 3: If $F = \emptyset$ then the exploration is completed.
- 4: Use the Breath-First algorithm to find the closest reachable frontier cell f_C and include it in the subset F_C of close frontier cells.
Note: The subset F_C is empty before the selection process starts.
- 5: If there are no other target cells for other robots close to f_C , i.e., no other target cells within the sensor range, this frontier cell is selected to be the robot target cell f_g .
- 6: If there is any target cell for any other robot within a sensor range then go to step 4 unless the Breath-First scanned all the frontier cells.
- 7: If the robot still without target cell, then the select closest frontier cell, i.e., the first f_C included in F_C to be the target cell f_g for the robot.
- 8: Plan the path to the target cell f_g . Follow the path to the target cell and in each movement step scan 72° of the environment by the laser scanner.
- 9: Once the target cell f_g is reached, go to step 1.

4.1.1 Rotating speed 72° per second

The rotating speed of the laser scanner is initially set to 72° per second. The exploration experiments were run as follows: Each strategy is tested with different numbers of robots (1 to 5) then the experiment is repeated five times and the average time to complete the exploration is recorded. For instance, stop-scan-replanning-go algorithm was tested with one robot, then this experiment was repeated five times, finally the average time to complete the exploration is recorded. Then it is tested with two robots and repeated five times, and as before, the average time is recorded. This procedure is repeated until the number of robots is five. Same procedure is repeated for the other algorithms. The results are shown in Fig. 3.

It is clear that the exploration time for the three proposed method Stop-scan-replanning-go, Scan-replanning-go and Continuously-replanning is less than the exploration time of classical Stop-scan-plan-go. It is also clear that the continuously-replanning strategy is the fastest. This appears to be due to the fact that performing complete scan for 360° , while the robot standing on the frontier cell, is time consuming and not important, and more importantly, in continuously-replanning strategy robots do not have to waste time moving toward recently explored spots (cells).

4.1.2 Rotating speed 18° per second

The rotating speed of the laser scanner is now set to 18° per second to investigate environment digitalization in a higher resolution. A number of exploration experiments were run as follows:

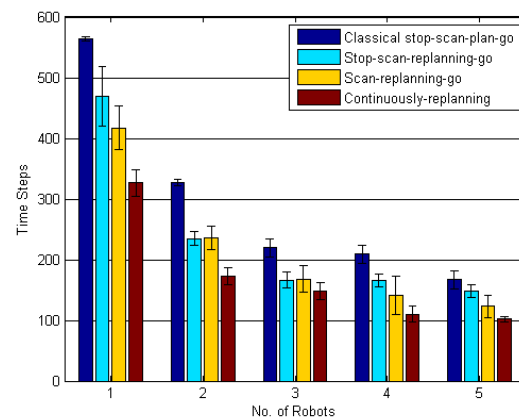


Fig. 3. Exploration time (time steps) versus number of robots when the rotating speed of the laser scanner = 72° per second for environment shown in Fig. 2 (left).

1. The three proposed strategies were tested with different numbers of robots, again 1 to 5, then each experiment is repeated five times and the average time to complete the exploration is recorded. The explored environment is shown in Fig. 2 (left) and the results are shown in Fig. 4 (left).
2. Same experiments mentioned above were repeated in the same environment but with some obstacles added to the environment as shown in shown in Fig. 2 (right). The results are shown in Fig. 4 (right).

Figure 4 (left) shows that the exploration time for the Classical stop-scan-plan-go strategy is the largest among other strategies. Moreover, the exploration time for Stop-

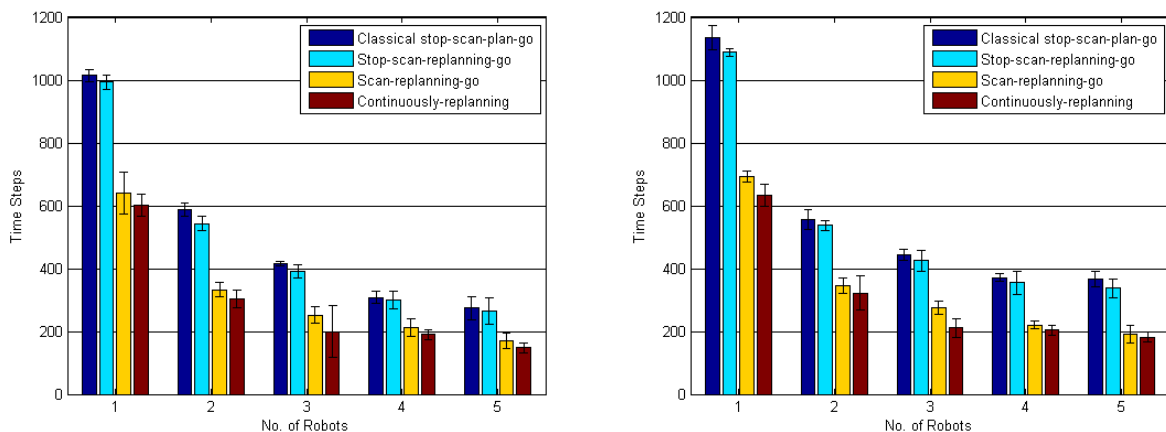


Fig. 4. Exploration time (time steps) versus number of robots when the rotating speed of the laser scanner = 18° per second for the environment without obstacles (left) and exploration time (time steps) versus number of robots for the environment with obstacles (right).

scan-replanning-go is more than the exploration time for Scan-replanning-go strategy and Continuously Replanning strategies. As before, this appears to be due to the fact that performing complete scan for 360° in the frontier cell is time consuming and not important. The figures also show that the Continuously Replanning strategy is still relatively better than Scan-replanning-go strategy. This appears to be due to the fact that robots do not have to reach the frontiers that have just been discovered.

4.2 Large outdoor environments

The developed exploration strategies were also tested with outdoor environments. In this section, exploration experiments for large outdoor environments (Jacobs University campus roads and yards) are presented. The environment used for testing the exploration strategies are shown in Fig. 5. Each one of the proposed strategies are tested as follows:

The rotating scanner speed is set 72° per second. Each method is tested with different numbers of robots (1 to 5) then the experiment is repeated five times and the average time to complete the exploration is recorded. The results are shown in Fig. 6.

The results shown in Fig. 6 confirm that to achieve shortest exploration time, robots should continuously re-plan the order of their next target cells and should not waste time moving toward recently explored cells. Instead they should instantly compute their new targets and start moving toward the new targets. More importantly, large environment were successfully explored within a reasonable simulation time. This is due to the reduction of the required computations improvement introduced in the developed strategies.



Fig. 7. The trajectories for the exploration strategy Stop-scan-replan-go after exploring the environment shown in Fig. 5 (left) and (middle).

To evaluate the performance of the proposed strategies in distributing the robots over the environment, the robots' trajectories are investigated. Figure 7 (left) shows the trajectories for the exploration strategy Stop-scan-replan-go after exploring the environment shown in Fig. 5 (left) with two robots. And Fig. 7 (right) shows the trajectories for the exploration strategy Stop-scan-replan-go after exploring the environment shown in Fig. 5 (middle) also with two robots. It is clear that the robots were efficiently distributed over the environment to reduce the overlap. The other proposed strategies use same distributing procedure.

4.3 Tests with Hilbert Curve obstacles distribution

We were looking to relate the optimal number of robots to the complexity of the environment and to evaluate the performance of the new proposed technique to spread the robots over the environment. For example, if there are three adjacent rooms in an office-like environment, it

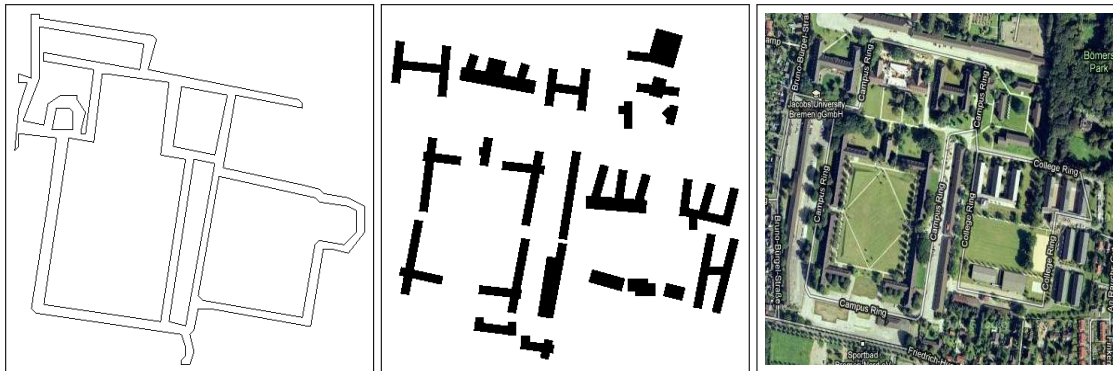


Fig. 5. Outdoor maps used for evaluation: campus roads and campus buildings at Jacobs University Bremen gGmbH, Germany. The rightmost map is a satellite view of the campus

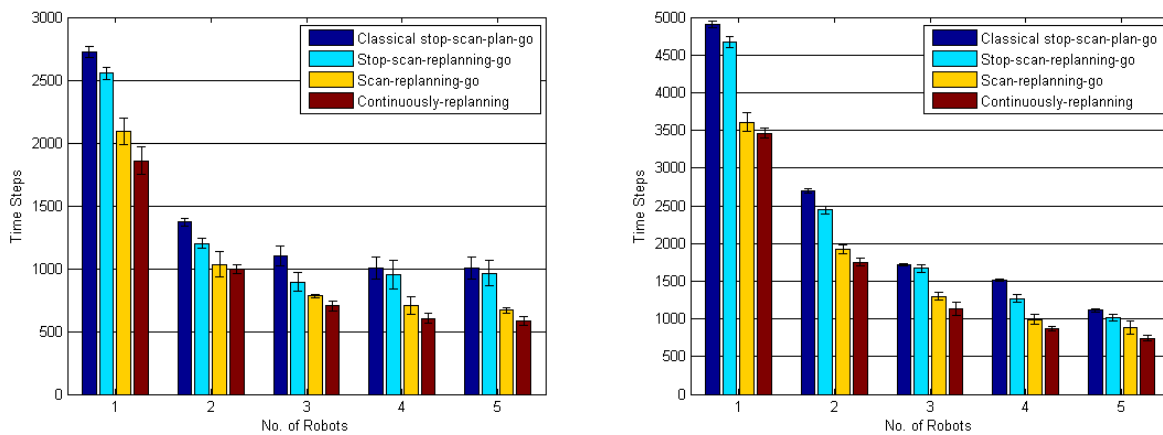


Fig. 6. Exploration time (time steps) versus number of robots for the environment show in Fig. 5 (left) and exploration time (time steps) versus number of robots for the environment in Fig. 5 (middle).

would be much more efficient to have one robot for each room rather than to make two or all of them explore same room and then they go to the next room. The later scenario is much more time consuming. Hilbert curve is used in this paper to evaluate how the proposed technique responds to different complexity levels of the environment.

Hilbert curve is a space filling curve that covers each point in a square grid with a size of 2×2 , 4×4 or any other power of 2. It was first described by David Hilbert in 1892 [22]. It is often used in image processing: especially image compression. It is also used in those operations where the coherence between neighboring pixels is important. The basic elements of the Hilbert curves are what are called “cups” (a square with one open side) and “joins” (a vector that joins two cups). The “open” side of a cup can be top, bottom, left or right. Every cup has two end-points. A first order Hilbert curve is just a single cup (see Fig. 8, left). It fills a 2×2 space. The second order Hilbert curve replaces that cup by four (smaller)

cups which are linked together by three joins (see Fig. 8, middle). The third order Hilbert curve is shown in Fig. 8 (right). Every next order repeats the process or replacing each cup by four smaller cups and three joins. Fig. 9 shows the cup subdivision rules in Hilbert curve where each cup is replaced with the four smaller cups [22].

The experiments were run with an environment with obstacles distributed according Hilbert curve shown in Fig. 8. The Stop-scan-replanning-go strategy is tested with each one of these environments and with different number of robots (1 to 8). The results are shown in Fig. 11. The results shown in Fig. 11 show that the optimal number of robots for first order Hilbert curve obstacles distribution is two robots, for second order Hilbert curve obstacles distribution is four robots and finally for third order Hilbert curve obstacles distribution is six robots. It could be argued that the optimal number of robots is, i.e., two times the order of Hilbert curve. There is no significant improvement when the number of robots is larger than the optimal

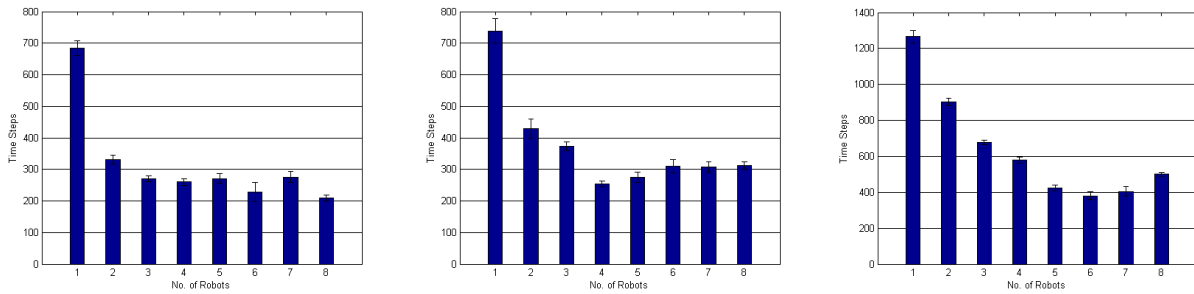


Fig. 10. Exploration time (time steps) versus number of robots for the Hilbert environment (cf. Fig. 8)

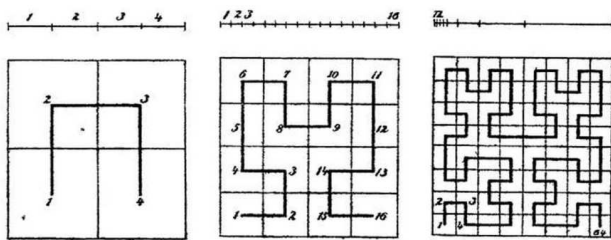


Fig. 8. First order Hilbert curve (left), second order Hilbert curve (middle) and third order Hilbert curve (right). Taken from [22].

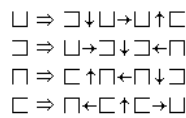


Fig. 9. Cup subdivision rules in Hilbert curve; each cup is replaced with the corresponding four smaller cups.

number of robots for the corresponding environment.

Figure 11 (left) shows the trajectories for the exploration strategies Stop-scan-replan-go after exploring the environment shown in Fig. 8 (middle) with two robots. Figure 11(right) shows the trajectories for the exploration method Stop-scan-replan-go after exploring the environment shown in Fig. 8 (middle) with four robots. In each case the exploration method has perfectly distribute the robots over the environment to keep the overlap to its minimum levels in order to reduce the exploration time.

5 CONCLUSIONS

This paper makes advantage of a constantly rotating laser scanner. Three exploration strategies based on the frontier-based exploration approach combined with an extension of food fill algorithm were developed and tested in simulation. One of the strategies involves stopping at frontier cells to take full 360° scans of the environment. Another one implied constant movement until the entire map

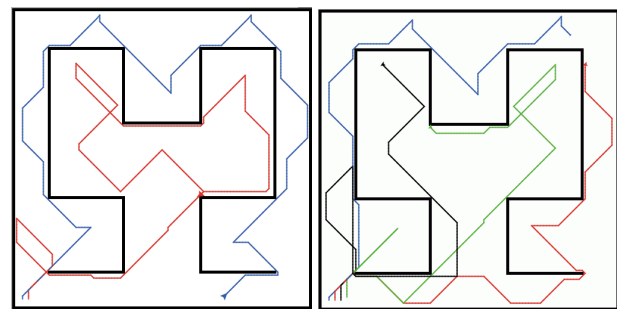


Fig. 11. The trajectories for the exploration strategy Stop-scan-replan-go after exploring the environment shown in Fig. 8 (middle) with two robots, (right): The trajectories for the exploration strategy Stop-scan-replan-go after exploring the environment shown in Fig. 8 (middle) with four robots.

is covered. While the last one employs a continuous replanning strategy with continuously rotating laser scanner. From the results of the experiments the following conclusions could be drawn:

1. Employing continuously rotating scanners for multi-robot systems improves the exploration efficiency by reducing the exploration time. The comparison with the classical exploration method shows the obtained effectiveness.
2. The continuously-replanning scan strategy is the fastest strategy. This appears to be due to the fact that performing complete scan for 360° while the robot standing on the frontier cell is time consuming and not important, and more importantly, in continuously-replanning strategy robots do not have to waste time moving toward recently explored spots (cells).
3. As in single robot exploration [7], Scan-replanning-go method is faster than stop-scan-replanning-go, i.e., full 360° scans in the frontier cells seems to be time consuming.

4. The developed exploration strategies are capable of exploring outdoor large environments. Exploration tests with large environment have confirmed the above mentioned conclusions.
5. More robots lead to less exploration time. But after certain number of robots, exploration time seems to be the same. This is due to the fact that overlap is directly proportional to the number of robots, especially when they start from adjacent positions.

Furthermore, in this paper Hilbert curve is used to model the environment complexity. This allowed for testing the proposed technique with different environment complexity levels. As a result, we could relate the optimal number of robots to the environment complexity level. Moreover, testing with different complexity levels showed the effectiveness of the proposed technique to perfectly distribute the robots over the environment to reduce the overlap.

ACKNOWLEDGMENT

This work was partially supported by the Deutsche Forschungsgemeinschaft (DFG Nu-230/6, Nu-230/7, and Nu-230/8).

REFERENCES

- [1] D. Holz, "Autonomous exploration and inspection," Master's thesis, Hochschule Bonn-Rhein-Sieg, Grantham-Allee 20, 53757 Sankt Augustin, Germany, 2009.
- [2] K. Wurm, C. Stachniss, and W. Burgard, "Coordinated multi-robot exploration using a segmentation of the environment," in *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS '08)*, (Nice, France), pp. 1160–1165, September 2008.
- [3] M. Julia, A. Gil, and O. Reinoso, "A comparison of path planning strategies for autonomous exploration and mapping of unknown environments," *Autonomous Robots*, vol. 33, pp. 427–444, 2012.
- [4] J. Zhao, X. Su, and J. Yan, "A novel strategy for distributed multi-robot coordination in area exploration," in *Proceedings of the IEEE International Conference on Measuring Technology and Mechatronics Automation (ICMTMA '09)*, vol. 2, pp. 24–27, 2009.
- [5] W. Burgard, M. Moors, C. Stachniss, and F. E. Schneider, "Coordinated multi-robot exploration," *IEEE Transactions on Robotics (TRO)*, vol. 21, no. 3, pp. 376–386, 2005.
- [6] M. Al-khawaldah and A. Nüchter, "Multi-Robot Exploration and Mapping with a rotating 3D Scanner," in *Proceedings of the 10th International IFAC Symposium on Robot Control (SYROCO '12)*, vol. 10, (Dubrovnik, Croatia), September 2012.
- [7] E. Digor, A. Birk, and A. Nüchter, "Exploration strategies for a robot with a continuously rotating 3d scanner," in *Proceedings of the Second International Conference on Simulation, Modeling and Programming for Autonomous Robots (SIMPAR '10)*, Lecture Notes in Computer Science, (Darmstadt, Germany), pp. 374–386, November 2010.
- [8] A. Nüchter, K. Lingemann, J. Hertzberg, O. Wulf, B. Wagner, K. Pervözl, H. Surmann, and T. Christaller, "The RoboCup Rescue Team Deutschland1," *KI – Künstliche Intelligenz*, no. 2, pp. 24–29, 2006.
- [9] O. Wulf, A. Nüchter, J. Hertzberg, and B. Wagner, "Benchmarking Urban 6D SLAM," *Journal of Field Robotics (JFR)*, vol. 25, pp. 148–163, March 2008.
- [10] T. Stoyanov and A. J. Lilienthal, "Maximum Likelihood Point Cloud Acquisition from a Mobile Platform," in *Proceedings of the IEEE International Conference on Advanced Robotics (ICAR '09)*, pp. 1–6, June 22–26 2009.
- [11] M. Bosse and R. Zlot, "Continuous 3D Scan-Matching with a Spinning 2D Laser," in *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA '09)*, pp. 4312–4319, May 2009.
- [12] J. Elseberg, D. Borrmann, and A. Nüchter, "Algorithmic solutions for computing accurate maximum likelihood 3D point clouds from mobile laser scanning platforms," *ISPRS Journal of Photogrammetry & Remote Sensing*, 2013 (submitted).
- [13] B. Yamauchi, "A frontier-based approach for autonomous exploration," in *Proceedings of the IEEE International Symposium on Computational Intelligence in Robotics and Automation (CIRA '97)*, pp. 146–151, 1997.
- [14] H. Yamauchi, S. Gumhold, R. Zayer, and H. P. Seidel, "Mesh Segmentation Driven by Gaussian Curvature," *The Visual Computer*, 2005.
- [15] A. F. Scott and C. Yu, "Cooperative multi-agent mapping and exploration in webots r," in *Proceedings of the 4th International Conference on Autonomous Robots and Agents (ICARA '09)*, pp. 56–61, 2009.
- [16] W. Sheng, Q. Yang, J. Tan, and N. Xi, "Distributed multi-robot coordination in area exploration," *Robotics and Autonomous Systems*, vol. 54, no. 21, pp. 945–955, 2006.
- [17] W. Burgard, M. Moors, and F. Schneider, "Collaborative exploration of unknown environments with teams of mobile robots," in *Advances in plan-based control of robotic agents*, 2002.
- [18] D. Fox, J. Ko, K. Konolige, B. Limketkai, D. Schulz, and B. Stewart, "Distributed multirobot exploration and mapping," *Proceedings of the IEEE*, vol. 94, pp. 15–25, July 2005.
- [19] V. Zipparo, A. Kleiner, B. Nebel, and D. Nardi, "Rfid-based exploration for large robot teams," in *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA '07)*, (Rome, Italy), pp. 4606–4613, May 2007.
- [20] R. Rocha, J. Dias, and A. Carvalho, "Cooperative multi-robot systems: A study of vision-based 3-d mapping using information theory," *Journal Robotics and Autonomous Systems (JRAS)*, vol. 53, no. 3-4, pp. 282–311, 2005.

- [21] R. Grabowski, L. Navarro-Serment, C. Paredis, and P. Khosla, "Heterogeneous teams of modular robots for mapping and exploration," *Journal Autonomous Robots*, vol. 8, no. 3, pp. 293–308, 2000.
- [22] D. Hilbert, "Über die stetige Abbildung einer Linie auf ein Flächenstück," *Mathematische Annalen*, vol. 38, no. 3, pp. 459–460, 1891.



Mohammad Al khawaldah was born in Al-Mafraq, Jordan, Dec. 1977, received his degrees as follows: BSc in Electrical and Electronic Engineering from University of Technology in Iraq, 1999, MSc in Mechatronics Engineering from BAU in Jordan, 2005 and PhD in Robotics from University of Hertfordshire in the UK, 2010. Al Khawaldah's main field of research is Robot Exploration. He has plenty of publications in the field of multi-robot exploration and map-building. He works as an assistant professor

in Al-Balqa Applied University since 2010 at Department of Mechatronics Engineering. His research interest includes Robotics, PLC and Control theory.



Andreas Nüchter holds a tenured associate professorship of Telematics (telecommunication, automation and informatics) at the University of Würzburg. Before, he headed as an assistant professor the Automation group at Jacobs University Bremen and was a research associate at the University of Osnabrück. Further, past affiliations were with the Fraunhofer Institute for Autonomous Intelligent Systems (AIS, Sankt Augustin) and the University of Bonn, from which he received the diploma degree in computer science in 2002 (best paper award by the German society of informatics (GI) for his thesis). He holds a doctorate degree (Dr. rer. nat) from University of Bonn. His work is focused on sensor systems, computer vision, robotics, and automation. His main research interests include 3D environment mapping, 3D vision, and laser scanning technologies, resulting in fast 3D scan matching algorithms that enable robots to map their environment in 3D using six degrees of freedom poses. The capabilities of these robotic SLAM approaches were demonstrated at RoboCup Rescue competitions, ELROB, and several other events.

AUTHORS' ADDRESSES

Mohammad Al khawaldah
Al-Balqa' Applied University
Hay Al-Mayamin, Salt, Jordan
email: mohammad.alkhawaldah@gmail.com

Prof. Andreas Nüchter, Ph.D.
Robotics and Telematics
University of Würzburg, Germany
Sanderring 2, 97070 Würzburg, Germany
email: andreas@nuechti.de

Received: 2013-09-10

Accepted: 2014-06-19