ATC Complexity and Controller Workload:

Trying to Bridge the Gap

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Abstract

Considerable research has been conducted to identify a useful set of Air Traffic Control complexity factors. It is now necessary to determine, on the one hand, how these factors affect ATC complexity and controller workload and, on the other hand, how ATC complexity and controller workload interact. This line of research should lead to elaboration of guidelines to improve sector configuration and traffic flow as well as to produce automation tools and procedures to reduce controller workload

   This paper addresses the problem of formulating a functional relationship between ATC complexity and workload using a parameter reflecting intrinsic air traffic complexity -a measure of disorder of aircraft trajectories assumed to estimate cognitive difficulty-, a computed index, the Traffic Load Index, and psychophysiological parameters to characterize workload. Preliminary results concerning workload assessment are reported.

Introduction

Facing the continued growth of civil aviation and thus the increased demand for Air Traffic Control (ATC) services, there is a need for increasing the capacity of the air space through adaptation of the existing airspace design, traffic flow, and control tools and procedures. As the ultimate link between carefully planned flights and the actual second-to-second flight courses, air traffic controllers play a vital role in ensuring the safety of aircraft in airspace. As stated by Majumdar and Ochieng (2002), a safer measure of capacity is based on air traffic controller workload than on internationally specified spatial separation. It is therefore of the utmost importance to understand how a given air traffic situation is related to the cognitive difficulty to control this situation and the associated workload. Indeed, numerous studies state that ATC complexity, a way to characterize air traffic situations, accounts for a large proportion of controller workload. Mogford *et al.* (1995)

emphasize that, although there may be objective, measurable features of sectors and aircraft, the concept of ATC complexity is subjectively defined by the controller. A number of studies have proposed a list of ATC complexity factors and found significant relationships between a large number of factors and controller workload (for a review, see Majumdar and Ochieng (2002) and Mogford *et al.* (1995). Obviously, there is a link between these two kinds of measure for traffic configuration is bound to influence workload, while control instructions, aiming to locally change traffic configuration, depend partly on workload. However, if it is reasonable to assume that as ATC complexity increases, controllers' workload increases, it would probably be reductionist to expect a simple linear relationship. As yet, the functional relationship between complexity factors and workload is largely unknown.

   Before elaborating on possible alternatives to a simple linear relationship, a couple of assumptions of the prevailing point of view are worth considering.

   Firstly, emphasis has been put on the cognitive aspect of controlling : parameters of the air traffic configuration are seen as input to be cognitively manipulated in order to produce solutions to traffic problems. If one wants to make predictions, one has to adopt a rather deterministic view and expect that the same inputs (traffic configuration) will bring about the same outputs (set of actions, experienced workload). Evidence from the literature tells us that this is not so and that there is not a unique relationship between traffic configuration parameters and actual control parameters (e.g. tasks and workload). In this paper, we would like to propose a slightly different point of view. We feel that controlling air traffic might not be so much a question of *problem solving* as a question of *perceiving* and *decision-making*. Without denying the validity of workload models based the cognitive difficulty to control a traffic situation per se, we feel that, for the expert, the difficulty is not so much to elaborate a solution for a given conflict as to accurately assess if action is indeed necessary and, if need be, when to best implement it. Indeed, controllers are highly trained for the sectors they control and the number

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of flight parameters they can manipulate is quite limited (heading, flight level, speed, rate of climb/descend), thereby restricting the number of possible actions. In contrast, continually monitoring the progression of aircraft trajectories and assessing their future positions is highly demanding in attentional and perceptual resources (visual assessments repeated through time). It follows that workload might be for a large part connected to resources management, a not so simple interface between inputs and outputs.

Secondly, from our point of view, models trying to derive estimates of workload from ATC complexity measures generally underrate auto-regulation of workload level by controllers. For example, some studies have looked at the quantitative aspects of the complexity factors and proposed differential weighting of the factors (for example, see Sridhar, Seth and Grabbe (1998) and Laudeman *et al.* (1998)) but the weight of each factor is fixed and the evolution of the actual context is not taken into consideration. In particular, the fact that the amount of workload experienced by the controller can be modulated by the strategies adopted to accomplish the required tasks is not taken into account.

In this paper, we would like to introduce an intermediate parameter comprehensively linking aircraft patterns to the experienced workload. This parameter is based on an evaluation of the amount of controller's resources demanded by each aircraft and on the management of the available resources by the controller. The goal of our study is to correlate ATC complexity measures, our new intermediate parameter and psychophysiological evaluations of workload.

Even though we are still in the process of correlating the ATC complexity measures, and therefore cannot report here data pertaining to these parameters, we think it is relevant to present as complete a picture as possible and to define nonetheless the ATC complexity metric we are developing.

ATC Complexity and Traffic

Most of the previously developed indicators of air traffic complexity rely on either a geometric description of a snapshot of the situation or an aggregation of hopefully relevant operational quantities. This last category of indicators includes the dynamic density (Laudeman *et al.* 1998), which combines various values (number of aircraft, number of speed changes, number of altitude changes, predicted conflicts…) into a weighted sum. The coefficients of the sum are then adjusted to match a subjective measure of the controller workload. This approach will of course depend on the way controllers are managing traffic. In particular, considering that the main thrust of US control is to create and manage standard flows (Miles-in-Trail) whereas the emphasis of European control is more on the management of individual aircraft, one can

expect to obtain different weights for US and European traffic. On the other hand, purely geometric indicators have been developed (Delahaye and Puechmorel 2000) that are aimed at extracting intrinsic complexity out of the traffic situation. A first step towards merging dynamic density and geometric considerations can be found in the work of Sridhar *et al.* (1998). However, the temporal aspect of air traffic is never used explicitly. Modeling the traffic as a dynamical system would allow encompassing geometric and temporal aspects in a single model, thus yielding a much more accurate description of the complexity

Air Traffic as a Dynamical System

A dynamical system is a mathematical model of a physical system evolving through time. In this case, given guidance law, the evolution of an aircraft is governed by the law of mechanics and thus can be modeled as a trajectory of a dynamical system in 3D space. The control sector can then be considered as a dynamical system for which the state space is the geometrical space in which aircraft are flying. However, a 3D state space dynamical system cannot model the aircraft route because of ambiguity introduced by the presence of crossing aircraft trajectories. Only when individual trajectories do not cross, may a 3-dimensional dynamical system represent the whole system. Traffic with crossing trajectories but no conflicts may be represented in dimension 4, while the presence of conflicts requires embedding the system in dimension 5.

Since we are essentially interested in estimating the complexity of an air traffic situation, it is meaningful to assume a very simple embedding by simply computing the fifth coordinate so that separation is assured.

At that point, there are two different approaches allowing the construction of a dynamical system model for a given air traffic flow. The first one is to assume that we are building a model by considering aircraft individually, then finding a control law for the whole system so that observed trajectories match predicted trajectories. The second approach is to find a black-box model in dimension 5 matching the observed trajectories. We have chosen to use the last model, which lacks simple interpretation but is easier to implement.

Recalling that a dynamical system is determined either by its trajectories or by the vector field occurring in the defining differential equation, one may find a model of observed traffic by functional approximation. Since neural networks are known to be universal approximates and are moreover easy to code and fast, it makes sense to use them as the core of our model.

Workload and Traffic

Workload, in spite of its ubiquity, is very hard to pinpoint. It is generally considered as a multifaceted construct that cannot be seen directly, but must be inferred from what can be seen or measured.

Workload is related to information processing theory. It is assumed that non-automated tasks require the allocation of resources and that workload reflects the overall level of demand for resources. The prevailing models define overload as an excessive demand on perceptual and cognitive resources (visual and auditory perception, memory and attention, among others) with respect to the processing capacities (Wickens 1984).

Measures of ATC workload are typically based on subjective ratings made by controllers either while controlling air traffic or just afterwards. Because subjective ratings interfere with controllers activities (thus affecting their perceived workload) and are prone to rater errors, objective workload estimates are being developed that may be used in place of subjective ratings. They are computed from routinely recorded ATC data that describe both aircraft and controller activities. Previous studies on ATC have used various task parameters - alone or combined - to generate a realistic workload index: number of aircraft, duration or content of radio exchanges and judgments by experienced observers (for a review, see Stein (1998)).

The number of aircrafts (N) a controller manages simultaneously at a given time has been the most used objective data to estimate his workload. Quite easy to record and closely linked to the "ideal" workload value, it has been proposed as a workload index in many studies. However, N is not a perfect index: how aircrafts are spread over space and time heavily bias this index (Cellier, De Keyser and Valot 1996). For example, when five aircrafts are present in the same sector, the load will not be equivalent for the controller if each flight path surely does not intersect with any of the four other ones, or if all of them develop two or three conflicts. Thus, as reported in the previous section, ATC complexity measures related to the cognitive difficulty of controlling the air traffic situation take into account traffic patterns as well as sheer traffic count.

From the controller's point of view, it is obvious that each aircraft does not amount to the same weight in terms of workload. N would represent a better basis for workload measurement if it could be modulated with some parameters pertaining to the amount and quality of potential interventions required from the controller.
Thus, air traffic can be classified into three categories:

- Aircraft being simply monitored by the controller who predicts no loss of separation. This category comprises aircraft whose flight paths do not intersect with each other, and as well those whose flight paths do intercept but with a spontaneous separation within the allowed safety limits.

- Aircraft in conflict for which a loss of separation in the future is suspected, regardless of the controller's decision to intervene, or not, to ensure this separation.

- Aircraft converging to the same airport and needing to be radar regulated (amount of incoming traffic exceeding temporarily the runway capacity). These flights often interfere with each other only in the final

part of their paths (no intersection), creating problems distinct from conflicts.

However, traffic patterns do not impinge directly and uniquely on workload. Spérandio (1984), studying approach ATC, showed a close relationship between three levels of traffic load (2 to 3, 4 to 6 and 7 to 9 aircrafts), and the cognitive processes and strategies brought into action by the operator. Changes in these strategies appeared attributable to workload variations, estimated through N. This author had already noted (Spérandio 1972) that air traffic controllers could modulate, to a certain extent, their own workload through the actions and the cognitive strategies they use, striving to maintain it at an optimal level. This workload auto-regulation is not only present in general strategies, but also in most actions. The basic mechanism is to diversely combine flight parameters that can be modified to resolve a conflict (heading, flight level, speed, rate of climb/descent) with the moment when this modification is brought into operation.

In other words, workload auto-regulation rests on the interval of time between a diagnosis (or real suspicion) of conflict, and the moment when a definite solving action is undertaken. Modulation of the length of this interval is the basic mechanism through which controllers can regulate their workload. This time interval has been called the *maturing time* (MT). MT has a course parallel to workload: a small MT, i.e. actions undertaken at the outset of the diagnosis, keeps workload at the lowest level allowed for a given problem, whereas a larger MT increases the attentional demand, thereby increasing workload. However, increasing MT also decreases the uncertainty upon which a decision to intervene has to be made. Moreover, the later a resolution is undertaken, the more adequate it will be (better precision for flight path modification or minimum coercion on aircraft, for example). This leads to a trade-off between uncertainty and time pressure: elapsing time decreases the uncertainty but increases the pressure (see Hendy, Liao and Milgram 1997) for a model). A balance has to be maintained, according to objective (traffic load) and subjective context (current workload level of the operator).

We see the trade-off described above (late/accurate/costly versus early/imprecise/economical control actions) as the mechanism underlying workload auto-regulation.

In order to integrate these two dimensions (uncertainty and time pressure), we developed a new workload measure, the Traffic Load Index (TLI) (for details, see Averty *et al*. 2003).

As will be seen from our rating system, the TLI is tightly linked to the management of the uncertainty about a potential conflict in real time conditions.

The Traffic Load Index (TLI)

Briefly, the TLI has been computed in the following manner: each aircraft in a given sector was rated with a basic load of 1. In order to represent the cognitive resources (attention, visual assessments of the separation

evolution) required to reach a decision about what to do, this load could be increased during the time interval of a conflict or a radar regulation in which aircraft were involved. This additional load was limited in time between two boundaries: the earliest and latest time to act with respect to the conflict or radar regulation in question. Two notions have been used to quantify the additional load of conflicts and regulations:

- *Gravity*, which represents the uncertainty related to the actual occurring of a given potential conflict (from slight suspicion to evidence).
- *Urgency*, which is the time pressure effect.

Thus, each aircraft was rated between 1 (simply monitored aircraft) and 3.5 (aircraft in conflict when spacing was quite sure to become inadequate to ensure safety). The rating was assessed for each aircraft with each radar update. The ratings of individual aircraft were then added over the whole sector, yielding a continuous TLI for a global traffic situation in a given sector.

It is reasonable to assume that time pressure and uncertainty, both directly linked to workload, have a bearing on the emotional state of controllers, most specifically during high traffic load situations, because real time constraints and risk awareness are bound to have an effect in the activation level (physiological arousal) of the organism. Therefore, in order to study the link between fluctuations of the TLI and controller workload, we decided to record several physiological parameters and to match them with computed TLI in real work situations.

Workload and Emotion

It is admitted that some workload assessment can be done through physiological parameters. Variations of physiological parameters during the task have been established for air traffic controllers (Smith 1980, Melton 1982). All these studies mainly investigate the effects of different workloads. The authors failed to show the existence of a specific physiological measure that would convey a reliable and accurate evaluation of workload. However, they did show a significantly increased physiological responsiveness during high workloads (heart rate, blood pressure, skin electrical resistance, cortisol and adrenaline rates).

One of the advantages of monitoring physiological parameters is the possibility to follow any variations on a continuous time scale. But, by itself, it mainly gives the *global* level of arousal (greatly connected to cognitive activity), and not the real difficulty of the task (Mairiaux 1984). Vernet-Maury, Deschaumes-Molinaro and Delhomme (1993) review the psychophysiological literature involved in mental workload measurement. These authors report a close link between cognitive and autonomic nervous system (ANS) activities as evidenced through variations in electrodermal responses, and

thermovascular and cardio-respiratory parameters. It thus appears that ANS activity may characterize workload of ATCs. It would be particularly useful if different ATC situations could relate to different ANS activity patterns. In other words, it will be quite enlightening to study the parallel evolution of objective traffic complexity measures, computed traffic parameters and their subjective effects (TLI), and ANS activity as a measure of workload.

Preliminary Experimental Results

The results presented here are part of the on-going study sketched above, i.e. comparison of the continuous parallel evolution of traffic patterns and workload.

Using data from real work situation, we correlated computed TLI with ANS recording (i.e. electrodermal, thermo-vascular and cardio-respiratory activities). Twenty-five controllers were monitored during about one hour each while controlling approach traffic.

After a preliminary study showing a very large agreement between experts rating the same situations, one active controller from the approach center of Lyon-St Exupery where we conducted our study accomplished the final rating. Assessment of conflicts and radar regulations, as well as weighing of additional loads was empirical, using radio and radar data from twenty-seven hours of real traffic of Lyon-St Exupery TRACON.

Analyses show a strong correlation between arousal and computed load: each of the five psychophysiological parameters shows activation when load increases, with the instantaneous heart rate showing the strongest correlation. When using the number of monitored aircraft as a parameter, the correlation with psychophysiological parameters and NASA-TLX results is not as strong as with the TLI, showing clearly that adding uncertainty and time pressure estimates is meaningful from the controllers' point of view.

Simple scan of ATC complexity measures with respect to the TLI and psychophysiological parameters reveal some interesting features: for example, traffic situations involving a lot of radar regulations tend to trigger less modeled complexity than traffic situations with a couple of conflicts; in contrast, these situations are rated highly in terms of TLI, which in turns is quite correlated with instantaneous heart rate.

Thus, results suggest that it is possible to compute parameters bridging the gap between ATC complexity and workload.

Conclusion

Even though the work presented here can only be seen as a progress report, we are quite hopeful that our multi-level approach will shed some light on the complex relationship between air traffic situations and triggered workload. Much

work is left to be done, not only in terms of data analysis but also on modeling the mechanisms underlying this relationship. In particular, if different control strategies are used to auto-regulate workload and thus maintain an acceptable level when faced with increased air traffic complexity, it would be of great interest to understand (and predict) when and how a change of strategy happens. It might even be possible to isolate among the large number of listed ATC complexity factors, those that are decisive to trigger a change of strategy. This information could then be used to tailor air space on the one hand and to sharpen the information presented on the controllers positions. .

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