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Introducing Structural Considerations into Complexity Metrics

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Abstract

Field observations and focused interviews of Air Traffic Controllers have been used to generate a list of key complexity factors in Air Traffic Control. The underlying structure of the airspace was identified as relevant in many of the factors. A preliminary investigation has revealed that the structure appears to form the basis for abstractions that reduce the difficulty of maintaining Situational Awareness, particularly the projection of future traffic situations. Three examples of such abstractions were identified: standard flows, groupings, and critical points. Preliminary approaches to developing metrics including these structural considerations are discussed.

Introduction

In the face of the continued increase in demand for Air Traffic Control (ATC) services, there is a clear need for a better understanding of the capacity of airspace. At present, sector capacity is normally expressed as a maximum instantaneous number of aircraft in a sector. However, anecdotal evidence and direct observations suggest that this maximum capacity level varies between sectors and with different traffic situations.

In this paper it is assumed that complexity is related to the cognitive difficulty of controlling the air traffic situation, which in turn is tied to the ability of controllers to maintain safe operations under normal and abnormal conditions. The objective is to understand those factors that influence complexity, particularly those factors which relate to the underlying structural elements in ATC. Various structural elements and the mechanisms by which they reduce complexity have been identified. Including their effects in complexity metrics is an important step towards developing useful measures of complexity for ATC applications.

Improved measures of ATC complexity would find many applications including: airspace design, airspace slot allocation and traffic flow management. As well, such measures can be used to compare the effectiveness of different airspace structures, and/or to evaluate new air traffic management concepts.

Previous Work on ATC Complexity

Significant research interest in the concept of ATC complexity was generated by the “Free Flight” operational concept. Integral to Free Flight was the notion of dynamic density. Conceptually, dynamic density is a measure of ATC complexity that would be used to define situations that were so complex that centralized control was required [RTCA, 1995].

Efforts to define dynamic density have identified the importance of a wide range of potential complexity factors, including structural considerations. However, the proposed complexity metrics have typically concentrated on only those factors that can be easily elicited from the geometry of an ATC situation [Delahaye et al., 2000; Laudeman et al., 1998; Sridhar et al., 1998;

Wyndemere, 1996]. Examples of factors based on geometric properties include aircraft densities, the proportion of aircraft maneuvering and encounter probabilities.

A few previous studies have attempted to include structural considerations in complexity metrics, but have done so only to a restricted degree. For example, the Wyndemere Corporation proposed a metric that included a term based on the relationship between aircraft headings and a dominant geometric axis in a sector [Wyndemere, 1996].

The importance of including structural considerations has been explicitly identified in recent work at Eurocontrol. In a study to identify complexity factors using expert judgment analysis, "Airspace Design" was identified as the second most important factor behind traffic volume [Kirwan et al., 2001].

Methodology

In order to investigate the relationship between structure and cognitive complexity, a series of site visits to ATC facilities in the United States, Canada, and France were conducted. The site visits included both en-route and terminal area control centers.

The site visits consisted of focused interviews with current controllers and observations of live operations. To understand how complexity is regulated through traffic management initiatives, discussions were held with members of Traffic Management Units (TMU). Training personnel were interviewed to determine if and how structure is used and taught in ATC training.

Additionally, representative traffic patterns were captured using various feeds of the Enhanced Traffic Management System (ETMS).[1] This tool allows visualization of structural elements in the current system. It has also been used to generate illustrations of the use of that structure to reduce complexity.

Key Complexity Factors

Based on the field observations, ETMS data analysis, and a review of the pertinent literature, a list of the key factors influencing cognitive complexity was developed and is presented in Table 1. Factors that appear to relate to the underlying structure are identified by an asterix (*). No attempt has been made to rank the factors. However, they have been found to fall into three categories: *Airspace Factors*, *Traffic Factors*, and *Operational Constraints*.

Airspace Factors are those factors related to properties of the airspace. Represented are both internal properties, such as the distribution of navigational aids, and external properties, such as sector shape and coordination activities. In general, these factors are quasi-static, characterizing the underlying context within which a traffic load exists.

A second category, *Traffic Factors*, are factors dependent on the instantaneous distribution of traffic. They represent more dynamic and transient effects than *Airspace Factors*. Most previous efforts focused on measures associated with *Traffic Factors*.

Finally, *Operational Constraints* are additional operational requirements that place restrictions on possible control actions. These factors tend to represent short-term or temporary variations in operational conditions.

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[1] It must be cautioned that the ETMS data was sometimes filtered to remove military and other potentially sensitive aircraft, and thus may under represent the real traffic situation.

Table 1. Key factors reported by controllers as influencing cognitive complexity. Items marked with a * are related to structural elements.

AIRSPACE FACTORS
Sector dimensions* *Shape* *Physical size* *Effective “Area of regard”*
Spatial distribution of airways / Navigational aids*
Letters of Agreement / Standardized Procedures*
Number and position of standard ingress / egress points*
Standard flows* *Number of* *Orientation relative to sector shape* *Trajectory complexity* *Interactions between flows (crossing points, merges)*
Coordination with other controllers* *Point-outs* *Hand-offs*
TRAFFIC FACTORS
Density of aircraft *Clustering** *Sector-wide*
Aircraft encounters *Number of* *Distance between aircraft* *Relative speed between aircraft* *Location of point of closest approach (near airspace boundary, merge points etc…)** *Difficulty in identifying* *Sensitivity to controller’s actions*
Ranges of aircraft performance *Aircraft types (747, Cessna)* *Pilot abilities*
Number of aircraft in transition *Altitude* *Heading* *Speed*
Sector transit time*
OPERATIONAL CONSTRAINTS
Buffering capacity*
Restrictions on available airspace *Presence of convective weather* *Activation of special use airspace** *Aircraft in holding patterns**
Procedural restrictions *Noise abatement procedures** *Traffic management restrictions (e.g. miles-in-trail requirements)*
Communication limitations

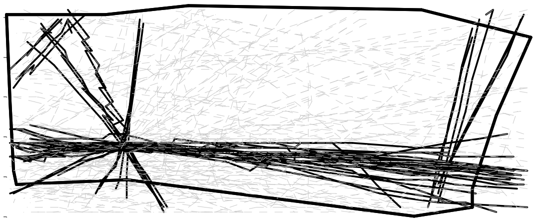

Figure 1. Image of 24 hours of traffic through Utica sector, identified by controllers as “easy” (268 aircraft).

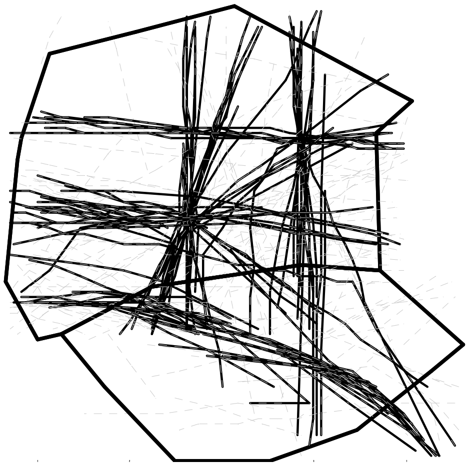

Figure 2. Image of 24 hours of traffic through Albany sector, identified by controllers as “hard” (231 aircraft).

Figure 1 and Figure 2 show images of 24 hours of traffic flow obtained from ETMS data. The thick lines represent trajectories of aircraft determined to be on standard flows. Respectively, they represent sectors that controllers identified during the focused interviews as “easy” (Utica) and “hard” (Albany). The differences between the standard flows in these sectors are consistent with the expected increases in complexity associated with the corresponding *Airspace Factors* identified in Table 1: there are more standard ingress and egress points, more standard flows and a greater amount of interaction between those flows in the “hard” sector.

One factor that controllers repeatedly emphasized was that events and influences beyond the nominal boundaries of the sector are important components of complexity. As shown in Figure 3, the "Area of Regard" is greater than the physical dimensions of the sector. Aircraft outside of the boundaries of a controller's sector can be important for decisions regarding aircraft currently within the sector. In field observations, controllers often spent as much attention on incoming aircraft and their impact on the sector as on the active aircraft in the sector.

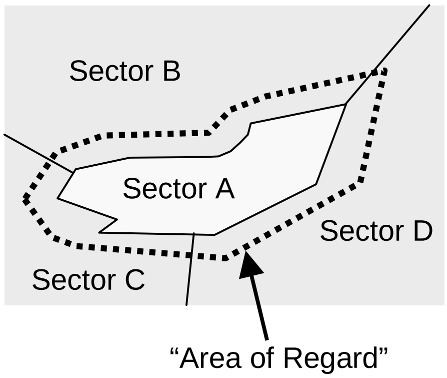

Figure 3. Dashed line illustrates how the "Area of Regard" extends beyond the physical boundaries of Sector A.

Generalized Model of Complexity and Structure

In order to generate an understanding of the effects of structure on complexity, a model has been developed relating structure and the four key processes in conflict resolution in air traffic control [Pawlak et al., 1996]:

- Planning
- Implementing
- Monitoring
- Evaluating

In the planning process, a controller identifies and schedules the series of control actions required to ensure the present air traffic situation evolves conflict-free within the constraints associated with the sector. These constraints encompass many of the *Airspace Factors* and *Operations Constraints* identified in Table 1 above (e.g. standard ingress/ egress points, avoidance of activated special use airspace, weather restrictions etc.).

Implementing is the performance of the actions required by the current plan. Monitoring involves checking the conformance of the current and projected air traffic situations against those expected based on the current plan. Finally, evaluating verifies the effectiveness of the plan in meeting all of the constraints and goals associated with the sector.

The ability to project future states of the air traffic situation was identified during analysis of the field observations as a critical component of each of the planning, monitoring and evaluating processes. For example, planning requires an accurate projection of future interactions between elements in the air traffic situation. As well, projections are important for monitoring, which requires checking that the current air traffic situation will evolve in conformance with the current plan.

Figure 4 shows a proposed model connecting the processes identified above with Endsley's model of Situational Awareness [Endsley et al., 1994]. The planning, monitoring, and evaluating processes are associated with the controller's decision process and are depicted as dependent on the controller's Situational Awareness. The output of the decision process is the performance of actions, or the implementing process. These actions feedback and modify the air traffic situation.

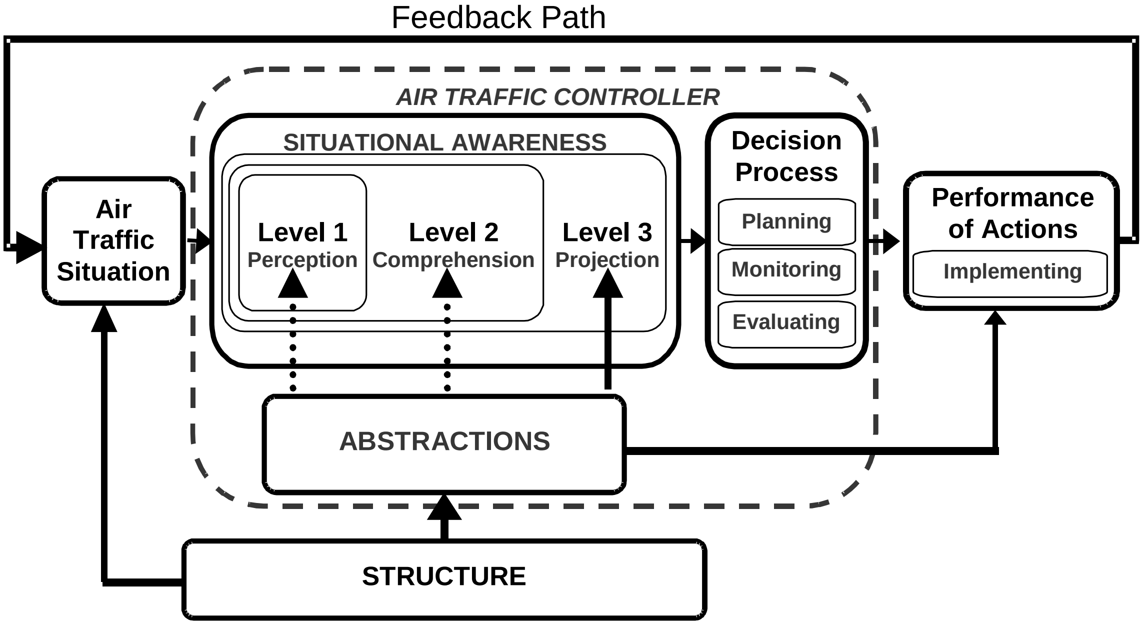

Figure 4. Generalized model illustrating how structure forms the basis for abstractions that influence Situational Awareness. (Adapted from [Endsley et al., 1994]).

It is hypothesized that controllers use structure as the basis for abstractions that simplify the maintenance of the Situational Awareness at each of the three levels identified by Endsley: perception, comprehension, and projection. This is possible because the structure associated with a sector will also modify the air traffic situation by prescribing and constraining its evolution (e.g. aircraft fly along defined airways).

In particular, by simplifying the task of creating and maintaining future projections of the air traffic situation, structure-based abstractions appear to:

- Consolidate the information required to project an aircraft's future path,
- Eliminate the need to consider some interactions within projected traffic situations,
- Reduce the degrees of freedom, or dimensionality, associated with some interactions.

Structure-based abstractions are thought to reduce the apparent complexity of the input space, thereby simplifying the decision-making process. In addition, as shown in Figure 4, the same abstractions can also act to simplify the performance of actions, or the implementing of the outputs from a controller's decision process.

Examples of Structure-Based Complexity Reduction Mechanisms

This preliminary investigation has identified three key structure-based abstractions that appear to reduce cognitive complexity in ATC. The key abstractions are:

- Standard Flows
- Groupings
- Critical Points

Each abstraction is described briefly below.

Standard Flows

Standard flows appear to be one of the most important structure-based abstractions used by controllers. Two structural bases that establish standard flows have been identified:

- Explicit structural elements
- Standardized operations

The first type of standard flow is based on explicit structural elements in the airspace such as navigational aids, airways, and documented standardized procedures, including standard ingress and egress points as documented in letters of agreement between adjacent sectors or facilities. An example of this type of flow is an arrival stream, as shown in Figure 5 for arrivals into Chicago from the east.

Figure 5. Example of standard arrival flows into O'Hare airport in Chicago.

The second type of standard flow emerges as a result of common practices, or standardized but unpublished patterns of operation. An example is the typical "trombone" vectoring sequence used to merge aircraft onto final approach.

An aircraft identified as a member of a standard flow carries with it an associated set of higher-level attributes such as expected future routing, ingress and egress points from the airspace, and locations of probable encounters. These attributes form a generalized expectation of an aircraft's trajectory through the airspace.

The standard flow abstraction emerges as a means of classifying aircraft into standard and non-standard classes on the basis of their membership in established flow patterns in a sector (see Figure 6). The task of projecting the future behavior of an aircraft that belongs to a standard flow is greatly simplified by the generalized expectation of its trajectory. In contrast, aircraft that are operating in ways that do not fall into the normal operating pattern, such as the "special case" aircraft in Figure 6, do not provide the same simplifications.

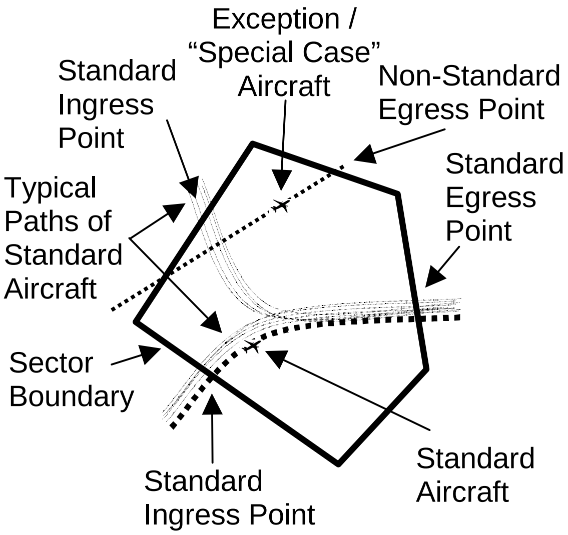

Figure 6. Standard flows form the basis for a structure-based abstraction that distinguishes between standard and non-standard aircraft.

The simplification of the projection task makes the standard flow abstraction powerful irrespective of the number of aircraft in the sector. Even if a snapshot of the instantaneous traffic situation does not reveal well-defined flows, the standard flow abstraction is still available, and can still act to simplify the projection task.

Groupings

The presence of an underlying structure in a piece of airspace provides the basis for creating groups of aircraft linked by common properties. This type of abstraction can take advantage of properties that are known to segregate a traffic situation into non- or minimally-interacting groups.[2] Consequently, the aircraft groups can be projected independently, reducing the cognitive complexity.

One simple example of a grouping abstraction is the standard flight levels that associate directions of travel with particular flight levels. For aircraft in level flight, this eliminates some aircraft-aircraft interactions from consideration in any projections, allowing controllers to project and manage each flight level independently.

As reported in Table 1, controllers have consistently reported altitude transitions as a key complexity factor [Laudeman et al., 1998; Sridhar et al., 1998; Wyndemere, 1996; Kirwan et al., 2001]. Aircraft that are transitioning between flight levels do not fit into the grouping abstraction and thus must be treated as special cases.

Grouping abstractions also explain an interesting result from the list of complexity factors in Table 1. A range of aircraft performance was identified as a key factor influencing complexity. If aircraft performance was uniform, grouping abstractions could be used even more widely to simplify the projection task. For example, a wide distribution of aircraft speeds makes the process of projecting future positions more difficult than the case where all aircraft are flying at a uniform speed.

The grouping abstraction can also operate on the basis of the simple proximity of aircraft. In this case, the use of a grouping abstraction can act to simplify the output from a controller, i.e. the execution of the results of the decision process. This may occur when large numbers of aircraft divert around convective weather. In the example shown in Figure 7, each group of aircraft deviating around the weather can be treated as a single entity for the purpose of co-ordination.

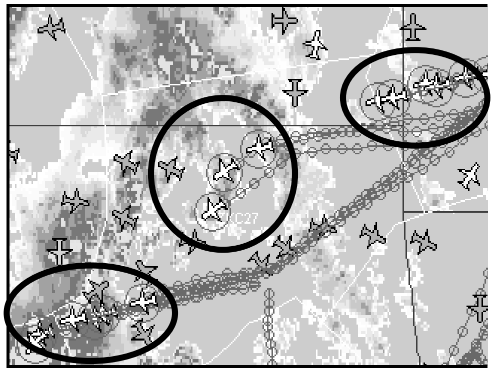

Figure 7. Example of groups of aircraft following common paths while diverting around convective weather.

Critical Points

Critical points are the final example identified to-date of a structure-based abstraction. The underlying structure, in the form of crossing and merge points of flows, will tend to concentrate the occurrences of encounters at common locations. In forming projections, a controller's attention can be focused on a finite number of critical locations. By reducing the number of dimensions over which projections must be made, a "critical point" abstraction based on the underlying structure can simplify the analysis and projection of an air traffic situation.

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[2] "Interactions" are not limited to solely aircraft-aircraft encounters, but can also include aircraft-airspace and aircraft-weather etc.

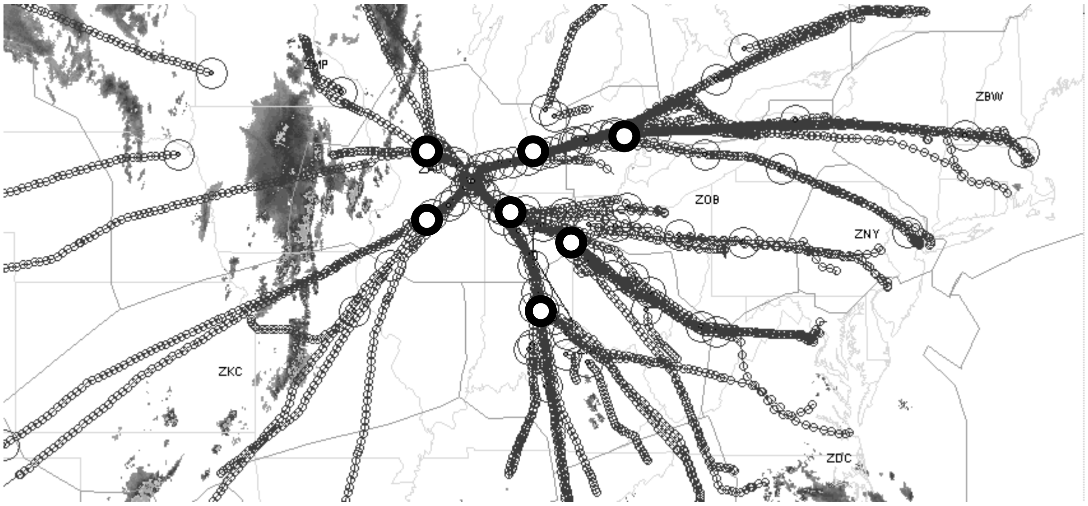

Figure 8. White dots are examples of critical points in the standard arrival flows into O'Hare airport in Chicago (21:00 EDT, May 3, 2001).

Focusing on the intersection points of aircraft flows eliminates the need for controllers to evaluate the potential for conflict over all possible pairs of aircraft within those flows [Pawlak et al., 1996]. Additionally, the typical responses associated with each critical point reduce the amount of cognitive effort that must be expended in evaluating encounters at the point. For example, the interaction between two aircraft approaching a merge point is reduced to a temporal or phasing problem. The same encounter geometry in the absence of a known critical point abstraction may require consideration of multiple dimensions, making the projection task more difficult.

Several examples of localized critical points in the form of merge points in an arrival stream can be seen in Figure 8, which shows the arrival flows into O'Hare airport in Chicago. Merges occur at well-defined spatial locations, allowing controllers to simplify their projection of the interaction between two aircraft in different arrival streams to a one-dimensional issue of time of arrival at the critical point.

Robustness of Structure-Based Abstractions to Off-Nominal Conditions

Each of the structure-based abstractions identified above reduces cognitive complexity by simplifying the task of projecting future traffic situations. In general, abstractions take advantage of expectations created during operations under normal conditions. However, controllers must be able to guarantee safe operation of the system under both normal *and* abnormal conditions. The robustness of an abstraction will determine how effective that abstraction can be as a traffic system deviates from nominal conditions.

Structure-based abstractions can continue to function under some degree of system perturbation. For example, a standard flow abstraction may tolerate a localized disturbance in the flow trajectory, such as a deviation around an isolated area of convective weather. However, disturbances may become so large that the underlying structure can no longer be used to support the standard flow abstraction. Under such conditions, the cognitive complexity will increase dramatically; this may be a part of the phenomenon of "losing the picture" that controllers sometimes report.

Including Structure-based Abstractions in Complexity Metrics

The identified structure-based abstractions motivate a variety of mathematical representations of cognitive difficulty. Three preliminary approaches to including structural considerations have been developed. Although none of the approaches have been fully developed, they represent examples of how structural considerations may be accounted for in metrics of cognitive complexity.

Explicit Inclusion of Structural Elements

One approach to account for the impact of structure on complexity is to include structural factors within the metric explicitly. For example, critical points have been identified as playing a key role in a complexity reduction mechanism; this suggests a term based on the number of merge points in a sector should be included in a complexity metric.

In order to provide metrics with intuitive meaning and to be consistent with the current basis for limiting traffic levels, it is proposed to represent the complexity in terms of the effective number of aircraft being controlled referenced to some baseline situation. The effect of structure on complexity is captured through the evaluation of a complexity multiplier function for each aircraft within the "Area of Regard." Further work is required to calibrate the relative weightings of each of the identified factors.

Situational Measures of Complexity: Cluster Approach

The grouping abstraction motivates a second approach to a complexity metric. Delahaye and Puechmorel introduced three geometrical metrics: proximity, convergence and insensitivity, which aim to capture respectively the level of aggregation of aircraft, the convergences in sectors and the difficulty in solving the induced conflicts [Delahaye et al., 2000]. G. Aigoin has extended and refined these concepts using a cluster-based analysis [Aigoin, 2001].

Two aircraft are said to be in the same cluster if the product of their relative speed and their proximity (a function of the inverse of the relative distance) is above a threshold. For each cluster, a matrix of relative dependence between aircraft is computed and the whole complexity of the cluster is then given by a weighted sum of some matrix norm. Those norms give an aggregated measure of the level of proximity of aircraft in clusters and the associated convergence with the relative speed. From the cluster matrix it is also possible to compute the difficulty of the cluster. The difficulty captures how hard it is to solve this cluster.

Multiple clusters can exist within a sector, and their interactions must also be taken into account (see Figure 9). A measure of this interaction has been proposed by G. Aigoin [Aigoin, 2001]. This technique allows multiple metrics of complexity to be developed such as average cluster complexity, maximum and minimum cluster complexities, and complexity speeds.

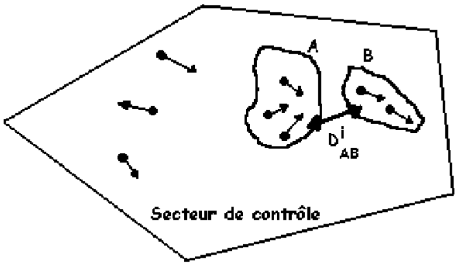

Figure 9. A cluster based analysis considers both *intra* and *inter* cluster complexities.

Kolmogorov Entropy Metrics: Structure Through Trajectory Disorder

Where the previous approach used clusters to parse aircraft states, an alternative mathematical representation has been developed based on measures of disorder of aircraft trajectories. The use of standard flows points to the importance of the distribution of aircraft trajectories within a sector. Specifically, measures of the disorder of trajectories in a sector will reflect the degree to which standard flows are being used and hence provide a proxy estimate of the cognitive difficulty.

In generating such measures, the classical probabilistic entropy is not relevant because the number of aircraft in a sector is too small to give accurate estimates of the associated statistic. However, topologic entropy (Kolmogorov entropy) can be adapted to capture this disorder as it works on the shape of trajectories.

The control sector is considered as a dynamical system for which the state space is the 3D geometrical space in which aircraft are flying. A 3D state space dynamical system cannot model the aircraft route because of ambiguity introduced by the presence of crossing aircraft trajectories. To circumvent such a limitation, the state space has been extended to the fourth dimension (x,y,z,t) and locally to a fifth dimension in order to produce artificial trajectories without crossing. This local increasing of the dimension is needed only when a conflict appears and will be used to increase the associated complexity in the sector.

The results from dynamical system theory can be applied to this model. The metric works on trajectories themselves, not only on the associated speed vectors. Therefore, it uses the full evolution of aircraft in the past and can capture the intent information associated with a flight plan provided to the model. For a given time window (this window is a parameter given to the model), the Kolmogorov Entropy is computed for each time step belonging to this window. If the necessary intent information is not available the model will do a linear extension of trajectories.

When the predictor is linear, the traffic is assumed to be routed on direct routes. From this direct routing the "natural" complexity of the demand without any action of the air traffic system can be observed. This approach can be used to estimate the impact of the geographical / temporal distribution of the demand on the complexity.

Conclusions

Understanding cognitive complexity is an important component of ensuring safe and efficient use of airspace. Based on complexity factors reported by controllers, structure appears to form the basis for abstractions that reduce the difficulty of maintaining situational awareness.

In this preliminary study, three key structure-based abstractions have been identified:

- Standard Flows
- Groupings
- Critical Points

These structure-based abstractions appear to play important roles in reducing the difficulty of projecting the future behavior of traffic situations. Not including the underlying structural elements on which these abstractions are based may artificially inflate the outputs of any cognitive complexity metrics. Three preliminary approaches to including structural considerations in complexity metrics have been discussed.

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List of Acronyms

ETMS	Enhanced Traffic Management System

Author Biographies

Jonathan Histon is a Masters student in the International Center for Air Transportation of the Department of Aeronautics & Astronautics at MIT. He obtained a B.Sc. (Honours Physics) in 2000 from Simon Fraser University, Canada. His main research interests are in applied cognitive engineering and human factors in transportation systems as applied to safety issues in system design.

Guillaume Aigoin is an engineer graduated from the ENAC (Civil Aviation National School), having received his Master’s Degree in Automatic Control from the LAAS Laboratory (Laboratoire d'Automatique et d'Analyse des Systemes) in 2001. His Master thesis dissertation focuses on the development of new complexity metrics for air traffic management systems.

Dr Delahaye is currently doing research on new optimization techniques to address problems related to Air Traffic Management. He received a Master’s degree in Signal Processing and completed a Ph.D in Computer Science and Automatic Control. He has spent one year at M.I.T as a visitor in the Aero-Astro Department. He currently works for the Air Navigation Research Center (CENA, Toulouse) and is a faculty member at the ENAC (Civil Aviation National School). He also does research in mathematical optimization techniques at the Applied Mathematics Research Center of the Polytechnique School.

R. John Hansman has been on the faculty of the Department of Aeronautics & Astronautics at MIT since 1982. He obtained his A.B. in Physics from Cornell University in 1976, his S.M. in Physics in 1980 and his Ph.D. in Physics, Meteorology, Aeronautics & Astronautics and Electrical Engineering from MIT in 1982. He is the Head of the Humans and Automation Division, the Director of the International Center for Air Transportation and of the Aeronautical Systems Laboratory at MIT. He conducts research in several areas related to flight vehicle operations and aviation safety. His current research activities focus on advanced cockpit information systems, including Flight Management Systems, air-ground datalink, electronic charting, advanced alerting systems, and flight crew situational awareness, cockpit human factors and information management.

Stephane Puechmorel is a research associate at the Math department of the ENAC School. He graduated from the Polytechnique School and obtained his Master degree in signal processing in 1990 and his Ph.D in pure math in 1992 from the National Polytechnic Institute of Toulouse. He conducts research on algebraic topology and infers new models for air traffic complexity.

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