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SOLUTION SPACE-BASED COMPLEXITY ANALYSIS OF ATC AIRCRAFT MERGING TASKS

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Air traffic controller workload is considered to be a limiting factor in the growth of air traffic. In this paper a new method of assessing controller task demand load will be developed and tested. Based on the hypothesis that workload is primarily caused by the complexity of the task to be conducted, the concept of the "solution space" is described. For any particular air traffic control problem, the solution space describes the constraints in the environment that limit (and therefore, guide) air traffic controller decisions and actions. The complexity of that particular control problem can then be analyzed by considering the properties of the solution space. The task of merging an aircraft into a stream of other aircraft that fly along a fixed route is considered. An experiment has been conducted in which subjects were instructed to solve merging problem scenarios of varying complexity. After completing each scenario, subjects were asked to rate the task complexity. High correlations are found between several solution space properties and reported complexity.

Air traffic controller (ATCo) workload is considered to be one of the main constraints in air traffic growth (Hilburn, 2004). It is important to be able to predict the effect of developments in the air traffic management system on the ATCo. Currently, these effects are mainly assessed using expert judgment. For reasons of cost and time, it is preferred to perform this analysis already during the initial fast-time simulation (FTS) phase.

The analysis of ATCo workload in FTS has been the subject of a large number of studies (Phillips & Marsh, 2000; Crutchfield & Rosenberg, 2007). The immediate flaw that is found in workload assessment using FTS programs is that it is impossible to assess the mental workload, i.e., the workload as *experienced* by the operator, as here subjective elements such as training, equipment, and stress level play an important role. Instead, developers of FTS programs aim to analyze the ATCo's task demand load (Stassen, Johanssen, & Moray, 1989), which is considered to be an objective measure of the complexity of the task to be performed by the controller. ATCo workload is hypothesized to be composed of a number of factors, such as level of training, type of equipment and sector complexity (Stein, 1985; Kirchner & Laurig, 1971). Sector complexity is often used as the means to describe ATCo task demand load. The underlying hypothesis is that – as in the current research – ATCo workload is coupled to task demand load (i.e., an increase in task demand load leads to an increase in workload), and that task demand load, in turn, is coupled to sector complexity.

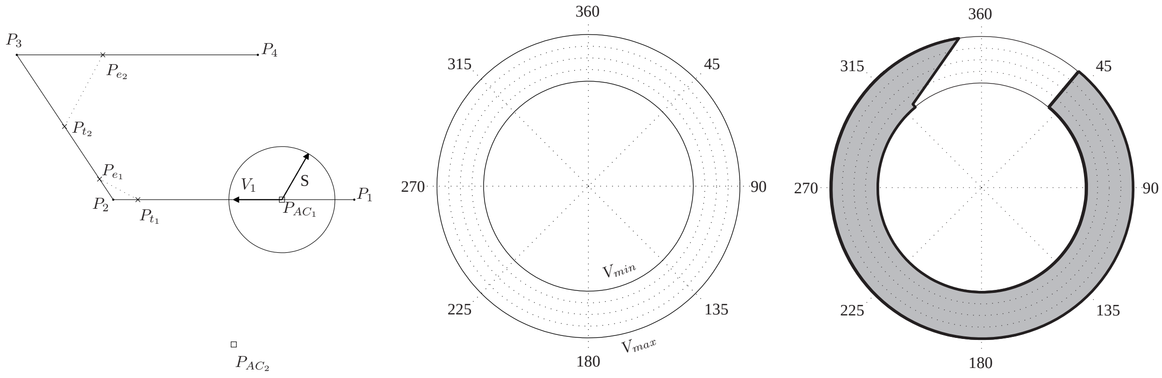
For the current generation of FTS programs, task demand load metrics are constructed using a weighted combination of scenario properties. Examples are the number of aircraft involved, the sector size, the ratio of climbing and descending aircraft, or the count of weighted controller events (Kopardekar & Magyarits, 2002; Majumdar, Ochieng, Bentham, & Richards, 2005). The properties that are relevant to the task demand load analysis, and what weighing factors need to be used, are determined through expert judgment and regression analyses. The validity of this method is questionable, however, since the scenarios that are being analyzed might differ heavily from the baseline scenarios used for the regression analysis. ATCo task demand load has proven to show non-linear behavior, and can vary greatly due to slight changes in the situation being controlled. Therefore, another, more objective and also more widely applicable method of task demand load analysis is required.

This paper aims to demonstrate how a new method of complexity analysis can be used to perform a task demand load analysis for air traffic control related problems, in a more accurate and objective manner than current techniques. In this method, the complexity of a particular controller task is analyzed by examining the – what we refer to as the – "solution space of the problem". The solution space can be defined as the subset of all possible vector (combined heading and velocity) commands that can be issued by ATC, that satisfy constraints of safety, productivity, and efficiency. These constraints are imposed by the situation at hand. To evaluate the validity of this method, only the task of merging aircraft is considered in this paper, in the horizontal two-dimensional plane.

The solution space of aircraft separation problems has been researched by Van Dam et al. (Van Dam, Mulder, & Van Paassen, 2008) from the pilot's perspective, and it was hypothesized that their systematic approach might also be applicable to the ATC problem. Basically, the solution space is a measure of the set of possible solutions that are at an operator's disposal to deal with a particular problem. In the present context, for any particular air traffic control problem the solution space describes the constraints in the environment that limit – and therefore, *guide* – the air traffic controller's decisions and actions.

As a first step in the development of the solution space method, the problem of merging aircraft onto a single fixed route is analyzed. Merging situation occur, for instance, as aircraft approach an airport and need to be lined up for landing. The solution space analysis is performed for aircraft that are not on the route and aims to find out what combinations of heading and velocity – the ATCo *vectors* – lead to a successful merge.

The solution space is defined as the state space that represents possible vector commands issued by ATC that satisfy particular well-defined constraints. For the current analysis these are: (1) *Productivity*: the vector must be such that the free aircraft flies toward the route; (2) *Safety*: the vector may not lead to loss of separation at any point in time; and (3) *Efficiency*: the vector must allow for direct route interception, no additional commands shall be necessary. The solution space computations are conducted in a number of steps, discussed in full detail in (Hermes, Mulder, Van Paassen, Boering, & Huisman, 2009).



(a) Overview of example problem (b) Initial solution space (c) Computed solution space

Figure 1: Example problem overview, initial and computed solution space.

An example problem is illustrated in Figure 1(a), showing a route that runs from fixed route points P_1 to P_4, via P_2 and P_3. An aircraft – referred to as the 'route' aircraft – is defined by its position P_{AC_1}, velocity V_1 and separation minimum S, flies along the route. It is assumed that the aircraft travels along the route with a constant velocity V_1, and has a fixed turning angular rate of three degrees per second. When more aircraft are flying along the route, the solution space calculations need to be repeated for all route aircraft.

Another aircraft – the 'free' aircraft – intends to intercept the route, and is initially located at P_{AC_2}. The goal of the analysis is to determine which combinations of heading and velocity commands can be given to the free aircraft, in such a way that the vector command satisfies the productivity, efficiency, and safety criteria. The initial solution space can be drawn like Figure 1(b), in which all possible combinations of heading and velocity are present. Note that the velocity possibilities are limited by the minimum and maximum velocity, V_{min} and V_{max}, respectively, of the free aircraft.

Certain combinations of velocity and heading commands meet the criteria of productivity, safety and efficiency, others don't. Areas in the solution space that contain these vectors are labeled *safe areas*. Areas containing vectors that do not satisfy one of the constraints are called *unsafe areas*. Figure 1(c) shows the solution space for this particular example, with the unsafe area indicated in grey (Hermes et al., 2009).

Using the method of solution space analysis on a merging problem, all properties of the scenario are systematically combined into a single metric. A solution space-based metric is therefore hypothesized to be a more objective and also scenario-independent metric than a weighted combination of scenario properties, in which the weights highly depend on the baseline scenarios considered.

In order to investigate if and how the solution space analysis can be used to assess the aircraft merging problem complexity, a validation experiment was performed. In this experiment, subjects were confronted with scenarios in which they were required to merge a free aircraft onto a route using heading and velocity instructions. Correlations were computed between properties of the initial solution space (the static solution space at the start of the scenario), such as size of safe areas, and the scenario complexity as experienced by the test subjects.

Method

Experiment set-up

Apparatus A stand-alone simulator was developed using MATLAB^{TM}. An interface was presented that consisted of two parts. The left part was a conventional Plan-View Display (PVD), where the route and the aircraft, represented as a square with a label, can be found. The right part was the command window, allowing subjects to give commands to the aircraft. Subjects could send heading and velocity commands (either one by one, or simultaneously), and the command to intercept the route.

Subjects and Instructions Nineteen subjects participated. Based on experience, they were divided in two groups. The first group, six subjects, aged 33 to 50 ($\mu = 39.3$, $\sigma = 6.4$), had operational ATC experience. The second group consisted of thirteen inexperienced subjects, aged 23 to 51 ($\mu = 29.2$, $\sigma = 8.2$).

Subjects were instructed to maneuver the free aircraft onto the route. They were free to choose any point on the route for interception, but were not allowed to merge in front of the first route aircraft, or behind the last route aircraft, because the stream of aircraft was finite. Their subgoal was to use as few commands as possible.

In practice most, if not all, subjects merged the free aircraft on the route segment that lied in-between the initial heading bandwidth BW_{head}. And surprisingly, although subjects were told that they could also command the motions of the route aircraft, they all worked only with the free aircraft.

Procedure Subjects first got familiarized with the interface using an interactive, explanatory tutorial. Then, a minimum of nine training scenarios, hypothesized to be ascending in complexity, were presented. Subjects were introduced with the questionnaire. Then, fifteen measurement scenarios were done, in randomized order (random in hypothesized complexity and random per subject).

Questionnaire The questionnaire consisted of the following six questions, constructed to find out how complex the subjects perceived the scenarios to be, and why they assessed it as such: (1) How *complex was the scenario* to solve? (2) Did you feel that *time pressure* influenced the complexity of solving the scenario? (3) Did you feel that *aircraft limits* influenced the complexity of solving the scenario? (4) Did you feel that *route design* influenced the complexity of solving the scenario? (5) Did you feel that *traffic* influenced the complexity of solving the scenario? (6) Did you feel that *initial conditions* influenced the complexity of solving the scenario? Each of these questions were answered using an 11-point (0-10) Likert scale.

Experiment scenarios

Aircraft All aircraft moved at a certain heading with a certain velocity (200 knots). They turned with a rate of three degrees per second, and accelerated/decelerated with three knots per second square. The simulation was run four times as fast as real-time, due to the relative simplicity of the task. The simulation was two-dimensional, altitude was not taken into account. All aircraft had a fixed V_{min} and V_{max} of 175 and 225 knots, respectively.

Airspace and routes The Dutch airspace was used as a background to increase the fidelity of the simulation. Subjects did not have to take sector boundaries into account when performing the task, however. Routes were constructed in such shapes and lengths as to create certain solution space diagrams and merging problems.

Traffic In each scenario, traffic was placed such that (in combination with route design) certain initial solution space properties were achieved. All traffic was present at the start of the scenario; aircraft disappeared from the PVD as they reached the end of the route. Route aircraft that were not on the actual route yet, traveled toward the first route point: no aircraft intercepted the route at any point aside from the first one.

Initial scenario properties Initial scenario properties that were hypothesized to be indicators of scenario complexity, were identified prior to the experiment, using results from literature and through expert judgment. The following properties were considered: (1) Number of route aircraft (N_{AC}); (2) Number of approaching aircraft (N_{AC_a}); (3) Distance to the route (d_{route}); (4) Turns in the route (N_{turns}); (5) Length of the route (l_{route}); and (6) Bunching (B), a measure of aircraft being in close proximity to each other. For every two aircraft that have intersecting or touching separation circles at scenario initialization, B is increased by one.

Initial solution space properties Several initial solution space properties were hypothesized to be possible complexity indicators. The following variables were examined: (1) Heading band range (BW_{head}); (2) Number of safe areas (N_{safe}); (3) Number of relevant aircraft ($N_{AC_{rel}}$); (4) Total solution space size (A_{safe_t}); (5) Size of largest safe area (A_{safe_l}); (6) Average safe area size (A_{safe_a}); and (7) Safe area size deviation (σ_{safe}).

Dependent measures

The questionnaire results consisted of the subjects’ answers to the six questions, and additional comments. As different subjects exhibit different rating behavior, all quantitative data were first corrected for inter-subject differences. This correction was performed by calculating the Z-scores for every test subject.

Hypothesis

Our main hypothesis was that, when using the initial solution space properties, a metric can be constructed that has a stronger (i.e., higher) correlation to the subjectively-reported complexity than the other metrics based on either the initial scenario properties or logged properties such as number of commands or separation violations.

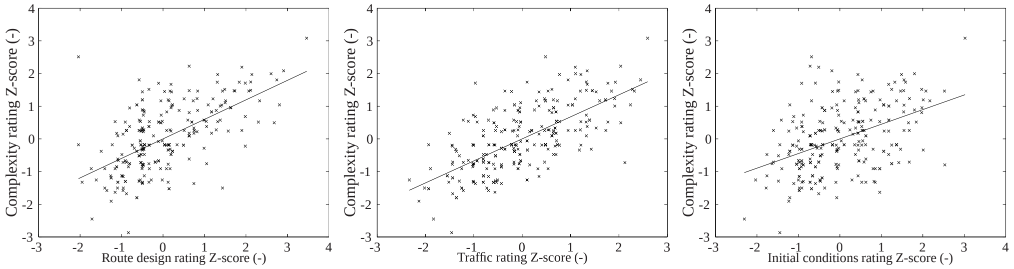
Results

A total of 285 experiment runs were performed using nineteen test subjects and a total of fifteen measurement scenarios. Using analysis of variance it was shown that no training effect was present in the data. Results from an outlier analysis and a group correlation analysis showed that the most illustrative results would be obtained if the full data set was used, and if all subjects were considered to be members of a single group (Hermes et al., 2009).

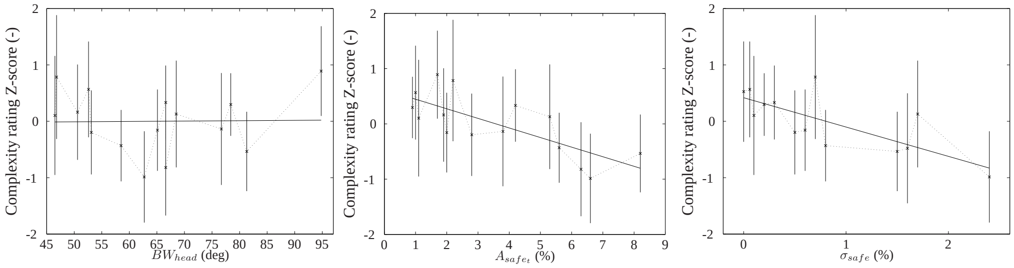
Correlation analyses

One-way analyses of variance were conducted, with the subjective complexity rating the dependent measure. Since all but one of the possible complexity predictors showed significant p-values ($p < 0.05$) in these ANOVAs, correlation analyses were performed in order to determine how well the possible predictors correlated with the test subject complexity ratings. For each possible predictor, a Pearson’s R value of linear correlation was calculated. This was done using data from all experiment runs individually *and* using the means of experiment data per scenario, that is, averaged over all subjects.

Correlation between complexity and other questionnaire variables Figure 2 shows the Z-score complexity rating plotted against some of the questionnaire variables (also Z-scores), together with a best-fit linear relationship. Although all questionnaire variables showed statistically significant correlation, subjects linked complexity most strongly to the “Traffic” involved in the scenarios, i.e., the presence of the other aircraft flying on or towards the route (means: R=0.9740, $p < 0.001$; all: R=0.6743, $p < 0.001$).



(a) Route design (b) Traffic (c) Initital conditions



(d) BW_{head} (e) A_{safe_t} (f) σ_{safe}

Figure 2: Complexity rating versus other questionnaire ratings (top) and initial solution space properties (bottom).

Correlation between complexity and initial scenario properties The number of aircraft N_{AC} (means: R=0.4454, $p = 0.0962$; all: R=0.2434, $p < 0.001$), bunching B (means: R=0.4237, $p = 0.1156$; all: R=0.2316, $p < 0.001$), and the number of approaching aircraft N_{AC_a} (means: R=0.3580, $p = 0.1901$; all: R=0.1957, $p < 0.001$), correlate to complexity strongest. Since these are all properties related to traffic, this finding supports the hypothesis that subjects linked complexity most strongly to traffic properties. It corresponds well with the questionnaire findings.

Correlation between complexity and logged properties Statistically significant correlation was found for the number of commands N_{com} (means: R=0.8244, $p < 0.001$; all: R=0.2361, $p < 0.001$) and the number of separation violations N_{SV} (means: R=0.7220, $p = 0.0024$; all: R=0.1978, $p < 0.001$). Hence, the correlations for the initial scenario traffic-related properties and the statistically relevant logged properties are in the same order of magnitude, with R values of approximately 0.2. Especially the fact that the number of aircraft and the number of commands correlate to complexity approximately equally strong is interesting, since they are both currently used as preliminary indicators of workload in FTS. This provides confidence regarding the validity of the present experiment.

Correlation between complexity and initial solution space properties In Figure 2, the Z-score complexity rating is plotted against some of the initial solution space properties, including the best-fit linear relationship. In the initial solution space properties correlation analysis, the safe area percentages A_{safe_t} (means: R=-0.7423, $p = 0.0015$; all: R=-0.4047, $p < 0.001$), A_{safe_l} (means: R=-0.7224, $p = 0.0024$; all: R=-0.3949, $p < 0.001$), and σ_{safe} (means: R=-0.7284, $p = 0.0021$; all: R=-0.3981, $p < 0.001$), correlated to complexity most strongly. The absolute R value for these three initial solution space properties is approximately twice as high as the absolute R values of the best predictors from the initial scenario properties and the logged properties. This leads to the conclusion that solution space properties, and specifically those that link to *solution space size*, were the best predictors of complexity in this experiment. This supports our main hypothesis, namely that a more accurate complexity predictor could be constructed using the solution space concept.

Regression analysis

In the regression analysis, initial solution space properties were combined in metrics in an attempt to obtain stronger correlations, and thus more accurate complexity predictors. The regression was performed using “means” calculations. By combining all seven initial solution space properties, an absolute R value of 0.839 could be achieved. Furthermore, it was observed that the total safe area size A_{safe_t} was present in the best 36 metrics, suggesting that this is the most important solution space property and the best complexity predictor. This finding is supported by the fact that a metric that contains only A_{safe_t} already has an absolute R value of 0.742, only 0.097 lower than the absolute R value for the best metric, the one including all descriptors. The relatively small increase in correlation in the regression analysis also suggests, however, that the initial solution space properties that were analyzed in this experiment are coupled. Whether this means that solution space *size* is the most relevant of all solution space properties, or that another property that has not been analyzed can add significant additional predictive capability, should be determined in a more elaborate study.

Overall, the results suggest that the solution space does indeed lead to more accurate complexity predictors. However, it is important to realize that the two-dimensional merging problem that was analyzed in this research is not the only, or main, task that an air traffic controller performs in a normal work setting. Yet, although the results should be treated with care, they certainly provide a solid basis for further research into the development of a complexity metric which is based on the solution space concept.

Conclusions and Recommendations

This study investigated whether the solution space of a two-dimensional air traffic merging problem can be used to assess the complexity of that problem more accurately and objectively than current metrics. An experiment was conducted which showed that the initial solution space properties, in particular those related to solution space size, are indeed more accurate complexity assessors than traditional metrics, while being at least as objective. This result provides a solid basis for expanding the solution space research. Possible future research paths include dynamic solution space analysis, three-dimensional air traffic control problems and the development of solution space based interfaces to support air traffic controller decision making and situation awareness.

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