Regulating arrival UAV flows between the AirMatrix and the droneport using a dynamic carousel circuit

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***Abstract*— There is a growing need of Unmanned Aerial Vehicles (UAVs, or drones) in commercial, civil, and military appli-cations. Tens of millions of annual flights are expected to fly in the airspace by 2050. To solve the potential safety issue and airspace congestion issue brought by the rise of drone operations, a dynamic carousel circuit is conceived and integrated with droneport operations. This study introduces the concept of the dynamic carousel circuit with a changing radius that can accommodate the growing demand of future drones, and develops a simulation model as well as an optimization algorithm to determine the optimum circuit radius, the moving speed of drones on the circuit, and the circuit altitude with forecasted drone demand. We strive to apply more realistic simulation with the residual endurance estimation model and the cubic trajectory planning model. The former model uses a practically applicable method to calculate the drone's endurance with the remaining battery level as input. The latter model generates a smooth landing trajectory and thus estimates the travel time of drones more accurately. Numerical tests were conducted to analyze the performance of the dynamic carousel circuit. The findings from this study show that the dynamic carousel circuit has the potential to increase droneport capacity, improve aviation safety, and enhance droneport operational efficiency.**

***Keywords*—Unmanned Aerial Vehicles; UAS Traffic Management; Droneport; Carousel Inspired Virtual Circulation; Dynamic carousel circuit**

I. Background

A. The rise of drone operations

In recent decades, a wide range of potential applications of Unmanned Aerial Vehicles (UAVs, commonly called drones) have been proposed, such as goods and passenger delivery, surveillance, search and rescue, aerial photography and videography, and agricultural monitoring, etc. Each application is expected to be prevalent and radically change conventional operations. Indeed, some of the categories, especially in the commute and e-commerce fields, are well-developed. According to these trends, dense drone operations have the potential to be expected in future urban and suburban areas. The statistic estimated by SESAR [1] has proved this trend.

With more requirements for logistics and transport raised, the e-commerce sector has been attracted by the significant increase in demand for drones to achieve a fast and economic parcel delivery, and companies such as Amazon [2], Uber [3], and DHL [4] have initiated various projects on drone delivery. The investigation is on the feasibility of drone delivery by looking at its economic viability and potential benefit to society [5], [6] and shows that drone delivery has a high potential to be implemented in the future. Moreover, many countries have started research on integrating drone operations into civil airspace safely and efficiently [7], [8]. Some regulations related to drone operations have been proposed, mainly brought focus on drone registration, identification system, tracking, communication systems, geofencing-like systems, UAS Traffic Management (UTM) architectures, and UTM-ATM integration and transition [8]. Although many organizations provide concepts and overviews of future drone operations and restrict drone operations in special-use airspace, there still are many challenges and concerns that must be addressed and solved to achieve these complex activities in the metropolis.

B. Potential concerns of drone operations in urban areas

1) Safety: Flying drones above high-rise residential areas will present a serious hazard for other ground vehicles, people, industrial facilities, and other airspace users [9]. Safety thus becomes a critical issue that must be addressed and regulated.

In a statistical analysis reported by Airbus [10], about 47% of commercial aviation accidents from a 20-year period (1999-2019) happened during the approach phases and 17% during landing phases. Just like commercial aviation, Remotely Piloted Aircraft System (RPAS) [11], also has a similar distribution of accidents regarding different flight phases. In the research carried by Wild et al. [12], the data of accidents and incidents from 152 RPAS events over 10 years (2006-2015) was analyzed. The study shows that take-off, landing, and approach phases account for 54% of RPAS accidents and incidents. Due to the limited capacity of landing ports, the complexity of the air traffic in terminal airspace, and the battery limitation of drones [13], [14], arrival traffic will face a critical safety issue during the approach phase compared with other phases of flight. Given a high probability of accidents during take-off, approach and landing phases, effective and safe traffic management services necessitate detail and regulative arrival and departure procedures similar to Air Traffic Control services for commercial aircraft.

2) Airspace congestion: Traffic congestion will cause extra fuel burn or energy consumption, low efficiency of the traffic flow, and safety concerns. As an increment of drone operations is expected in a near future, it is likely to encounter congestion in urban very low level (VLL) airspace. While sharing similarities with ATM, UTM requires a radically different approach as there are drastic distinctions in vehicle density and environment complexity. The airspace congestion issue, therefore, is another barrier for future UTM with higher levels of autonomy. Alleviating airspace congestion can be achieved by improving the capacity of UTM, utilizing three-dimensional airspace, and providing supplemental airspace control.

For conventional air traffic management, the airport is a key determinant in the air transport system for increasing traffic capacity. In addition, it allows aircraft to arrive and depart efficiently, easily, and safely, while at the same time enabling the movement of people and cargo on and off the aircraft. The right infrastructure, similar to an airport, to support drone operations and growing demand will be a good solution for the airspace congestion problem.

C. Infrastructure for approach and departure drones

Present research works are mainly focused on UTM urban airspace architecture, demand prediction, and vehicle design [15]. Some of them also presented the infrastructure design for UTM, including the multi-level fulfillment center for parcel delivery drones [2], the vertiport designed for passenger delivery drones [13], and other logistics infrastructure providing automated services. All of them are aimed to accommodate and serve a specific type of drone operations. There is currently no proposal for the automation infrastructure that is able to accommodate the widespread use of Unmanned Aerial Systems (UAS) operations in unregulated airspace. The initial aim of this research is to promote the secure use of low-altitude airspace, especially during approach and departure phases, for a wide range of applications of drones. Instead of the utilization of existing infrastructure, a multi-level facility called droneport is introduced to manage different flight phases for drones considering thousands of daily operations and provide warehousing too, allowing more efficient use of the airspace while improving safety. Aside from that, the traffic pattern is also an enabler to achieve safe, effective and efficient traffic management for droneports.

In this study, we addressed the issues that will arise if large-scale fully autonomous drone operations are implemented in a near future. Aiming at managing approaching and departing drones safely and efficiently, we proposed a traffic pattern, called the Carousel Inspired Virtual Circulation (CIVC) method, for traffic management in dense-populated urban airspace around droneports [16]. As an improvement of CIVC, the dynamic carousel circuit can adjust its radius according to the demand change, and regulate a large number of drones flying in and out of the droneports to meet the required capacity. Our previous work [17] introduced droneport concept and estimated the future demand of drones that should be accommodated in the droneport. The current work investigates the issues in droneport traffic management, and ensures the sequencing and scheduling of arrival and departure flights in a safe manner to be fulfilled.

The rest of the report is organized as follows. The next section provides an overview of the prior arts. section 3 presents the configuration of the dynamic carousel circuit. A simulation model and an optimization algorithm are introduced in section 4, followed by the numerical tests and analysis in section 5. Finally, the paper concludes with a discussion and outlook.

II. Related works

In the vicinity of droneports, especially when drone number is raised to an extent and many take-off and landing occurs every minute, the traffic control of drones in the air is one of the key issues. With a large number of drones concentrated in the airspace around droneports, specific requirements and procedures must be established in order to reduce the collision risk to an acceptable level and ensure safety in the air as well as on the ground. In the airport operation, terminal control area (TCA) controllers closely monitor the approaching flights on radar and instruct pilots to the final approach pattern, at which point pilots are passed to the approach controller for landing preparation [18]. The final approach pattern is essential for ensuring that air traffic is flown out safely. Generally, helicopters operate in a similar traffic pattern, but at a lower altitude, which is 500 feet above ground level (AGL) [19] compared to 1000 feet AGL for fixed wing traffic pattern [20].

In droneport operation, several previous studies have investigated the procedures for UAVs landing and take-off near the airfield. Today UAS are rarely designed for civil purposes mainly because of the absence of a regulation basis respecting UAVs' operations and airworthiness. Therefore, with the rapid increase in the number of civil UAS applications in a near future, many issues will arise if many UAVs coexist with manned aircraft. Pastor et al. [21] studied one of the issues - the integration of UAS operation in the depart, arrival, and approach phases with airport operation. This study supposed that the UAS has similar operation procedures with Instrumental Flight Rules (IFR) flight, and analyzed four different scenarios: (1) controlled airport with IFR procedures exist, (2) non-controlled airport with IFR procedures exist, (3) controlled airports without IFR exist, (4) non-controlled airports without IFR exist. The authors then proposed an approach pattern for UAS based on the Visual Flight Rules (VFR) procedures in general aviation. In this proposed landing procedure, the UAS will enter the holding pattern and wait for joining the aerodrome pattern. The authors also introduced a take-off procedure for the UAS. In order to not interrupt the air traffic, the UAS is required to fly along with the landing pattern from the runway to a selected End of Departure Way-Point (EDWP) that is near the airport but also far enough from possible traffic in the airport.

There are also researches mainly focusing on the future scenarios with extensive UAVs in high-density urban airspace or lower airspace. These studies commonly emphasize the development of the UTM system in urban areas, and the policies, frameworks, and infrastructure of UAS operation. Hoekstra et al. [22] introduced a project about the whole UTM system and proposed four possible options for compensation of necessary waiting times during take-off and landing: speed adjustments, path stretching, holding patterns, and hovering.

The Point Merge, which is currently used in a lot of airports for ATM operations and is considered as a traffic pattern for UAV operations [23]. However, Sunil et al. considered the point merge method to construct the whole airspace structure for urban areas, which is not suitable to integrate with other UTM systems such as AirMatrix. Another method, CIVC, has high geometric flexibility and therefore allows UAVs land on multiple runways. However, the lack of a proper sequencing algorithm has limited its performance to dispatch a continuous traffic flow.

Flight arrival and departure scheduling (FAADS) [24] is always a key challenge in ATM, as congestion delay is expected to increase with time [25]. As has been previously remarked, UAS technology is evolving and the demand of UAV is expected to increase rapidly. Subsequently, arrival and take-off procedures for droneport operations will generate bottlenecks, due to the congested traffic restricted by the capacity of droneport and the limited battery of drones [13]. Hence, droneport operations will face the same challenge with ATM. Consequently, a sequencing algorithm is necessary for take-off and landing patterns.

Inspired by commercial aviation, few studies have carried out on the sequencing and scheduling for Electric Vertical Takeoff and Landing (eVTOL) aircraft. Pradeep [26] applied a heuristic approach, named insertion and local search (ILS) [27], with the combination of mixed integer linear programming (MILP) and time advance (TA), to the sequencing and scheduling problem in urban air mobility (UAM) context for a mixed fleet (winged/wingless) of eVTOLs. However, the author only considered minimum time separation and vehicle dynamics constraints, while the flight time supported by electric batteries is a significant factor for the eVTOL sequencing and scheduling problem [28]. Motivated by this gap, Kleinbekman et al. [29] studied a double landing-pad vertiport for eVTOLs and formulated the problem considering the minimum time separation, electrical battery discharge, and vehicle dynamics.

In this paper, we contribute to the area of UTM especially during drone's takeoff and landing phases. More precisely, we propose a traffic pattern to regulate arrival and departure drones with proper sequencing rules.

III. Dynamic carousel circuit

The growth in the volume and diversity of drone operations appears to bring new risks to other airspace users, as well as pedestrians and other ground-level features. Therefore, the ground infrastructure for traffic regulation, is one of the major foci of current UAM research to reduce the risks and manage drone operations. However, projects in this area are mostly focused on designing the ground infrastructure for a specific mission, such as Uber [13] and Amazon [30]. We propose the droneport as a future ground infrastructure to accommodate a broader range of UAS operations.

Inspired by airport configuration, the infrastructure of a droneport is defined in two categories, outdoor and indoor, which are airside and landside. The outdoor infrastructure accommodates the movement of drones around the droneport and consists of the outdoor navigation system, emergency landing area, maintenance hub, warehouses, and walking corridors. The indoor infrastructure accommodates the movement of drones inside the droneport and includes the indoor navigation system, taxiways, landing and charging pads, and walking corridors. The mainstream of traffic is from AirMatrix [31], a UTM system with sense-and-avoid capabilities covering whole VLL airspace in urban areas. This AirMatrix system connects all droneports and other UTM facilities. Once a drone leaves the AirMatrix and enters the droneport airspace, the transfer of control will happen, and droneport control system will take control of this drone.

Given the expected large number and various types of drones operating in the AirMatrix network, there is a need to have efficient air traffic management to control the departure and approach of drones. Taking into account the shape of the droneport, a carousel circuit is introduced as the air traffic pattern for departure and approach procedures, as depicted in Figure 1. This figure shows the initial design of the multi-layer and double-lane circuit configuration. The center building is the droneport.

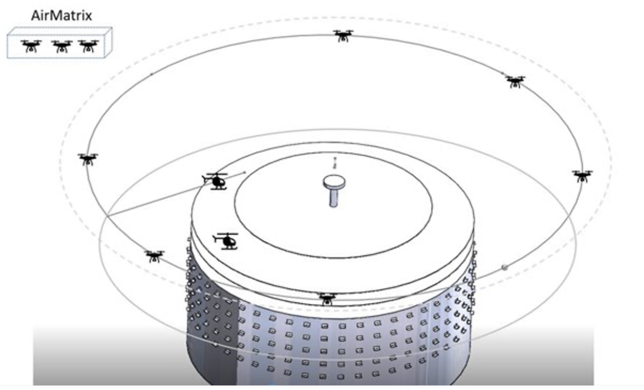


Figure 1: Conceptual depiction of the dynamic carousel with the droneport design.

Departure drones and approach drones use different lanes, following an anti-clockwise circular motion or a clockwise circular motion depends on the wind effect. Carousel circuits can be multi-level in order to split the heavy traffic flow into different carousel circuits. If a drone is assigned to a landing gate in a lower altitude, it can follow the carousel circuit at the corresponding level and wait for taxi clearance. Between each level of the carousel circuit, proper traffic rules should be applied to avoid congestion and collision. For example, the transition between different levels of the carousel circuit can only be allowed when a drone is in a specific node. We can refer to the general rule for priorities of ground vehicles when emerging from crossroads.

To reduce traffic congestion and improve the efficiency of the carousel circuit, a queue management strategy should be implemented in the droneport system. Drone arrivals are based on time-invariant stochastic generation. Each landing gate spends time to accommodate each drone and the required service depends on the types of the drone. Because the number of gates is finite, some drones will have to wait to be served. The waiting capacity, which is assumed finite, is the maximum number of drones that may stay on the carousel circuit waiting to be served. The system capacity is the maximum number of drones that are being served inside the droneport and waiting for service on the carousel circuit. The queue discipline defines how the customers are selected by the servers or vice versa. In this study, we only consider the First come-first served (FCFS) and Priority (PRI) disciplines. Priority discipline will be only used for the emergency scheme, such as low battery case. The drone separation rule is significant in modeling the queuing theory.

Additionally, as the drone traffic demand grows, it is highly desirable to implement demand and capacity balancing and ensure the safety of incoming and outgoing flights. In this situation, a dynamic carousel circuit is applicable and conducive for a droneport with growing demand. Its radius will be adjusted based on predicted demand.

Dynamic carousel circuit, equipped with efficient queue management, connects the droneport and the AirMatrix network and also regulates drones with fluctuating demand. The following section develops a simulation model to validate the dynamic carousel circuit concept.

IV. Simulation

The aim of this section is to conduct a simulation about of the droneport landing procedures via applying the dynamic carousel circuit. In order to manage flights while maximizing safety and efficiency, which consists of ensuring safe separation, avoiding hazardous conflict, reducing congestion delay, increasing throughput, and enhancing the fuel operation efficiency. The carousel circuit will then be improved based on the simulation results. The simulation consists of three phases in the arriving process, which are: the approaching phase, the queuing phase, and the landing phase. The overall framework of this study is shown in Figure 2.

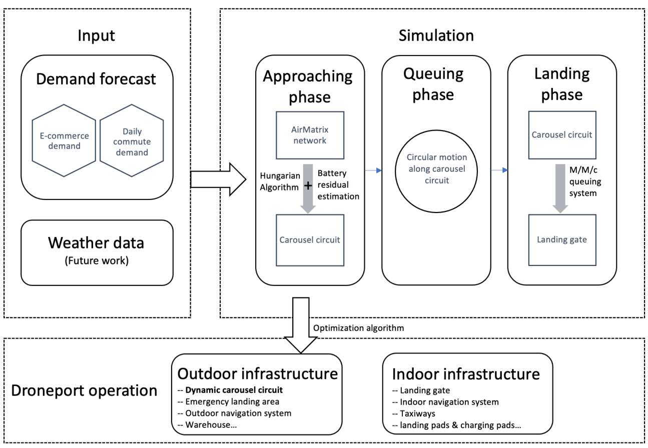


Figure 2: Research framework

A. Initialization

The incoming drones are assumed to appear around the droneport according to a Poisson distribution with a certain arrival rate, which is indicated by the length of the time probability distribution between two successive drone arrivals. The arrival rate is determined by the droneport demand and simulation duration. We assume that each drone is assigned a landing gate before approaching the droneport. In reality, a drone will be commanded to land on the area managed by its operator, and it will be assigned to a landing gate near its landing area, thus saving energy and improving management efficiency. In this simulation, the drone is designed to approach the droneport area with a pre-defined landing gate and residual battery level. The landing gate assignment is generated randomly, while the residual battery level follows a normal distribution.

To generate the input data of this simulation, an initialization model is used to construct the arrival time, the assigned landing gate, and the residual battery level. This model returns a matrix of input values for the following simulation phases.

$$\left\{\left(t^a_{v,l}, G_v, B^{'}_{v,l}\right)\right\}^{V_e}_{v=1}, \quad (1)$$

$$t^a_{(v+1),l} = t^a_{v,l} + u_{(v+1)}, \quad (2)$$

$$G_v = n, n \in N_g. \quad (3)$$

where $t^a_{v,l}$ is the arrival time of the v^{th} drone at the fix point $l \in N_a$ on the AirMatrix network, G_v is its assigned landing gate, and $B^{'}_{v,l}$ is the residual battery level of the v^{th} drone at the fix point l. u_v follows the exponential law with parameter $\lambda_p = \frac{V_e}{T}$. V_e is the total number of arrival drones estimated for a time period T. N_a is the set of all fix points on the AirMatrix network, and N_g is the set of all landing gates on the droneport.

B. Approaching phase

The mainstream of traffic is from the AirMatrix, which is above the droneport airspace. Distinguish from the dynamic carousel circuit, drones are not allowed to hover in the AirMatrix network except in emergencies. During the approaching phase, the drone will approach the droneport in the same orientation as its assigned landing gate. The initial position of a drone in this phase is set to be in the AirMatrix airspace with a higher altitude and a larger range than the carousel circuit.

As described in the previous section, the wind conditions are assumed to generate a clockwise circulation. In this simulation, the slots on the carousel circuit are represented by many virtual blocks circulating alongside the carousel circuit. In each time step, the positions of these virtual blocks will be refreshed and predicted via their moving speed while ensuring safe separation. The main objective in this phase is selecting available virtual blocks to the approaching drones from the AirMatrix so as to minimize the total travel time and the battery consumption. Hungarian algorithm [32] is implemented to solve this assignment problem. Since each virtual block can accommodate only one drone and each drone can be assigned to only one available virtual block, the assignment constitutes an independent set of the cost matrix H.

$$H(t)=\begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1Y} \\ h_{21} & h_{22} & \cdots & h_{2Y} \\ \vdots & \vdots & \ddots & \vdots \\ h_{X1} & h_{X2} & \cdots & h_{XY} \end{bmatrix} = \left[h_{xy}\right], \quad (4)$$

$$h_{xy} = \tau_{xy} + B_{x}^{'}, \quad (5)$$

$$x = N_{v}^{'}(t)(1), N_{v}^{'}(t)(2), ...N_{v}^{'}(t)(X), \quad (6)$$

$$y = N_{b}^{'}(t)(1), N_{b}^{'}(t)(2), ...N_{b}^{'}(t)(Y), \quad (7)$$

$$N_{v}^{'}(t) = \left\{\{v,l\}, l \in N_a : \alpha_{l}^{v}(t) = 1, \forall v \in V_a\right\}, \quad (8)$$

$$N_{b}^{'}(t) = \left\{j \in N_b : \alpha_{j}^{v}(t) = 0, \forall v \in V_a\right\}. \quad (9)$$

where the cost matrix value h_{xy} consists of two elements. τ_{xy}, also $\tau_{v,lj}$, is the travel time for drone v from fix point l on the AirMatrix network to the position of the virtual block $j \in N_b$ on the carousel circuit at time t. N_b is the set of all virtual blocks on the carousel circuit. $B_{x}^{'}$, also $B_{v,l}^{'}$, is the the residual battery level of drone v, which ensures that a drone with a low battery level has high priority in the final decision. This term will be calculated from the residual battery function which will be described later. X and Y are the numbers of elements in the two sets $N_{v}^{'}(t)$ and $N_{b}^{'}(t)$. $N_{v}^{'}(t)$ is the set of arrival drones at time t, and $N_{b}^{'}(t)$ is the set of available virtual blocks at time t. V_a is the set of arrival drones estimated in a period T. $\alpha_{l}^{v}(t)$ and $\alpha_{j}^{v}(t)$ are the decision binary variables at time t. They equal to 1 if the fix point l or the virtual block j is occupied by the drone v at time t and 0 otherwise.

The travel time is estimated by iteratively predicting the meeting position of the drone v and the virtual block l, and its subsequent approach trajectory is computed using cubic interpolation. The approaching fix points from the AirMatrix network forming a circle illustrated as the outer ring, and the inner ring represents the carousel circuit. As shown in Figure 3, a drone exits the AirMatrix along a direction pointing to the center of the carousel circuit and joins the circuit following the virtual block moving angle.

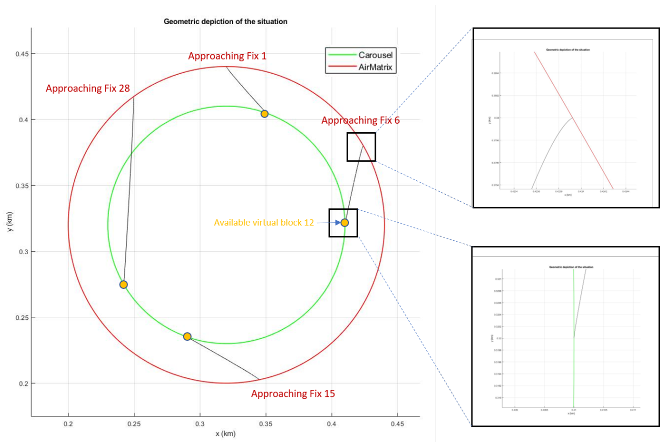


Figure 3: Top-down view of the cubic trajectory from the approaching fix point 6 on the AirMatrix to the metering fix point 12 on the carousel circuit.

C. Queuing phase

After joining the queue on the carousel circuit, the drone will take a circular motion together with other occupied and unoccupied virtual blocks. In this phase, the carousel circuit acts as the approaching pattern to reduce the collision risk. In order to adapt to weather conditions, the time-based separation [33] is implemented in determining the positions as well as the number of virtual blocks. Except for those virtual blocks, there are numbers of metering fix points on the circuit, which are placed in the same orientation as the landing gates. The drone will be allowed to exit the circuit only when two conditions are met:

- The drone arrives at the designated metering fix point, which has the same orientation as the assigned landing gate.
- The assigned landing gate is available to serve a drone.

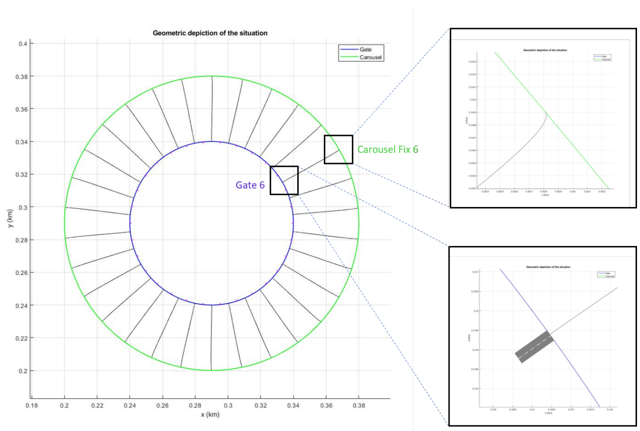


Figure 4: Geometric depiction of the cubic trajectory from the metering fix point 6 on the carousel circuit to the landing gate 6.

If the assigned landing gate is not available when this drone arrives the designated metering fix point, the drone is required to continue the circulation.

D. Landing phase

Once the drone leaves the circuit, it will approach the landing gate following a planned cubic trajectory shown in Figure 4. The outer ring represents the carousel circuit, and the inner ring is the droneport facade containing many openings for landing gates. As depicted in this figure, a drone exits the carousel circuit along its velocity vector and approaches the landing gate lining up with the virtual runway.

Two successive drones on the carousel circuit are allowed to follow the same landing trajectory as long as they observe the minimum time separation. In this simulation, a landing gate, as a service center, is able to accommodate two drones at the same time. Each landing gate is equipped with a simple M/M/c queuing system [34], which has c servers. The service time is the length of the time probability distribution that a drone spends being attended by a landing gate. In the droneport operation, the carousel circuit acts as a queue, droneport is the service center, and the flights are customers. It is supposed that the demand for the landing pads is ultimately satisfied by the droneport.

E. Residual endurance estimation model

It is a critical issue if a drone runs out of battery. Consequently, a safe and efficient droneport operation must include battery monitoring to prevent the aforementioned case. This simulation is designed to simulate the approaching procedures of the droneport without getting the battery level below a specific value. To achieve this aim, a residual endurance estimation algorithm is developed in this study based on the endurance estimation model designed by Hwang et al. [35]. We expand the capability of this model to calculate the residual endurance of a multirotor UAV with the remaining battery level as an input. The pseudocode of this model is shown in Algorithm 1.

Algorithm 1: Drone endurance estimation

Data: Battery voltage drop gradient k, nominal battery capacity C_0, fully charged voltage V_0, standard voltage V_s, rated discharge time t_0, Peukert's coefficient p, discharge rate λ.
Input : Current residual battery level b_0
Input : Forward flight speed U
Output: Remaining endurance t_b

Initialization;
Current voltage: $V_1 = b_0 * (V_0 - V_s) + V_s$;
Initial required current: $I_1 = \frac{P_{re}}{V_1}$;
Current capacity: $C_1 = C_0 - \frac{V_0 - V_1}{k}$;
Required propulsion power $P_{re} = power(U)$ ($power$ function is developed based on multirotor drone aerodynamic.);

while *capacity_error* $> \epsilon$ **do**
  $t_b = (i-1) * timestep \ (i = 1, 2, 3, 4, ...)$;
  // Calculate the decreased battery voltage
  $V_{i+1} = V_0 - k * (C_0 - C_i)$;
  // Calculate the required current
  $I_{i+1} = \frac{P_{re}}{V_{i+1}}$;
  // Calculate the actual available capacity
  $C_{i+1} = t_0^{1-p} * C_0^p * (I_{i+1}^{1-p} - I_1^{1-p}) + C_1 - \sum_{n=2}^{i+1} I_n * timestep$;
  // Calculate the error
  $capacity\_error = (C_{i+1} - (1-\lambda) * C_0)/((1-\lambda) * C_0)$;
end

In other respects, uncertainties are also critical parts in modeling the simulation. These uncertainties, include the convective weather and the flight arrival time, will affect the landing and takeoff decisions from the droneport control center. The former one can be modeled using a probabilistic modeling method and historical local convective weather data. However, the convective weather is not considered in this study due to a lack of research on the effect of weather on drone's performance. Meanwhile, the latter uncertainty is solved in this simulation model.

F. Optimization

The simulation model mentioned above assesses impacts on capacity of changes in droneport operational conditions and methods. In practice, some possible changes to increase the throughput are reducing separation, increasing final approach speed, changing the length of approach trajectory, and sequencing of drones queuing for landing. In this study, we introduced the dynamic carousel circuit which is capable of changing its radius according to the demand. A large circuit increases the delay time spent in the queuing system, while a small circuit reduces the throughput. An optimum radius is thus a significant requirement to carry out an efficient droneport operation. Apart from that, the flying speed along the circuit and circuit altitude are some variables that can be optimized. Increasing the flying speed will result in a shorter delay time. However, under a certain time separation, the capacity of the carousel circuit will be reduced, and hence partial approaching drones may not be able to join the circuit. As for the circuit altitude, a higher circuit requires a longer travel time from the circuit to the landing gate, while shortening the travel time from the AirMatrix to the circuit.

Based on the aforementioned information, an optimization model is introduced to determine the optimum circuit radius, speed, and altitude.

$$\min \sum_{v \in V_e} \tau_{v,lm_v} + \tau_{v,m_v m_g} + \tau_{v,m_g n} + \beta \cdot \left(B'_{v,lm_v} + B'_{v,m_v m_g} + B'_{v,m_g n} \right)$$

$$\text{s.t. fail} = 0,$$

$$B'_r > 5\%.$$

τ_{v,lm_v}, $\tau_{v,m_v m_g}$, and $\tau_{v,m_g n}$ are the travel time costs for drone v during the approaching phase, queuing phase, and landing phase, respectively. B'_{v,lm_v}, $B'_{v,m_v m_g}$, and $B'_{v,m_g n}$ are the battery consumption for drone v during those three phases. m_v and m_g are the entry and exit point of drone v on the carousel circuit, where the latter one has same orientation as G_v. β is the associated cost coefficient for the battery consumption term.

In this optimization algorithm, two constraints associated with the simulation are considered.

- All the drones from the AirMatrix network can join the carousel circuit without hovering above the droneport airspace. The value of fail means the number of drones that are not assigned to any available virtual blocks during approaching phase.
- The remaining battery levels of the landed drones B'_r are higher than 5%. We refer to the drones passing the landing gates as the landed drones.

V. Numerical Analysis

In this section, we will carry out the numerical tests for the simulation model and the optimization algorithm.

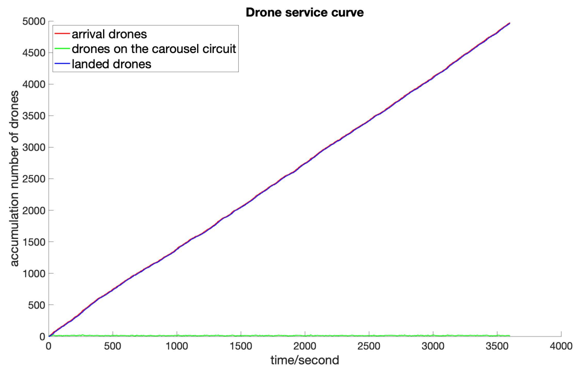
The data of the test case is generated based on the arrival rate, which is calculated by the number of drones expected to land on the droneport for one hour. The droneport demand was estimated in our previous study [17], and the peak hour demand of delivery drones was predicted to be 14360 drones per hour. In this study, we assume that there are 3 levels of these two-lane carousel circuits. We simulate a one-level carousel circuit with only one lane for arrival drones in this study. Consequently, we set 5000 arrival drones as the hourly demand of a one-level and single-lane carousel circuit. Each landing gate follows the $M/M/2$ queueing rule. Other parameters defined in the simulation are summarized in I. The battery-related parameters are collected from a LiPo battery (Tattu) [35].

TABLE I. Important parameters employed in the simulation

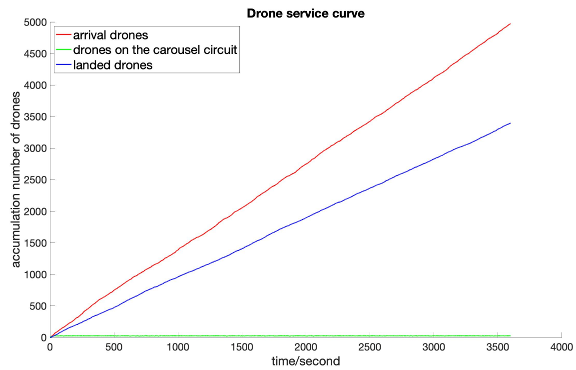
Parameter	Symbol	Value	Units
Time separation	t_s	3	sec
Landing gate service time	t_g	1	sec
flight speed (phase 1, 3)	U_{al}	10	m/s
AirMatrix altitude	h_a	70	m
Landing gate altitude	h_g	40	m
Total arriving drones	D	5000	
Nominal capacity	C_0	32000	mAh
Rated discharge time	T_0	0.2	hr
Battery voltage drop gradient	k	1.2	
Fully charged voltage	V_0	49	V
Standard voltage	V_s	22.2	V
Peukert's coefficient	p	1.05	
Discharge fraction	λ	0.7	

Genetic Algorithm (GA) [36] is applied to perform the optimization model. This study aims to validate the dynamic carousel circuit used in droneport operations via determining the optimum radius of the carousel circuit, the flight speed of drones moving on the circuit, and the altitude of the circuit. The goal of the optimization is to minimize the total travel time cost and battery consumption, thus proving that the dynamic carousel would be suitable for growing demands of drones.

The results from this optimization algorithm are shown in Figure 5. Serving same demand of drones, the dynamic carousel circuit with optimized radius, operating speed and altitude performs better than the other. The optimized dynamic carousel circuit has a radius of 70.709 meters, operating speed of 3.0039 m/s, and altitude of 12.804 meters above the landing gates. It has a capacity of 49 drones, whereas the non-optimized one with a radius of 60 meters has a capacity of 25 drones. The non-optimized carousel circuit takes more than 64260.7 seconds to serve the same demand of drones than the optimized one, and it has 921 drones that fail to access the carousel circuit. The gap between red line and blue line indicates the failure. The green line in Figure 5(b) is maintained at high level, which shows that the carousel circuit is always fully occupied. Moreover, a dynamic carousel circuit with high operating speed is more likely fail to meet the demand. If the speed is higher than 7 m/s, almost all attempts have more than 1000 failures, which means at least 20% arrival drones are not able to access the carousel circuit. In order to perform an analysis for the dynamic carousel circuit, we carry out few numerical tests with higher demand. The results show that the flight speed and circuit altitude will not change much with different demand. This means these two variables can be fixed based on a droneport configuration. In the case of 7000 arrival drones, a 70.709-meter circuit will result in 467 failures. However, a demand of 6000 arrival drones has no failure with a 70.709-meter circuit, but the total travel time cost increases 12835 seconds. The results show that a carousel circuit with fixed radius is not efficient and effective to accommodate drones with fluctuating hourly demand.



(a)



(b)

Figure 5: The drone service curve (a) with optimized dynamic carousel circuit; (b) without optimized dynamic carousel circuit.

This optimization proves the efficiency of the dynamic carousel circuit changing with forecasted demand. Given an estimated incoming flow, a carousel circuit with a changeable radius is able to reduce delay and energy consumption, compared to a carousel circuit with a fixed radius. Nevertheless, the simulation conducted in this study neglects the effect of weather. It will enhance the realism in this simulation if we consider weather uncertainties. Moreover, considering departure drones will influence the performance of the M/M/c queuing system at the landing gates.

VI. Conclusion and Future Work

We investigated a bottleneck of droneport operation - traffic management. As the drone traffic demand growing, there needs to be a way to implement demand and capacity balancing and ensure the safety of incoming and outgoing flights. Therefore, we introduced the dynamic carousel circuit with a changing radius that can accommodate the growing demand for future drones. The carousel circuit is designed to act as a traffic pattern that regulates drones coming in and coming out of the droneport. Based on this concept, a simulation model and an optimization algorithm were developed. The simulation consists of three phases of the arriving drones: approaching phase, queuing phase, and landing phase. Only a one-level and one-lane circuit was simulated to manage approaching drones, since this simulation is aimed to validate the dynamic carousel circuit based on estimated demand. Additionally, the simulation model is equipped with a residual endurance estimation model and cubic trajectory planning, which makes the simulation more practical. An optimization algorithm using GA solver was applied to find the optimum radius of the dynamic carousel circuit, the moving speed of drones on the circuit, as well as the circuit altitude with an estimated demand and stochastic arrivals. The results from numerical tests show that the optimum radius can be calculated from growing demand and the dynamic carousel circuit is capable to manage the peak hour demand in the future. The dynamic carousel circuit has the potential to increase droneport capacity, improve aviation safety, and enhance operational efficiency.

As a complement to this study, future studies will look into multi-level and multi-lane circuits with transition rules applied between each level. Moreover, the convective weather uncertainty will be monitored using Markov Chain in the simulation.

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