Toward Air Traffic Complexity Assessment in New Generation Air Traffic Management Systems

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***Abstract*—The characterization of complex air traffic situations is an important issue in air traffic management (ATM). Within the current ground-based ATM system, complexity metrics have been introduced with the goal of evaluating the difficulty experienced by air traffic controllers in guaranteeing the appropriate aircraft separation in a sector. The rapid increase in air travel demand calls for new generation ATM systems that can safely and efficiently handle higher levels of traffic. To this purpose, part of the responsibility for separation maintenance will be delegated to the aircraft, and trajectory management functions will be further automated and distributed. The evolution toward an autonomous aircraft framework envisages new tasks where assessing complexity may be valuable and requires a whole new perspective in the definition of suitable complexity metrics. This paper presents a critical analysis of the existing approaches for modeling and predicting air traffic complexity, examining their portability to autonomous ATM systems. Possible applications and related requirements will be discussed.**

***Index Terms*—Air traffic management (ATM), autonomous aircraft, complexity metrics.**

I. Introduction

An AIR TRAFFIC management (ATM) system is a multiagent system where several aircraft compete for a common congestible resource represented by airspace and runways space while trying to optimize their own cost, evaluated in terms of, e.g., travel distance, fuel consumption, and passenger comfort. Coordination between aircraft is needed to avoid conflict situations where two or more aircraft get very close to one another. This is, in fact, a fundamental task of an ATM system, whose objective is to guarantee safety and efficiency in air travel, despite the airspace system time-variability due, e.g., to temporary structural modifications when the access to some areas is forbidden because of military missions or bad weather conditions and to disturbances such as an aircraft that enters/leaves the airspace due to departing/landing at airports.

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The continuing growth in air traffic demand is pushing the limits of the current ground-based ATM system. As reported in [1], the average daily traffic above Europe in 2006 counted 26 286 flights per day, with an increase of 4.1% with respect to 2005, whereas the total delay increased by 4.6%, much more than expected based on the 4.1% of air traffic growth. The need for improving the system capacity while preserving the current safety guarantees has spurred research in two directions:

1. developing methods for the dynamic allocation of the resources involved in the current ATM system, possibly introducing automated tools for supporting decision making (see, e.g., the special issue [2]);
2. conceiving new operational concepts in ATM.

The characterization of the *air traffic complexity* turns out to be a key aspect within both these directions of research. In general terms, the concept of air traffic complexity was introduced to measure the difficulty and effort required to safely manage air traffic. In the current ground-based ATM system, where the airspace is structured into sectors, and a team of air traffic controllers (ATCs) is in charge of guaranteeing safety in each sector, complexity is ultimately related to the *workload*, i.e., the effort exerted by humans in managing air traffic. Complexity measures are eventually employed to redistribute and reassign human resources and to reconfigure sectors to adapt the capacity of the ATM system to the air traffic demand. Besides planning and redesign, improved measures of complexity could be useful for evaluating ATM productivity and assessing the impact of new tools and procedures [3]. Air traffic complexity has also been studied in relation with different issues such as the occurrence of operational errors (events where two or more aircraft violate the separation standard and the cause is attributed to air traffic control) or incidents [4]–[10], controller decision making [11], the design of decision support and flight planning tools [12]–[14], conflict risk [15]–[17], and conflict resolution [18].

On a longer term perspective, the whole ATM system must be rethought, and its degree of automation must be increased. New Generation ATM systems are currently developed within the Single European Sky ATM Research (SESAR; see [19]) and Next Generation Air Transportation System (NextGen; see [20]) projects. In both of these projects, it is envisaged that an increased air traffic volume can be efficiently managed by allowing for a (partial) delegation of the ATM effort to the involved aircraft, which will be endowed with some degree of autonomy in choosing their preferential routes while sharing with the ATCs part of the responsibility in maintaining the appropriate separation with the other aircraft. According to this perspective, the iFly European project Safety, complexity and responsibility based design and validation of highly automated Air Traffic Management studies an advanced airborne self-separation design for en route autonomous aircraft ATM (A^3TM).

A notion of air traffic complexity could be particularly useful in the new ATM systems to assess and predict traffic conditions that may be overdemanding to the autonomous aircraft design. This task is crucial for avoiding encounters that appear safe from the individual aircraft perspective but are, in fact, safety critical from a global perspective.

Complexity measures that have been, to some extent, successful within the current human-based centralized ATM system may turn out to be inappropriate within an autonomous aircraft ATM system, and novel metrics must be defined to meet the new challenges posed by the autonomous aircraft concept. This paper discusses the desired characteristics and possible envisaged applications for complexity metrics within A^3TM and evaluates the suitability and portability of existing complexity metrics to new generation ATM systems.

The paper is structured as follows. Section II illustrates the notion of air traffic complexity within the current ground-based ATM system and describes the main approaches to air traffic complexity modeling and prediction proposed in the literature. A discussion on the closely related issue of ATC workload concludes this section. The challenges posed by new generation ATM systems are discussed in Section III, with emphasis on the possible applications where complexity metrics are envisaged to play a significant role and on the requirements posed on these complexity metrics. Existing complexity metrics are critically revised in Section IV based on the characteristics that are relevant in view of a possible application to the A^3TM design. Finally, some conclusions are drawn in Section V.

II. Air Traffic Complexity Within the Current Ground-Based Air Traffic Management System

A. Structure and Functioning of Ground-Based ATM

In the current ground-based ATM system, the coordination of the multiaircraft airspace system is operated on two different time scales by the air traffic control and traffic flow management functions.

The air traffic control function operates on a short/mid-term horizon, with the goal of maintaining the appropriate separation between aircraft in the different stages of their flights from departure to destination. For this purpose, the airspace is structured into air traffic control centers (ATCCs) that are partitioned into sectors, each controlled by a team of two to three ATCs. The basic unit in mid-term air traffic control is plotted in Fig. 1.

In the feedback control scheme, the controlled system is represented by a sector, and the ATC is the feedback controller, who interacts with the controlled system through sensing and actuating interfaces. The exogenous input to the control system represents aircraft that enter/exit the sector under consideration and models the interactions with neighboring sectors. Information on the controlled system behavior and on the exogenous input is provided to the ATC through "sensors" (radar, software

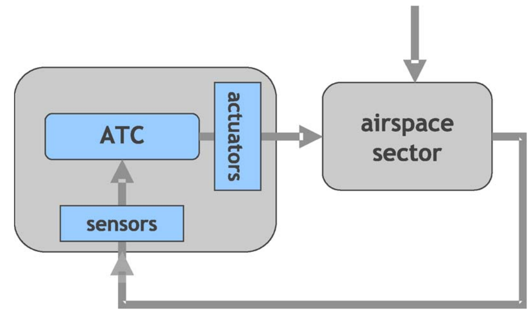

Fig. 1. Air traffic control unit in ground-based ATM.

equipment, and radio connections), whereas the control strategy is implemented by issuing commands (speed, altitude, and heading changes) to the pilots through radio connections (the "actuators"). Sectors are designed so that the nominal flow of traffic through each sector can safely be handled by the ATCs who are in charge of that sector.

The traffic flow management function operates on a long-term horizon by defining the flow patterns so as to ensure a smooth and efficient organization of the overall air traffic, accounting for the sector capacity constraints when optimizing flows. In the event of increased demand or rerouting required due to weather conditions or special airspace usage constraints, traffic flow management techniques such as staff reallocation and alternative airspace configurations are used for maintaining the ATC workload constant to avoid compromising safety and efficiency levels [21], [22].

B. Air Traffic Complexity Metrics

Air traffic complexity, which is intended as a "... measure of the difficulty that a particular traffic situation will present to an ATC ..." [23], appears fundamental to evaluate how the current ground-based ATM system is operated and can also be used to provide guidelines on how to obtain more manageable sectors by reconfiguring the airspace and by modifying traffic patterns. In [24], it is suggested that the capacity of an ATCC could be increased by a timely prediction of the traffic complexity bottleneck areas and a reconfiguration of the traffic patterns to evenly balance traffic complexity between sectors. A "complexity resolution" algorithm that dynamically modifies flight profiles is introduced to reduce the predicted complexity of more critical sectors and balance the complexity of adjacent sectors. In [25], a methodology for the optimal design of airspace sectors is proposed. The airspace is partitioned into hexagonal cells, and each cell is assigned a workload measure. Then, the airspace sectors are constructed by clustering algorithms using optimization methods. In [26], indicators of sector workload are studied, which could operationally be useful to traffic management coordinators (TMCs), who take decisions that affect how much traffic ATCs will have to handle.

Several metrics have been proposed in the literature for the characterization of air traffic complexity. A description of selected metrics is provided next. See the comprehensive literature review in [3] and the technical report in [4] for more details on complexity metrics that explicitly account for the ATC workload.

1) Aircraft Density (AD): In the current practice, the complexity of air traffic is generally accounted for in terms of the number of aircraft and on a per-sector basis [3], [22]. The number of aircraft in a sector is the air traffic characteristic that has been most cited, studied, and evaluated in terms of its influence on workload. In the U.S., the peak aircraft count (the largest number of aircraft in a sector during any minute of a 15-min time interval) is compared with an acceptable peak traffic count value and is adopted for operational traffic flow management decisions such as rerouting flights out of an overloaded sector [26]. Similarly, the European flow management staff determines the airspace configuration schedule (successive aircraft configurations during the day) by splitting or merging sectors based on the number of ATCs on duty and the traffic load assessed by flight counts and sector capacities. A decision support system for traffic management (the enhanced traffic management system) is used for this purpose, whose monitor/alert function is based on a comparison of the prediction of traffic volume in the sector against some established threshold volume that represents the maximum number of aircraft that the ATCs are willing to accept in that sector.

2) Dynamic Density (DD): Researchers unanimously agree that air traffic indicators other than the number of aircraft per sector are relevant to ATC workload. These indicators are related to both structural and flow characteristics of air traffic [3], [4]. The former characteristics are fixed for a sector and given by spatial and physical attributes such as terrain configuration, the number of airways, airway crossings, and navigation aids (*static air traffic characteristics*). The latter characteristics vary as a function of time and depend on features such as the number of aircraft, weather, aircraft separation, closing rates, aircraft speeds, mix of aircraft and flow restrictions (*dynamic air traffic characteristics*). These static and dynamic factors interact in a nonlinear complex way to produce air traffic complexity [27]–[29]. A list of "complexity factors" is provided in the literature review [3].

DD is an aggregate measure of complexity, where traffic density and other dynamic traffic characteristics are combined either linearly or through a neural network [13], [22], [26], [30]–[34]. The characteristics are identified as critical for real-time decision making through interviews to qualified ATCs and include variables such as the number of aircraft that undergo trajectory changes or require close monitoring due to reduced separation. The weights are determined based on subjective ratings obtained by showing different traffic scenarios to the interviewed ATCs, or by a regression analysis of their physical activity data. As a result, DD is a complexity measure that incorporates subjective and objective workload measurements.

Different DD measures have been proposed in the literature, depending on the complexity factors that they include. The choice of the complexity factors often relates to the specific ATCC, which makes DD a sector-dependent metric. The structure of the airspace was identified as the second most important factor behind traffic volume [35]. Histon *et al.* [33], [36] investigated how this structure can be used to support abstractions that ATCs appear to use to simplify traffic situations. A DD metric that includes a structural term based on the relationship between aircraft headings and the dominant geometric axis in a sector was proposed in [30]. In addition, emphasis was given to the traffic and airspace characteristics that impact the cognitive and physical demands placed on the ATC. The relation of DD with cognitive factors is investigated in [3].

3) Interval Complexity (IC): IC is a time-smoothed version of a DD-like measure that has been introduced in [24] as an estimate of the ATC workload in a sector.

The IC of a sector is defined as the average over a 5–10-min time window of the linear combination of the following three complexity factors: 1) the number of aircraft flying within the sector; 2) the number of aircraft that fly on nonlevel segments; and 3) the number of aircraft that fly close to the border of the sector. Nonlevel flights and flights that are close to the boundary, in fact, require special attention and procedures to be followed by the ATC. The weights in the linear combination depend on the specific sector.

4) Fractal Dimension (FD): FD is an aggregate metric for measuring the geometrical complexity of a traffic pattern by evaluating the number of degrees of freedom used in the airspace by the existing air routes [37]. This information is independent of sectorization and does not scale with traffic volume. Currently, aircraft cruise on linear routes at specified altitudes, corresponding to a geometrical dimension of 1. In the future, it is expected that flights will be allowed to move from these linear routes. If all of the airspace were covered by routes, the FD would be 3. However, there will still be preferred routes (due to the position of connected airports or to wind currents), thereby decreasing the actual dimension of the route structure. Analysis of air traffic using a gas dynamics analogy also shows a relation between FD and the conflict rate (the number of conflict per hour for a given aircraft).

5) Input–Output (IO) Approach: In [38] and [39], air traffic complexity is defined in terms of the control effort needed to avoid the occurrence of conflicts when an additional aircraft enters the traffic. To this purpose, an input–output system similar to that in Fig. 1 is introduced, where the air traffic within the region of the airspace under consideration is the system to be controlled, and an automatic conflict solver is the feedback controller. The input to the closed-loop system is represented by a (fictitious) additional aircraft that enters the traffic, whereas the output is given by the deviation of the aircraft that are already present in the traffic from their original flight plans as issued by the feedback controller to safely accommodate the incoming aircraft. Optimization of the conflict resolution maneuvers is performed by means of a mixed-integer programming (MIP) solver [40]. The overall amount of corrective action needed to recover a conflict-free condition is taken as a measure of the air traffic complexity. A "complexity map" is constructed as a function of the entering position and bearing of the incoming aircraft. A scalar value can be extracted from this complexity map, taking, e.g., the "worst-case" value for the corrective action needed to safely accommodate the additional aircraft. Note that different measures of the control effort and different solvers could be used and that the choice of the conflict solver has a large impact on complexity evaluation [39].

6) Intrinsic Complexity Metrics: Some researchers were not very inclined to acknowledge a direct cause–effect relation between complexity and workload, nor that the relationship between these two factors could adequately be mathematically expressed. This has led to a radically different view of the complexity issue, which aims at building metrics of the "intrinsic" complexity of the air traffic distribution in the airspace without incorporating any measure of the ATC workload [41]. According to this viewpoint, complexity metrics should capture the level of disorder and the organization structure of the air traffic distribution, irrespective of its effect on the ATC workload.

Two classes of intrinsic complexity metrics are presented in [41], both based on the measurements of the aircraft velocities and positions. The first class consists of a geometrical approach where complexity is a function of the relative position vectors and relative velocity vectors of the aircraft. The second class describes traffic flow organization using the topological Kolmogorov entropy of a dynamical system that models air traffic. The approach based on topological entropy was further developed in later work [42]–[44], where the authors explore both the linear and nonlinear system modeling of air traffic to derive topological entropy measures for air traffic complexity characterization and, ultimately, to produce maps of local complexity to be used for the identification of critical air traffic areas.

Inspired by this work, in [45], the air traffic is represented through an interpolating velocity vector field, and complexity is evaluated based on the characteristics of the latter. Essentially, if the vector field is smooth, aircraft can follow nonintersecting trajectories, and the introduction of an additional aircraft causes a marginal increase in complexity. On the other hand, locations of the airspace where the vector field loses continuity correspond to critical areas. The main challenge of the approach is to compute the separation boundary (between smooth field regions) in real time.

In [46], to capture the complexity associated with the lack of organization, an air traffic situation is modeled by an evolution equation, with the aircraft trajectories interpreted as integral lines of some dynamical system. The Lyapunov exponents (LEs) of the dynamical system provide an indicator of the air traffic complexity, allowing for the identification of different organizational structures of the aircraft speed vectors such as translation, rotation, divergence, convergence, or a mix of them. For systems that are described by nonlinear differential equations, LEs measure the rate of exponential convergence or divergence of nearby trajectories and can be taken as indicators of the level of order/disorder of a system. The idea is that the larger the positive LE, the higher the rate at which one loses the ability to predict the system behavior. Areas characterized by high air traffic complexity are then easily identified by plotting the largest LE as a function of the airspace position, thus obtaining a complexity map over the considered airspace area. The main challenge from a computational viewpoint is represented by the calculation of the vector field that smoothly interpolates a given set of aircraft positions and velocities.

C. Workload Issue

A discussion on air traffic complexity would be incomplete without the characterization of the workload concept, because air traffic measurements and workload are often incorporated within a single aggregate complexity indicator to describe the ATC-perceived complexity. This is achieved by empirically correlating the measured workload to the available measurements of airspace configuration and traffic patterns. Unfortunately, a clear globally accepted definition of ATC workload is not available in the literature [47], and its quantitative evaluation is difficult.

Workload depends both on the task load, i.e., the difficulty and demands of a task, and on the physical and mental effort required to accomplish that task [5]. The former factor is affected not only by the air traffic but by the available interfaces for sensing the air traffic situation and for implementing the control strategy, whereas the latter factor is affected by the internal and subjective response to task load (cognitive strategies and individual variables). The amount of workload experienced by ATCs is also modulated by the adopted information processing and decision-making strategies [3], [48]–[50].

There are very few constraints on how controllers should handle traffic beyond maintaining adequate separation between aircraft. Thus, the space of possible solutions is large and can accommodate a variety of conflict resolution strategies. As traffic volume increases, ATCs adapt their information processing and decision-making strategies in an attempt to regulate workload [48], [51]. Controllers use more economical control procedures and more standard strategies to control air traffic at higher traffic densities, often resorting to heuristics developed with the experience. They react to task load fluctuations with compensatory strategies such as shedding or deferring tasks, prioritizing tasks, or becoming more cautious in bad weather [52]. This way, they preserve their cognitive resources available for the task. Various elements affect the workload, e.g., the task/operator interaction, individual factors (age, skill, experience, anxiety level, etc.), and contingent factors (time pressure, noise, fatigue, stress, distraction). The workload history also affects the perceived complexity, because a long period of heavy load tends to reduce the ATC efficiency.

Workload can be measured using direct subjective indicators (e.g., self-report measures and a controller's rating obtained through questionnaires) or indirect indicators, including behavioral/physical (e.g., key strokes, slew ball entries, number of control actions, communication time, decision and action frequency) and physiological (e.g., EEG/EMG/EOG, blood pressure, heart rate measures, eye blink rate, respiration, biochemical activity, pupil diameter) indicators. Various data collection methods are listed in [3]. The issue of evaluating ATC performance and workload based on data collected from operational and simulated air traffic control is discussed in [53], where an extensive taxonomy of air traffic control measurements adopted in the literature is provided.

Both direct and indirect workload measurements are very expensive to collect, because they require the active participation of ATCs. Subjective measures suffer from several drawbacks, e.g., memory effects and unwillingness to report damaging information. In [54] and [55], the relevance of measures of the controller activity for real-time decision support is evaluated. Communication measures are found to be correlated with subjective workload but not to provide any incremental benefit when used for prediction of its future behavior. Certain physical parameters related to the interaction with the workstation (e.g., route displays and strips requests) are found to be not well correlated with controller performance and mental workload, whereas other parameters (e.g., data entries) are significantly correlated. Behavioral measurements generally miss the cognitive aspects of controller activity.

In [56] and [57], one attempt is made to model human–machine interaction for ATC according to a system-engineering approach. Queuing theory is used in [56] to analyze ATC workload, and the resulting mathematical model is validated on ATC operational data to predict average delay and server occupancy as a function of demand. A control-theory-based approach is considered in [57] to describe the ATC system. Apparently, the proposed model that involves different functions (planning, controlling, communicating, and data management) has not empirically been validated. Finally, in [58]–[60], the airspace configuration, with sectors possibly split or merged, is suggested as a measurable variable of the ATC workload to determine factors that are relevant to complexity evaluation through a correlation analysis based on neural networks.

In conclusion, although nearly all of the studies found a statistically significant correlation between air traffic factors and workload, the evaluation of workload is a long-debated issue and an inherently ill-posed problem. Indeed, one of the strongest motivations for investigating complexity metrics that are independent of the ATC workload has been the difficulty of obtaining reliable and objective workload measures.

III. Air Traffic Complexity Within the New Generation Air Traffic Management Systems

A. Autonomous Aircraft ATM

In the envisioned next generation ATM systems, the aircraft will be endowed with more degree of autonomy in trajectory management while sharing with the ATCs the responsibility for separation maintenance. In self-separation airspace, the aircraft will be allowed to modify their flight plan to optimize performance in terms, e.g., of the distance traveled and fuel consumption while satisfying some constraint on their exit condition to provide the necessary matching with the traffic in the managed airspace outside the self-separation area. This flexibility with respect to the ATC-managed airspace offers each single aircraft the possibility of improving the efficiency of its own flight. In turn, pilots will have to take over the ATC tasks for separation assurance with the support of airborne separation assistance systems (ASASs) that rely on advances in communication, navigation, and surveillance technologies. Action Plan 23 is a joint Federal Aviation Administration (FAA) and Eurocontrol initiative that is specifically devoted to the study of the applications that support the transfer of separation responsibility from the ground to the flight deck.

This shift toward a distributed ATM will be enabled by the introduction of novel information-sharing systems, such as the System Wide Information Management (SWIM) system management system developed within SESAR and the Net-centric Infrastructure System (NIS) developed within NextGen, together with the availability of new airborne and communication capabilities. Aircraft will communicate with each other (air-to-air communication) and with the ground (air-to-ground communication) to get up-to-date information on the other aircraft position, velocity, and intent, on locally sensed weather data, on global weather conditions and forecast, and on areas to avoid.

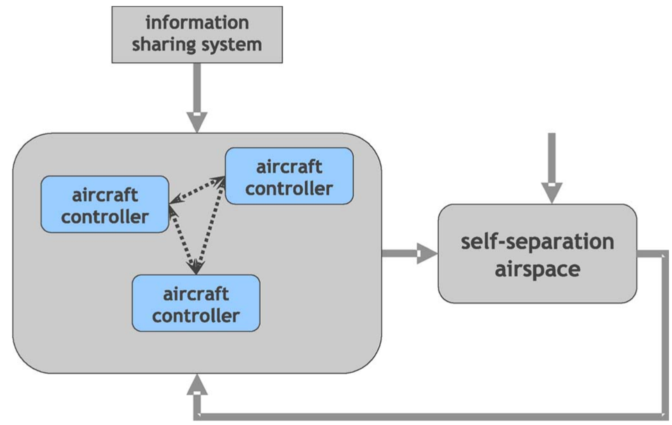

Fig. 2. Control scheme in autonomous aircraft ATM.

The ATM function will then be realized through a (partially) decentralized control scheme (see Fig. 2), where each aircraft evaluates the criticality of forthcoming encounters based on the information on the current position and intended destination of neighboring aircraft and eventually coordinates with them to avoid the actual occurrence of conflict (intent-based conflict detection and resolution). Ground control will then assume a new role that consists of a higher level, possibly automated, supervisory function as opposed to lower level human-based control.

The performance and safety of each aircraft flight will be affected by the traffic present in the self-separation airspace. More specifically:

- Performance deteriorates when the aircraft passes through an area with highly congested traffic, because this requires several tactical maneuvers.
- Safety is compromised when the aircraft is involved in a multiaircraft conflict that exceeds the capabilities of the onboard conflict resolution system.

These situations could be timely predicted by adopting the appropriate notion of air traffic complexity, which would then play an essential role within the strategic and hazards prevention phases of the ATM process. Complexity evaluation could, in particular, support the following functionalities of an airborne autonomous aircraft system.

- *Onboard trajectory management*, which aims at optimizing the effectiveness of the flight within the self-separation airspace, compatibly with the strategic flow management constraints (exit conditions from the self-separation airspace) and the presence of areas to avoid (e.g., restricted areas and bad-weather zones) provided by an independent (typically ground-based) system. The areas to avoid could include regions with high "complexity," which would potentially require an entering aircraft to perform too many tactical maneuvers to pass them through.
- *Intent-based conflict detection* and *resolution*, which aims at predicting and solving conflict situations on a

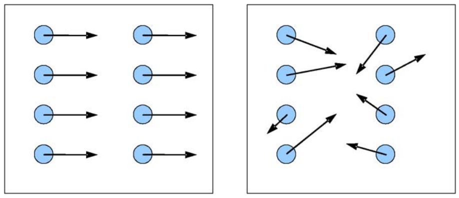

Fig. 3. Different air traffic situations with the same density.

mid-term (up to 10–15-min) time horizon based on the aircraft intent information. In addition to the potential loss of separation, the conflict detection function could predict "complex" situations that are likely to overload the conflict solver. In turn, the conflict solver could favor resolution maneuvers with lower complexity to avoid further alerting and resolution actions.

B. Features of Air Traffic Complexity Metrics

The structure and functioning of A^{3}TM systems, as well as the envisaged control applications, pose novel and specific requirements to complexity metrics, as described hereafter.

1) Accounting for Traffic Dynamics: As aforementioned, traffic density is the one most important factor that determines the complexity of air traffic, irrespective of the specific application. It is probably the most often considered factor, and the term "congested area" is usually used to identify areas with high traffic density. However, traffic density alone conveys only partial information on complexity. This fact has already been acknowledged in ground-based ATM, where it has been noted that, under certain circumstances, controllers accept traffic beyond the prescribed threshold, whereas in other cases, they reject it, although the number of aircraft is well below the threshold [61]. The dynamics of the traffic plays a major role in this. For example, the two patterns in Fig. 3 involve the same number of aircraft at the same initial positions, but the different dynamics lead to a coherent organized traffic flow in one case and to a chaotic situation in the other one.

In the current ATM perspective, an ordered traffic flow is generally considered a low-complexity situation, regardless of the number of aircraft involved, whereas only a relatively low number of aircraft is considered acceptable if the traffic pattern is chaotic. It is debatable, however, that the traffic order will be an equally important feature in future automated ATM systems (see, e.g., the discussion in [62]). Nevertheless, it is clear that density, on its own, is a crude estimator of complexity and that traffic dynamics must also be accounted for.

2) Independence of the Airspace Structure: A^{3}TM operates in a sector-free context, where aircraft that fly in the self-separation airspace are allowed to select their preferential routes subject to some constraints. As such, the complexity metrics in A^{3}TM should not present any structural dependence on the sector characteristics. Given that the traffic density is a relevant factor for complexity characterization [3], [35], the identification of aircraft clusters (i.e., groups of closely spaced aircraft) can complement and accelerate complexity assessment by isolating airspace areas where attention needs to be concentrated.

Aircraft clustering was originally studied in connection with the conflict resolution problem [43], [63]–[66]. The work in [63], in particular, studies conditions under which separation assurance can be delegated to the cockpit, based on the idea of clusters of conflicting aircraft. A methodology for identifying aircraft clusters is suggested in [67] and [68] as the first step toward obtaining a sector-independent evaluation of airspace congestion; aircraft clusters are isolated first, and then, congestion is assessed based on complexity evaluation in each cluster. In some sense, aircraft clusters can play within the autonomous ATM system a role similar to sectors within the centralized human-operated ATM system.

3) Tailoring to the Look-Ahead Time Horizon: In view of the autonomous aircraft application, time dependence should be better focused, introducing approaches for air traffic complexity assessment tailored to the specific time horizon. As for the foreseen applications in A^{3}TM to onboard trajectory management and intent-based conflict detection and resolution, we can distinguish between a long- and a mid-term look-ahead time horizon, respectively.

Long-term complexity metrics should be computed based on the aircraft flight plan over the reference time horizon for onboard trajectory optimization, which may extend to the whole duration of the autonomous part of the flight. They should detect critical situations that would require several tactical maneuvers to be solved along the planned trajectory of each single aircraft and identify highly congested regions that would require an entering aircraft too many adjustments of its flight plan to pass them through. Long-term complexity should be recomputed from time to time to take care of possible modifications of the aircraft flight plans. Unexpected deviations on a finer time scale shall be accounted for by the mid-term complexity metrics.

Mid-term complexity metrics should support the intent-based conflict detection and resolution functions by timely detecting situations that could overload the onboard conflict resolution module. They should be computed based on the trajectories reconstructed from the state and intent information on a time horizon of 10–15 min, possibly accounting for uncertainty in the aircraft trajectory prediction due, e.g., to wind prediction [69].

4) Independence of the Control Effort: A complexity metric can be classified as *control dependent* or *control independent* based on whether it accounts for the controller in place explicitly or only indirectly through its effect on the air traffic. Complexity metrics that incorporate the ATC's workload measurements are clearly control dependent. In principle, control dependent metrics could also be employed in an airborne self-separation framework, e.g., by incorporating some measure of the control effort involved in solving a conflict in terms of deviation from the original trajectory and computational effort. This approach, however, is not feasible in practice. Consider that, in A^{3}TM, control is delegated to the aircraft according to a partially decentralized control scheme (see Fig. 2), with pilots supported in their trajectory and separation management tasks by automated tools that implement certain optimization and conflict resolution strategies. In addition, different levels of automation could be realized. The pilot could be provided with a set of possible options to choose from or only be informed of the decision taken by some automated system, whose characteristics would depend on the adopted optimization and resolution strategy. As a result, the A^{3}TM controller has a decentralized time-varying structure, which is difficult to characterize for the purpose of control effort evaluation, and involves pilots as human-in-the-loop components, with the related problems of their workload evaluation. In practice, therefore, a control independent measure of complexity appears to be better suited for an A^{3}TM system.

One possible way of taking into account the difficulty of managing traffic without explicitly referring to the controller in place would be to adopt the notion of *flexibility* of the aircraft trajectory, i.e., the extent to which a trajectory can be modified without causing a conflict with neighboring aircraft or entering a forbidden airspace area. In principle, the larger the flexibility of a trajectory is, the easier it is to find some resolution maneuver to avoid the occurrence of a conflict due to some unexpected deviation of a neighboring aircraft from its planned path, irrespective of the specific control strategy used to select the best resolution maneuver. The use of flexibility measures in an airborne self-separation framework is the object of an ongoing research activity by the National Aeronautics and Space Administration [70]–[72]. The concept of flexibility is used differently, depending on the time horizon. In the short/medium-term horizon, flexibility is used as a criterion for rating different conflict resolution maneuvers so that the adopted solution is the easiest to adapt to unexpected behavior by intruder traffic. In the long-term horizon, a flexibility preservation function is adopted to plan the aircraft trajectory by minimizing its exposure to disturbances such as weather cells and dense traffic areas. These two notions that are tailored to different look-ahead time horizons appear well suited for the aforementioned applications to onboard trajectory management and intent-based conflict detection and resolution.

5) Goal-Oriented Output Form: Air traffic complexity is both a time- and space-dependent feature, which is typically expressed in aggregate form by condensing either the space or the time information (or both) of the traffic situation under consideration. Output forms range from a scalar value, describing the traffic complexity in a certain region (e.g., a sector) at a specific time instant, to a spatial complexity map. With regard to the prospective applications, scalar-valued metrics (possibly projected over some look-ahead time horizon) could be better suited to the mid-term conflict detection and resolution function, providing synthetic information on the level of complexity encountered by the aircraft along its current trajectory. On the other hand, complexity maps can be used to identify critical areas of the airspace that the aircraft should avoid and hence are more suitable for the long-term trajectory management task.

IV. Discussion on the Reviewed Complexity Metrics in View of the Autonomous Aircraft Application

It is difficult to compare the results from all the different studies on air traffic complexity because of the wide variety of indicators used to assess it. Here, we focus on the approaches reviewed in Section II-B and classify them with respect to the features that are relevant to the autonomous aircraft context described in Section III-B. A schematic view of this classification is reported in Table I.

As previously discussed, complexity metrics where workload and air traffic measurements are incorporated within a single aggregate indicator are control dependent. In addition, these metrics depend on the adopted notion and measure of workload and inherently incorporate various human factors aspects. Workload-oriented metrics are sector-based (in [24], reference is even directly made to the complexity of a sector as an estimate of the ATC workload of that sector) and often show structural dependence on the sector characteristics, which further limits their applicability to a sector-free context such as autonomous aircraft ATM.

AD is both a workload-oriented and sector-based metric, because it is given by the number of aircraft in a sector, which is compared with a threshold determined based on the capabilities of ATCs to safely handle air traffic in that sector. Even within a ground-based ATM context, AD presents some drawbacks, because it does not take into account a few aspects that may greatly influence the actual workload levels experienced by ATCs. These factors include traffic pattern, traffic mix, weather, the time variability of the traffic volume (a traffic volume that highly fluctuates over time is more likely to generate conflicts and appears more complex to the controller than a uniform traffic flow [73]), and the duration of a high-workload period. Also, AD is very sensitive to the entry and exit times of a few flights that would actually not change the amount of sustained workload. Finally, human factors are also neglected, although operational errors are more likely to occur *after* rather than during a peak in traffic count [7].

Despite all these drawbacks, AD is currently considered the best available indicator of complexity in terms of the simplicity of its calculation, which does not require other information than aircraft count, and of its operational interpretation, because to reduce complexity, one should just limit the number of aircraft that enter the sector.

The DD and IC metrics are also workload-oriented and sector-based and are even more critically dependent on the workload evaluation method and the sector characteristics. They are, in fact, parametric models where different complexity factors in a sector are combined linearly or through a neural network with coefficients that are finely tuned based on a quantitative evaluation of the perceived workload in that specific sector. The computed weights are extremely variable from sector to sector and therefore need to be reestimated and revalidated for each sector (and possibly periodically retuned). From an operational viewpoint, having too many complexity factors to analyze makes it difficult for decision makers such as TMCs to understand which specific complexity factor is responsible for a high-workload situation and, hence, to decide what action to take to reduce complexity [26].

The IO approach provides another control dependent measure of complexity, which is evaluated in terms of the control effort needed to safely accommodate a fictitious additional aircraft but avoids the workload issue by using a specific centralized conflict solver in place of the ATC. A similar approach could be adopted to tune the coefficients in the DD

TABLE I
CLASSIFICATION OF THE REVIEWED COMPLEXITY METRICS

metric	input data	method	accounting for traffic dynamics	sector-independent	look-ahead time horizon	control-independent	output form
Aircraft density	number of aircraft in the sector	comparison with a workload-based threshold	no	no (evaluated per sector)	instantaneous measure, extendable with trajectory prediction	no (threshold tuned on workload)	scalar value
Dynamic density	number of aircraft and other indicators of traffic characteristics in the sector	linear and nonlinear regression tuned on workload data	yes (through synthetic indices)	no (tuned to the specific sector)	instantaneous measure, extendable with trajectory prediction	no (regression weights tuned on workload)	scalar value
Interval complexity	number of aircraft and other indicators of traffic characteristics in the sector over a 5 to 10 minutes horizon	linear and nonlinear regression tuned on workload data, plus averaging	yes (through synthetic indices)	no (tuned to the specific sector)	short/mid term	no (regression weights tuned on workload)	scalar value
Fractal dimension	aircraft trajectories	covering measure	yes	yes	long term	yes	scalar value
Input/output approach	aircraft timed trajectories	optimization of conflict resolution maneuvers for all possible initial conditions of an additional aircraft	yes (indirectly through trajectory changes to accommodate a new aircraft)	yes	short/mid term	no (based on control effort evaluation)	map (control effort to accommodate an additional aircraft as a function of its initial conditions)
Lyapunov exponents	aircraft timed trajectories	dynamical systems modelling of trajectories and calculation of Lyapunov exponents	yes	yes	short/mid/long term	yes	map (largest Lyapunov exponent as a function of airspace position)

and IC aggregate complexity metrics, replacing the ATC with some conflict solver.

Note that all the DD, IC, and IO control dependent metrics could, in principle, be adapted to an autonomous aircraft context by substituting the evaluation of the control effort with the evaluation of the trajectory flexibility, as suggested in Section III-B, when discussing the “independence of the control effort” feature.

The control independent FD and LE metrics appear to be more directly applicable to new generation ATM systems. In fact, because they depend only on the air traffic characteristics, they can be used to evaluate both uncontrolled and controlled aircraft trajectories, and in the latter case, they require no knowledge of the controller in place, which is only indirectly accounted for through the effect of its action on the air traffic organization.

With regard to the time dependence aspect, measures that are computed based on the aircraft future trajectories (e.g., FD, IO, and LE) naturally evaluate complexity over some look-ahead time horizon. As for FD, in particular, it can be considered a geometrical feature of a limit shape obtained by observing trajectories on an infinite time period. As such, it is a complexity metric that is potentially suitable for long-term applications. Unfortunately, it has a great drawback, which limits its operational impact, in that the timing information of the aircraft routes is completely lost in this type of analysis. It was, in fact, originally proposed as a measure for comparing traffic configurations that result from various operational concepts [37], with the key feature of allowing to decouple the complexity due to airspace partitioning in sectors from the complexity due to traffic flow features and of being independent of workload aspects.

Measures that are computed based on the air traffic state rather than the whole aircraft trajectories can be used to predict complexity in the future when combined with trajectory prediction (by projecting the air traffic state and recomputing the complexity measure). In [22], it is suggested that DD can be projected over a suitable time horizon by using trajectory prediction tools, so as to forecast future workload levels and use this information for traffic management. Good prediction accuracy is reported in the 5-min scale, which is suitable for short-term control applications. Extension of the prediction horizon to 20 min could be of use for mid-term control applications. The projection of the IC metric on a further extended time scale of 20–90 min could be used for selecting appropriate “complexity resolution” actions that minimize and balance traffic complexities between adjacent sectors of a certain airspace region.

Note that the reliability of the complexity prediction on some look-ahead time horizon depends on the accuracy of the aircraft trajectories prediction. Surprisingly, to our knowledge, uncertainty in the trajectory prediction is not accounted for in any of the (deterministic) approaches in the literature. Only recently, a probabilistic approach to air traffic complexity characterization has been proposed, where the uncertainty that affects the future aircraft position is modeled as a stochastic process [74], [75].

With regard to the output form, AD, DD, IC, and FD are all scalar metrics, but only AD, DD, and IC are extendable in time through aircraft trajectories prediction. The output of the IO method is a map of the control effort as a function of the initial conditions of a hypothetical additional aircraft that enters the considered airspace region. As such, this map provides only indirect information on the spatial distribution of complexity in the airspace, which hampers its use for the identification of complex areas to avoid. On the other hand, the spatial complexity maps derived based on LEs could support decision making in the trajectory management function by isolating critical areas.

V. CONCLUSION

New generation ATM systems will have a decentralized and distributed control structure, with separation and management tasks shared between the ground and the flight deck. This poses new and formidable challenges in the ATM system design.

This paper has addressed, in particular, the problem of assessing air traffic complexity in an autonomous aircraft context. Prospective applications have been described, i.e., onboard trajectory management and conflict detection and resolution. The corresponding requirements on complexity metrics have been discussed, and existing metrics have been critically revised, discussing their portability and adaptability to the new context. In particular, the elusive notion of control effort, which is generally incorporated in the complexity measure, has been found to be one of the main obstacles toward a definition of reliable complexity indicators. In addition, time dependence has been somewhat overlooked in the literature and needs to be better focused, because very different control functions are envisaged in the autonomous aircraft framework, depending on the time horizon considered.

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