A Throughput-Based Capacity Metric for Low-Altitude Airspace

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This paper proposes a throughput-based metric for estimating airspace capacity to accommodate future air traffic in low-altitude airspace. It is motivated by the need to assess the impact of future large-scale air traffic demand on communities and existing urban airspace. In this paper, we simulate unmanned traffic in a representative area and measure the variation of traffic flow. We evaluate three conflict detection and resolution algorithms and two minimum separation requirements and present their effects on throughput. We find that, beyond an algorithm-specific aircraft inflow rate, throughput tends to decrease before the system safety reduces, and hence this metric is promising for evaluating airspace capacity. Further, we find that such a metric in conjunction with other capacity metrics may be useful in evaluating the adequacy of a conflict detection and resolution method for large-scale system operations at or close to capacity.

I. Introduction

With the expected introduction of unmanned aircraft to move goods [1] and people [2–4] and conduct other novel operations like structural monitoring, surveying, etc, future airspace could be filled with traffic orders of magnitude higher than it can bear today. How many such aircraft operations can be accommodated in low-altitude airspace given a set of technological capabilities, operational requirements and protocols, while maintaining safety, stability, performance efficiency and an optimal flow of traffic?

In this paper, we address that question by proposing a throughput-based airspace capacity metric. Historically, airspace capacity has been constrained by manual air traffic controller workload [5–8]. The system has evolved with very stringent requirements on safety, as any loss of flight is catastrophic. This may change for unmanned operations for two main reasons. First, the constraint of a manual controller is relaxed. Automated traffic management should accommodate higher traffic densities. It has been shown to do so to some extent even for manned aviation [9, 10]. Second, not all crashes will be catastrophic. Most may instead result in property damage and not injury or death. Hence, this opens up the opportunity to explore new approaches to estimate capacity for operations in low-altitude airspace.

Our throughput idea is inspired by the concept of the fundamental diagram [11], a component of kinematic wave theory. An extensive application of the concept in road transportation [12] relates the freeway traffic flow to the traffic density (Fig. 1). This has been researched for over seven decades and is well understood and utilized in road transportation [13]. Further, the expected future demand of over 100,000 flights per day [14] (just for package delivery in a single metropolitan region) is closer to volumes traditionally handled in road transportation. Hence, it provides a reasonable starting point for further research into estimating airspace capacity for novel air traffic operations.

Intuitively, as inflow into an airspace volume increases from zero, the throughput (i.e. number of aircraft traversing the airspace per unit time) increases as well. This induces a corresponding rise in accumulation (density). However as aircraft begin to excessively impede each other to avoid losses of separation, the traffic becomes congested and throughput decreases. The aircraft must slow down or deviate significantly from their intended path. The throughput

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should eventually drop to a minimum steady-state value at a maximum aircraft density that preserves safety. The presence of a peak throughput value suggests that operating beyond that regime will be inefficient, even if it is still safe. Therefore, this constrains the capacity of the airspace.

In our current work, we study whether such traffic behavior is actually exhibited by aircraft traversing an airspace. The study is restricted to small Unmanned Aircraft Systems (sUAS) traffic in this paper. Furthermore, capacity is a function of technology. Technology dictates the conflict detection and resolution (CD&R) [15] capability and the allowable minimum separations between the aircraft. Hence, we evaluate the throughput behavior for different CD&R algorithms and separation minima and use a simulation paradigm to produce the results.

The rest of this paper is structured as follows. We first present a review of related work that motivates this effort under section II. Section III lays out our approach in detail. Metrics, CD&R methods and the simulation platforms are discussed under section IV. In V we present the results showing the peak throughput behavior with different CD&R methods and separation minima. Section VI concludes this paper with a discussion of proposed extensions of the work.

II. Literature Review

Approaches in manned aviation literature frequently estimate capacity as a function of controller and pilot workload [5–8]. Capacity is derived from air traffic complexity measures such as Monitor Alert Parameter (MAP) [16], the maximum number of aircraft an Air Traffic Control (ATC) controller can handle at any given time and Dynamic Density (DD) [17, 18], a weighted summation of factors that affect the air traffic complexity. There is an inherent assumption of a structured airspace and Air Traffic Management (ATM) that includes monitors, sectors and airways [19–21]. Capacity is then estimated using fast-time and real-time simulation methods [22] in a highly subjective manner biased by the judgment of human air traffic controllers during the experiments, who are also assumed to be the bottleneck of the system. A second approach called the Eurocontrol Care-Integra models the ATM system as a combination of several information processing agents, each with an associated information processing load (IPL) [23]. The system reaches capacity when one of the agents overloads. This is deterministic for machine agents but again needs subjective judgment for human agents. However, it finds the bottleneck in the system instead of assuming it. Road transportation practice uses a third approach that pins down the bottleneck by measuring the change in lane throughput as a function of the freeway traffic density (see Fig. 1).

Our throughput-based capacity metric is inspired by the latter two approaches. Further, the fundamental diagram approach was recently studied for highly structured one-dimensional sUAS traffic flow in sky lanes in urban areas and shown to exhibit a threshold behavior [24]. We want to explore if this also holds true for unstructured free-flow traffic in an area (2D) and eventually in an airspace volume.

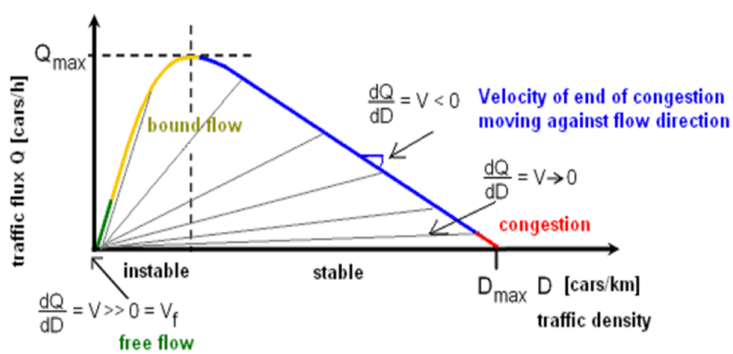

Fig. 1 Fundamental Diagram of Traffic Flow

Future operations both for sUAS and Urban Air Mobility (UAM) [4] may be free flight in nature; i.e. individual flights could be responsible for determining their own courses, independent of a global plan or system. Unmanned Aircraft Systems (UAS) Traffic Management (UTM) should therefore support user-preferred flight trajectories to the extent possible. Any chosen metrics should account for this. ATM architectures that transfer some of the separation responsibility to the cockpit for manned free flight were researched by Bilimoria et al. as part of their Distributed Air/Ground Traffic Management (DAG-TM) concept [9, 10, 25, 26]. Based on their work, the following types of metrics can potentially be used to evaluate any UTM architecture for free flight (the sample measures used for manned ATM [9] are listed in parenthesis): Safety (number of actual conflicts and conflict alerts), Performance (Change in direct operating cost), Stability (number of forced conflicts (domino effect)) and DD (aircraft density, average proximity and average point of closest approach). Of these, we focus on the first two as the basis of our chosen comparative metrics.

Next comes the choice of a CD&R algorithm. CD&R methods in aviation literature have been primarily developed for large aircraft [15] flying at higher altitudes and lower densities than the expected future sUAS traffic. An example of a simple rule used by Krozel et al. [9] is shown in Figure 2. Smaller unmanned aircraft provide a unique opportunity for simpler conflict resolution algorithms. Proposed future operations [27] might primarily be done by aircraft that have Vertical Take Off and Landing (VTOL) capability and better maneuverability. Under these considerations, we chose three simple algorithms in this work. We discuss these further under section IV-IV.B

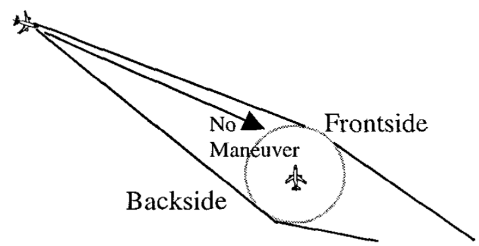

Fig. 2 CDR geometry based on choosing the lower cost choice between the frontside and backside maneuver [9]

Finally, we need a simulator that can simulate sUAS traffic densities so that the throughput behavior can be studied. Existing simulation and evaluation tools developed for ATM (like BlueSky, TMX, ACES, AEDT, FACET) may not fit for our purposes – they are designed to handle manned-aircraft with a much lower traffic density than our study. They take into account interactions with a variety of actors (air traffic controllers, etc.) that are not needed in low-altitude UTM questions of traffic behavior and capacity. The fast-time Fe3 simulator developed by NASA Ames [28] provides the capability of statistically analyzing the high-density, high-fidelity, and low-altitude traffic system. It can be used for effectively evaluating policies and concepts, and performing parameter studies in a higher-fidelity environment like the one in which we are interested. Hence, we use it in conjunction with a simple kinematic model-based Matlab simulator developed for simpler algorithms.

III. Approach

Airspace capacity is the maximum number of aircraft that can traverse an airspace in a given time under a set of requirements. Throughput is a way of quantifying the capacity per unit time. Prior analysis [14] suggested that demand for sUAS package deliveries could be as high as 100,000 flights per day in a metropolitan region like the San Francisco Bay Area. A threshold-based definition was used to study these estimates and establish airspace capacity for such a metropolitan region in terms of "flights per day" considering safety and performance efficiency [29]. Such a macroscopic approach, although useful for long-term planning and design of an airspace system, provides no direct method of real-time control. On the other hand, the flow density relation is used as a tool to control road traffic by regulating inflow in real time and improve throughput. Hence, if the peak throughput behavior is exhibited by air traffic, a similar air traffic control method could also be explored for operating the airspace at or close to capacity.

There is no empirical data on sUAS traffic in the airspace today on which to base our methods. Hence, we start by considering a representative area, subjecting it to increasing steady state inflow rates of air traffic and measuring the mean outflow rate, which we call throughput of the airspace. Next, to study the feasibility of the throughput metric, we pick other metrics to compare against, use parameters that model the technology, and develop a computational process that quantifies the metrics as a function of the technology parameters.

The primary goals of air traffic management are to maximize safety, capacity, and efficiency. In Section IV we discuss the safety and efficiency metrics that are evaluated along with the throughput metric. We make the following operational assumptions about the aircraft and their operations: (a) All aircraft are sUAS with strictly VTOL capability; (b) Their flight plans are straight line paths from entry to exit on the boundary of the study area. These paths change as aircraft fly through the airspace and avoid conflicts with other aircraft using a given CD&R algorithm; and (c) All sUAS have nominal and maximum speeds constrained by the capabilities of typical sUAS in use today. Our setup is two dimensional. Any losses of separation are horizontal (a simplification to evaluate the throughput-based capacity metric). We plan to extend this to a volumetric study in the future. The detailed simulation setup and the chosen metrics and CD&R methods are described next.

IV. Simulation

We first define the notion of a conflict and loss of separation. Any sUAS should stay out of a minimum separation exclusion zone (a disc with radius D) around another sUAS. A loss of separation occurs when two sUAS come within this minimum separation. Given their projected paths in the horizontal plane, if an sUAS is predicted to eventually enter within the minimum separation of another sUAS, the two aircraft are said to be in conflict. Figure 3 illustrates a loss of separation occurring between two sUAS.

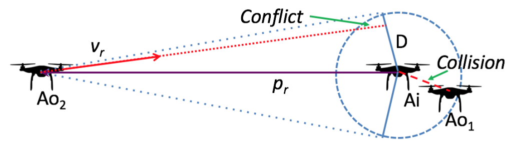

Fig. 3 Conflict and Loss of Separation. Ao **- Own sUAS,** Ai_1 **&** Ai_2 **- Intruder sUAS. The aircraft are shown in relative frame of reference**

We make the following assumptions. We only consider multi-copters, which means that the aircraft can hover. The nominal flight speed is assumed to be 15 ms^{-1} with a maximum value of 20 ms^{-1}. The maximum acceleration that today's sUAS can achieve is about 2g. If 1g is used to overcome the weight, close to 1g is available for horizontal maneuvers while keeping the aircraft in safe operational limits. To avoid pushing aircraft to their maximum capability all the time, we limited the maximum acceleration to 0.5g. We chose a representative area as a square of 0.5km width. The origins and destinations of aircraft are uniformly distributed along the edges and are spaced such that two aircraft don't enter or exit within loss of separation distance. These are randomly connected to form the flight paths such that no aircraft has an origin and destination on the same edge. This ensures that every aircraft enters the study area. Finally, we estimate the different metrics for two different separation minima - 5 meters and 10 meters.

A. Metrics

1. Throughput

Our primary metric - *Trip Exits per min* captures the average traffic outflow rate through the area (i.e. throughput). Measuring trip exits per second would be too small to capture substantial intended boundary crossings and measurements over an hour would be too long to provide any real-time control over an area.

2. Safety

Safe operation of the airspace is of utmost importance. Following the proposed requirements by MITRE [30] and its use in our prior macroscopic capacity estimation work, we choose the necessary safety metric as the *Total Losses of Separation* observed over the simulation interval.

3. Performance Efficiency

Higher operating costs (fuel, wear, etc.) lower performance. They are typically caused by longer travel times and distances, which are in turn usually the byproduct of safer operation. We capture this in the current work by measuring the *Percentage Extension in Travel Time*. This is a direct derivative of the *Change in Direct Operating Cost* as proposed by Krozel et al. [9].

B. CD&R methods

Approaches to CD&R may be broadly classified into three categories - force field based, trajectory projection based and offline look-up table-based. We chose three simple CD&R methods that capture different types of control, represent different categories of CD&R approaches and can together encompass most types of aircraft. This makes them flexible for future extensions of this study to different classes of aircraft. First is avoidance by slowing down to “Hover." This captures the effect of pure speed control and encompasses aircraft that can stop in flight. It uses a trajectory projection-based approach. Second is a simplified implementation of “Potential Field" method as used by

Mueller [31]. This uses a simultaneous speed and direction control. Since the minimum speed can be set greater than 0, it captures all aircraft with a stall speed constraint. It belongs to the broad category of force field-based CD&R approaches. The third is an algorithm derived from the ICAROUS [32] architecture, that is based on DAIDALUS [33], a reference implementation of RTCA-228 Minimum Operational Performance Standards (MOPS)(Appendix G) for UAS DAA (Detect and Avoid) [34]. This also uses speed and direction control and is extendable to all aircraft with a stall speed constraint. It acts as a more complex example of trajectory prediction-based approaches under formal consideration. In the rest of this paper, we will refer to this ICAROUS-based algorithm as "ICb" for brevity.

We used a kinematic model-based simulator in Matlab to study the throughput behavior for Hover and Potential Field and used the same flight data to study ICb as implemented on the fast-time simulation platform Fe3. Fe3 is highly-parallelized and implemented on Amazon Web Services(AWS) Graphical Processing Unit(GPU) instances. It includes various six-degree-of-freedom vehicle models and CD&R algorithms and also incorporates vehicle communication and sensor models and wind models. Although other components, such as no-fly zones, near-ground static and dynamic obstacles and avoidance, and community effect via noise and pollution, are still under development, Fe3 provides essential functionality necessary for our study.

V. Results

In this section, we present our results that describe the throughput-based capacity metric. Figures 4, 5 and 6 show the variation of throughput for hover, potential field and ICb. The figures on the left compare throughput to number of losses of separation during the simulation and the figures on the right compare it to the percentage extension of travel time. In all the figures, solid line and dotted line represent 5 meters and 10 meters minimum separation, respectively. The metrics are evaluated as a function of different steady-state inflow rates. The average area outflow rate measured as Trip Exits per min is plotted in blue. The losses of separation and the mean percentage extension of travel time measured over the entire simulation are plotted in orange on the left and right figures respectively.

We observe the following general trends. In all figures, a peak throughput behavior is exhibited at an intermediate steady-state traffic inflow (between 60 to 80 flights per min for Hover and ICb and between 40 to 60 flights per min for Potential Field). Any losses of separation and noticeable extensions of travel times occur at or beyond the peak throughput. In other words, peak throughput is achieved even before safety of the system is compromised. Therefore, in this airspace, the optimal inflow to be maintained is decided by throughput rather than safety. When the tolerance is higher (smaller minimum separation), the throughput is also higher as the aircraft can be safely packed closer together.

Under the same steady-state inflow conditions, for example between 60 and 80 flights per min, the highest throughput is shown by both Hover and ICb (about 50 trip exits per min) but Hover exhibits it at a slightly higher inflow rate. Potential Field shows lower peak throughput than the other two. It also peaks at an inflow rate of 40 trips per min, almost half that of the other two. However, this loss comes at a much higher level of safety. This is shown by the loss of separation numbers at and beyond peak throughput. Both Hover and ICb start deteriorating in terms of safety beyond their respective throughput peaks, while Potential Field maintains its low losses of separation (below 4) well beyond. Further, the number of losses of separation rise rapidly for the Hover and ICb cases but they stay low for potential field. Practically, this gives flexibility to the system to operate at peak, while for the other two, from a risk standpoint, it is preferable to operate to the left of the peak.

Next we compare the performance efficiency. ICb fares better than Hover in terms of travel time extension. For example, close to the peak throughput, hovering extends mean travel time by 1% for the 5m separation case, while the value for ICb is around 0.8%. The percentage extension is almost thrice at peak (about 3%) for Potential Field. The difference is more pronounced beyond the peaks. In the entire simulation, Hover exhibits a maximum mean travel time extension of 3%. The same metric for ICb is 1.2%, while it is slightly more than thrice for Potential Field at 10%. But as stated earlier, what Potential Field loses in efficiency, it compensates for in safety.

These behaviors are explained as follows. Our hover approach slows down aircraft to a stop without deviating them from their trajectory. Hence beyond peak throughput, first there is an excessive slowdown that reduces the throughput. Next, when all aircraft begin to stop while the inflow is still maintained, several aircraft don't have enough distance/time to stop safely. Hence, they start entering each others' minimum separation distances, especially closer to the boundaries. The number of losses of separation rises fast and exit rates continue to fall. However, the aircraft within separation minima are either stopped or moving very slowly. This is comparable to a jam on a freeway where cars are bumper to

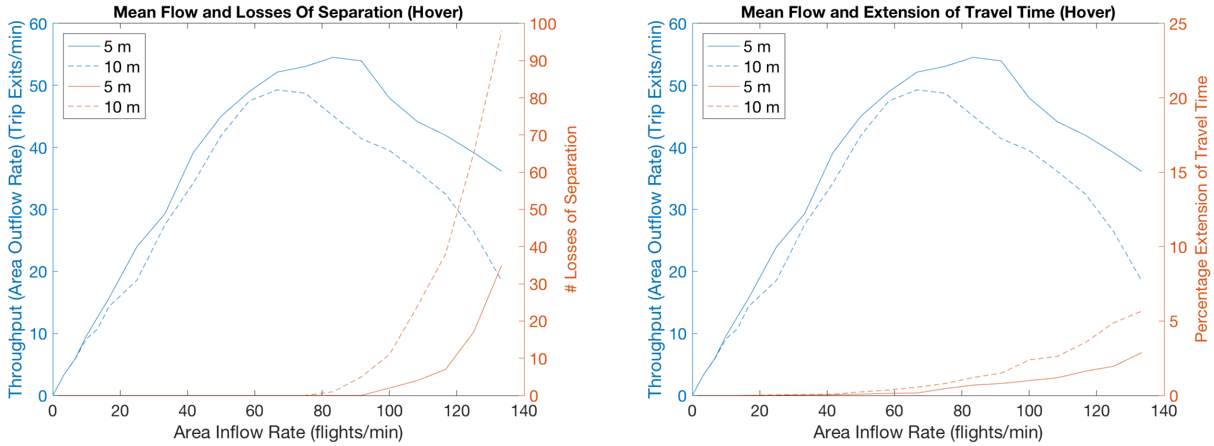

Fig. 4 Results for Hover to Avoid

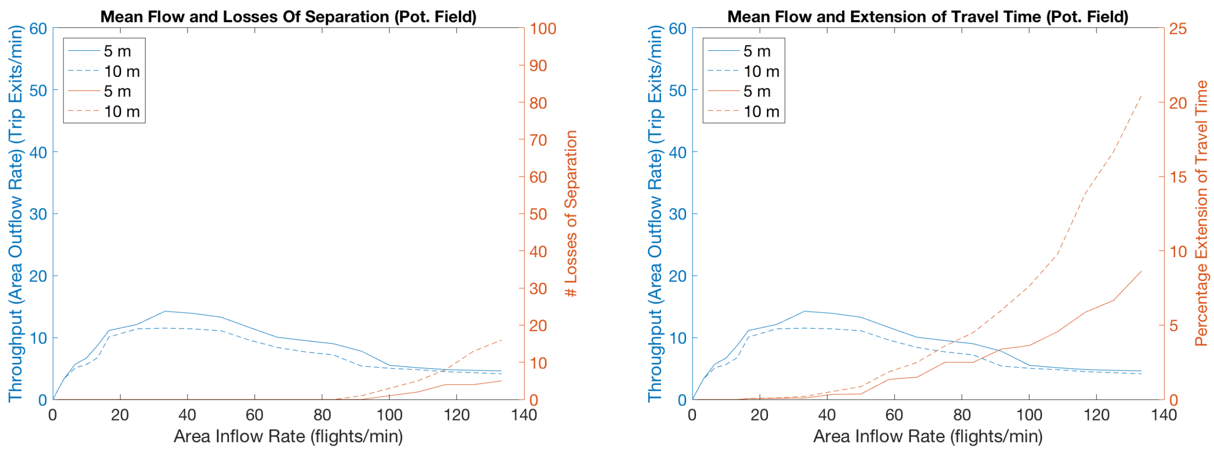

Fig. 5 Results for Potential Field

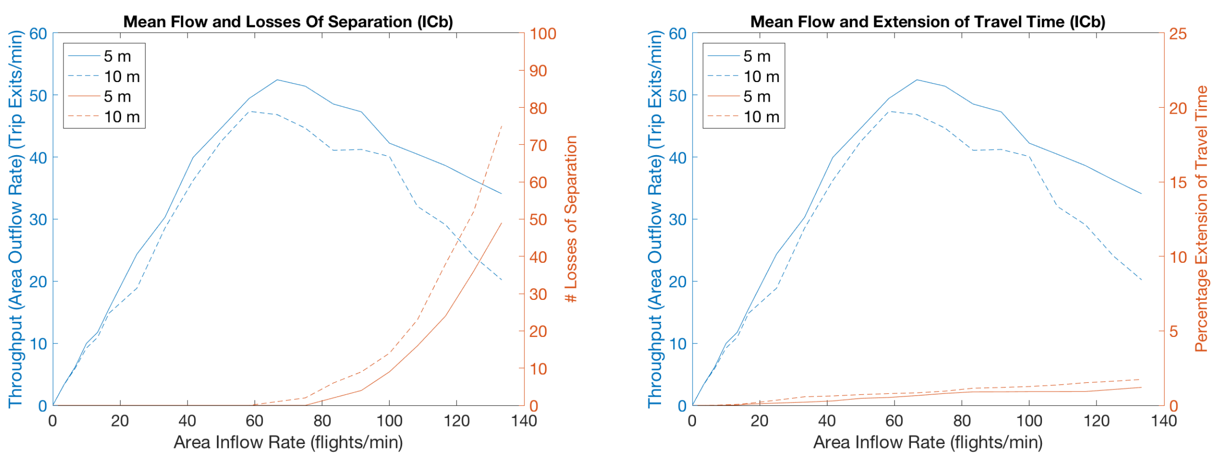

Fig. 6 Results for ICb

bumper but not crashing into each other. Hence, it is not necessarily unsafe.

ICb picks the resolution maneuver from the recovery bands provided by DAIDALUS that has the least secondary conflicts and simultaneously minimizes the deviation from the nominal trajectory. This results in low travel time extensions and higher throughput. As more aircraft accumulate in the airspace, the recovery bands become narrower and hence lead to higher number of losses of separation.

In the potential field approach, the aircraft at or close to minimum separation have large repulsive forces, which ensure that the aircraft are kept away from each other and hence very safe. The small number of losses of separation happen when excessive aircraft have accumulated in the system and either the repulsive forces start overwhelming the aircraft operation limits or an aircraft trying to reach its destination ends very close to an originating aircraft. Both of these scenarios can be minimized by implementing appropriate entry and exit rules or providing buffer zones at high inflow rates. Safety is achieved by spreading the aircraft beyond the primary study region boundaries. To understand this better, let us assume that the study region was an urban area. This approach pushes out aircraft at the edges of the area into suburban airspace. Hence, a higher amount of contingency airspace is required.

Based on the above insights we find that the throughput metric is not only useful to understand airspace capacity as a function of technology, but our comparative approach also provides a basis for evaluating CD&R methods in terms of the capacity, safety and efficiency they can achieve at high density system level operations.

VI. Conclusions and Future Work

We have developed a throughput-based airspace capacity metric for unmanned air traffic in low-altitude airspace. Throughput, safety and performance metrics were evaluated for uniformly distributed air traffic inflow over a square area of 0.5 km width. We used three CD&R methods — Hover, Potential Field and ICb, and two separation minima — 5 meters and 10 meters in our simulations.

Our results show the throughput behavior as a function of the steady-state air traffic inflow in a representative area. The system stays safe (i.e. no losses of separation) without excessive impact on performance (less than 5.5% mean extension of travel time) until after the accumulation of air traffic has lead to a reduction in throughput. This suggests that the throughput peak may quantify the airspace capacity. The CD&R algorithms themselves exhibited different throughput peaks. Further, smaller separation requirements allowed better throughput no matter which algorithm was used. We also observed that measuring throughput in comparison to safety and efficiency metrics could be used as a tool to evaluate the adequacy of a CD&R algorithm for large-scale operations.

A next step in the evaluation of this approach is to use other other robust CD&R methods such as Airborne Collision Avoidance System X (ACAS X) developed for multi-copters [31]. This would capture an offline look-up table-based CD&R method, which we didn't explore in this paper. We also need to measure the effect of sensor and navigational uncertainties (such as deviations from trajectory, delays in aircraft detection, wind, etc), static and dynamic obstacles (e.g., buildings and temporary flight restrictions) and specific traffic flow patterns.

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