Functional modeling for risk assessment of automation in a changing air traffic management environment

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ABSTRACT

The ERASMUS project proposes to reduce the number of aircraft conflicts by minor adjustments of their speed. Various versions of applications are under consideration, one issue being whether to inform controllers and involve pilots or to let automation act autonomously. The Functional Resonance Analysis Method (FRAM) provides a framework and a method for systematically describing and evaluating functions and performance variability. This method is used as a means to indicate and evaluate the effects and impact on controller and pilot work resulting from ERASMUS automation. Various instantiations of a partial model resulting from the application of FRAM are presented, illustrating how air traffic management automation human factors and risk assessment issues may be addressed with this method.

1. INTRODUCTION

Envisioning and analysing the potential effects of automation is an essential part of the system development process, in air traffic management (ATM) and other complex, safety-critical domains. Moreover, ATM automation is a currently active development area (e.g., Kuchar & Yang, 2000) considering the expected further increase in air traffic for the coming decades. Airlines, manufacturers, and system designers are eager to see the potential of data precision and computing capacity realized to be able to accommodate higher traffic levels while assuring safety and efficiency. The EU FP6 ERASMUS project (En Route Air Traffic Soft Management Ultimate System) proposes to decrease the occurrences of aircraft conflicts by minor adjustments of their speed (after an idea of Villiers, 2004). Various controller-ERASMUS interaction strategies are considered, one being whether to inform controllers and involve pilots or just let automation act autonomously.

However, previous studies demonstrate that the introduction of automation rarely is unproblematic (e.g., Bainbridge, 1983; Billings, 1997; Dekker & Woods, 1999). The modelling effort reported here provides a means to identify and evaluate the effects and impact on controller and pilot work resulting from ERASMUS automation.

Describing or modelling the tasks and functions that people and machines perform is a prerequisite for a systematic evaluation. Many models of the (cognitive) tasks of controllers have been published (e.g., Barbarino et al., 1999; Blom et al., 2001; Kallus et al., 1999; Mattsson, 1979; Niessen & Eyferth, 2001; Rodgers & Drechsler, 1993; Seamster et al., 1993; Voller & Low, 2004). Most of these model only the controller’s tasks, for the purpose of aiding in training and selection or general research and development. Models that allow the explicit assessment of man-machine systems, i.e., controller(s)-pilot(s)-aircraft-automation systems, are rare. Notable exceptions are the MIDAS modelling framework (Corker, 2000) and to some extent
the cognitive modelling efforts in the ERATO development process (Leroux, 2000). This study aims to apply modelling concepts and methods from the perspectives of Cognitive Systems Engineering (CSE; Hollnagel & Woods, 2005) and specifically the Functional Resonance Analysis Method (FRAM; Hollnagel, 2004) to ERASMUS. Three concepts are thereby indispensable: functions, performance variability, and risk.

The CSE perspective on automation is characterized by a view that the allocation of functions between people and machines should be designed to sustain and strengthen the joint system’s ability to perform efficiently (Hollnagel & Woods, 2005). The aim of the joint cognitive system (JCS) of people and technology is to remain in control of its tasks and accomplish its goals. The functions that the joint cognitive system performs in order to reach these goals thereby become paramount. In the case of ERASMUS, the joint cognitive system that this modelling effort addresses is the controller(s)-pilot(s)-aircraft-ERASMUS system (see Figure 1).

CSE focuses on the observable performance of these functions and on the variability of these functions in practice. By addressing the potential performance variability of the JCS functions, potential risks to retaining control may be found. The Functional Resonance Analysis Method (FRAM) provides a framework and a method to systematically describe and evaluate functions and performance variability and may therefore be used as a means of risk assessment in automation design.

2. METHOD

FRAM (Hollnagel, 2004) characterizes socio-technical systems by the functions they perform rather than by how they are structured. It captures the dynamics by modelling non-linear dependencies and performance variability of system functions. FRAM proposes that normal performance (success) and failure both are emergent phenomena, neither of which can be attributed to features of specific system components, such as failure probability. Performance variability is natural in socio-technical systems, and furthermore necessary to enable people to cope with intractability and underspecification. In FRAM, functional resonance describes how a ‘detectable signal’ (i.e., an undesirable event) may emerge from the unintended interaction of the weak (‘undetectable’) variability of many signals. To arrive at a description of functional variability and resonance, and to determine recommendations for damping unwanted variability, a FRAM analysis consists of four steps:

Step 1 identifies essential system functions, and characterizes each function by six basic parameters. Functions are described in terms of six aspects, in terms of their input (I, that which the function uses or transforms), output (O, that which the function produces), preconditions (P, conditions (states) that must be fulfilled to perform a function), resources (R, that which the function needs or consumes), time (T, the time available and factors that affect time availability), and control (C, that which supervises or adjusts the function), and may be described in a table and subsequently visualized in a hexagonal representation (FRAM module, Figure 2).

Step 2 characterizes the (context dependent) potential variability through common performance conditions (CPCs) and variability phenotypes. Eleven common performance conditions (CPCs) are identified within FRAM to be used to elicit potential variability: 1) availability of personnel and equipment, 2) training, preparation, competence, 3) communication quality, 4) human-machine interaction, operational support,
availability of procedures, work conditions, goals, number and conflicts, available time, circadian rhythm, stress, team collaboration, and organizational quality. These CPCs address the combined human, technological, and organizational aspects of each function. The combined effect of the CPCs, which itself is non-linear, is the main determinant of the variability of the functions. A shorthand way of expressing this is by invoking the control mode of a function (Hollnagel, 1998), where the levels of control and the variability roughly are inversely related. That is, if the level of control is high then the variability of a function is low, and vice versa. The variability can be characterised in a qualitative manner using the control modes, or using equivalent concepts such as stability, predictability, sufficiency, and boundaries of performance. The human/machine failure modes that are related to CREAM and FRAM (Hollnagel, 2004) can be used to characterise the potential consequences of functional variability in terms of the quality of the output. This can be expressed either as failure modes, or variability phenotypes.

The possible variability phenotypes are: timing, 2) duration, 3) distance, 4) speed, 5) direction, 6) force/power/pressure, 7) object, 8) sequence, and 9) quantity/volume. Two more were added for this study: 10) position, and 11) accuracy. The CPCs and variability phenotypes are interrelated and are used together to assess potential variability. The variability phenotypes are used to describe the ways in which variability may manifest itself in the output of a function. In turn this variability in the output of a function may affect other functions via their couplings (see step 3).

Step 3 defines the functional resonance based on possible dependencies/couplings among functions and the potential for functional variability. The output of the functional description of step 1 is a list of functions each with their six aspects. These functions may be coupled via their aspects. For example, the output of one function may be an input to another function, or provide a resource, fulfil a pre-condition, or enforce a control or time constraint. The couplings between functions are found by analysing and identifying common or related aspects. These couplings may then be combined with the results of step 2, the characterization of variability, to specify how the variability of one function may have an impact on the variability of another, hence spread through the JCS. For example, if the output of a function may vary, other functions that requires this output as, e.g., a resource may be affected, hence perform with increased variability and/or itself produce an unexpected output. Many such occurrences and spreading of variability may lead to a resonance effect; the added variability under the normal detection threshold becomes a discernible 'signal', a risk or hazard.

Step 4 identifies barriers for variability (which in the case of safety are damping factors) and specifies required performance monitoring. Barriers are hindrances that may either prevent an unwanted event to take place, or protect against the consequences of an unwanted event (Hollnagel, 2004). Besides recommendations for barriers, FRAM is aimed at specifying recommendations for the monitoring of performance variability, to be able to detect potentially harmful variability. Performance indicators may thus be developed by considering the variability of functions and their couplings.

The focus is here on step 1 to 3. The model is based on several published models in the literature on air traffic control, interviews with (former) controllers, and observations of
controllers on position in control centres and in experimental settings.

3. RESULTS
A set of functions in en-route air traffic control and cruise flight is identified from previously published task analysis efforts, observations in ACCs, and ACC position and cockpit simulators, and used as an input to the FRAM model. The functions of the envisioned ERASMUS applications are included, resulting in a model of the functions of the joint controllers-pilots-aircraft-ERASMUS system. The functions are evaluated by assessing common performance conditions, variability phenotypes, and the potential for and effects of propagation of variability among functions.

Based on observations, interviews, and the aggregation of identified functions in published models of en-route control (abbreviated by first author(s) below: Barbarino et al., 1999; Blom et al., 2001; Kallus et al., 1999; Mattsson, 1979; Niessen & Eyferth, 2001; Rodgers & Drechsler, 1993; Seamster et al., 1993; Voller & Low, 2004), nine controller functions have been identified that are relevant for the evaluation of ERASMUS:

1. **Monitoring**: Monitoring (identified by Blom; Rodgers & Drechsler; Voller & Low) of the current traffic situation and anticipating future situations. This function includes what others have called building up and maintaining a mental picture of the traffic situation (Barbarino; Kallus; Niessen & Eyferth; Voller & Low) or of situation(al) awareness (Barbarino; Kallus; Seamster), but also e.g., checking and evaluating separation (Rodgers & Drechsler), searching for conflicts (Kallus), and integrating, predicting, and anticipating deviations (Blom). The literature, interviews and observations show that these activities may inseparable in actual performance since they are performed in a continuous and intertwined fashion. Besides the radar screen, a wide range of electronic tools for measurement and assessment of current and future aircraft trajectory data (ATD) including separation may be available, e.g., prediction tools, dynamically marked flight plan visualizations, other medium-term conflict detection (MTCD) tools and visualizations – depending on the specifics of the ACC. These artefacts are intertwined with the above mentioned activities as well, as they are part of the controller’s continuous visual scanning and thereby part of the joint cognitive system performing monitoring.

2. **Planning traffic flow**: Develop and revise a control plan (Seamster) for the resolution of conflicts (Rodgers & Drechsler; Seamster; Kallus) and provision of separation (Barbarino), while taking into account pilot requests (Kallus; Voller & Low) and airspace constraints. Several models mention a “library of standard solutions” while planning for conflict resolution. Depending on the situation, different strategies or criteria may be employed for choosing solutions, e.g., combinations of elegance, efficiency, and safety (Leroux, 2000; Sperandio, 1978). Controllers have stated during interviews that they in many cases see one or very few “standard” solutions to conflicts while monitoring, or in other cases have to revert to more elaborate analysis and reasoning about how to solve problems. These views are based on “library solutions”, situation-dependent strategies, and training and experience.

3. **Maintain aircraft trajectory data (ATD)**: Review and update aircraft trajectory data (Blom, Voller & Low) including flight plans and their amendments (Barbarino, Rodgers & Drechsler), issued clearances, plans, requests, and expected conflicts (as observed in experiments and observational studies). Various artefacts such as flight data maintenance systems, paper or electronic flight strips or editable electronic flight labels, and/or electronic marking tools, are used depending on the specifics of the ACC.

4. **Coordination**: Coordinate with other sectors (most models) when regulations/procedures dictate this, or when this is considered good practice (e.g., when non-routine situations arise), including e.g., changes to flight plans,
(intended) clearances that affect traffic in other sectors, early transfer of aircraft responsibility, and skipping radio contact because of fast and conflict-free transfer through the sector.

5. **Issuing clearances**: Formulate and issue clearances (most models) via radio communication or data link. This includes assuring that the message has been understood through assuring and correcting read back (radio) or assuring will-comply message reception (data link).

6. **Receiving/initiating hand off**: Receive and issue transfer of control (most models).

7. **Monitoring weather**: Monitoring present and forecast weather (most models). Weather information sets constraints on traffic plans and expectations on future aircraft trajectories.

8. **Providing pilots with information**: Providing pilots with information other than clearances or instructions, either on request or on controller’s initiative. Some models (e.g., Voller & Low; Blom) distinguish between communication of clearances and other (complementary) radio communication similarly to what is done here, as opposed to categorizing all radio communication as one function (e.g., Barbarino). For the present purposes, and to assess variability in communication in detail, the radio communication function is split into **Providing pilots with information** and **Issuing clearances**.

9. **Maintaining technical equipment**: Checking the functioning of or updating data in the technical equipment other than information for specific flights (e.g., airspace constraints, Rodgers & Drechsler), and suppressing/restoring automation alerts (Blom, Rodgers & Drechsler).

Each of these functions may be characterized by the six function aspects mentioned above. Table 1 illustrates some of the aspects of the **Monitoring** function. Inputs are aircraft trajectory data (ATD) such as ground speed, flight level (FL), and flight plan (FPL), for all relevant aircraft, and expected wind effects. These inputs are made available through other functions, such as functions performed by ATD and weather data display systems. The output states of the function may be that an understanding of the situation is established, and potential conflicts and abnormal ATD are detected. As a precondition, ATD needs to be available and correct, for the executive and planner controllers (who are resources), can produce adequate output. The time available depends on the overall situation, as this function is performed continuously. The continuous nature of this function also implies that outputs should be seen as being highly dynamic. Controls include experience and training of controllers, as well as standard operating procedures (SOPs) for **Monitoring**.

<table>
<thead>
<tr>
<th>Monitoring</th>
<th>Description</th>
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<tbody>
<tr>
<td>Inputs</td>
<td>ATD: ground speed, FL, track, requested FL, FPL, radar image Expected wind effects</td>
</tr>
<tr>
<td>Outputs</td>
<td>Situation understanding for relevant flights established Potential conflicts detected Abnormal ATD detected</td>
</tr>
<tr>
<td>Preconditions</td>
<td>ATD available and correct</td>
</tr>
<tr>
<td>Resources</td>
<td>Executive and planner controllers</td>
</tr>
<tr>
<td>Time</td>
<td>Dependent on situation, continuous activity competing with other activities</td>
</tr>
<tr>
<td>Controls</td>
<td>Experience Training SOPs</td>
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</tbody>
</table>

Table 1. Identification of function aspects, example of the function **Monitoring**.

The function that the ERASMUS system performs may be summarized by a 10th function: **Issuing CTOs**. Although it may be technically interesting to know which sub-functions this function comprises, these functions need not be specified in detail as long as the significant variability that should be taken into account here is specified. Thus we need only specify the aspects of the input-output behaviour of the ERASMUS server. Roughly, the function may be described as in Table 2 below. Aircraft trajectory data (ATD) and previously rejected CTOs are inputs to the function. The output is a number of CTOs, at specified time intervals,
e.g., every 3 minutes. Computing power is a resource and internal server logic controls the function.

<table>
<thead>
<tr>
<th><strong>Issuing CTOs</strong></th>
<th><strong>Description</strong></th>
</tr>
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<tbody>
<tr>
<td>Inputs ATD</td>
<td>Rejected earlier CTOs</td>
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<tr>
<td>Outputs CTOs</td>
<td>Preconditions</td>
</tr>
<tr>
<td>Resources Computing power</td>
<td>Time Issued every 3 minutes</td>
</tr>
<tr>
<td>Controls Internal server logic</td>
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Table 2. Identification of function aspects, example of the function Monitoring.

Based on a description of a prototype used in a cockpit simulator in one of the experiments that are part of the project, the following four functions performed by the pilot-cockpit system have been identified that are relevant for the evaluation of ERASMUS:

11. **Acknowledging reception of CTO**: Once a CTO is received in the cockpit (input), it is shown on the data link control display unit (DCDU, a resource). The pilot transmits a standby message to indicate acknowledgement (output).

12. **Loading CTO in FMS**: Once the standby is transmitted, the received CTO is loaded in the flight management system (FMS) through interaction with the multifunction control display unit (MCDU, a resource). The CTO is added (output) as an extra waypoint in the secondary flight plan, and is shown (output) on the navigation display (ND).

13. **Assessing CTO feasibility**: Once the CTO is loaded into the FMS (input to the function), it may be assessed for feasibility and accepted or rejected.

14. **Sending ‘wilco’ or ‘unable’ to ATC**: Following the decision to accept or reject (input), a ‘wilco’ or ‘unable’ message is communicated to ATC (output) through interaction with the DCDU (resource).

By using step 2 of FRAM, the potential variability of each function may be assessed. In cases where data is available about actual performance of the functions, the CPCs outlined above may be used as a check-list to assess functions as they are actually performed in practice. In the present case of evaluating an envisioned system, a CPC assessment in this way is impossible because data on actual use are yet to be collected. However, each function’s dependence and sensitivity to the CPCs may be assessed. For example, Monitoring is highly dependent on the correct functioning of the equipment that is used for visualizing aircraft trajectory data, and also the HMI is of importance for the variability of input. Regarding availability of personnel and team collaboration, the availability of a planning controller participating in the monitoring activity is of importance regarding control of the controllers’ monitoring activity. Finally, the number of goals influences the time available for Monitoring.

Besides the CPCs that may be used to assess an entire function for potential variability, variability phenotypes may be applied to the function aspects. To illustrate this again for the Monitoring function, for example, the timing of when aircraft trajectory data (input) is available varies. The accuracy of the specific data also vary, for example requested flight levels may be inaccurate, flight plans may be incorrectly filed or outdated, and radar may be inaccurate in mountainous areas. As an example of the output variability, the understanding of the position and timing of expected conflicts between aircraft varies. As an example of variability in the time aspect, the duration of the time available for monitoring is highly variable.

The ERASMUS server function Issuing CTOs is mostly variable in its output in that CTOs vary in duration and distance (the time/distance during which aircraft fly under CTO varies), and the speed that the CTO entails for the aircraft varies (depending on the settings of the server, about +/- 6% of the current speed of the aircraft). (CPCs are not assessed for purely technical functions.)

Variability in pilot-aircraft functions lie in variability introduced by the HMI of the various displays involved, resulting in variability in the duration of reading and assessing information
displayed, and the subsequent timing of answers to automation queries, possibly exceeding timeout limits. Deliberation by the pilots about whether a CTO would be acceptable with regard to, for example, aircraft performance, fuel economy, or punctuality, may also influence the timing of replies to ERASMUS-sent CTOs.

Step 3 of FRAM identifies potential couplings between functions and assesses how the way they are coupled may allow variability to spread. For specific situations, instantiations of functions may be established, assigning specific values to the entities identified as function aspects and realising specific couplings. Once potential couplings are realised or instantiated, the possible spreading (dampening, amplifying) of the variability (the resonance) may be assessed. Various ways of coupling and spreading may occur, illustrated with the help of Figure 3. First, the consequences of variability may combine if the outputs of several functions are used by another function (as either input, precondition, resource, time, or control). For example, the aspect of (ground) speed of aircraft is an input to the Monitoring function, and is variable depending on wind direction and force, among other factors. At the same time, accepted CTOs entail speed changes for aircraft, which add to the variability of aircraft speed. From a FRAM analysis one can imagine that, from a controller (monitoring) perspective compared to an unaffected “normal” speed, a speed change by ERASMUS combined with a head or tail wind may lead to an increased variability of the Monitoring function. Second, CPCs co-determine the variability of a function, hence, the function’s quality of the output. For example, the variability of pilot-accepted and implemented speed changes of ERASMUS CTOs may affect the input aircraft trajectory data (ATD) of the Monitoring function. This may however go unnoticed if the controller has little time available for monitoring, if many conflicting goals need to be attended to, or if the HMI prohibits effective assessment of aircraft speed. Third, variability of the quality of a function’s output may be either detected and/or corrected, or used as is by another function. For example, from a controller perspective the variability in assessments of feasibility of the CTO by the pilot-aircraft system is assumed to be mostly undetected and simply used by the Monitoring function as described above. When the variability introduced by ERASMUS does get detected, it mostly does not need dampening because it helps rather than disturbs conflict resolution. Fourth, the variability in the quality of the output of one function may result in a change in the CPCs of another function. For example, the variability of Monitoring an especially complex traffic situation may influence the available time conditions for other functions such as Planning, an unexpectedly high number of clearances to be issued in a short period of time may influence the performance conditions for Coordination, etc. Fifth, variability may arise due to inputs not being available, thus disabling couplings between functions. This could happen if ERASMUS works in a subliminal mode and pilots wish to negotiate with controllers about the various solutions to conflicts available to them, including the ERASMUS solution (indicated by the dashed line in Figure 3).

Once instantiations associated with scenarios are established, the potential for variability may be described, considering dependencies among functions’ common performance conditions, and variability phenotypes, as described above. The model that is established may be used to generate questions for human factors, risk and safety assessment. Following the previous five illustrations of emergent variability, such questions may be: Which variability of airspeed may occur due to wind effects? Which variability of airspeed occurs due to ERASMUS? What is the range of combined effects of wind and ERASMUS? How is the Monitoring function’s output affected considering this range of input variability and conditions such as various HMI settings, levels of traffic load, and coordination demands? If Monitoring output (e.g., situation understanding) varies, how does this affect functions that potentially are coupled, such as Planning the traffic flow, and the conditions of performing these functions (how is their
available time affected, are conflicting goals generated, etc.)? This should be done for all functions and all potential couplings among functions, using variability phenotypes and CPCs.

4. DISCUSSION AND CONCLUSION
The study illustrates the application of FRAM as a method for prospective analysis and risk assessment of future automation systems in ATM. It also makes clear that the model does not produce the usual flow-charts that result from sequential task descriptions but instead describes functional dependencies. This also seems to be closer to descriptions that controllers give of their work. It accounts for how system constituents (controller-pilot-ERASMUS) are interrelated. Furthermore we have sketched how FRAM can make it easier to identify potential risks in the future use of the modelled system, by combining common performance conditions and variability phenotypes with couplings among functions. The future work with this model during the project will continue to assess human factors issues with the ERASMUS automation in a model-based fashion, and may include HMI solutions that are considered as alternatives to the subliminal application of ERASMUS. Future scenarios’ may be included taking into account envisioned traffic situations and airspace designs such as in the SESAR programme.

5. ACKNOWLEDGEMENT
This research was performed within the EU ERASMUS project (see http://www.atm-erasmus.com/). The research staff of the project is gratefully acknowledged for discussions and comments that have contributed to the writing of this paper, as well as participants of the 2nd FRAM workshop and Daniel Sonnerfjord for useful discussions. Also, the (former) controllers that were our informants are thankfully acknowledged for their explanations and agreement to our observations of their work.

Figure 3. Some of the functions and potential couplings exemplified.
6. REFERENCES


