Lecture Notes in Electrical Engineering 695

José Alexandre Gonçalves
Manuel Braz-César
João Paulo Coelho *Editors*

CONTROLO 2020

Proceedings of the 14th APCA International Conference on Automatic Control and Soft Computing, July 1–3, 2020, Bragança, Portugal

Springer

Lecture Notes in Electrical Engineering

Volume 695

Series Editors

Leopoldo Angrisani, Department of Electrical and Information Technologies Engineering, University of Napoli Federico II, Naples, Italy
Marco Arteaga, Departament de Control y Robótica, Universidad Nacional Autónoma de México, Coyoacán, Mexico
Bijaya Ketan Panigrahi, Electrical Engineering, Indian Institute of Technology Delhi, New Delhi, Delhi, India
Samarjit Chakraborty, Fakultät für Elektrotechnik und Informationstechnik, TU München, Munich, Germany
Jiming Chen, Zhejiang University, Hangzhou, Zhejiang, China
Shanben Chen, Materials Science and Engineering, Shanghai Jiao Tong University, Shanghai, China
Tan Kay Chen, Department of Electrical and Computer Engineering, National University of Singapore, Singapore, Singapore
Rüdiger Dillmann, Humanoids and Intelligent Systems Laboratory, Karlsruhe Institute for Technology, Karlsruhe, Germany
Haibin Duan, Beijing University of Aeronautics and Astronautics, Beijing, China
Gianluigi Ferrari, Università di Parma, Parma, Italy
Manuel Ferre, Centre for Automation and Robotics CAR (UPM-CSIC), Universidad Politécnica de Madrid, Madrid, Spain
Sandra Hirche, Department of Electrical Engineering and Information Science, Technische Universität München, Munich, Germany
Faryar Jabbari, Department of Mechanical and Aerospace Engineering, University of California, Irvine, CA, USA
Limin Jia, State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University, Beijing, China
Janusz Kacprzyk, Systems Research Institute, Polish Academy of Sciences, Warsaw, Poland
Alaa Khamis, German University in Egypt El Tagamoa El Khames, New Cairo City, Egypt
Torsten Kroeger, Stanford University, Stanford, CA, USA
Qilian Liang, Department of Electrical Engineering, University of Texas at Arlington, Arlington, TX, USA
Ferran Martín, Departament d’Enginyeria Electrònica, Universitat Autònoma de Barcelona, Bellaterra, Barcelona, Spain
Tan Cher Ming, College of Engineering, Nanyang Technological University, Singapore, Singapore
Wolfgang Minker, Institute of Information Technology, University of Ulm, Ulm, Germany
Pradeep Misra, Department of Electrical Engineering, Wright State University, Dayton, OH, USA
Sebastian Möller, Quality and Usability Laboratory, TU Berlin, Berlin, Germany
Subhas Mukhopadhyay, School of Engineering & Advanced Technology, Massey University, Palmerston North, Manawatu-Wanganui, New Zealand
Cun-Zheng Ning, Electrical Engineering, Arizona State University, Tempe, AZ, USA
Toyoaki Nishida, Graduate School of Informatics, Kyoto University, Kyoto, Japan
Federica Pascucci, Dipartimento di Ingegneria, Università degli Studi “Roma Tre”, Rome, Italy
Yong Qin, State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University, Beijing, China
Gan Woon Seng, School of Electrical & Electronic Engineering, Nanyang Technological University, Singapore, Singapore
Joachim Speidel, Institute of Telecommunications, Universität Stuttgart, Stuttgart, Germany
Germano Veiga, Campus da FEUP, INESC Porto, Porto, Portugal
Haitao Wu, Academy of Opto-electronics, Chinese Academy of Sciences, Beijing, China
Junjie James Zhang, Charlotte, NC, USA

The book series *Lecture Notes in Electrical Engineering* (LNEE) publishes the latest developments in Electrical Engineering - quickly, informally and in high quality. While original research reported in proceedings and monographs has traditionally formed the core of LNEE, we also encourage authors to submit books devoted to supporting student education and professional training in the various fields and applications areas of electrical engineering. The series cover classical and emerging topics concerning:

- Communication Engineering, Information Theory and Networks
- Electronics Engineering and Microelectronics
- Signal, Image and Speech Processing
- Wireless and Mobile Communication
- Circuits and Systems
- Energy Systems, Power Electronics and Electrical Machines
- Electro-optical Engineering
- Instrumentation Engineering
- Avionics Engineering
- Control Systems
- Internet-of-Things and Cybersecurity
- Biomedical Devices, MEMS and NEMS

For general information about this book series, comments or suggestions, please contact leontina.dicecco@springer.com.

To submit a proposal or request further information, please contact the Publishing Editor in your country:

China

Jasmine Dou, Associate Editor (jasmine.dou@springer.com)

India, Japan, Rest of Asia

Swati Meherishi, Executive Editor (Swati.Meherishi@springer.com)

Southeast Asia, Australia, New Zealand

Ramesh Nath Premnath, Editor (ramesh.premnath@springernature.com)

USA, Canada:

Michael Luby, Senior Editor (michael.luby@springer.com)

All other Countries:

Leontina Di Cecco, Senior Editor (leontina.dicecco@springer.com)

**** Indexing: The books of this series are submitted to ISI Proceedings, EI-Compendex, SCOPUS, MetaPress, Web of Science and Springerlink ****

More information about this series at http://www.springer.com/series/7818

José Alexandre Gonçalves ·
Manuel Braz-César · João Paulo Coelho
Editors

CONTROLO 2020

Proceedings of the 14th APCA International Conference on Automatic Control and Soft Computing, July 1–3, 2020, Bragança, Portugal

Springer

Editors
José Alexandre Gonçalves
Escola Superior de Tecnologia e Gestão
Instituto Politécnico de Bragança
Bragança, Portugal

Manuel Braz-César
Escola Superior de Tecnologia e Gestão
Instituto Politécnico de Bragança
Bragança, Portugal

João Paulo Coelho
Escola Superior de Tecnologia e Gestão
Instituto Politécnico de Bragança
Bragança, Portugal

ISSN 1876-1100 ISSN 1876-1119 (electronic)
Lecture Notes in Electrical Engineering
ISBN 978-3-030-58652-2 ISBN 978-3-030-58653-9 (eBook)
https://doi.org/10.1007/978-3-030-58653-9

© The Editor(s) (if applicable) and The Author(s), under exclusive license
to Springer Nature Switzerland AG 2021
This work is subject to copyright. All rights are solely and exclusively licensed by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

Going to a conference is always an opportunity to establish contacts with other researchers and to grow culturally. Often, from informal conversations fostered by the conference's social programme, synergies are generated, leading to new ideas and partnerships. Indeed, networking is the fundamental reason for being present at any conference. Moreover, every time we visit a new country, distinct realities are observed and a kind of mild acculturation happens. Experiences gathered from travelling shape our vision of the world and promote cultural enrichment. The CONTROLO 2020 Conference was intended not only to be a scientific event, but also to give the opportunity for the control community to know Bragança, the Polytechnic Institute of Bragança, and to network face-to-face in friendly, safe, stimulating and international environment. The city was prepared to receive this scientific community, with a welcome reception at the Castle of Bragança and a gala dinner at the gardens of the Abade de Baçal Museum, providing all the participants to get in touch with some of the most important landmarks of the Bragança cultural heritage. The ideal situation would be to communicate in person but, due to the current pandemic situation, the CONTROLO 2020 Conference was forced to change to an online event. In spite of all these difficulties, the decision to maintain the date of this event has demonstrated the resilience of APCA in adapting to extreme conditions. In addition, it was also important in this decision-making, to ensure that the dissemination of the research and development works, submitted and accepted for publication, would be made public in due time.

A total of 93 papers, originating from 39 different countries, were submitted for publication, from which 76 were accepted, after an evaluation process that totalled more than 300 reviews. Besides its six special sessions and a MATLAB course, the CONTROLO 2020 Conference had the honour of having five of the most relevant personalities in automatic control community in its five plenary sessions, namely professors André Preumont, Eduardo Camacho, Karl Johansson, Kevin Passino and Sebástian Dormido. We hope that all interested readers can benefit scientifically from this conference proceedings.

Best Regards,
CONTROLO 2020 Local Organizing Committee

Using Multi-UAV for Rescue Environment Mapping: Task Planning Optimization Approach

Ricardo Rosa[1,5](✉), Thadeu Brito[2], Ana I. Pereira[2,3], José Lima[2,4], and Marco A. Wehrmeister[5]

[1] Federal Institute of Education, Science and Technology - Paraná, Cascavel, Brazil
ricardo.rosa@ifpr.edu.br
[2] Research Centre in Digitalization and Intelligent Robotics (CeDRI), Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253 Bragança, Portugal
{brito,apereira,jllima}@ipb.pt
[3] Algoritmi Center, University of Minho, 4710-057 Braga, Portugal
[4] INESC Technology and Science, Porto, Portugal
[5] Federal University of Technology - Paraná (UTFPR), Curitiba, Brazil
wehrmeister@utfpr.edu.br

Abstract. Rescuing survivors in unknown environment can be extreme difficulty. The use of UAVs to map the environment and also to obtain remote information can benefit the rescue tasks. This paper proposes an organizational system for multi-UAVs to map indoor environments that have been affected by a natural disaster. The robot's organization is focused on avoiding possible collisions between swarm's members, and also to prevent searching in locations that have already discovered. This organizational approach is inspired by bees behavior. Thus, the multi-UAVs must search, in a collaborative way, in order to map the scenario in the shortest possible time and, consequently, to travel the shortest reasonable distance. Therefore, three strategies were evaluated in a simulation scenario created in the V-REP software. The results indicate the feasibility of the proposed approach and compare the three plans based on the number of locations discovered and the path taken by each UAV.

Keywords: Unmanned Aerial Vehicles · Multiple UAV · Collaborative environment mapping · Path planning

1 Introduction

Unmanned Aerial Vehicles (UAVs), commonly known as drones, are continually evolving; every year, more sophisticated UAVs are available on the market. This technological advance allows researchers and professionals to use UAVs in several activities, such as search and rescue [1], surveillance, inspection, forest monitoring, agriculture, among others [2,3]. The variety in these applications makes them a tool with broad potential, as can be seen in infrastructure inspections.

© The Editor(s) (if applicable) and The Author(s), under exclusive license to Springer Nature Switzerland AG 2021
J. A. Gonçalves et al. (Eds.): CONTROLO 2020, LNEE 695, pp. 507–517, 2021.
https://doi.org/10.1007/978-3-030-58653-9_49

When performing inspection tasks, UAVs bring a better three-dimensional understanding of the environment [4]. This has a large importance when scanning an unknown region after a disaster. UAV can be used to search for victims in places where access is steep or inaccessible. A single UAV is not able to cover a large area in a short time, but multiple UAVs are. These robots acquire data and images remotely and send them immediately to an operations center. Thus, the rescue team can better plan its actions, making the most appropriate decisions on how to perform the rescue tasks to save the survivors as quickly as possible and to decrease the risk of rescuers life.

However, when multiple robots perform a task as a team, they can interfere with each other in carrying out individual (sub-)tasks. Coordination mechanisms are mandatory to prevent collisions between robots [5]. Such a coordination can be based on local decisions (i.e. the robot makes a decision based on its local information) or global decisions (i.e. the individually robot or a global entity uses information from all robots to decide what to do). The current literature presents a variety of heuristics to manage the multi-robot region exploration. For instance, [5] proposes to choose the target exploration region based on some relevant feature, e.g. distance to the next communication device - the likelihood for a region to be chosen is higher if it is closer to a communication element.

This work proposes a multi-UAV management system to map indoor environments that have been affected by a natural disaster. The proposed approach is inspired in bees organization and how they build their hives. That is, several UAVs navigate and explore the unstructured internal environment in the same way that bees travel through space when they build a honeycomb. This method employs multiple (homogeneous) aerial robots; ground robots are not considered. The size of the hexagons is fixed at a radius size of 0.5 m. Some procedures to plan and coordinate the set of UAVs need to be applied and tested before used in real situations. In this way, the focus of this work is to create a simulated environment to develop a coordination strategy for these robots, and thus accomplish the exploration of the simulated scenario.

One UAV is enough to map the unstructured and unknown environment. Although, more UAVs will map faster but more complex planning is needed. In our work, a set of three UAVs is used to map the unstructured environment before the team rescuers begin their exploration. All procedures are implemented and tested in the V-REP robot simulator, allowing to validate the proposed approach. Three strategies were tested, and two cases were used to map the unstructured environment before rescue teams entered the environment. In addition, it is essential to highlight the main contributions of this work. First, a comparison between different strategies to identify the best task planning to map an internal dynamic environment. Second, is to analyze the efficiency of using one or more UAVs in a collaborative procedure. The results of these two contributions can determine the quality of the path planning schedule of the multi-UAVs that are exploring an unstructured simulated environment. That is, it is expected that the proposed procedure will manage the multi-UAVs in order to, as quickly as possible, explore all the unknown scenario.

The paper is organized as follows. Section 2 presents the related work. Then, the developed algorithms and the simulation environment are explained in Sect. 3. Results are presented in Sect. 4, and finally, the last section draws the conclusions and points out future work directions.

2 Related Work

The control of one UAV is treated by some researchers as complex, due to the multiple directions it may have, so controlling multiple UAVs has a higher complexity considering all the possibilities. Therefore, [6], defines that the cooperative control is divided into three areas: complexity, information structure, and uncertainty. The difficulty in moving in unknown environments and with dynamic obstacles is pointed out by [7] and demonstrates the importance of communication between the UAVs to optimize the discovery of the environment through a path planner. Recent surveys, such as [13–15], highlight the challenges and issues on coverage and path planning using UAVs.

In [9], the problem of controlling multiple UAVs is addressed as algebraic and dynamic constraints, formulating the problem as optimal control. That work goal is to treat reconfiguration of UAVs with bio-inspired algorithms, combining Particle Swarm Optimization (PSO) and Genetic Algorithm (GA).

Sometimes UAVs can be shot down because of the events in the hazardous environments. In [8], an algorithm is proposed to regroup the UAVs when a member of the group is knocked over. In this way, the UAVs team carry out flight training in order to always carry on the mission. Considering a low-lying urban environment, [10] presents two safety systems for UAVs. The first system is developed to identify the static objects on the map, through geographic data of the environment. The second method makes the relation between the static map with unknown objects found, identifying them as dynamic objects.

The work presented in [11] merges the Dijkstra algorithm and Simulated Annealing (SA) to streamline the process aiming to decrease the search time for survivors in a real earthquake situation. Even if the developed system has failures in the mathematical model, a reduction in search time and obstacles avoidance is demonstrated. Another approach [12] to the problem of co-operation between drones assigns basic problems to each element of a UAV team by determining Pareto dominate the front.

Similar to cited previous works, this paper focuses on offering a task planning method for multi-UAVs. The difference between the studies listed is in the definition of a search strategy to command the UAVs not to perform the paths already found. Hence, the main goal is to optimize the search of the UAVs to map all the environment. In this way, the rescue teams can reduce the time of service or decision making in a catastrophe environment.

3 Multi-UAV Indoor Environment Mapping

A simulation environment in the V-REP platform is used to validate the proposed approach and the implementation of the proposed algorithms was performed in MATLAB. Therefore, the following subsections are designed to demonstrate the work developed.

3.1 Overview

The proposed approach, to develop a UAVs management system, is inspired by how the honey bees build their hive. Honey bees use hexagonal pattern cylinders to construct a complex structure progressively by adding waxes produced and manipulated by several bees [16].

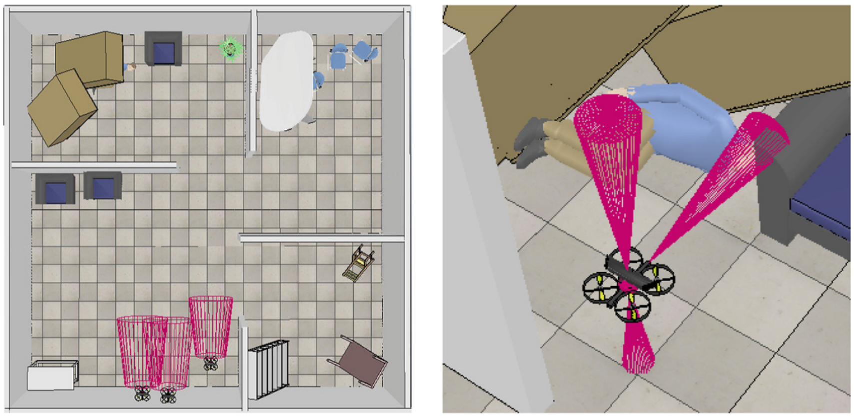
The proposed indoor mapping approach aims to produce a 3D occupancy map (based on the ideas of the Octomap [17]) that may be used by the rescue teams in the victims rescue planning. To improve the search, multi- UAVs will create the 3D map from the scenario collaboratively, i.e. several UAVs will explore/navigate the indoor environment to inform the rescue teams. Consequently, the team can detect the obstacles that may hinder their movements. The 3D maps provide not only the information on the space occupancy (i.e. the possible accesses to the places with the indoor environment) but also other information such as photos and thermal images of the region.

In this context, the main objective is to map the neighbour cells as faster as possible. Case the cell has neighbours (up to six cells), the UAV informs if the neighbour cells are reachable/unobstructed. Therefore, a maximum of six new cells is included in the global list of unvisited cells which indicates the places that need to be visited/explored by the UAVs team. While the global list contains someplace to search, the management system of the multi-UAVs is enabled. Then, the task manager starts to select an available cell from a list based on a given criterion. This selection is addressed in Subsect. 3.3. Besides, the Point Cloud is used to build the 3D occupancy map, but a discussion on this is out of the scope of this paper due to space limitations. On the other hand, it is essential to highlight that the UAVs will not use such a 3D map for localization, navigation, or obstacle avoidance.

3.2 Simulation Environment

A simulation scenario was used as a case study to analyze the behavior of the management system of multi-UAV and also validate the proposed approach using V-REP [18] platform. The V-REP has APIs that allow communication with many programming languages. Due to this, the proposed management system is implemented in MATLAB because of its robust library kits. Figure 1 shows the simulated environment in V-REP software.

The scenario is an area of 10 m $\times$ 10 m, with four rooms divided by walls, demonstrated by Fig. 1a. Three similar UAVs (i.e. the same configurations) are used for the simulation. The selected architecture is composed by four-rotor



(a) Full scenario with three UAVs waiting for start

(b) Isometric view of one UAV searching.

Fig. 1. Simulated scenario in V-REP software.

UAV arranged on a "X" frame type, as shown in Fig. 1b. The UAVs can perform Vertical Take-Off and Landing (VTOL) and are equipped with a front laser sensor which produces a Point Cloud that represents the environment within the sensor range at a given position. The simulation starts with the first UAV, called U_1, performing the first cell exploration, i.e. the construction of the first hexagonal cell, which is identified with an ID number, e.g. C_1 for the first cell. When any UAV is chosen to explore one cell given by the management system, it rotates in order to detect six faces of the hexagon using the laser sensor. Considering a radius of 0.5 m (this is the size of each UAV structure), the UAV assesses each face in order to check whether it can reach the center of a possible adjacent hexagon, i.e. a new neighbour cell. If possible, it means that adjacency exists and a new neighbour cell is identified and its identifier is placed in the global list of unvisited cells, SC. Once the first UAV (U_1) finishes the first cell (C_1) exploration, it navigates to one neighbour cell. This decision is performed by the management system, and it is the work's focus explained in the next subsection. In this way, the indoor environment is released for other UAVs to be explored. For this, each UAV requests a cell to explore from the global list of unvisited cells. At the end of the cell exploration, its identifier is removed from the unvisited cells list and added into the visited cells list. The indoor environment mapping process continues until the unvisited cells list is empty. By ensuring that all UAVs begin their exploration from cell C_1, it is possible to maintain the uniformity of the topological map, avoiding the area overlap of two cells with distinct identifiers.

3.3 Strategies to Select the Cell to Visit

An important issue is how the set of UAVs will deal with the cluster of the global list of unvisited cells, SC, and which cell should be chosen to be explored first. In this work, is used the simulation scenario in V-REP with three different strategies to evaluate the best approach to select the new cell to search. To implement the management system is used the MATLAB and its libraries, and the command to coordinate the multi-UAV is sent to V-REP.

The management system implementation establish a set of of n UAVs, $SU = \{U_1, ..., U_n\}$, and a set of nc of unvisited cells $SC = \{C_2, ..., C_{nc}\}$. All UAVs elaborate the set SC in a collaborative way, where each UAV, U_j, collaborates for the global list SC through its particular list of unvisited cells SC_j in a given time when exploring a given cell. To perform the path between each selected UAV and the chosen cell, it is applied the Dijkstra's Method [19]. It is crucial to highlight that Dijkstra's is a common and established method for path planning. Therefore, it is used only to execute the trajectories when any UAV need to navigate between the cells.

In this work, three strategies to selected the cell to be explored were tested as detailed.

Strategy 1: based on First In First Out (FIFO) order. In this case, the oldest cell inserted in the global list of unvisited cells, SC, will be the first to visit and mapped.

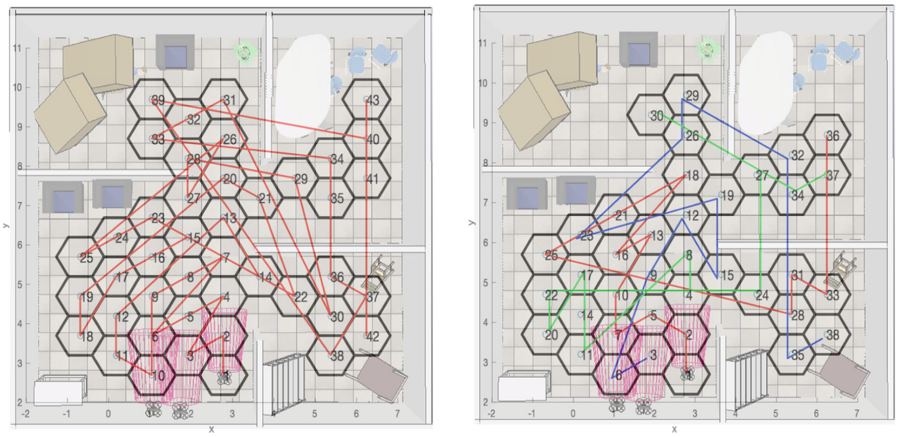
Strategy 2: based on Euclidean distance with respect to the first cell C_1. Considering that each cell has associated GPS coordinates, the cell that will be chosen to visit is the cell $C_j = \arg\min ||C_1 - C_i||$, for $i = 2, ..., |SC|$.

Strategy 3: based on Relative Euclidean distance with respect to the first cell C_1 and the location of each UAV. In this case, the selected cell that will be visited by UAV, U_l, located in the cell $C_j = \arg\min \sum_{i=1}^{|SC|} ||C_1 - C_i|| + ||C_l - C_i||$.

4 Simulations and Results

The proposed approach to manage the search tasks of UAVs to map a catastrophic environment has been validated via simulation. The V-REP simulator runs on a computer with 6-Core Intel Xeon 3,33 GHz CPU, 6 GB of RAM, and a GPU ATI Radeon HD 5770. The three proposed strategies were analysed on how they affect the UAVs behavior in the simulation of two different situations: Case 1 - the mapping is done by one UAV; Case 2 - three UAVs accomplish the same mapping.

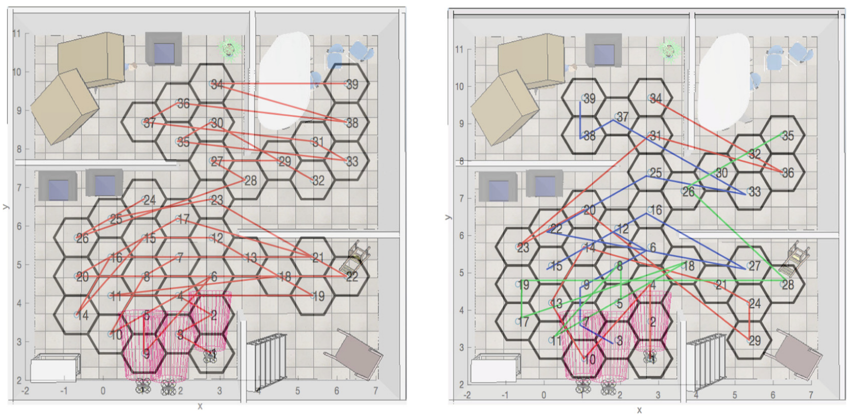
Strategy 1 - FIFO. Mapping the simulated scenario always begins in Cell 1. In Fig. 2, the red lines represent the order of UAV task planning and not the actual path. The red lines indicate the way the UAV received the cells from the global list of positions to be searched. For example, it is possible to verify that during the execution of Strategy 1, the UAV starts in Cell 1, and it explores the scenario in a sequential manner, that is, going through all the cells obeying the increasing numerical order (Fig. 2a). Next, the same Strategy 1 is tested with the three UAVs. The operation of this approach can be seen in Fig. 2b. To differentiate each task planning, the red line indicates the task schedule of U_1, the yellow line is a U_2 mark, and the blue line is the third UAV. In the same way, as in the previous test, the marking of these three lines represents only the decisions of the task manager to supply the cells that are in the list of not researched.



(a) Strategy 1 - One UAV (b) Strategy 1 - Three UAVs

Fig. 2. Task planning with Strategy 1 for environment mapping

Strategy 2 - Euclidean Distance. The tests of the second approach take place under the same conditions as the previous test, that is, the same simulation scenario, the same number of robots in each analysis situation, the same computational configuration. The result obtained is shown in Fig. 3, where, once again, the objective is to verify the behavior of UAV task planning. Therefore, Fig. 3a represents the Case 1, when the system management determines the next cells to be explored by the shortest distance from the initial cell. For example, C_3 is chosen before C_2 because it has the center point closest to C_1. In the next stage, Strategy 2 is applied to Case 2, that is, with 3 UAVs exploring the scenario with the second proposed method (illustrated by Fig. 3b).



(a) Strategy 2 - One UAV (b) Strategy 2 - Three UAVs

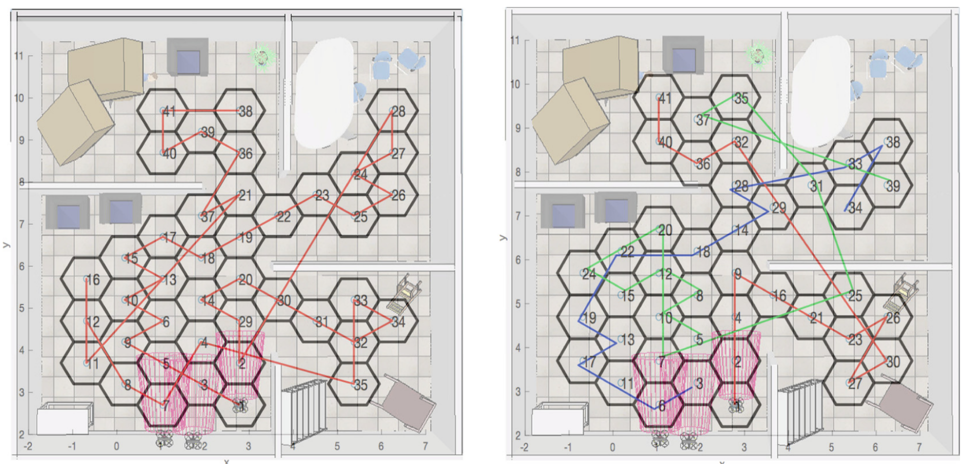
Fig. 3. Task planning with Strategy 2 for environment mapping

Strategy 3 - Relative Euclidean Distance. The third test is shown in Fig. 4 with Strategy 3 for both proposed situations. It is performed in a similar way to that presented in Strategy 2, however, in this test the decision of the task management system is based not only on the distance between the chosen cell and the initial cell. In this approach, two distances are considered, the first one is from the cell selected to be explored with the initial cell, and the second one is the distance from the idle UAV with the chosen cell. Both Cases are executed with Strategy 3 and shown in Fig. 4a and Fig. 4b, respectively.

To compare the different strategies it was considered that each movement between two neighbour cells needs 10 s and to map the environment of a given cell a UAV needs 60 s. The Table 1 presents the obtained results, where TN represents the time needed to map all the environment (in seconds) and NC represents the number of total Cells identified by the UAVs.

Table 1. Time needed by the set of UAVs to mapping the environment (seconds).

	Strategy I		Strategy II		Strategy III	
	TN	NC	TN	NC	TN	NC
Case 1 (1 UAV)	3870	43	3550	39	3150	41
Case 2 (3 UAVs)	3440	38	3580	39	3260	41



(a) Strategy 3 - One UAV (b) Strategy 2 - Three UAVs

Fig. 4. Task planning with Strategy 3 for environment mapping

Considering the rate between the total TN and the value of NC, it is possible to conclude that, in average, the Strategy I has 90 s, Strategy II has 91 s and Strategy III has 70 s.

Therefore, considering Strategy I, it is possible to verify that the time increases 1% for Strategy I and, for Strategy III, the time decreases 15%.

As it can be identified in Table 1, the different number of cells for different strategies is due to the dynamic and real simulation environment.

Considering the Case 2, with three UAVs, the best strategy was the III, where it was possible to identify 41 cells. In terms of rate, the Strategy I obtains 91 s, Strategy II 92 s and Strategy III obtains 80 s, that means a decrease time of 12% with respect to Strategy I. The Fig. 4 presents the final result in the simulator environment.

It is possible to conclude that Strategy III obtains better results with a lower time and will be the selected one for further developments and implementations.

Discussion. To validate the proposed approach, it is expected that UAVs will be able to spread in the best possible way. During the analysis, it is noted that the use of each task management method changes the identification number of each cell found (shown in Sect. 3.1). This behavior is explained by the fact that each method makes the UAVs spread more and more (or less) from the initial point, so the order of the cells can be different when compared between the proposed Strategies. So, for the comparison between the Strategies to be fair, it must be established that the performance must take into account the spatial position of each cell.

For example, based on Figs. 2, 3 and 4, it is possible to compare the performance of each strategy by observing the behavior in the exploration of C_{25} (in Strategy 1), with the exploration of C_{23} (in Strategy 2) and the research during C_{24} (in Strategy 3). These three cells correspond to the same spatial point. In this case, considering this spatial point, it is possible to notice that in Strategies 1 and 2, UAVs make fewer jumps and thus carry out the mapping in a uniform way in relation to C_1. In other words, UAVs take longer to distance themselves from C_1. It is possible to observe that in these two strategies each UAV needs more interactions to reach cells with higher values. It is enough to observe the behavior at the same spatial point to verify the number of necessary interactions that each UAV took to arrive at a coordinate.

The number of cells found should be the same for all strategies, since the space is the same size for all tests. A possible explanation for the number of cells found not being equal during the three tests is the tolerance that the simulator can deliver in terms of sensing. When comparing the three tests, it is observed that the identification of cells in the corners of the environment walls can cause disturbances in the laser sensor used in each UAV.

5 Conclusions and Future Work

This paper presented a multi-UAVs task planning system for mapping unknown indoor environments. The proposed approach was inspired on how bees build their hive. The multi-UAVs explored the indoor environment in order to map it in a efficient way. The proposed strategies were tested and validated in simulation environment and with case studies that simulates the rescue of people in difficult access places. Two cases were tested, with one UAV and with three UAVs to map the unstructured environment. The obtained results allow to conclude that the task planning should combine the distance from initial Cell, to ensure a uniform mapping from the initial place, and also information about the cell location of the UAV. As future work, the strategy III should be combined with a populational optimization algorithm to minimize the time and the travelled distance. According to the final task manager method, an implementation with a real scenario and UAVs should be arranged.

Acknowledgements. This work is supported by Grant #337/2014 (Fundação Araucária - Brazil), the grant from the bi-national cooperation scheme of UTFPR - IPB and by FCT – Fundação para a Ciência e Tecnologia within the Projects Scope UIDB/05757/2020.

References

1. Oliveira, D., Wehrmeister, M.A.: Using deep learning and low-cost RGB and thermal cameras to detect pedestrians in aerial images captured by multirotor UAV. Sensors **18**(7), 2244, 1–33 (2018)
2. Otto, A., et al.: Optimization approaches for civil applications of unmanned aerial vehicles (UAVs) or aerial drones: a survey. Networks **72**(4), 411–458 (2018)
3. Shakhatreh, H., et al.: Unmanned aerial vehicles (UAVs): a survey on civil applications and key research challenges. IEEE Access **7**, 48572–48634 (2019)
4. Jordan, S., et al.: State-of-the-art technologies for UAV inspections. IET Radar Sonar Navig. **12**(2), 151–164 (2017)
5. Burgard, W., Moors, M., Stachniss, C., Schneider, F.E.: Coordinated multi-robot exploration. IEEE Trans. Robot. **21**(3), 376–386 (2005)
6. Chandler, P.R., Pachter, M., Rasmussen, S.: UAV cooperative control. In: Proceedings of the 2001 American Control Conference, vol. 1, pp. 50–55. IEEE (2001)
7. Rathbun, D., et al.: An evolution based path planning algorithm for autonomous motion of a UAV through uncertain environments. In: Proceedings of the 21st Digital Avionics Systems Conference, vol. 2. IEEE (2002)
8. Vincent, P., Rubin, I.: A framework and analysis for cooperative search using UAV swarms. In: Proceedings of the 2004 ACM Symposium on Applied Computing, pp. 79–86. ACM (2004)
9. Duan, H., Luo, Q., Shi, Y., Ma, G.: Hybrid particle swarm optimization and genetic algorithm for multi-UAV formation reconfiguration. IEEE Comput. Intell. Mag. **8**(3), 16–27 (2013)
10. Yin, C., et al.: Offline and online search: UAV multiobjective path planning under dynamic urban environment. IEEE Internet Things J. **5**(2), 546–558 (2017)
11. Deng, L., et al.: Post-earthquake search via an autonomous UAV: hybrid algorithm and 3D path planning. In: 2018 14th International Conference on Natural Computation, Fuzzy Systems and Knowledge Discovery (ICNC-FSKD), pp. 1329–1334. IEEE (2018)
12. Chen, H.X., Nan, Y., Yang, Y.: Multi-UAV reconnaissance task assignment for heterogeneous targets based on modified symbiotic organisms search algorithm. Multidisc. Digit. Publishing Inst. **19**(3), p734 (2019)
13. Cabreira, T.M., Brisolara, L.B., Ferreira Jr., P.R.: Survey on coverage path planning with unmanned aerial vehicles. Drones **3**, 4 (2019)

14. Goerzen, C., et al.: A survey of motion planning algorithms from the perspective of autonomous UAV guidance. J. Intell. Robot. Syst. **57**, 65 (2010)
15. Galceran, E., Carreras, M.: A survey on coverage path planning for robotics. Robot. Auton. Syst. **61**(12), 1258–1276 (2013)
16. da Rosa, R., Wehrmeister, M.A., Brito, T., Lima, J., Pereira, A.: Honeycomb Map: a bioinspired topological map for indoor search and rescue unmanned aerial vehicles. Sensors **20**(3), 907 (2020). https://doi.org/10.3390/s20030907
17. Hornung, A., et al.: OctoMap: an efficient probabilistic 3D mapping framework based on octrees. Auton. Robots **34**(3), 189–206 (2013)
18. Rohmer, E. Singh, S.P.N., Freese, M.: V-REP: a versatile and scalable robot simulation framework. In: IEEE/RSJ International Conference on Intelligent Robots and Systems (2013)
19. Sedeño-Noda, A., Colebrook, M.: A biobjective Dijkstra algorithm. Eur. J. Oper. Res. **276**(1), 106–118 (2019)