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Path Planning for Unmanned Aerial Vehicle (UAV) using Rotated Accelerated Method in Static Outdoor Environment

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Abstract: Generating path planning for unmanned aerial vehicles (UAV) is important to provide a smooth navigation flight path from source to destination. In the past, fast iterative methods that apply the use of full-sweep iteration were suggested. In this study, a fast iterative method known as Rotated Successive Over-Relaxation (RSOR) is introduced. The algorithm is implemented in a self-developed 2D Java tool, UAV Planner. The proposed method was tested using several simulation scenarios which demonstrated the efficiency of the algorithm by finding the path in term of smoothness, computational time efficiency and number of iterations, with a different number of outdoor static obstacles in the form of hills. The results show that RSOR gives a faster computational time and less iterations to generate a path for UAV platform when compared to previous methods.

Keywords: Unmanned Aerial Vehicle, Path Planning, Laplace, Harmonics Potential.

静态室外环境中采用旋转加速法的无人机航路规划

摘要：为无人飞行器（无人机）生成路径规划对于提供从源到目的地的平滑导航飞行路径很重要。 过去，提出了使用全扫描迭代的快速迭代方法。 在这项研究中，介绍了一种称为旋转连续过度松弛（RSOR）的快速迭代方法。 该算法在自行开发的 2D 爪哇工具无人机计划器中实现。 在几种模拟情况下对提出的方法进行了测试，通过在平滑度，计算时间效率和迭代次数方面找到路径，并以不同形式的山丘形式的室外静态障碍物来证明算法的有效性。结果表明，与以前的方法相比，RSOR 提供了更快的计算时间和更少的迭代次数，从而可以为无人机平台生成路径。

关键词：无人机，路径规划，拉普拉斯，谐波潜力。

1. Introduction

Unmanned Aerial Vehicles (UAVs) are unmanned aircraft or flying robots. They are capable of performing autonomous tasks without humans aboard, or when remotely controlled by humans [3]. UAVs are known as drones or UAS, and the two terms have become interchangeable in recent years [4]. This research proposes a method for planning the path for low-flying unmanned aerial vehicles (UAVs) in complex terrain based on the theory of fluid flow. First, the 2D terrain map is generated using a hill algorithm. UAVs are unmanned flying machines capable of carrying out autonomous mission that can fly without a human pilot aboard [1]. UAVs have been used by the world's armed forces for wartime operations for more than 60 years for battlefield observations, and more recently in civil applications such as fire control and other kinds of surveillance, postal services, agriculture and wildlife to name a few [2]. UAVs should be able to manoeuvre in complex terrain, and plan their own paths while avoiding obstacles. To generate a suitable path for UAV, path planning should consider not only the potential impact of terrain on flight safety but also the performance constraints on UAV. Therefore, path planning needs to be done quickly, especially for real-time processing in an environment with more obstacles

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as expected in terrains.

Fig. 1 Fluid flow or streams

2. Related Works

This study aims to solve the problem of finding a reliable path that enables a UAV to navigate from an initial position to a specified endpoint, without colliding with obstacles in a structured environment. The UAV navigation problem is solved generally by computing the solutions of Laplace's equation (i.e. harmonic potential fields (HPF)). In the past, the HPF was widely used in many areas of research due to it not experiencing local minima problems. These HPF were computed using standard point iterative methods. These point methods, however, were too slow for practical use, particularly when dealing with a large environment. Therefore, in this study, new algorithms based on the new mathematical formulae, using an accelerated block iteration procedure, will be developed to speed up the computation of HPF. The new sequential algorithms can be further improved with the availability of parallel computing technology. These algorithms, however, are sequential in nature and are not suitable for parallel implementation. In addition, although there exists robotics programming language that inherently supports parallel processing, this platform is only appropriate for the robot controller to read input from sensors, send commands to motors, and perform minimal amount of computation. If this parallel platform is used for large data processing, it will drastically affect the performance of the controller during the actual operation of the robot when it must respond quickly to the dynamic of the environment and its own motion. Therefore, any given knowledge (i.e., map of the environment) in raw form must be processed before it can be fed and useful to the controller. Even if the researcher decides to employ the existing, widely-used robotic programming language that inherently supports parallel processing, such as the Urbi platform, the process of converting sequential algorithms into the parallel version cannot be simply automated, as it requires a new set of formulations, careful data structure construction, appropriate data and tasks splitting, and process or thread synchronization.

Thus, further study in this project is important to develop new algorithms that are suitable for parallel implementation. Furthermore, these parallel algorithms need to be verified. Therefore, the performance of the newly developed algorithms will be analyzed. Additionally, the performances of the implemented parallel algorithms will be compared to their corresponding sequential algorithms. The overall performances of the proposed algorithms in solving the robot navigation problem in a structured environment will also be investigated.

Fig. 2 Different types of UAVs

3. Methodology

The harmonic function satisfies Laplace's equation:

$$\nabla^2 u = \sum_{i=1}^{n} \frac{\partial^2 u}{\partial x_i^2} \tag{1}$$

Term x_i is the i-th Cartesian coordinate, and n is the dimension. In the case of UAV path construction, the boundary consists of all obstacles and goals in a configuration space representation. Harmonic functions satisfy the min-max principle [6]; therefore, the spontaneous creation of a false local minimum inside the region is avoided if Laplace's equation is imposed as a constraint on the functions used. Numerical solutions for Laplace's equation are readily obtained from finite difference methods.

Although this system can be solved using direct methods, more efficient iterative methods are used to compute the solutions since their application in the path planning problem often results in a large linear system with a sparse coefficient matrix. The main advantage of iterative solutions is that storing large matrices is unnecessary. However, one of the disadvantages of iterative methods compared with direct one is slow convergence or even divergence. Thus, iterative methods in practice require an appropriate stopping criterion. The numerical solution for (1) can be solved effectively using the SOR method. In [5], Hadjidimos introduced the AOR method, which is a two-parameter generalization of the SOR method. It was shown that in certain cases, the AOR method has a better convergence rate than the classical Jacobi, Gauss-Seidel, or SOR methods. Later, an extension of the AOR method known as the two-parameter over-relaxation (TOR) method was examined and produced encouraging results.

In recent decades, complexity reduction approaches have been applied vigorously to compute the solutions of linear systems such as Poisson and Laplace's equations. The basic idea of complexity reduction approaches such as half-sweep iteration is to reduce the computational complexity of the solution methods. The half-sweep iteration concept is first envisioned via the explicit decoupled group (EDG) [7] method for solving the Poisson equation. The EDG method is actually an extension of the standard explicit group (EG) [8] method while its faster variant that employs weighted parameters via SOR is known as the EDGSOR method. Since then, the EDG and EDGSOR methods have been employed to solve linear systems generated from various problems [1-3]. The half-sweep iteration technique and its variants were utilized in many iterative methods for computing linear systems' solutions [4-7].

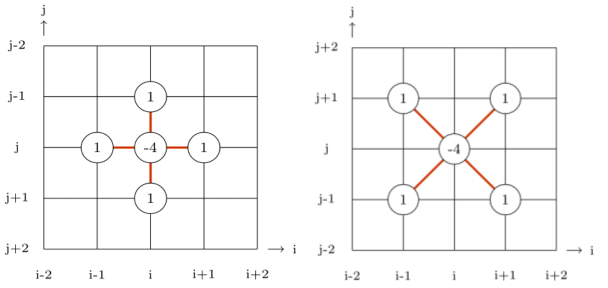
Equation (Eq.) (1) is rewritten in a two-dimensional space to solve the path planning problem for UAV as follows:

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = 0. \tag{2}$$

The finite difference approximation equation for Eq. (2) is defined as:

$$u_{i,j} = \frac{1}{4}(u_{i-1,j} + u_{i+1,j} + u_{i,j-1} + u_{i,j+1}) \tag{3}$$

Eq. (3) is used to implement the Gauss-Seidel (GS) iterative method, and its computational molecule is shown in Fig. 2.



(a) (b)

Fig. 3 Computational equation for Equation (1): (a) full sweep and (b) half-sweep

Based on Eq. (3), the GS iterative scheme can be written as:

$$u_{i,j}^{(k+1)} = \frac{1}{4}(u_{i-1,j}^{(k+1)} + u_{i+1,j}^{(k)} + u_{i,j-1}^{(k+1)} + u_{i,j+1}^{(k)}). \tag{4}$$

Table 1 Simulation parameters

No.	Parameters	Values
1	Area Coverage	256x256, 512x512, 1024x1024
2	Number of Hills	40, 80, 120
3	Methods	SOR, AOR, RSOR

3.1. The Successive Over-Relaxation (SOR) Method

The SOR employs a weighted parameter, ω, to the Gausss-Seidel iteration, and is given below:

$$u_{i,j}^{(k+1)} = \frac{\omega}{4}(u_{i-1,j}^{(k+1)} + u_{i+1,j}^{(k)} + u_{i,j-1}^{(k+1)} + u_{i,j+1}^{(k)} + (1- \ \omega)u_{i,j}^{(k)}$$

(5)

The Accelerated Overrelaxation (AOR) method is presented as follows:

$$u_{i,j}^{(k+1)} = \frac{\omega}{4}(u_{i-1,j}^{(k)} + u_{i+1,j}^{(k)} + u_{i,j-1}^{(k)} + u_{i,j+1}^{(k)}) + (1-\omega)u_{i,j}^{(k)} + \frac{r}{4}(u_{i-1,j}^{(k+1)} - u_{i-1,j}^{(k)} + u_{i,j-1}^{(k+1)} - u_{i,j-1}^{(k)}) \tag{6}$$

The RSOR is reflected below:

$$\begin{aligned} U_{i,j}^{(k+1)} &= \frac{r}{4}\left[U_{i-1,j}^{(k+1)} - U_{i-1,j}^{(k)} + U_{i,j-1}^{(k+1)} - U_{i,j-1}^{(k)}\right] + \frac{r}{4}\left[U_{i+1,j}^{(k+1)} - U_{i+1,j}^{(k)} + U_{i,j+1}^{(k+1)} - U_{i,j+1}^{(k)}\right] \\ &\quad + \frac{\omega'}{4}\left[U_{i-1,j}^{(k)} + U_{i+1,j}^{(k)} + U_{i,j-1}^{(k)} + U_{i,j+1}^{(k)}\right] + (1-\omega')U_{i,j}^{(k)}, \\ U_{i-1,j+1}^{(k+1)} &= \frac{r}{4}\left[U_{i-2,j+1}^{(k+1)} - U_{i-2,j+1}^{(k)} + U_{i-1,j}^{(k+1)} - U_{i-1,j}^{(k)}\right] + \frac{r}{4}\left[U_{i,j+1}^{(k+1)} - U_{i,j+1}^{(k)} + U_{i-1,j+2}^{(k+1)} - U_{i-1,j+2}^{(k)}\right] \\ &\quad + \frac{\omega'}{4}\left[U_{i-2,j+1}^{(k)} + U_{i-1,j}^{(k)} + U_{i,j+1}^{(k)} + U_{i-1,j+2}^{(k)}\right] + (1-\omega')U_{i-1,j+1}^{(k)}. \end{aligned} \tag{7}$$

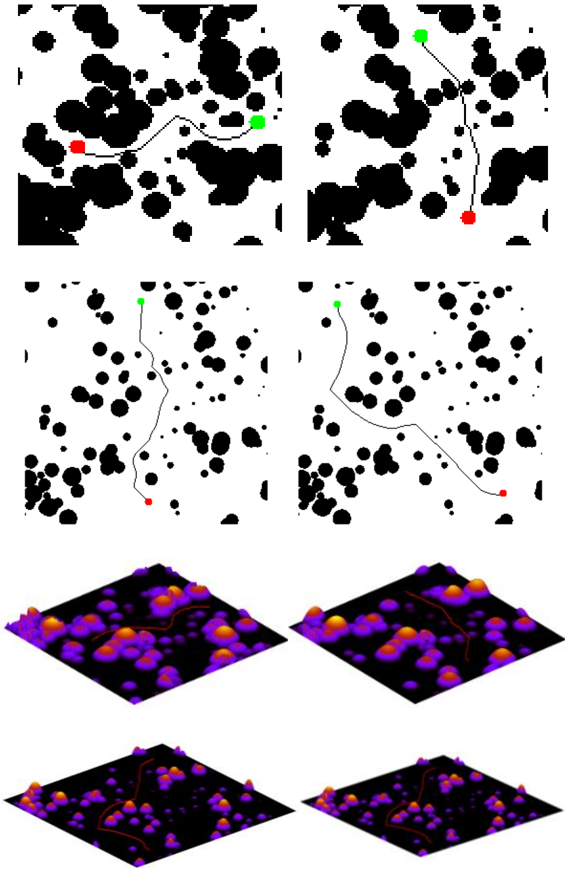


Fig. 4 Generated random 2D and 3D path for (a) 128x128 and (b) 256x256 areas

Therefore, this system will be used for traffic and emergency management. As shown in Fig. 4, several environments will be used to study traffic flow and emergency conditions.

Fig. 5 Drone used for pesticides spray in padi field, Kedah, Malaysia

4. Results and Discussion

In this section, the simulation results displaying the path planning of UAV in various obstacle environments will be shown. The experiments considered three different static, outdoor environment sizes, composed of three different, randomly generated numbers of hills (40, 80, and 120 hills). As mentioned previously, the optimum values of weighted parameters were chosen in the range: (1, 2). Clearly, in terms of iteration number, the RSOR iterative method provided a high performance compared to other considered methods, ω r ω′. Meanwhile, execution times for rotated families proved to be slightly faster than the standard methods.

Figs. 6, 7, and 8 show the results for numbers of iterations, tested in different numbers of obstacles (40, 80, and 120 hills). The results show that the lesser the area's space (meaning more obstacles), the lower the number of iterations. The results also show that the proposed RSOR significantly outperformed the previous methods, in all areas tested in these simulations.

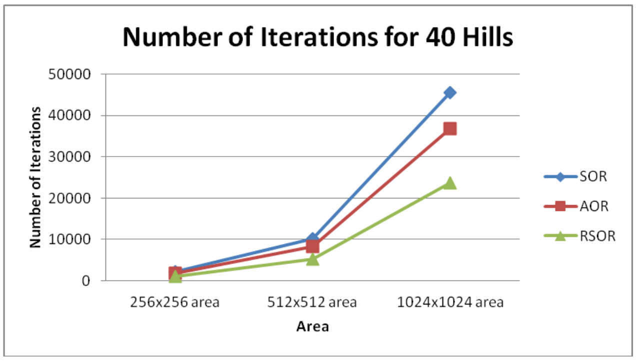


Fig. 6 Number of iterations against iterative methods for different sizes of the environment in 40 hills obstacle

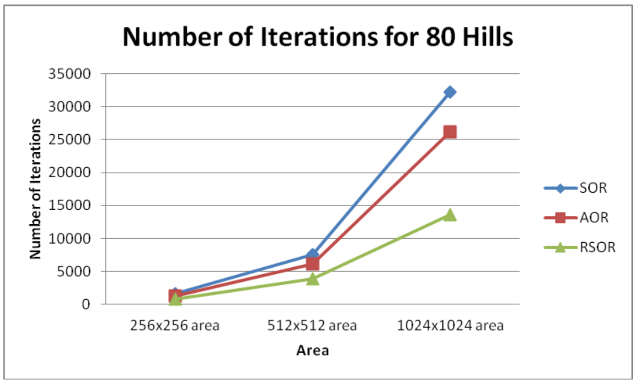


Fig. 7 Number of iterations against iterative methods for different sizes of environment and 80 hills obstacle

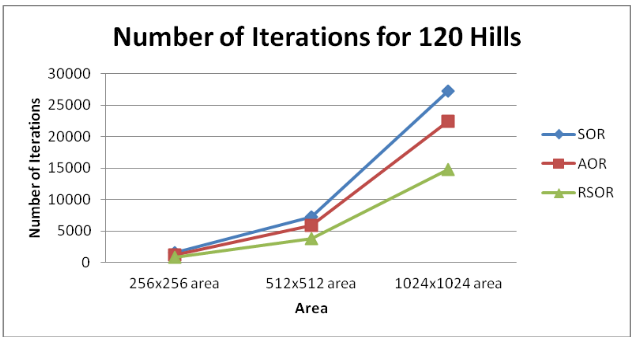


Fig. 8 Number of iterations against iterative methods for different sizes of environment and 120 hills obstacle

The next experiment will test the performance of this new method in terms of computational time (in milliseconds). Tables 2, 3, and 4 show the results for computational time, tested in different numbers of obstacles (40, 80, and 120 Hills). The results show that the lesser the area's space (meaning more obstacles), the lower the computation time. The results also show that the proposed RSOR significantly outperformed the previous methods, in all areas tested in these simulations.

Table 2 Computational time (milliseconds) for 120 hills obstacles

Method\Hills	**256x256**	**512x512**	**1024x1024**
SOR	0 min, 1 sec, 247 ms	0 min, 21 sec, 686 ms	5 min, 16 sec, 214 ms
AOR	0 min, 0 sec, 909 ms	0 min, 16 sec, 764 ms	5 min, 28 sec, 574 ms
RSOR	0 min, 0 sec, 436 ms	0 min, 6 sec, 535 ms	1 min, 44 sec, 709 ms

Table 3 Computational time (milliseconds) for 80 hills obstacles

Method\Hills	**256x256**	**512x512**	**1024x1024**
SOR	6 min, 15 sec, 17 ms	0 min, 22 sec, 608 ms	6 min, 15 sec, 17 ms
AOR	5 min, 11 sec, 168 ms	0 min, 17 sec, 475 ms	5 min, 11 sec, 168 ms
RSOR	2 min, 2 sec, 401 ms	0 min, 6 sec, 527 ms	2 min, 2 sec, 401 ms

Table 4 Computational time (milliseconds) for 40 hills obstacles

Method\Hills	**256x256**	**512x512**	**1024x1024**
SOR	0 min, 1 sec, 826 ms	0 min, 30 sec, 299 ms	8 min, 57 sec, 546 ms
AOR	0 min, 1 sec, 511 ms	0 min, 23 sec, 715 ms	7 min, 46 sec, 646 ms
RSOR	0 min, 0 sec, 419 ms	0 min, 8 sec, 905 ms	3 min, 50 sec, 339 ms

5. Conclusion

Using the accelerated method, an efficient path planning algorithm for autonomous UAV was obtained, providing significant improvement in decreasing the number of iterations, and using the least computational time. This outcome means that the time to compute the path for UAV/drones quickens, and the number of mathematical iterations to generate the path would be significantly reduced using the proposed algorithms. Due to the recent advanced numerical techniques, and the availability of faster machines today, this experiment demonstrated that solving Laplace's Equation (1) numerically to resolve the UAV path finding problem, was certainly very promising and attainable. Compared to the prior existing SOR method, the RSOR iterative method proved to be high performing in terms of the number of iterations and the computational time. The obstacles' shapes do not adversely influence efficiency; instead, the computation quickens as the obstacles' regions are ignored during the calculation.

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References

[1] KHATIB O. Real-Time Obstacle Avoidance for Manipulators and Mobile Robots. *Proceedings of the* IEEE International Conference on Robotics and Automation, St. Louis, Missouri, 1985, pp. 500-505. https://doi.org/10.1109/ROBOT.1985.1087247

[2] CONNOLLY C. I., BURNS J. B., and WEISS R. Path planning using Laplace's equation. Proceedings of the IEEE International Conference on Robotics and Automation, Cincinnati, Ohio, 1990, pp. 2102-2106. https://doi.org/10.1109/ROBOT.1990.126315

[3] AL SAID N., & GORBACHEV Y. An Unmanned Aerial Vehicles Navigation System on the Basis of Pattern Recognition Applications. *Journal of Southwest Jiaotong University*, 2020, 55(3). http://jsju.org/index.php/journal/article/view/599

[4] MOSTAFA S. A., MUSTAPHA A., RAMLI A. A., DARMAN R., ZEEBAREE S. R. M., MOHAMMED M. A., GUNASEKARAN S. S., and IBRAHIM D. A. Applying Trajectory Tracking and Positioning Techniques for Real-time Autonomous Flight Performance Assessment of UAV Systems. *Journal of Southwest Jiaotong University*, 2019, 54(3). https://doi.org/10.35741/issn.0258-2724.54.3.7

[5] CONNOLLY C. I., & GRUPPEN R. A. The applications of harmonic functions to robotics. *Journal of Robotic Systems*, 1993, 10(7): 931-946. https://doi.org/10.1002/rob.4620100704

[6] SAUDI A., SULAIMAN J., and HIJAZI M. H. A. Fast Robot Path Planning with Laplacian Behaviour-Based Control via Four-Point Explicit Decoupled Group SOR. *Research Journal of Applied Sciences*, 2014, 9(6): 354-360. https://doi.org/10.36478/rjasci.2014.354.360

[7] MUTHUVALU M. S., & SULAIMAN J. Quarter-Sweep Arithmetic Mean (QSAM) iterative method for second kind linear Fredholm integral equations. *Applied Mathematical Sciences*, 2010, 4(59): 2943-2953.

[8] DAHALAN A. A., AZIZ N. S. A., and SULAIMAN J. Performance of Quarter-Sweep Successive over Relaxation Iterative Method for Two-Point Fuzzy Boundary Value Problems. *Journal of Engineering and Applied Sciences*, 2016, 11(7): 1456-1463. https://doi.org/10.36478/jeasci.2016.1456.1463

参考文:

[1] KHATIB O. 机械手和移动机器人的实时避障。电气工程师学会机器人和自动化国际会议论文集，密苏里州圣路易斯，1985，第 500-505 页。https://doi.org/10.1109/ROBOT.1985.1087247

[2] C. I.，BURNS J. B. 和 WEISS R. 使用拉普拉斯方程进行路径规划。电气工程师学会机器人技术与自动化国际会议论文集，俄亥俄州辛辛那提，1990，第 2102-2106 页。 https://doi.org/10.1109/ROBOT.1990.126315

[3] AL SAID N. 和 GORBACHEV Y。基于模式识别应用的无人机导航系统。西南交通大学学报，2020，55（3）。 http://jsju.org/index.php/journal/article/view/599

[4] MOSTAFA S.A.，MUSTAPHA A.，RAMLI A.A.，DARMAN R.，ZEEBAREE S.R.M.，MOHAMMED M.A.，GUNASEKARAN S.S. 和 IBRAHIM D. A. 将轨迹跟踪和定位技术应用于无人机系统的实时自主飞行性能评估。西南交通大学学报，2019，54（3）。https://doi.org/10.35741/issn.0258-2724.54.3.7

[5] CONNOLLY C. I. 和 GRUPPEN R. A. 谐波函数在机器人技术中的应用。机器人系统杂志，1993，10（7）：931-946。https://doi.org/10.1002/rob.4620100704

[6] SAUDI A.，SULAIMAN J. 和 HIJAZI M.H.A. 通过基于四点显式解耦组SOR的基于拉普拉斯行为的控制进行快速机器人路径规划。 应用科学学报，2014，9（6）：354-360。https://doi.org/10.36478/rjasci.2014.354.360

[7] MUTHUVALU M. S. 和 SULAIMAN J. 第二类线性弗雷德霍尔姆积分方程的四分之一扫描算术平均值（质量管理体系）迭代方法。应用数学科学，2010，4（59）：2943-2953。

[8] DAHALAN A. A.，AZIZ N. S. A. 和 SULAIMAN J. 针对两点模糊边值问题的四分之一扫频连续松弛迭代方法的性能。工程与应用科学学报，2016，11（7）：1456-1463。https://doi.org/10.36478/jeasci.2016.1456.1463