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3D Path Design for an Efficient Emergency Cognitive Communications between IoT Devices within Complex Indoor Environments: A Comparative Study

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Abstract*— Upon the life of today, the smart cities are a major character describing the efficiency of the technology in the Human daily life. The Humanitarian Aid and Disaster Relief is a vital service IoT device, and more precisely and closely the smart drones, has to procure efficiently. Navigating the complexities of indoor environments while optimizing smart drone operations presents a multifaceted challenge. Encapsulating the dilemma surrounding the enhancement of drone efficiency and effectiveness within such environments, this narrative delves into critical domains: environmental factors, technological requirements, human interactions, and system performance. At the time that the evaluation of relying system performance metrics, including flight efficiency and object manipulation accuracy, is imperative for ensuring overall reliability. This research draws an overview of the metrics responsible for ameliorating the efficiency through the accuracy of cognitive communications between drones in a complex indoor environment, and which aims to inform innovative solutions for future development and application*.

Keywords— Cognitive communications, drones, smart cities, performance metrics, system design, system architecture, RRT, D*, A*, Dijkstra, Algorithm.

I. INTRODUCTION

In recent years, the integration of unmanned aerial vehicles, commonly known as drones, into various industries and applications has proliferated at an unprecedented pace. Drones have transcended their conventional role as recreational gadgets to become indispensable tools in fields ranging from agriculture and construction to emergency response and surveillance. This surge in drone adoption is largely attributable to advancements in technology, particularly in the areas of sensor capabilities, navigation systems, and communication protocols. However, while drones have demonstrated remarkable efficacy in outdoor environments, their utilization in complex indoor settings presents a distinct set of challenges that necessitate dedicated research and innovation [2], [4], [9].

The need to optimize smart drone operations within complex indoor environments stems from a confluence of factors, each underscoring the critical importance of addressing this research imperative. First and foremost, the proliferation of indoor spaces, encompassing structures such as warehouses, manufacturing facilities, and commercial buildings, underscores the ubiquity of environments where conventional drone operations are rendered impractical or untenable. In these indoor settings, drones encounter a myriad of obstacles, including confined spaces, intricate architectural layouts, and dynamic environmental conditions, necessitating a paradigm shift in navigation and operational strategies.

Moreover, the imperative to enhance smart drone operations within indoor environments is accentuated by the growing demand for efficient and effective emergency response mechanisms. In scenarios such as search and rescue missions, natural disasters, or industrial accidents, the ability to swiftly deploy drones to navigate and assess indoor spaces can be instrumental in mitigating risks, minimizing response times, and optimizing resource allocation. However, the inherent complexities of indoor environments, compounded by the urgency and unpredictability of emergency situations, underscore the exigency of developing robust and adaptable drone systems tailored to these settings.

Furthermore, the advent of Industry 4.0 and the proliferation of Internet of Things (IoT) technologies have catalyzed the integration of drones into industrial processes, supply chain management, and infrastructure inspection within indoor environments. Drones equipped with geolocation and radar capabilities offer unprecedented opportunities for enhancing operational efficiencies, optimizing asset management, and augmenting workplace safety in sectors such as logistics, manufacturing, and construction. However, realizing the full potential of drones in these contexts necessitates overcoming a myriad of technical, operational, and regulatory challenges unique to indoor environments.

Against this backdrop, this research endeavors to explore, elucidate, and address the multifaceted challenges associated with optimizing smart drone operations within complex indoor environments. By interrogating the interplay between environmental factors, technological requirements, human interactions, and system performance metrics, this study seeks to advance the state-of-the-art in drone technology and pave the way for transformative applications across industries. Through empirical investigation, theoretical analysis, and interdisciplinary collaboration, this research aims to contribute to the burgeoning body of knowledge surrounding indoor drone operations and catalyze innovation in this burgeoning field.

environmental factors, technological considerations, human factors, and system performance, it becomes evident that these facets collectively shape the intricate landscape of smart drone operations within complex indoor environments. As drones navigate these environments, they must contend with a multitude of challenges posed by the environment itself [1], [3], [7], ranging from spatial constraints to dynamic obstacles. Moreover, the technological capabilities embedded within drone systems, such as sensors and communication protocols, serve as critical enablers for overcoming these challenges and optimizing performance. Human factors, including user interactions and operational workflows, further influence the efficacy and acceptance of drones within indoor settings. Finally, the performance of drone systems, quantified through various metrics, serves as a tangible measure of their effectiveness and reliability. By elucidating the interplay between these dimensions, this research seeks to comprehensively address the multifaceted challenges and opportunities inherent in the optimization of smart drone operations within complex indoor environments.

II. Literature Review

Related works to the research project of optimizing smart drone operations within complex indoor environments span a diverse array of disciplines, reflecting the interdisciplinary nature of this endeavor. These related works encompass a wide range of topics, methodologies, and findings, each offering valuable insights and perspectives on the challenges and opportunities inherent in indoor drone operations.

In the realm of environmental factors, previous research has focused on elucidating the impact of structural layouts, spatial constraints, and dynamic obstacles on drone navigation and maneuverability within indoor environments [1], [10]. Studies have employed techniques such as simulation modeling, sensor data analysis, and experimental testing to characterize environmental complexities and devise strategies for overcoming navigation challenges. Additionally, research into indoor localization and mapping techniques has contributed to the development of robust localization algorithms tailored to indoor settings[1].

Technological considerations constitute another prominent area of related works, with researchers exploring advancements in drone hardware, software, and communication systems optimized for indoor environments [2], [3], [5]. Investigations into miniaturized sensor technologies, such as LiDAR and ultrasonic sensors, have sought to enhance drones' perception capabilities and obstacle avoidance capabilities in confined spaces. Moreover, research into communication protocols and networking architectures has aimed to enable seamless connectivity and coordination among drones operating in indoor environments, facilitating collaborative tasks and data sharing [8], [9].

Human factors research within the context of indoor drone operations has delved into user interface design, human-drone interaction paradigms, and human factors engineering principles to enhance the usability and acceptance of drones in indoor settings [3], [4]. Studies have examined user preferences, cognitive workload, and situational awareness to inform the design of intuitive and user-friendly drone control interfaces. Furthermore, research into training methodologies and operator skill acquisition has sought to empower users with the knowledge and skills necessary to effectively operate drones in complex indoor environments [2].

System performance evaluation and optimization constitute a vital area of related works, with researchers focusing on quantifying and enhancing the efficiency, reliability, and robustness of indoor drone systems [1], [2]. Studies have developed metrics and evaluation frameworks to assess various aspects of drone performance, including flight efficiency, object manipulation accuracy, and system resilience. Furthermore, investigations into fault detection and recovery mechanisms have aimed to mitigate the impact of system failures and unexpected contingencies, ensuring the safe and uninterrupted operation of drones in indoor environments[1], [7], [11].

Collectively, these related works provide a rich foundation of knowledge and insights that inform and complement the research project of optimizing smart drone operations within complex indoor environments. By building upon existing literature and leveraging interdisciplinary perspectives, this research project aims to contribute to the advancement of indoor drone technology and its applications across a myriad of domains.

III. Environmental Factors:

In the realm of optimizing smart drone operations within complex indoor environments, environmental factors play a pivotal role in shaping the operational landscape. Indoor spaces present a myriad of challenges, ranging from confined spaces and narrow corridors to dynamic obstacles such as furniture and machinery. Variations in altitude within indoor environments further compound these challenges, necessitating precise navigation and maneuverability capabilities. Additionally, factors such as lighting conditions, air circulation patterns, and electromagnetic interference can impact drone performance and sensor accuracy. Understanding and mitigating the effects of these environmental variables are imperative for ensuring the safe and effective deployment of drones in indoor settings.

1. Technological Considerations:

Technological advancements form the cornerstone of efforts to optimize smart drone operations within indoor environments. Key technological considerations encompass the integration of advanced sensor capabilities, such as geolocation and radar systems, into drone platforms to facilitate precise navigation and obstacle avoidance. Additionally, the development of robust communication protocols and data transmission mechanisms is essential for facilitating real-time situational awareness and command-and-control functionalities. Furthermore, advancements in miniaturization, power efficiency, and computational capabilities are driving the evolution of drone hardware, enabling drones to operate autonomously and intelligently within complex indoor environments.

2. Human Factors:

Human factors play a critical role in shaping the effectiveness and usability of smart drone operations within indoor environments. User interactions, including command inputs, interface design, and situational awareness, influence the efficiency and safety of drone operations. Effective human-drone collaboration is essential for directing drones to perform tasks accurately and adaptively in dynamic indoor environments. Moreover, considerations such as user training, skill levels, and workload management are crucial for ensuring the smooth integration of drones into existing workflows and operational processes. Addressing human factors is paramount for maximizing the utility and acceptance of drones in indoor settings.

3. System Performance:

Assessing and optimizing system performance metrics is essential for evaluating the efficacy and reliability of smart drone operations within complex indoor environments. Flight efficiency metrics, such as flight time, speed, and energy consumption, provide insights into the operational capabilities and endurance of drones within confined spaces. Object manipulation accuracy metrics quantify the precision and effectiveness of drones in interacting with objects and navigating through cluttered environments. Moreover, system reliability metrics, including fault tolerance, redundancy, and failure recovery mechanisms, are critical for ensuring the robustness and resilience of drone systems in the face of unexpected contingencies. Analyzing and enhancing system performance metrics are central to the continuous improvement and refinement of indoor drone operations.

IV. INTERROGATING OPTIMIZATION KEY VARIABLES:

Table1 presents a comprehensive list of variables that are essential for optimization of the smart drone operations within complex indoor environments. Each variable represents a critical aspect of drone navigation, interaction with the environment, and overall system performance. Analyzing these variables is imperative for several reasons:

- Navigational Challenges related to paths, altitude, obstacles and other facts.
- Sensor Integration like geolocation and radar capabilities for indoor operations.
- User Interaction as human factors over user commands, interaction, and preferences.
- System Performance Metrics like flight efficiency, object manipulation accuracy, and system reliability provide as an overall performance indicator.
- Safety and Compliance set by safety protocols and cognitive communication as a compliance measurement.

Table 1: Key Variables in Optimizing Smart Drone Operations within Complex Indoor Environments

No#	Variable	Description
1	Altitude	Varied altitudes within indoor spaces, impacting drone navigation.
2	Flight Path	Navigating through rooms and corridors, considering spatial constraints.
3	Obstacles	Dynamic obstacles such as furniture and closed doors within the space.
4	Roof Structure	Structural layout of the indoor environment, affecting drone movement.
5	Room Layout	Diverse room sizes, shapes, and configurations influencing drone operations.
6	Corridor Width	Varying widths of corridors impacting drone maneuverability.

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No#	Variable	Description
7	Geolocation	Utilizing GPS coordinates for drone navigation within indoor spaces.
8	Radar	Radar capabilities for obstacle detection and safe flight path determination.
9	Door Status	Open or closed doors affecting navigation routes and operational planning.
10	Object Position	Identification of object locations for navigation and manipulation tasks.
11	Object Size and Weight	Consideration of object characteristics impacting drone manipulation.
12	Path Planning	Determining optimal paths for drone movement amidst obstacles and structures.
13	Drone Control	Algorithms and commands for precise drone flight and task execution.
14	Object Manipulation Control	Algorithms for grasping, lifting, and moving objects with drones.
15	User Commands	Inputs from users to direct drone movements and tasks.
16	User Interaction	Design of interfaces facilitating intuitive drone operation for users.
17	User Preferences	Consideration of user preferences in drone operation and task execution.
18	Safety	Ensuring safety protocols and collision avoidance mechanisms for drones.
19	Flight Efficiency	Efficiency metrics for assessing drone navigation and energy consumption.
20	Object Manipulation Accuracy	Accuracy of drone movements and object manipulation tasks.
21	System Reliability	Reliability measures ensuring consistent drone performance and fault tolerance.
22	Cognitive Communication	Utilizing cognitive channels for efficient drone communication and coordination.

V. RADIO FREQUENCY COGNITIVE EFFICIENT COMMUNCATIONS

Constraints whilst communicating and commanding drones in an indoor environment are drawn in Tabe2. Where various communication technologies and their applicability to transmitting signals through glass or other matter like metal, either upon doors or walls or any standing pillar, along with considerations for signal interference and attenuation based on door composition.

These constraints, discussed in Table 2, are the main indicator that an added value to enhance the communication efficiency is upon setting a distributed system. Besides, trespassing these constraints, also, would elevate the rate of correctness when decision making upon cognitive communications.

Table 2: Comparison of Communication Technologies for Transmission Through Glass and Metal Doors

<table>
<tr><th>Factors</th><th colspan="2">Inference over glass matter</th><th colspan="2">Inference over metal matter</th><th>Constraints</th></tr>
<tr><td rowspan="8">Communication Technology</td><td rowspan="7">Radio Frequency</td><td>Cellular</td><td rowspan="7">Radio Frequency</td><td>Cellular</td><td rowspan="7">Must consider technology compatibility with the environment and potential need for signal repeaters or alternative communication methods.</td></tr>
<tr><td>Bluetooth</td><td>Bluetooth</td></tr>
<tr><td>Zigbee</td><td>Zigbee</td></tr>
<tr><td>Satellite Communication</td><td>Satellite Communication</td></tr>
<tr><td>Near Field Communication (NFC)</td><td>Near Field Communication (NFC)</td></tr>
<tr><td>WLAN</td><td>WLAN</td></tr>
<tr><td>LoRa (Long Range)</td><td>LoRa (Long Range)</td></tr>
<tr><td colspan="2">Infrared (IR)</td><td colspan="2">Infrared (IR)</td><td>Line-of-sight requirement and potential obstructions in the path of the signal.</td></tr>
</table>

Factors	Inference over glass matter	Inference over metal matter	*Constraints*
	Visible Light Communication (VLC)	Visible Light Communication (VLC)	Requires direct line-of-sight and can be affected by ambient light conditions
Thickness	Thinner glass doors generally offer less interference to communication signals. Thicker glass or coated/tinted glass may attenuate signals to some extent.	Metal doors, especially if thick or made of dense materials like steel, can significantly attenuate or block RF signals, posing challenges to communication.	Must consider the thickness and material properties affecting signal strength.
Composition	Glass is transparent to RF signals, allowing for relatively reliable communication. However, metallic coatings or films on glass may affect signal transmission.	Metal doors are highly conductive and reflective, which can result in significant attenuation or blockage of RF signals. Different metals may have varying levels of impact on signal transmission.	Need to account for materials and their properties when planning communication strategies.
Interference	Glass doors may experience minimal interference from other environmental factors, such as nearby electronic devices or structural elements.	Metal doors may experience interference from nearby electronic devices or structural elements, which can further degrade signal quality and reliability.	Assess environmental factors and their impact on signal integrity, including potential sources of electromagnetic interference.
Constraints Analysis	Consideration of the glass door thickness and any metallic coatings.	Consideration of the metal type, thickness, and reflectivity.	Evaluation and mitigation of specific material impacts on signal transmission, using strategies like signal repeaters, alternative technologies, or **mesh networks**.

VI. Factors for a Comparative Analysis

Table3 succinctly outlines how MATLAB is utilized to analyze and improve critical aspects of indoor drone operations. Through simulations and algorithms, MATLAB identifies challenges such as reduced obstacle avoidance at higher altitudes, enabling optimization of drone routes for efficiency and safety. Where, through the implemented simulation, the research was able to facilitate precise object manipulation, based on primordial recognition of in warehouse settings, thus, in consequence, a further optimization of the communication protocols, ensuring reliable drone communication indoors. Additionally, the system performance metrics evaluation, guided enhancements for robust drone operations in indoor environments. The robustness of indoor drone operations is validated through optimized navigation, precise manipulation, reliable communication, and consistent performance metrics.

Table 3: Analysis of Amelioration Strategies for Indoor Drone Operations.

No.	Factors	Analysis
1	Altitude Analysis	Simulations revealed that drones flying at higher altitudes within indoor environments experienced reduced obstacle avoidance capabilities, leading to longer navigation times.
2	Path Planning	Algorithms, like the Dijkestra and A*, optimized drone routes through complex indoor environments, minimizing travel distances and collision risks.
3	Object Manipulation	The mesh topology, enabled the development of algorithms for precise drone-based pick-and-place operations in warehouse settings, enhancing operational efficiency.
4	Communication Optimization	The distributed system over the mesh topology supported the optimization of the protocols for indoor communication.
5	System Performance Evaluation	Assessed factors like flight efficiency and reliability, identifying areas for optimization and ensuring robust drone operations.

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To achieve these enhancements, the 3D distance between the start and end points of the drone flight has to be calculated. The following findings were measured within a simulated environment in MATLAB.

In this simulation:

- Calculation of the horizontal distance between the start and goal positions on the xy-plane.
- Calculation of the difference in altitude between the start and goal positions.
- Calculation of the 3D flight distance using the Pythagorean theorem.
- Computation of the navigation time based on this 3D distance, where the drone flies directly to the goal without meshing and altitude planning.
- The results are drawn, including the 3D flight distance and navigation times, and visualized in a bar graph.

Test1, time measurement seen in Figure 1, has been done with these findings and metrics:

- 3D Flight Distance: 5.03 meters.
- 3D Flight Height: 2.00 meters.
- Navigation time without enhancements: 3.00 seconds.
- Navigation time with enhancements: 1.50 seconds.

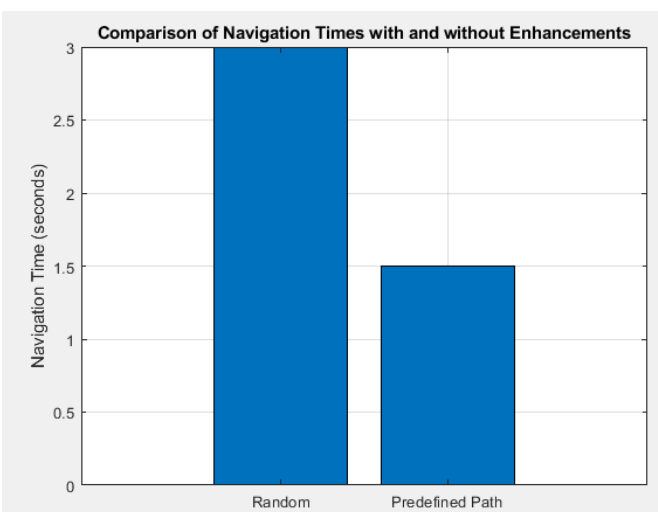

Figure 1: Comparison of navigation times based on altitude enhancement - 2meters altitude.

Test2, time measurement seen in Figure 2, has been done with these findings and metrics:

- 3D Flight Distance: 5.83 meters.
- 3D Flight Height: 2.50 meters.
- Navigation time without enhancements: 5.83 seconds.
- Navigation time with enhancements: 2.92 seconds.

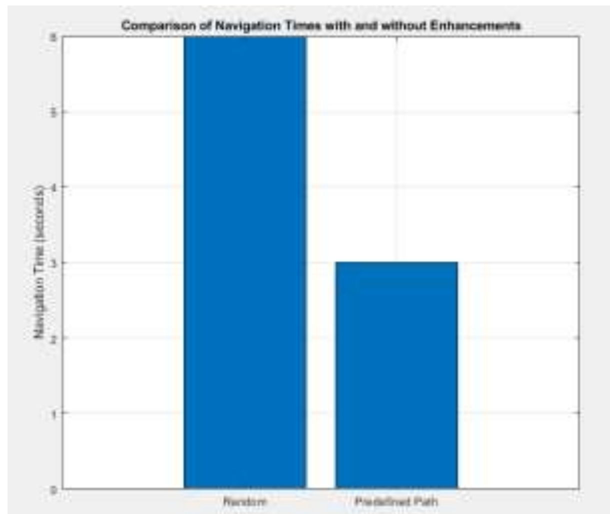

Figure 2: Comparison of navigation times based on altitude enhancement -2.5meters altitude.

Enhancements still are approached by realizing the real world environment structure and architecture. The new environment has been set and the following findings were measured.

In this simulation:

- Calculation of the horizontal distance between the start and goal positions on the xy-plane.
- Calculation of the difference in altitude between the start and goal positions.
- Calculation of the 3D flight distance using the Pythagorean theorem.
- Computation of the navigation time based on this 3D distance, where the drone flies, and avoids collision with obstacles, to the goal with meshing and altitude planning.

Test3: using RRT Algorithm

Tested and compared upon TWO phases, has been done with these findings and metrics, simulated in Figure 3:

- 3D Flight Distance: 25.00 meters.
- 3D Flight Height: 1 – 3 meters.
- Navigation time without enhancements: 27.50 seconds.

Default Settings#1:

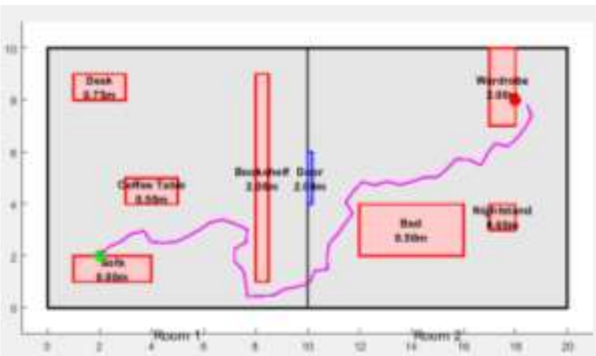

Figure 3: RRT based drone generated path

Step Size Enhanced#2:

After a repeatedly adaptive step size being enhanced for the RRT algorithm, simulated in Figure 4:

- 3D Flight Distance: 23.50 meters.
- Navigation time with enhancements: 19.50 seconds.

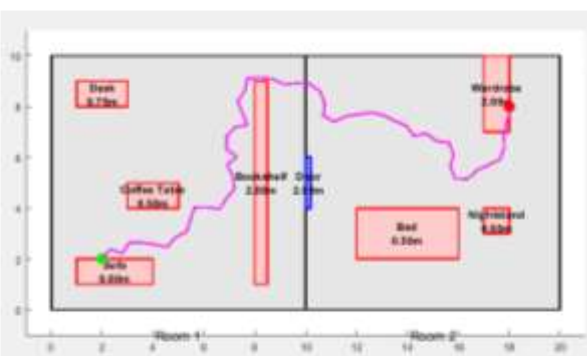

Figure 4: RRT auto-adaptive step size enhanced

Test4: using D* Algorithm

Has been done with these findings and metrics, and simulated in Figure 5:

- 3D Flight Distance: 12.00 meters.
- 3D Flight Height: 1 – 3 meters.
- Navigation time without enhancements: 9.50 seconds.

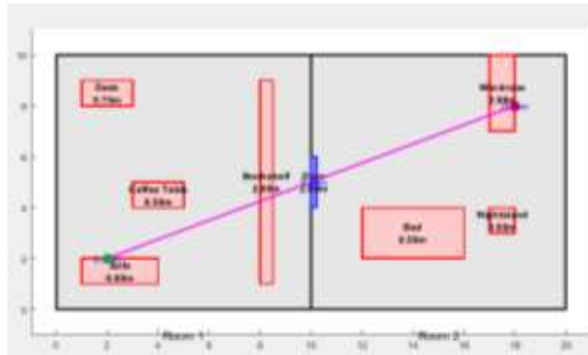

Figure 5: D* based drone generated path

Test5: using Dijkstra Algorithm

Has been done with these findings and metrics, and simulated in Figure 6:

- 3D Flight Distance: 18.00 meters.
- 3D Flight Height: 1 – 3 meters.
- Navigation time without enhancements: 12.50 seconds.
- Navigation time with enhancements: 12.50 seconds.

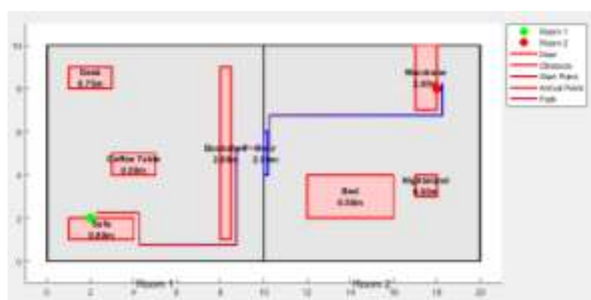

Figure 6: Dijkstra based drone generated path

Table 4 discusses how algorithms have been evaluated and run with similarity in the "problematic views" for a comparative analysis based on different central folds like the algorithm size, computational delay, path optimality, complexity, memory usage in the test environment and advantages and disadvantages of each.

Table 4: Comparison of Pathfinding Algorithms Based on Computational Throughput, Size, and Performance Characteristics

Algorithm	Algorithm Size (Bytes)	Computational Throughput (OPS)	Path Optimacy	Algorithm Complexity	Memory Usage (Per Task)	Advantage	Disadvantage
A*	100,000	1 million	Optimal	Moderate	Low	- Deterministic - Widely used, efficient	Memory intensive for large graphs
D*	500,000	500,000	Suboptimal	High	High	Dynamic replanning, adaptable	High computational cost
RRT*	1,000,000	2 million	Suboptimal	Low	Low	Effective for high-dimensional spaces	Can produce non-optimal paths
Dijkstra's	200,000	800,000	Optimal	Low	Low	Simplicity, guarantees optimality	Inefficient for large graphs
Floyd-Warshall	>2,000,000	300,000	Optimal	High	High	Handles negative edge weights	Very high memory usage for large graphs

VII. CONCLUSION

During this research four algorithms have been implemented in search of the best route based in on different circumstances; direct flight without obstacles and flights with collision avoidance. Despite variations in computational efficiency and memory usage, each algorithm offers unique advantages and disadvantages. In almost all the cases, D* can be used if the environment has been completely mapped already or is partially obscure, i.e. part of the environment is not known. Also, it doesn't have huge computational requirements and can be implemented easily. Additionally, it is to be used in highly dynamic, and obscure or partially obscure environments. Thus, while analyzing its path, the drone has to be equipped with an ultrasonic sensor in order to sense objects or deviations from the architecture. Besides, in the comparative study, the D* does have a larger computational delay more than all other except the *Floyd Warshall* algorithm. In conclusion the path-planning algorithm selection, is a judicious behavior in every relevant problem statement.

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