DITHER: Digital Twin for Energy Estimation of Heterogeneous Swarm of Robots

Omar Hammami
U2IS
ENSTA Paris
Palaiseau France
omar.hammami@ensta-paris.fr

Chunyu ZHANG
U2IS
ENSTA Paris
Palaiseau France
chunyu.zhang@ensta-paris.fr

***Abstract*—The increasing adoption of Unmanned Aerial Vehicles (UAVs) in industrial applications such as construction inspection and infrastructure monitoring necessitates the development of efficient path planning and energy management strategies. This paper presents DITHER, a Digital Twin system designed for energy consumption profiling and management in UAV-based construction inspection tasks. The proposed system integrates real-time data acquisition, energy consumption profiling, and path optimization using a hybrid approach combining path planning and energy efficiency models. Experiments conducted with a DJI Tello UAV show that the digital twin framework facilitate UAV operational in complex inspection tasks by balancing energy consumption and path length. The proposed system can be extended to support multi-UAV collaborative operations in future research.**

Keywords— Digital Twin, UAV Path Planning, Energy Management, Construction Inspection

I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) have seen rapid growth in their use for applications such as infrastructure inspection, construction monitoring, and search and rescue missions. UAVs provide an efficient means of acquiring data in complex or hazardous environments, but their operational effectiveness is limited by energy constraints and complex path planning requirements. In construction inspection tasks, UAVs must navigate cluttered environments with obstacles such as buildings and power lines while adhering to strict energy consumption limits. This necessitates the development of advanced path planning and energy management strategies that can be dynamically adapted to changing environmental conditions.

The traditional path planning approaches, such as Dijkstra and A* algorithms often overlook the energy consumption profile of the UAV, which is critical for applications involving long-duration flights or limited opportunities for recharging. To address these limitations, this paper introduces DITER, a Digital Twin system designed for energy-aware path planning and real-time optimization in UAV-based construction inspection tasks. The proposed system leverages a hybrid optimization approach that integrates dynamic environment modeling, energy consumption profiling, and real-time path adaptation to enhance the operational efficiency of UAVs. The key contributions of this work are as follows:

- A comprehensive digital twin framework that synchronizes real-world UAV operations with a virtual environment to enable real-time monitoring and control.
- An energy consumption profiling methodology that categorizes energy usage into mobility and onboard equipment consumption, allowing for detailed energy management strategies.
- A hybrid optimization model that combines path length minimization and energy efficiency, ensuring that UAVs can complete inspection tasks while maintaining optimal energy utilization.

The proposed system is evaluated through experiments using a DJI Tello UAV in a simulated construction inspection scenario. The experimental results demonstrate that DITHER can effectively reduce energy consumption and improve path planning efficiency. The paper concludes with discussions on the potential extension of the digital twin framework to multi-UAV collaborative operations and complex dynamic environments.

II. RELEVANT RESEARCH

Recent work in digital twin technology for UAV energy management has demonstrated improvements in energy efficiency and operational adaptability. Key studies have shown that integrating DT with real-time analytics, task offloading, and adaptive path optimization enables UAVs to manage energy consumption more effectively in complex and dynamic environments. For instance, Cyrille et al. [1] achieved substantial energy reductions through DT-driven energy management, while Li et al.'s "Flexedge" framework [2] allowed UAVs to offload tasks to nearby edge resources, enhancing both efficiency and responsiveness. Further, Zhao et al. [3] demonstrated how DT-enabled multi-UAV systems can dynamically adjust trajectories in response to environmental changes, which is crucial for energy optimization in urban IoT applications. Collectively, these studies underscore the potential of DT frameworks to support UAVs in navigating

2025 IEEE International systems Conference (SysCon) | 979-8-3315-0818-0/25/$31.00 ©2025 IEEE | DOI: 10.1109/SYSCON64521.2025.11014871

operational challenges by optimizing both energy usage and task performance.

Building upon these foundational studies, our paper introduces the DITHER system, a novel DT framework specifically designed for UAV-based construction inspection tasks. DITHER uniquely combines real-time energy profiling, adaptive path planning, and hybrid optimization within a single digital twin architecture, addressing the energy demands and operational complexities inherent in construction environments. Unlike prior studies focused on single aspects such as task offloading or multi-UAV coordination, DITHER synchronizes the UAV's real-time status with a virtual environment to optimize the trade-off between path length and energy consumption comprehensively. This approach not only enhances UAV efficiency in obstacle-rich construction sites but also offers scalability for future multi-UAV collaborative tasks, positioning DITHER as a robust solution for energy-aware UAV operations in high-demand scenarios.

III. Methodology Of Robot Digital Twin System

A. *Architecture of Robot Digital Twin System*

The architecture of our system is structured into five layers: the device layer, transmission layer, digital twin layer, application layer, and industry layer (Fig. 1). In the device layer, the architecture includes a robot database, detection device database, and detection target database. The robot database stores configurations of different types of robots used for various construction inspection tasks, while the detection device database contains sensor-related information, such as the parameters and capabilities of detection equipment. The detection target database manages data on the inspected structures and their attributes.

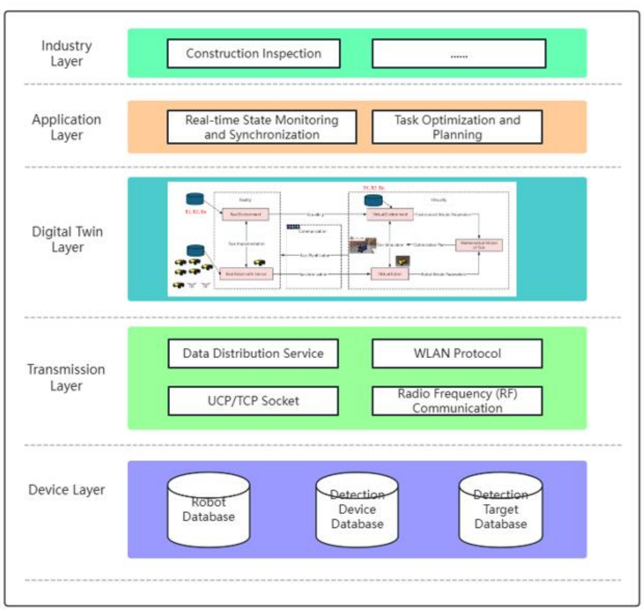

Fig. 1. Architecture of digital twin system.

The transmission layer incorporates multiple communication protocols to ensure reliable data exchange between the robots and local computers. This includes transmitting control commands to the robots and receiving inspection results, thus maintaining effective coordination between the physical and digital systems. In the digital twin layer, virtual counterparts of physical entities, such as robots and detection targets, are created to simulate operational scenarios. The digital twin enables task simulation and optimization, facilitating improved decision-making for construction inspection tasks. At the application layer, real-time state monitoring and synchronization are achieved through a detailed representation of the robots' operations within the virtual environment. Task optimization and planning are conducted based on the analysis of digital twin data, supporting the efficient deployment of resources and execution of inspection missions. The industry layer focuses on construction inspection applications, integrating findings from the application and digital twin layers to implement comprehensive inspection strategies tailored for real-world scenarios. The modular design of the architecture allows it to be adapted to various inspection-related applications within the construction and broader industrial inspection fields, enhancing its versatility and adaptability within the inspection domain.

B. *Workflow of Robot Digital Twin System*

The workflow of the digital twin system is depicted in Fig. 2, showcasing the integration of virtual and real environments to support task planning and optimization. The system includes three primary databases: robots with various configurations, real-world environment attributes, and corresponding virtual environment models, ensuring the system's adaptability to diverse construction inspection scenarios. Through the ROS2 platform, synchronization between the real and virtual worlds is achieved, enabling continuous information exchange and updates between physical and digital entities.

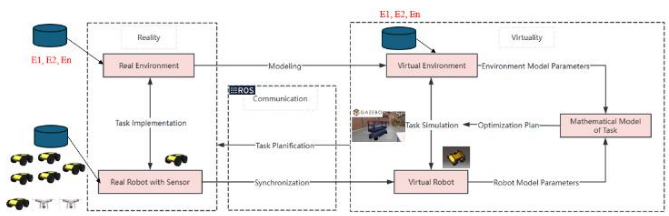

Fig. 2. Workflow of our robot digital twin system.

In the real-world environment, robots equipped with sensors are deployed to execute inspection tasks, gathering data and performing actions as required by the task objectives. In the virtual environment, various inspection tasks can be simulated, enabling the estimation of task completion metrics such as time efficiency and resource consumption. Additionally, task modeling incorporates parameters from both the environment and the robot, allowing for the evaluation of different task execution strategies.

The simulation results provide guidance for real-world task implementation by offering insights into optimal execution plans, thereby supporting more effective decision-making and enhancing overall performance in construction inspection applications.

IV. Verification Of Robot Digital Twin System

In this section, we first introduce the experimental UAV, Tello, followed by the development of a digital twin system and a comprehensive energy consumption profiling for the UAV. We then present a mathematical model tailored to UAV-based construction inspection tasks, specifying the parameters of the inspection target and the characteristics of the UAV used in our experiments. These parameters are incorporated into the model, and the optimal solution is derived using Gurobi optimization.

A. *Digital Twin System for Experiment UAV*

In this part, we introduce our experimental platform, the Tello UAV. The Tello drone, as depicted in Fig. 3, is a small and cost-effective drone developed through a collaboration between Ryze Technology, DJI, and Intel. It has been widely adopted in various research endeavors. In this study, several experiments were conducted to evaluate the energy consumption of the Tello, and a digital twin system for this UAV was implemented.

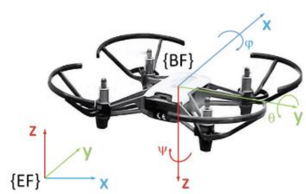

Fig. 3. DJI Tello quadrotor with coordinate systems of the Earth frame $\{B_F\}$ and body frame $\{B_F\}$ [4].

Our research builds upon an open-source Tello_ROS [4] package available on GitHub. This resource serves as a ROS2 interface for Tello and Tello EDU drones and is composed of four separate ROS packages: tello_driver, tello_msgs, tello_description, and tello_gazebo. These components enable the control of the Tello drone, facilitate sensor data acquisition, and support the operation of a Tello simulation model in Gazebo. To create the digital twin system for Tello, we primarily focused on synchronizing the real-world robot's state with its simulated model by integrating sensor data.

The Tello drone's official SDK specifies that its onboard sensors gather data such as orientation, linear velocity, linear acceleration, battery status, motor runtime, relative height, barometric altitude, time-of-flight distance, and chip temperature. For state synchronization of the robot, a Kalman filter was utilized to correct linear velocity using linear acceleration data, achieving sensor data integration. As shown in Fig. 4, the synchronization between the real Tello UAV and its digital twin in Gazebo was effectively accomplished during the experiments.

Fig. 4. State synchronization during the task.

B. *Mathematical Model of Construction Inspection Task*

This section presents a comprehensive mathematical model for UAV-based construction inspection tasks, focusing on path planning with scanning and charging requirements. The objective is to optimize the path of a single UAV to scan a planar wall, minimizing total time, energy consumption, and costs, while adhering to operational constraints. The problem is defined as follows:

1) ***Objective:***

Plan the UAV's path to scan a regular planar wall by navigating through a grid, minimizing total time, energy consumption, and overall costs.

2) ***Description:***

- The UAV's operations (up, down, left, right) as shown in Fig. 5, have distinct energy and time consumptions.
- The UAV has a limited battery capacity and needs to recharge at designated charging stations to ensure that energy consumption between any two recharges does not exceed the battery capacity.
- The whole area including the wall's surface is represented as a grid with Free Flight Zones and Restricted Zones:
    - **Free Flight Zones** ($F \subseteq C$): Areas where the UAV can freely navigate.
    - **Restricted Zones** ($R = C \setminus F$): Areas where UAV entry is prohibited.
- Within Free Flight Zones, grid points are classified into:
    - **Scanning-Required Areas** ($S \subseteq F$): Grid points where the UAV must perform scanning.
    - **Non-Scanning Areas** ($N = S \setminus F$): Grid points where the UAV can pass without stopping.
- Free Flight Zones contain Charging Stations ($C_{stations} \subseteq F$), which may be located in either Scanning-Required Areas ($C_S \subseteq S$) or Non-Scanning Areas ($C_N \subseteq N$).
- The UAV must scan each Scanning-Required grid cell exactly once.
- The UAV can charge to full battery capacity (E_{max}) when at a charging station.
- Charging and scanning can occur simultaneously if the charging station is located in a scanning-required area.

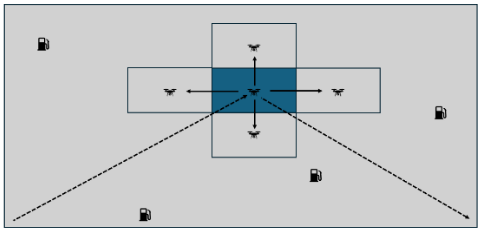

Fig. 5. UAV's typical operations during the task.

3) Notation and Variables

- **Grid Definition:**

The whole area is represented as an $M \times N$ grid, with each grid point defined as $C = \{(i,j) \mid 1 \leq i \leq M, 1 \leq j \leq N\}$.

- **Movement Operations:**

The UAV can move up, down, left, or right to adjacent grid points on the grid, with time and energy consumptions defined as $t_{(i,j),(k,l)}$ and $e_{(i,j),(k,l)}$, respectively.

The UAV should take off to begin the task. For each charging, it will land, be charged and take off again, the time and energy consumptions for take-off and landing are defined as $t_{takeoff\&landing}$ and $e_{takeoff\&landing}$, respectively.

- **Battery Parameters:**

Maximum battery capacity: E_{battery} , here we define $E_{\max} = E_{\text{battery}} - e_{takeoff\&landing}$, we will use $E_{\max}$ instead of E_{battery} to simplify the operation of the UAV and ensure that the drone always has enough energy to land.

Time consumption for charging from 0 to $E_{\max}$: t_{charge}.

Number of recharges: N_{charge}.

- **Cost Calculation:**

$$TotalCost = c_{\text{time}} \times T + c_{\text{charge}} \times N_{\text{charge}} \tag{1}$$

- **Scanning Constraints:**

Energy and time consumption for scanning are represented as E_{scan} and t_{scan}, respectively.

4) Decision Variables

The following variables are defined to formulate the mathematical model:

Binary variable $p_k^{(i,j)} \in \{0,1\}$ indicating if the UAV is at grid point (i,j) at step k.

Binary movement variable $x_{k,(i,j),(m,n)} \in \{0,1\}$, which is 1 if the UAV moves from (i,j) to (m,n) at step k.

Binary scanning variable $y_k^{(i,j)} \in \{0,1\}$ representing whether the UAV scans at grid point (i,j) at step k.

Binary charging variable $y_k^{\text{charge}} \in \{0,1\}$ indicating whether the UAV charges at step k.

Continuous battery level variable $e_k \geq 0$ representing the remaining battery level at step k.

Continuous energy recharged variable $u_k \geq 0$ at step k.

Auxiliary variable $w_k \geq 0$ representing $e_k \cdot y_k^{\text{charge}}$.

5) Objective Function

The multi-objective optimization aims to minimize the following objectives:

Total Cost:

$$\min c_{\text{time}} \times T + c_{\text{charg}}$$

Total Time:

$$\min \sum_k \sum_{(i,j),(m,n)} t_{(i,j),(m,n)} \cdot x_{k,(i,j),(m,n)}$$

$$+ \sum_k \sum_{(i,j)} t_{scan} \cdot y_k^{(i,j)} + \sum_k \frac{t_{charge} \cdot u_k}{E_{max}}$$

$$+ \sum_k \left(1 + y_k^{charge}\right) \cdot t_{ta}$$

Total Energy:

$$\min e_0 + \sum_k u_k -$$

6) Constraints

The following constraints are defined to ensure the feasibility of the UAV's path:

- **Path Start and End Points**

$$p_1^{(i_0,j_0)} = 1$$

$$p_K^{(i_{\text{end}},j_{\text{end}})} =$$

All other $p_1^{(i,j)} = 0$ for $(i,j) \neq (i_0, j_0)$ and $p_K^{(i,j)} = 0$ for $(i,j) \neq (i_{\text{end}}, j_{\text{end}})$.

- **Path Continuity Constraints:**

$$\sum_{\substack{(m,n)\in F \\ (i,j),(m,n)\,are\ adjacent}} x_{k,(i,j),(m,n)} = p_k^{(i,j)}$$

$$\forall k \in \mathcal{K} \setminus \{K\}, \forall (i,j)$$

This ensures that if the UAV is at (i,j) at step k, it must move to exactly one adjacent grid point at step $k+1$.

- **Position Uniqueness Constraints:**

Ensure the UAV at unique position after each step:

$$\sum_{(i,j)\in F} p_{i,j,k} \leq 1, \forall k \in \mathcal{K}$$

- **Movement Relationship Constraints:**

For each step $k \in \mathcal{K} \setminus \{K\}$ and for all adjacent (i,j) and (m,n) in F:

$$p_{k+1}^{(m,n)} \geq x_{k,(i,j),(m,n)} \tag{9}$$

This ensures that if the UAV moves from (i,j) to (m,n) at step k, it must be at (m,n) at step $k+1$.

- **Coverage Constraints:**

Ensure that all required grid points are scanned exactly once:

$$\sum_{k=1}^{K} y_k^{(i,j)} = 1, \forall (i,j) \in S \tag{10}$$

- **Scanning Constraints:**

Ensure that scanning occurs only when the UAV is at the grid point:

$$y_k^{(i,j)} \leq p_k^{(i,j)}, \forall k \in \mathcal{K}, \forall (i,j) \in S \tag{11}$$

- **Initial Battery Level:**

$$e_1 = E_{\max} \tag{12}$$

- **Battery Level Limits:**

$$0 \leq e_k \leq E_{\max}, \forall k \in \mathcal{K} \tag{13}$$

- **Battery Energy Dynamics:**

For each step $k \in \mathcal{K} \setminus \{K\}$:

$$e_{k+1} = e_k + u_k - E_{\text{scan}} \sum_{(i,j) \in S} y_k^{(i,j)} - \sum_{\substack{(i,j),(m,n) \\ (i,j),(m,n) \in F \text{ and adjacent}}} e_{(i,j),(m,n)} \cdot x_{k,(i,j),(m,n)} \tag{14}$$

Together with previous condition, it will make the UAV has sufficient power to get next grid. Besides, the UAV can flexibly choose the order of charging and scanning according to the battery level.

- **Charging Constraints:**

When $y_k^{\text{charge}} = 1$, the UAV charges an amount:

$$u_k = (E_{\max} - e_k) \cdot y_k^{\text{charge}} \tag{15}$$

Since u_k involves the product of a continuous variable (e_k) and a binary variable $\left(y_k^{\text{charge}}\right)$, we need to linearize this expression, we introduce an auxiliary variable w_k to represent $e_k \cdot y_k^{\text{charge}}$. The constraints for linearizing $w_k = e_k \cdot y_k^{\text{charge}}$ are:

$$w_k \leq e_k \tag{16}$$

$$w_k \geq e_k - E_{\max} \cdot \left(1 - y_k^{\text{charge}}\right) \tag{17}$$

$$w_k \leq y_k^{\text{charge}} \cdot E_{\max} \tag{18}$$

$$w_k \geq 0$$

Then, (u_k) can be expressed as:

$$u_k = E_{\max} \cdot y_k^{\text{charge}} -$$

- **Charging Station Constraints:**

The UAV can only charge at designated Charging Stations $((C_{\text{stations}} \subseteq F))$:

$$y_k^{\text{charge}} \leq \sum_{(i,j) \in C_{\text{stations}}} p_k^{(i,j)},$$

This ensures that charging occurs only when the UAV is at a Charging Station.

- **Variable Domain Constraints:**

$$x_{k,(i,j),(m,n)} \in \{0,1\}$$

$$y_k^{(i,j)} \in \{0,1\}$$

$$y_k^{\text{charge}} \in \{0,1\}$$

$$e_k \geq 0,$$

$$u_k \geq 0,$$

$$w_k \geq 0, \forall k \in$$

The basics mathematical model of construction inspection task has been built in this part, it's a Mixed Integer Linear Programming problem with multiple optimization objective, it serves as the basis for optimizing the path planning problem ensuring efficient and reliable execution of construction inspection tasks by the UAV.

C. Study Case

In this section, we focus on optimizing the UAV's path during the construction inspection task with a specific case. The inspection target, illustrated in Fig. 6, is a dormitory building located on XCampus. The UAV used for the task is the Tello drone with related parameters detailed in Table I.

TABLE I. EXPERIMENTAL PARAMETERS FOR UAV INSPECTION

Parameter	Value
Wall Width	7 m
Wall Height	12.20 m
UAV Speed	0.4 m/s
Camera Field of View	(2 m, 1.5 m)
Distance Between UAV and Wall	2 m
Tello Cost, Life	115EUR, 40h
Battery Cost, Life	30EUR, 250 Times
Take-off and Landing	Time & 9.25 s
Scanning Time	2 s
Charging Time	1.5 h

Fig. 6. Construction Inspection Target.

We first divide the entire inspection area into grids based on the UAV's field of view dimensions. The resulting grid structure allows us to define the free flight areas, scanning-required zones, and charging station locations, as depicted in Fig. 7. In this figure, the red grids represent areas with obstacles, the blue grids indicate the charging stations, and the grids marked with the letter "S" denote the areas that require scanning.

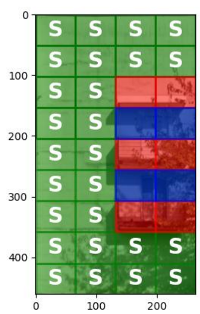

Fig. 7. Grid Dividing Result.

After defining the parameters, specifying the inspection areas, and inputting the battery level changes for typical operations during the task (as shown in Table II, which is derived from real-world UAV testing), hierarchical optimization is performed using the Gurobi optimization solver. The primary optimization objective is to minimize the total cost, followed by minimizing the total time as the second priority, and finally, minimizing total energy consumption as the third target. Fig. 8 illustrates the optimal path planning, from the results we can see that the drone passed all scanning grids and avoided obstacles without charging in the middle, this approach provides a set of optimal solutions that balance energy consumption, coverage efficiency, and inspection time.

TABLE II. BATTERY LEVEL CHANGE OF TYPICAL OPERATIONS FOR TELLO

Operation	Battery Level Change
Idel State	-2.87E-02 %/s
Hovering State	-1.18E-01 %/s
Take-off and Landing	-4.82E-02 %
Horizontal Movement	-3.75E-1 %/m
Vertical Movement (ascending)	-1.44 %/m
Vertical Movement (descending)	-1.23 %/m

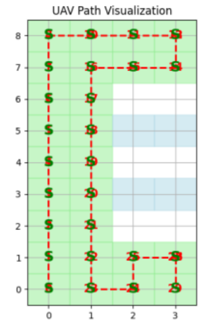

Fig. 8. Optimal Solution for Path Planning.

V. FUTURE WORK: SWARM

Currently, the DITHER system focuses on energy management for individual robots in isolated environments but lacks support for inter-robot communication and collaboration. For inspecting large, complex structures, coordination between diverse robots (e.g., aerial and ground units) is essential to share data and distribute tasks in real time. Future development will extend DITER's capabilities to create an integrated platform—DITEHR—for building inspections using heterogeneous robot teams. This enhanced system will enable real-time synchronization between robots and their digital twins, allowing comprehensive inspections of complex structures.

VI. CONCLUSION

This paper presents DITHER, a Digital Twin system designed to optimize energy consumption and path planning for UAV-based construction inspection tasks. By leveraging a hybrid optimization approach that combines dynamic environment modeling and energy profiling, DITER effectively enhances the operational efficiency of UAVs in complex scenarios. Experimental results using a DJI Tello UAV validate the integration of our system, while the consideration of path planning optimization further enhances its capabilities. The integration of a digital twin framework enables real-time monitoring and control, providing a platform for both simulation and practical implementation of UAV inspection tasks. The proposed energy consumption profiling methodology allows for detailed analysis and optimization of energy usage, making it suitable for applications where energy constraints are a critical concern. Future work will focus on extending the DITER system to support multi-UAV collaborative operations and adapting the framework to more complex environments. These advancements will further enhance the system's capability to handle large-scale inspection tasks and improve overall mission success rates.

REFERENCES

[1] N.A. Cyrille, N. Jean Calvin, M.M. Ghislain, "Critical review on integrated real-time energy management strategy and digital twin applied to hybrid electric UAVs," \textit{Electrical Engineering}, 2024.

[2] B. Li, W. Xie, Y. Ye, L. Liu, Z. Fei, "Flexedge: Digital twin-enabled task offloading for UAV-aided vehicular edge computing," \textit{IEEE Transactions on Vehicular Technology}, 2023.

[3] L. Zhao, S. Li, Y. Guan, S. Wan, A. Hawbani, "Adaptive multi-UAV trajectory planning leveraging digital twin technology for urban IIoT applications," \textit{IEEE Transactions on Network Science}, 2023.

[4] W. Giernacki, J. Rao, S. Sladic, A. Bondyra, M. Retinger, and T. Espinoza-Fraire, ``DJI Tello quadrotor as a platform for research and education in mobile robotics and control engineering," 2022 International Conference on Unmanned Aircraft Systems (ICUAS), Dubrovnik, Croatia, 2022, pp. 735-744, doi: 10.1109/ICUAS54217.2022.9836168.