A FRAMEWORK FOR RESOURCE MANAGEMENT IN AIR TRAFFIC SYSTEMS

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ABSTRACT

In this paper, we present a software framework for the air traffic system that includes and integrates several architectural components devoted to the dynamic allocation, exchange and self-adaptation of resources.

Some of these components, namely the allocation and the adaptation of resources, are managed at a centralized level by a single authority, whereas the resource exchange component is envisioned as a decentralized decision process aiming to enlarge the participation of resources' users in the decision process. Several variants of the resource exchange component can be proposed differing for the underlying mechanisms of resource exchange. By means of Petri net’s formalisms and results, we compare and validate the mechanisms underlying the resource exchange components.

The architecture of the air traffic system herein proposed is consistent with the Collaborative Decision Making (CDM) philosophy and provides a solution towards a full implementation of CDM.

Keywords: Air Traffic System, Software Architecture, Resource Allocation, Resource Trading, Resource Adaptivity.

INTRODUCTION

The Air Traffic System can be schematically sketched as a set of resources that are used by self-interested stakeholders (airlines) to satisfy the transportation demand. The resources are time slots available at the air traffic system elements, i.e., airports and airspace sectors. The number of time slots gauges the capacity of air traffic system. Capacity at airports is limited by the runway systems, whereas the capacity of en-route airspace sectors is limited by the maximum workload acceptable for air traffic controllers [6]. These capacity constraints are becoming a limiting factor in many regions of the world. In fact, as air traffic grows and/or capacity is reduced - mainly due to adverse weather conditions -, demand can exceed capacity at key points of the air transportation network and at critical times. These local overloads create delays which propagate to other parts of the air network, amplifying congestion as increasing number of local capacity constraints come into play. Last year, more than 20% of US flights were delayed or cancelled (according to the US Bureau of Transportation Statistics). Similar statistics have been reported by European authorities.

Airlines (stakeholders) are very sensitive to a reduction of these delays and call for an efficient use of the available resources. Currently, the resources are allocated to stakeholders by a central authority, the Air Traffic Management (ATM), according to some priority mechanisms with full respect of the cardinal principle of safety first. In the air traffic system, airlines are reluctant to disclose their objectives thus posing some limits on the efficiency of the centralized resource management system. To overcome this issue, it is possible to envisage a larger involvement of the stakeholders in the decision process for resource management, for instance, by allowing the trading of resources among airlines. Herein, trading is meant as an exchange of resources without necessarily implying any monetary compensation for the exchange of resources. Several deployments of the resource trading component are possible, each characterized by the degree of decentralization of the decision process within resource trading component and on the role played by the central authority.

In this paper, we present a general software framework for resource management that is based on the integration of dynamic allocation, trading, and self-adaptation mechanisms. This framework, which is fully integrated, clearly fits to the air traffic system and it is important to note that it is consistent with the decision paradigm of Collaborative Decision Mak-
ing enabling a more active participation of airlines in the ATM decision process.

The central authority (ATM) performs a first allocation of resources and supervises the resource trading among the stakeholders. The result of the trading process is communicated to the central authority, which integrates all the partial results communicated by the stakeholders and it might either accept the new allocation, or try to adapt the resources to the new allocation plan, when this new allocation plan is not appropriate from the centralized point of view/objectives. If the adaptation is possible, then the system adapts itself and accepts the new resource allocation plan. Otherwise, the central authority rejects the new allocation plan (indicating also which are the problems) and requires the stakeholders to resume the trading process.

In what follows, we describe in more detail the components of the proposed framework.

DESCRIPTION OF THE SOLUTION FRAMEWORK

The framework for resource management herein proposed is depicted in Figure 1. It includes the Air Traffic Management (ATM) authority which is in charge of the correct and efficient use of resources and several stakeholders (Resource Stakeholders - RS), which are the users of the resources. RS may ask ATM for resources allocation and modifications in the resource allocation.

ATM allocates the available resources and accepts/rejects the requests of allocation changes received from the stakeholders. ATM holds a supervision role on the resource allocation process because it has complete knowledge of both the resources (e.g., current number, availability) and the constraints of the air traffic system (e.g., number of available time slot, safety, etc.). Moreover, this supervision role may be dictated by legal considerations. Indeed, the ATM is in charge of guaranteeing the safety of air traffic operations. The allocation, trading, and self-adaptation of resources have to satisfy a set of constraints, which can be either general, domain specific, or both.

The Resource Allocation (RA) module assigns the available resources to stakeholders based on some criteria of performance, e.g., the efficient use of resources. So far, the criterion most widely used for the allocation of resources has been the minimization of total delay. In addition to the set of resources to be allocated and the set of stakeholders, RA receives as input the current resource allocation plan if any, and the constraints of the air traffic system (see Figure 2). The RA module is equipped with a supervision capability on the use of resources thus guaranteeing a feasible and efficient allocation of resources. This functionality requires in input the results of the trading and the self-adaptation processes. To provide these functionalities, the RA uses assignment optimization models and methods of the type of those described in [2, 3].

The Resource Trading (RT) module, depicted in Figure 3, is used by the stakeholders to exchange resources with the other stakeholders and to communicate with ATM and . Each stakeholder has a RT module. The communication with the ATM includes resource allocation/modification/usage/cancellation requests, which may or may not be a result of a trading process. The communication with other stakeholders concerns the exchange requests, thus implying a trading process. Each RT receives as input the current resource allocation plan, if any, the application domain constrains, and the resource trading requests from other stakeholders. The stakeholder decides on an exchange of resources with other stakeholders based on its individual objectives and exploiting customized optimization models and methods. By customization of the optimization models we mean that the optimization models may consider specific constraints and objectives of the stakeholder, therefore different stakeholders may have different optimization models [5, 8].

The proposed framework also includes a module for self-adaptation of the resources (see Figure 4). In the air traffic domain resources may change over time in quantity and type as a consequence of both exogenous
and endogenous causes or factors. The self-adaptation module, if implemented, acts on the endogenous factors. For instance, by modifying the airspace sectorization, the ATM is able to modify the capacity of airspace sectors (i.e., airspace resources). The self-adaptation process is triggered by the stakeholders resource requests (e.g., requests for new allocations or the results of the trading process).

The Self-Adaptation (SA) module computes a distance measure $d$ between the available resources $C$ and the new allocation resource plan $P$ which would accommodate the stakeholders requests. If this distance is lower than a given threshold $d(C, P) < \delta$ then the system tries to adapt itself and modifies the available resources (whenever this is possible) in order to accommodate the stakeholders requests. If the distance $d$ is greater than the given threshold, then the SA does not perform any adaptation. In any case, RA is notified of the SA results. The self-adaptation process is based on the MAPE (monitoring, analyzing, planning, and executing) feedback loop, which is exploited in the implementation of self-adaptive and self-management systems [1, 7]. We address self-adaptation at the architectural level in an approach similar to the one proposed by Garlan et al. [4].

VALIDATION AND COMPARISON OF TRADING MECHANISMS.

To validate and to compare the different trading mechanisms that might be proposed for the RT module, we adopt a Petri net approach. More specifically, Petri net model allows us to verify their behavioral properties by means of simulation and analysis techniques.

Petri nets are a widely used formalism for modeling concurrent and distributed systems. In Petri net theory a distributed system is described by a set of local states and a set of local events (or transitions). An event can happen when its pre-conditions (which are some local states) hold; and the occurrence of an event changes some of the local states. In this context, it is possible to clearly detect when two events are independent and they can occur concurrently.

The nature of the local states characterizes the type of the Petri net. In the basic type, the local states are logical conditions, which can be either true or false.

In place and transition nets, the local states, which are called places, contain a number of tokens representing indistinguishable resources shared by the components of the system. The global state of the net is given by the distribution of tokens in places (number of tokens in each place), and the transition from one state to another is represented by a different distribution of the tokens.

In high-level nets, tokens become individuals, which can carry data. The occurrence of events changes not only the distribution of tokens, but also their values. For our analysis purpose, we model the communication protocols among the architectural components by a high-level Petri net. In Figure 5, we show a simple example of a transition’s firing (occurrence) in a high-level Petri net which models the trading of resources between two components (stakeholders). Using standard notation of Petri net theory, we represent by circles the places and by squares the transitions. $r_A(r_B)$ is the place representing the set of resources owned by $A$ ($B$). Place $s_A^1(s_B^1)$ is a control state triggering the transition $t_A$ ($t_B$). The transition $t$ takes place once it is possible to select a token from all the input places, i.e., the places which have an outgoing arc pointing to the transition. The firing of a transition has the effect of changing the distribution of tokens in its input and output places. The output places are the places with an incoming arc from the transition $t$. All the arcs are labeled with variables and the occurrence of a transition assigns to each variable a selected token. In other words, at the occurrence of a transition a token “travels” along the arcs labeled with the same variable.
In the shown example the firing of \( t \) has the effect of moving the resource \( a (b) \) from \( r_A(r_B) \) to \( r_B(r_A) \) and a token from \( s^1_A \) to \( s^2_A \) and one from \( s^1_B \) to \( s^2_B \) (see Figure 6).

**Fig. 5:** Configuration before the exchange of resources.

**Fig. 6:** Configuration after the exchange of resources.

Analysis techniques for Petri nets allow to verify if a model satisfies properties like absence of deadlocks, absence of starvation, and more general safety and liveness properties.

Such techniques can be classified in two main groups: structural and dynamic. Structural techniques are based on the structure of a net, and allow to determine some invariant properties. Dynamic techniques can require the generation of the global state space, namely the set of all reachable global states, and allow to determine a larger set of properties, but at a greater cost, since the number of reachable global states can grow exponentially with respect to the number of the elements of a net. Recently, significant progress has been made on the development of dynamic techniques based on the so called unfolding of a net, whose size can be much smaller than the size of the marking graph, while containing the same amount of information on reachable global states.

For the air traffic domain herein considered, relevant properties are the absence of deadlocks of the system and absence of starvation for all the single components (stakeholders). As a direction of future research, we are planning to extend the model comparison and validation of the trading mechanisms to evaluate the convergence of the proposed trading mechanism to solutions which are convenient for all the stakeholders.

**REFERENCES**


