

# *Hybrid Modelling and Automation of Air Traffic Controller Decision Process : Separation Assurance*

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**Abstract—** In this paper we represent a new hybrid systems description for modeling the decision process of air traffic controllers in en route and approach operations. Using this model, we design an automation algorithm which allows automatic safety assurance using the decision process of the controller. By using real-life ALL\_FT+ European flight information data, we have shown that the algorithm can detect conflicts and recommend solutions in seconds. The workload of controllers can be reduced with proposed automation tools and the capacity of the current system can be enhanced.

**Keywords-** automation, hybrid modeling; en route controller; approach controller

## I. INTRODUCTION

The basis of current air traffic system was constituted by The International Civil Aviation Organisation, which was organized after The Chicago Convention in 1944. Nowadays, the system is still reliable but air transport goes on to grow. Number of commercial aircraft movements is 26 million per year. If it grows as expected rate, number of flights will become 48.7 million per year in 2030 [1]. In the current Air Traffic Management (ATM) operations, controllers monitor the flight trajectories through the radar screens, and make cognitive judgments with a support of some automation tools to interpret and resolve conflicts. The major current barrier of the airspace capacity is the controller work load generated from two sources; a) routine task load based on coordination, routine verbal communication and data management, b) tactical task load associated with conflict detection, situation monitoring and conflict resolution [SESAR Conops]. As the traffic increases, routine task load increases proportionally, while tactical task load increases approximately square of the increase in traffic due to the cross-relations between the flight trajectories.

The traditional responsibilities of the controllers based on verbal communication and clearance decisions will evolve through the use of new functionalities and tools coming from SESAR and NextGen visions [NextGen, Sesar Conops]. The paradigm shift from clearance-based to trajectory-based control with Trajectory Based Operations (TBO) functionalities will not only redefine existing roles of the

controllers, but also create additional responsibilities for the controllers. Therefore the future ATM operations will require enhanced and high-level automation support for routine decision-making procedures. Moreover, integration of the air-to-ground data-links will turn separation management tasks into a function of the some variables such as aircraft performance, environmental conditions and airspace capabilities.

Through these objectives, the paper proposes automation tools perform routine separation provision tasks of controller for two different types of flight modes. The method utilizes hybrid automata formalism to model controller action obtained from both Arrival/Departure (APP) and En-route (ACC) “what-if” procedures. The hybrid models are envisioned to solve conflicts considering to aircraft performance limitations and environmental model without changing the current flight plan of the aircraft. It is supposed that, airspace and flow capacity considerations are handled strategically in the context of 4D Reference Business Trajectory (RBT) planning, and aircraft execute their own flight intent trajectories subject to tactical ATC intervenes. The ACC and APP automata ensure that the aircraft maintains a safe separation from other aircraft during both en-route and arrival/departures respectively.

Different types of approaches have been studied in the literature associated with separation assurance automata and enhancing airspace capacity. A kind of separation loss detection and resolution algorithms are defined as NP-hard [5][6]. These approaches mostly focus on free flight phenomena where aircraft are responsible from their self-separation. These approaches are further from the current system and these are not implemented real situation. [7] proposes conceptual, procedural and technological integration of air-ground system. General schema is defined for this transition system and this study supports necessity of new automation support tools. [8] proposes another system architecture which focuses to reduce controller workload associated with tactical separation assurance tasks. A controller decision model, which is a hybrid automaton, is presented in [9] but this model ensures separation in 2D, complexity of this model increase proportionally with power

of manoeuvre set and power increases proportionally with the number of aircrafts.

Rest of the paper organised as follows; Section II gives details about the aircraft motion and dynamical models. Section III explains procedural action library of the controller in both Arrival/Departure and En-route modes, and Section IV introduces hybrid automata models for these action sets. Algorithmic implementations using built-in hybrid models and their complexity analysis are discussed in the Section V. Real flight data implementation and their results are given in Section VI.

## II. MODELLING OF FLIGHTS

We use an aircraft and FMS model for simulation of Air Traffic Control (ATC) actions, which simulate their behaviour from the point of view of ATC. In this section, aircraft and FMS models are represented. These models were presented by Lygeros and Glover, detailed modelling of aircraft, FMS and wind can be reached from [11][12]. As seen in Figure 1, we revise the model in some aspects. In our model, ATC can affect to FMS directly and get information about the situation of state variables which is not presented at Lygeros and Glover model.

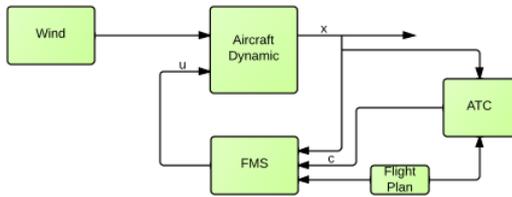


Figure 1. Block diagram of model components

Each flight have same model parts which are:

- The flight plan
- The aircraft dynamic
- The flight management system
- Wind model
- ATC actions

The model is a hybrid processes which consist of:

- Continuous dynamics, because of the aircraft motion,
- Discrete dynamics, because of the flight plan and the logic variables embedded in the FMS and ATC actions, and
- Stochastic dynamics, because of the wind.

### A. Flight Plan

The flight plan has a sequence of way-points,  $\{o(i)\}_{i=0}^M$  in three dimensions,  $o(i) \in \mathbb{R}^3$ . Each way-point has a time variable which is related to aircraft's arrival time to the way-point,  $\{t(i)\}_{i=0}^M$ . Way-point data use for representation of flight's routes at real flights and this data come from ALLFT data set. Time variables in flight plans are ignored except one which is related to access to sector. Instead of other time variables in flight plans, we use speed profiles provided by BADA [13] for generation of time variables, we assume aircrafts have same speed between two way-points.

### B. Aircraft Dynamic

Point Mass Model (PMM) can be used for modelling of aircraft dynamics from the view of ATC, and then equations of flight dynamics can be derived easily. The model is a control system has three control inputs and six state variables. The state variables of the aircraft are the horizontal position ( $x_1$  and  $x_2$ ), altitude ( $x_3$ ), the true airspeed ( $x_4$ ), the heading angle ( $x_5$ ) and the mass of the aircraft ( $x_6$ ). The control inputs of the aircraft are the engine thrust ( $u_1$ ), the bank angle ( $u_2$ ) and the flight path angle ( $u_3$ ). Wind affects aircraft movement as a disturbance which is modelled where by its speed,  $w = (w_1, w_2, w_3) \in \mathbb{R}^3$ . After some algebra, the equations of aircraft motion are:

$$\dot{x} = \begin{pmatrix} x_4 \cos(x_5) \cos(u_3) + w_1 \\ x_4 \sin(x_5) \cos(u_3) + w_2 \\ x_4 \sin(u_3) + w_3 \\ -\frac{C_D S \rho(x_3) x_4^2}{2 x_6} - g \sin(u_3) + \frac{u_1}{x_6} \\ \frac{C_L S \rho(x_3) x_4}{2 x_6} \sin(u_2) \\ -\eta u_1 \end{pmatrix} \quad (1)$$

In this equation set, aerodynamic lift and drag coefficients are symbolized as  $C_L$  and  $C_D$ , total wing surface area is symbolized as  $S$ , air density is symbolized as  $\rho(x_3)$  and thrust-fuel consumption coefficient is symbolized as  $\eta$ . These coefficients and other constant parameters like bounds on speed and bounds on the mass are provided by BADA database.

### C. Flight Management System

The FMS works like a controller. It generates control inputs ( $u$ ) according to state variables ( $x$ ), flight plan information and ATC actions. FMS model has 8 discrete modes. These discrete modes are: flight level (FL), way-point index (WP), acceleration mode (AM), climb mode (CM), speed hold mode (SHM), flight phase (FP), reduced power

mode (RPM) and troposphere mode (TrM). These modes are defined relative to BADA [13] for determination of control inputs. Detailed information about these modes can be reached at [11][12].

FMS controller can be divided into two components. One of them is vertical and along track motion control with  $u_1$  (thrust) and  $u_3$  (flight path angle) and the other one is horizontal motion control with  $u_2$  (bank angle).

Speed and the Rate of Climb/Descent (ROCD) are set by thrust and flight path angle. In our model, FMS tries to track a desired speed,  $V_{nom}$ , which is affected by altitude and aircraft type and it is determined by the airline. This speed can be changed at the rate of 2% by ATC for increasing or decreasing of aircraft speed at operation. If aircraft cruises at a constant altitude, the FMS will set the flight path angle to zero so equations produce zero ROCD. Then thrust is used to control the speed through the equation

$$\dot{x}_4 = -\frac{C_D S \rho(x_3)}{2} \frac{x_4^2}{x_6} - g \sin(u_3) + \frac{u_1}{x_6} \quad (2)$$

In climbing or descending motion, the thrust is set to a fixed value. Thus speed can be controlled with flight path angle. ROCD is set with equation

$$\dot{x}_3 = x_4 \sin(u_3) + w_3 \quad (3)$$

Horizontal position control can be achieved with bank angle ( $u_2$ ). First, heading angle is controlled through the equation

$$\dot{x}_5 = \frac{C_L S \rho(x_3)}{2} \frac{x_4}{x_6} \sin(u_2) \quad (4)$$

Second, horizontal position of the aircraft ( $x_1$  and  $x_2$ ) can be adjusted with heading angle ( $x_5$ ) through the equations

$$\dot{x}_1 = x_4 \cos(x_5) \cos(u_3) + w_1 \quad (5)$$

$$\dot{x}_2 = x_4 \sin(x_5) \cos(u_3) + w_2 \quad (6)$$

#### D. ATC Actions

In our model ATC can intervene 4 main parameters of the model. ATC can revise way-point index which is related to direct routing action, can increase or decrease  $V_{nom}$  value and can set flight path angle and bank angle to fixed value for a time period. The detailed description of these actions is main subject of this study. It will be presented further sections.

### III. DECISION PROCESS OF ATC

This section provides detailed information about the decision process of Air Traffic Controller. Procedural actions of controllers for en route and approach operations are defined and decision mechanisms are represented.

Air Traffic Controllers are responsible from separation of aircrafts, organization of air traffic flow and providing information for the pilot. Mostly, controllers make a decision with these information sets:

- Calculated information based on filed flight plans
- Transmitted information by pilot with radio
- Transmitted information by other controller with phone
- Perceived information by facilities located on ground

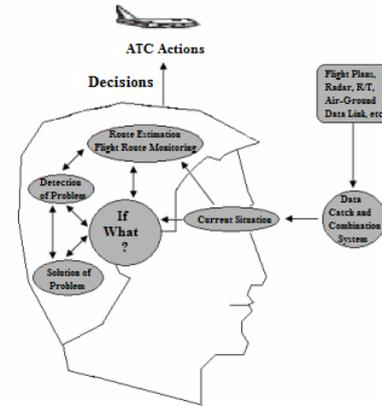


Figure 2. Decision Process of Air Traffic Controller [14]

This information is transmitted to the controller with human-machine interface. Decision process of controller with future estimation in midterm is presented in Figure 2.

Controller evaluates information and analyse current situation. Then asks if – what questions through all process. Route estimation and flight route monitoring are the other parts of the process. Afterwards, controller detects the problem and finds solution to this problem, and transmits a controller action to the pilot.

#### A. Decision Mechanism of En route Controller

ACC controllers do not separate aircrafts from flight route when important causes are not existed. First, ACC controller checks flight levels of aircrafts which enter sector. If vertical separations (1000ft) are ensured, controller won't any action to aircrafts. Flight levels are determined relative to flight directions; east direction flights exists in odd flight levels (310-330-350 etc.) and west direction flights exists in even flight levels (320-340-360 etc.). So flights in reverse directions have vertical separation. If controller chooses altitude change action between the same direction flights in the same flight level, controller will increase or decrease altitude amount of 2000ft. Primary choice of the controller is always to decrease the altitude following the aircraft's capability.

Controller checks flight routes in the same level flights. If any intersection points exist between flight routes, controller will estimate horizontal separations of aircrafts.

When horizontal separation losses are estimated by controller, controller asks if-what questions. If aircrafts do not follow the same route after conflict point, controller will try direct routing action and bank angle for both aircrafts which of them is a solution for conflict; controller transmit this action to pilot. Controller intervenes to way-point index of aircraft in direct routing action (Figure 3); for example if third way-point of first flight is conflict point of first and second flights, controller can say that does not go to third way-point, goes to fourth way-point directly. If aircrafts follow the same route after conflict point, controller will try direct routing action, altitude change action and delaying motions which of them is a solution for conflict; controller transmit this action to pilot. Two different delaying motions can be defined; one of them is reducing of speed, another one is vector for spacing (Figure 4). Vector for spacing consist of a deviation of the aircraft from flight plan for a time period.



Figure 3. Direct Routing Action

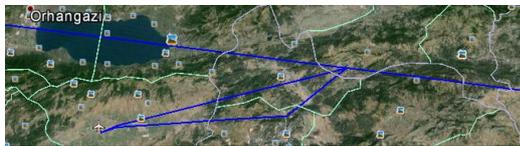


Figure 4. Delaying Motion with Vector for Spacing

After horizontal separations are ensured, if longitudinal separation losses are estimated after intersection point, flights controller will try direct routing action. The routing action cover aircraft that will have same routes after intersection point. The controller will chose will choose altitude change action or delaying motions and will transmit this action to pilot.

#### B. Decision Mechanism of Approach Controller

APP controller is responsible for arrival and departure flights. Controller takes over departure flights from Tower (TWR), places these flights to routes and turns over to ACC and takes over arrival flights from ACC, sequences these flights for landing and turns over to TWR.

Standard Instrument Departure (SID) procedure, which is a departure procedure together with the departure route, is defined for each departure flights. When any separation losses are estimated by the controller, controller intervenes to flights. If any separation losses are estimated for arrival flights, controller will try direct routing action, delaying motion and horizontal motion to a defined altitude. If any separation losses are estimated for departure flights, controller will try direct routing action, delaying motion. When controller finds a

solution for separation loss; controller transmits this action to pilot.

Standard Terminal Arrival Routes (STAR) procedures are also defined for arrival flights. First, controller sequences arrival flights relative to the estimated arrival time. Vertical separation (1000ft), horizontal separation (3nm) and longitudinal separation (5nm), which is necessary for Instrumental Landing (ILS), is ensured one by one by the controller. If any separation losses are estimated, controller will try to delay motions.

Detailed information about controller actions, separations, STAR, SID, and ILS can be reached from ICAO Doc.4444 [15] and AIP of Turkey [16].

#### IV. MODELLING OF AIR TRAFFIC CONTROLLER

In reality, controller looks all flights in sector and the controller compares flight routes of aircrafts and looks to aircraft current states, then predicts when the aircraft goes to which point and determines separation losses. If any separation loss is predicted between two flights, controller will make an action which ensures separation. Controller has several action types, tries these actions on flight plans procedurally. Controller determines action which is a solution to separation problem and controller says this action to the pilot/FMS.

We constitute two models in this section which symbolize real air traffic controller decisions in en route and approach airspaces. These models are used to find a solution to separation problem between two aircrafts, and these models will generalize for all flights separation assurance in next section.

These models are represented with deterministic automata. Automata is a formal definition method accepting an appropriate language which has well defined rules; detailed information about automata can be reached from [17][18]. Automata can be presented in directed graph representation or state transition diagram; it is used directed graph representation of this study.

An automaton has events and states which are represented as circles and arcs in directed graph representation. The model has transition functions which defines the relation of transitions between states. In deterministic automata, pny one transition can happen from one state to another.

In formal language, a deterministic automaton (G) is a five-tuple

$$G = (X, E, f, x_0, X_m) \quad (7)$$

$X$  : is the set of states  
 $E$  : is the finite set of events  
 $f : X \times E \rightarrow X$  is the transition function  
 $x_0$  : is the initial state  
 $X_m$  : is the set of market (or final) states

#### A. ACC Automaton

It is defined air traffic controller in en route as a deterministic automaton:

$$ACC\_Automaton = (X, E, f, x_0, X_m) \quad (8)$$

ACC Automaton has eight discrete states which symbolize defined controller actions.

- $q_0$  is initial state which refer to no action. Controller does not intervene to aircraft in  $q_0$
- $q_1$  denotes direct routing for first aircraft
- $q_2$  denotes altitude change for first flight
- $q_3$  denote delaying motion for second flight with reducing of speed
- $q_4$  denote delaying motion for second flight with vector for spacing
- $q_5$  denotes altitude change for second flight
- $q_6$  denotes direct routing for both of them
- $q_7$  denotes bank angle for both of them

$$X = \{q_0, q_1, q_2, q_3, q_4, q_5, q_6, q_7\} \quad (9)$$

$$x_0 = q_0 \quad (10)$$

ACC Automaton can finish action at any of states, this meaning that all states are final states:

$$X_m = \{q_0, q_1, q_2, q_3, q_4, q_5, q_6, q_7\} \quad (11)$$

ACC Automaton has six different events which are a function of aircraft's states. These functions have logic outputs which are zero or one. The finite set of events:

$$E = \{e_1, e_2, e_3, e_4, e_5, e_6\} \quad (12)$$

For definition of events, we define six different functions which have logic outputs. These functions inputs are aircraft's states and flight plans of aircrafts. The functions are helper functions to determine aircraft's separation in flight route. Controller looks to aircraft current state and flight plan, then predicts when the aircraft goes to which point and determine values of these functions relative to this prediction.  $a_0$  is an altitude check function which controls altitudes of two flights, it will be 1 or 0. If altitudes of two flights are same at any point of flight plans,  $a_0$  will become 1 otherwise become 0.  $a_1$  is an intersection check function which controls routes of two flights. If any intersection has become in routes,  $a_1$  will become 1 otherwise become 0.  $a_2$  is a horizontal separation

check function which controls horizontal separation (5nm) of two flights. If separation is ensured in routes,  $a_2$  will become 1 otherwise become 0. We inspect also longitudinal separation with  $a_3$  function. Another important thing is that do two flights follow the same route after intersection point? If two flights follow the same route,  $a_4$  function will become 1. Last function is a horizontal separation check function which controls intervened flight with other all flights in sector in same flight level, if separation is ensured,  $a_5$  function become 1 otherwise become 0.

The relation between events and helper functions are:

$$\cap \rightarrow \text{and}, \cup \rightarrow \text{or}, a \rightarrow a \text{ is } 1, \bar{a} \rightarrow \text{not } a (a \text{ is } 0)$$

$$\begin{aligned}
 e_1 &= \bar{a}_0 \cup (a_0 \cap \bar{a}_1) \cup (a_0 \cap a_1 \cap a_2 \cap \bar{a}_4) \cup (a_0 \cap a_1 \cap a_2 \cap a_4 \cap a_3) \\
 e_2 &= [(a_0 \cap a_1 \cap a_2 \cap a_4 \cap \bar{a}_3) \cup (a_0 \cap a_1 \cap \bar{a}_2 \cap a_4)] \\
 e_3 &= (a_0 \cap a_1 \cap a_2 \cap a_4 \cap a_3 \cap a_5) \\
 e_4 &= (a_0 \cap a_1 \cap a_4 \cap \bar{a}_5) \\
 e_5 &= (a_0 \cap a_1 \cap \bar{a}_4 \cap \bar{a}_2) \\
 e_6 &= (a_0 \cap a_1 \cap \bar{a}_4 \cap a_2 \cap a_5) \\
 e_7 &= (\bar{a}_0 \cap a_5) \\
 e_8 &= (a_0 \cap a_1 \cap \bar{a}_4 \cap \bar{a}_5)
 \end{aligned} \quad (13)$$

The transition functions are defined as:

$$f : X \times E \rightarrow X$$

$$\begin{aligned}
 f(q_0, e_1) &= q_0 & f(q_2, e_7) &= q_2 & f(q_5, e_8) &= q_0 \\
 f(q_0, e_2) &= q_1 & f(q_3, e_4) &= q_4 & f(q_6, e_6) &= q_6 \\
 f(q_0, e_5) &= q_6 & f(q_3, e_3) &= q_3 & f(q_6, e_8) &= q_7 \\
 f(q_1, e_4) &= q_2 & f(q_4, e_3) &= q_4 & f(q_7, e_6) &= q_7 \\
 f(q_1, e_3) &= q_1 & f(q_4, e_4) &= q_5 & f(q_7, e_8) &= q_2 \\
 f(q_2, e_4) &= q_3 & f(q_5, e_7) &= q_5 \\
 f(q_2, e_8) &= q_5 & f(q_5, e_4) &= q_0
 \end{aligned} \quad (14)$$

And directed graph representation of deterministic automaton of en route controller is represented in Figure 5.

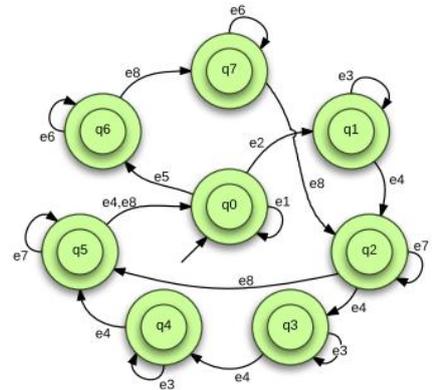


Figure 5. Deterministic Automaton of En route Controller

#### B. APP Automaton

Approach controller is defined as a deterministic automaton:

$$APP\_Automaton = (X, E, f, x_0, X_m) \quad (15)$$

APP Automaton has seven discrete states.

- $q_0$  is initial state which is defined as no action
- $q_1$  denotes direct routing for second flight (departure flight)
- $q_2$  denotes delaying motion for second flight which is applied with reducing of speed (ROCD)
- $q_3$  denotes horizontal motion for second flight at a defined altitude. In  $q_3$ , departure flight are climbed to a defined altitude, moved along track and climbed to original route for separation with arrival flight
- $q_4$  denotes direct routing for first flight
- $q_5$  denote delaying motion for second flight with vector for spacing
- $q_6$  denote delaying motion for second flight with reducing of speed

$$X = \{q_0, q_1, q_2, q_3, q_4, q_5, q_6\} \quad (16)$$

$$x_0 = q_0 \quad (17)$$

APP Automaton has seven finish states:

$$X_m = \{q_0, q_1, q_2, q_3, q_4, q_5, q_6\} \quad (18)$$

The finite set of events:

$$E = \{e_1, e_2, e_3, e_4, e_5, e_6\} \quad (19)$$

We define eight different helper functions in order to describe events. The helper function  $a_0$  controls routes of arrival flight and departure flight. If any intersection has become in routes,  $a_0$  will become 1 otherwise become 0.  $a_1$  controls routes of departure flight and another departure flight in order to define intersection situation. Separation must be controlled between two flights,  $a_2$  is defined as vertical separation (1000ft) check function.  $a_3$  is defined as horizontal separation (3nm) check function for this purpose.  $a_4$  controls separations between two sequenced arrival flights, if separations are ensured,  $a_4$  will become 1. We have a function ( $a_5$ ) with the aim of preventing of closing between sequenced flights. If first aircraft is more speed than second aircraft, function will become 1. Last two functions are related with separation check between all flights.  $a_6$  is a function which controls separation of a departure flight with all other departure flights. If all separation is ensured,  $a_6$  will become 1 otherwise become 0.  $a_7$  function makes this control between an arrival flight and other all arrival flights.

The relation between events and helper functions are:

$$\cap \rightarrow \text{and}, \cup \rightarrow \text{or}, a \rightarrow a \text{ is } 1, \bar{a} \rightarrow \text{not } a (a \text{ is } 0)$$

$$\begin{aligned} e_1 &= a_0 \bar{a}_2 \bar{a}_3 \\ e_2 &= ((a_0 \cap a_2) \cup (a_0 \cap \bar{a}_2 \cap a_3)) \cap a_6 \\ e_3 &= a_1 \bar{a}_2 \bar{a}_3 \\ e_4 &= ((a_1 \cap a_2 \cap a_5) \cup (a_1 \cap \bar{a}_2 \cap a_3 \cap a_5)) \cap a_6 \\ e_5 &= \bar{a}_4 \\ e_6 &= a_4 \cap a_5 \cap a_7 \\ e_7 &= (a_0 \cap \bar{a}_2) \cup (a_0 \cap a_2 \cap \bar{a}_3) \cup \bar{a}_6 \\ e_8 &= (a_1 \cap \bar{a}_2) \cup (a_1 \cap a_2 \cap \bar{a}_3) \cup \bar{a}_6 \\ e_9 &= \bar{a}_4 \cup \bar{a}_7 \end{aligned} \quad (20)$$

The transition functions are defined as:

$$\begin{aligned} f : X \times E \rightarrow X \\ \begin{aligned} f(q_0, e_2) &= q_0 & f(q_2, e_2) &= q_2 & f(q_5, e_8) &= q_6 \\ f(q_0, e_4) &= q_0 & f(q_2, e_7) &= q_3 & f(q_5, e_9) &= q_6 \\ f(q_0, e_6) &= q_0 & f(q_3, e_2) &= q_3 & f(q_6, e_4) &= q_6 \\ f(q_0, e_1) &= q_1 & f(q_3, e_7) &= q_0 & f(q_6, e_6) &= q_6 \\ f(q_0, e_3) &= q_4 & f(q_4, e_4) &= q_4 & f(q_6, e_8) &= q_6 \\ f(q_0, e_5) &= q_5 & f(q_4, e_8) &= q_5 & f(q_6, e_9) &= q_0 \\ f(q_1, e_2) &= q_1 & f(q_5, e_4) &= q_5 & & \\ f(q_1, e_7) &= q_2 & f(q_5, e_6) &= q_5 & & \end{aligned} \end{aligned} \quad (21)$$

And directed graph representation of deterministic automaton of approach controller is represented in Figure 6.

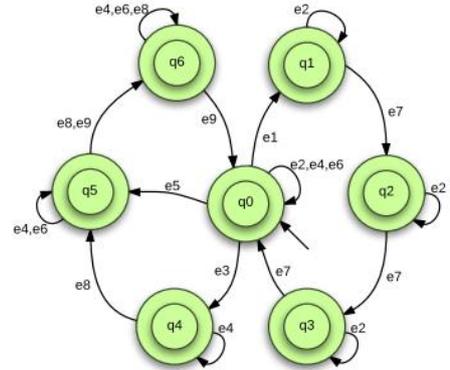


Figure 6. Deterministic Automaton of Approach Controller

## V. ALGORITHM FOR IMPLEMENTATION

In this section, models which are developed in Section IV for two flights are generalized for all flights in sector with two different algorithms and complexity analysis of these algorithms are discussed.

### A. ACC Algorithm

Structure of “ACC Controller Algorithm” is constructed and used for implementation of modelling of en route controller which controls all flights in the sector.

**Algorithm 1: ACC Controller Algorithm**

**input** : Flight plans of all enroute flights and current state variables  
**output** : Controller actions and new flight routes of all enroute flights

- 1 **if** a new aircraft comes to sector **then**
- 2   **Check** separation of all flights in sector
- 3   **if** any unseparated flight exist **then**
- 4     **for** all unseparated flights in sector **to do**
- 5       **Set** flight1 to most old aircraft in unseparated flights
- 6       **for** all unseparated flights with flight1 **to do**
- 7          **Set** flight2 to most close unseparated flight to flight1
- 8          **Generate** controller action from ACC Automata for flight1 and flight2
- 9          **Set** new flight1 and new flight2 routes to new flight routes

In this algorithm, each flight is compared individually with all flights in sector, predicted losses of separation are determined and flights which have loss of separation are saved. Then, the highest level of conflicting flight trajectory is taken from saved separation losses. This flight is compared with other flights one by one which have loss of separation; this comparison is made between two flights sequentially. These two flights are passed from ACC Automaton and controller action is determined. This procedure is applied between all conflicting flight trajectories. This algorithm is run when a new aircraft comes to the sector.

**B. APP Algorithm**

As well as “ACC Controller Algorithm”, we use “APP Controller Algorithm” for approach.

First, arrival flights are sequenced relative to estimated arrival times. Then, estimated losses of separations are determined in three different types. These types are loss of separation between two arrival flights, loss of separation between two departure flights and, loss of separation between departure and arrival flights.

In second part of algorithm, three loops are executed in a loop. These three loops try to find a controller action with APP Automaton to three different types of separation losses. These three loops are repeated until all separations are ensured in sector. This algorithm is run when a new aircraft comes to the sector. Just like the en route phase the algorithm always priorities the highest level of conflict as the beginning of deconflicting.

**C. Computational Complexity of Algorithms**

We note that the presented algorithms have two parts which are conflict detection and separation assurance. These two parts have different computational complexity. The main difference between these parts is that first part is not affected from number of flight, which have loss of separation, in sector but second part is affected.

In first part of the en route and approach algorithms, each aircraft trajectory is checked with other aircrafts’ trajectories for determination of conflicts. So the conflict detection part of the algorithms are affected from number of flights in sector

and number of way points of each aircraft. In en route algorithm, the computation time of first part is proportional with (22). This situation is presented in Figure 7 for en route algorithm and Figure 8 for approach algorithm.

$$\propto \sum_{i=1}^m \sum_{j=1}^{n_i} \sum_{\substack{k=1 \\ k \neq j}}^{n_i} (wp_j \times wp_k) \quad (22)$$

In (22); m is the number of flight levels; n<sub>i</sub> is the number of flights in flight level i; wp<sub>j</sub> is number of way point in flight j and wp<sub>k</sub> is number of way point in flight k.

**Algorithm 2: APP Controller Algorithm**

**input** : Flight plans of all approach flights and current state variables  
**output** : Controller actions and new flight routes of all approach flights

- 1 **if** a new aircraft comes to sector **then**
- 2   **Generate** sequence for arrival flights from first coming aircraft to last aircraft
- 3   **Check** separation of all flights in sector
- 4   **repeat**
- 5     **if** any unseparated flight exist between arrivals **then**
- 6       **for** all unseparated flights between arrivals **to do**
- 7          **Set** flight1 to first coming aircraft in unseparated arrival flights
- 8          **for** all unseparated arrival flights with flight1 **to do**
- 9            **Set** flight2 to most close unseparated arrival flight to flight1
- 10          **Generate** controller action from APP Automata for flight1 and flight2
- 11          **Set** new flight1 and new flight2 routes to new flight routes
- 12     **if** any unseparated flight exist between arrivals and departures **then**
- 13        **for** all unseparated flights between arrivals and departures **to do**
- 14          **Set** flight1 to first coming aircraft in unseparated arrival flights
- 15          **for** all unseparated departure flights with flight1 **to do**
- 16            **Set** flight2 to most close unseparated departure flight to flight1
- 17          **Generate** controller action from APP Automata for flight1 and flight2
- 18          **Set** new flight1 and new flight2 routes to new flight routes
- 19     **if** any unseparated flight exist between departures **then**
- 20        **for** all unseparated flights between departures **to do**
- 21          **Set** flight1 to first departing aircraft in unseparated departure flights
- 22          **for** all unseparated departure flights with flight1 **to do**
- 23            **Set** flight2 to most close unseparated departure flight to flight1
- 24          **Generate** controller action from APP Automata for flight1 and flight2
- 25          **Set** new flight1 and new flight2 routes to new flight routes
- 26 **until** any unseparated flight does not exist

In approach algorithm, the computation time of first part is sum of three conflict detection algorithms which are between arrivals and arrivals, departures and arrivals, departures and departures; each conflict detection algorithm is proportional with (23)

$$\propto \sum_{i=1}^n \sum_{\substack{j=1 \\ j \neq i}}^m (wp_i \times wp_j) \quad (23)$$

In (23); wp<sub>j</sub> is number of way point in flight j and wp<sub>k</sub> is number of way point in flight k for three of conflict detection algorithms. n is the number of flights in arrival, m is the number of flights in departures for conflict detection between arrival and departure. n equals to m, and n is the number of flights in departures for conflict detection between departure and departure. n and m are the number of flights in arrivals for conflict detection between arrival and arrival. The algorithms

have same computation times for same number of arrivals and departures. This situation is presented in Figure 8.

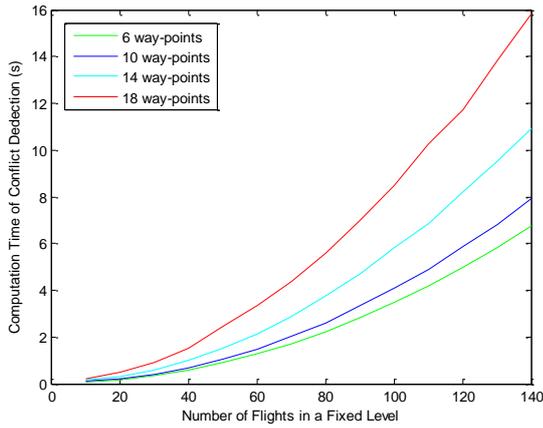


Figure 7. CD for Enroute

In second parts of algorithms, a set of control strategy is applied to conflicting flight trajectories one by one. So this part of algorithms is affected from number of aircrafts which have loss of separation and each aircraft is checked with other aircrafts for assurance of separation after controller action is tried; this is a conflict detection check for only one aircraft which is presented in Figure 9 for en route algorithm and Figure 10 for approach algorithm. So this part of algorithm is also affected from number of flights in the sector and the number of way points of each aircraft.

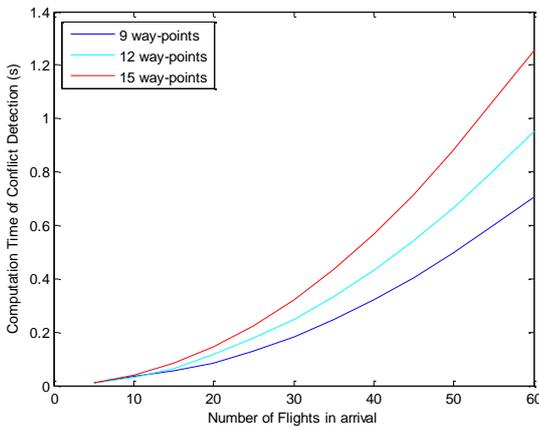


Figure 8. CD for Approach

In en route algorithm, the computation time of second part is proportional with (24)

$$\propto \sum_{i=1}^m \sum_{j=1}^{n_i} \sum_{k=1}^l a_k (wp_j \times wp_k) \quad (24)$$

In (24); m is the number of flight levels; n<sub>i</sub> is the number of flights in flight level i; l is the number of flights which have loss of separation; wp<sub>j</sub> is number of way point in flight j and wp<sub>k</sub> is number of way point in flight k. In this part of

algorithm, computation time is also proportional with number of controller actions which is tried until solution (a<sub>k</sub>).

In approach algorithm, the computation time of second part is proportional with (25)

$$\propto \sum_{i=1}^n \sum_{j=1}^m a_j (wp_i \times wp_j) \quad (25)$$

In (25); n is the number of flights in arrival, m is the number of flights in arrival, which have loss of separation, for conflict detection between one arrival flight and other arrival flights. Here n is the number of flights in departure, m is the number of flights in departure, which have loss of separation, for conflict detection between one departure flight and other departure flights.

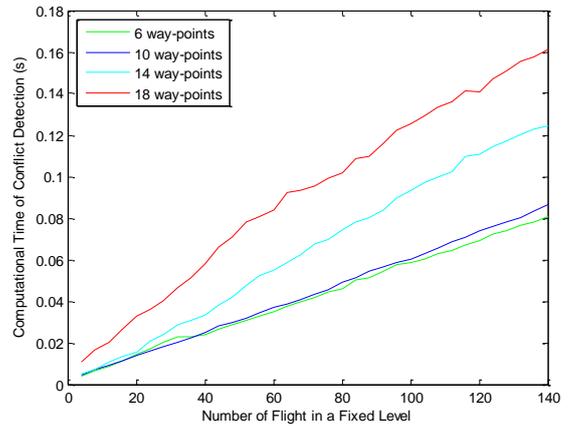


Figure 9. CD for 1 aircraft in Enroute

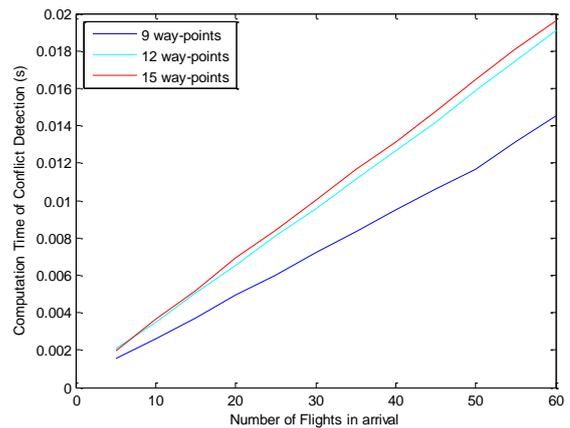


Figure 10. CD for 1 aircraft in Approach

In real traffic data, number of loss of separation increase with increasing number of flights in sector, so separation assurance part of algorithm have a strong power law characteristic which is presented in Figure 11 for en route and Figure 12 for approach. These figures are obtained with three different aircraft set, each having a ten way point index.

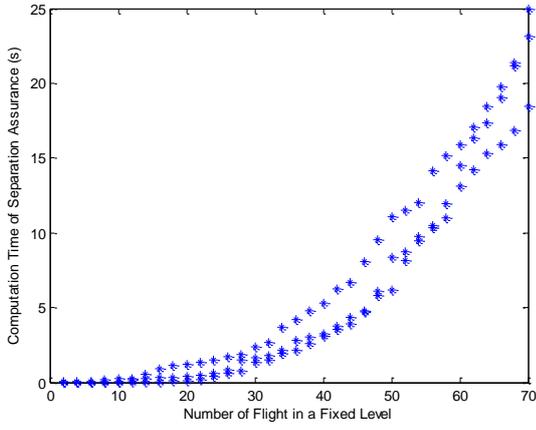


Figure 11. SA for Enroute

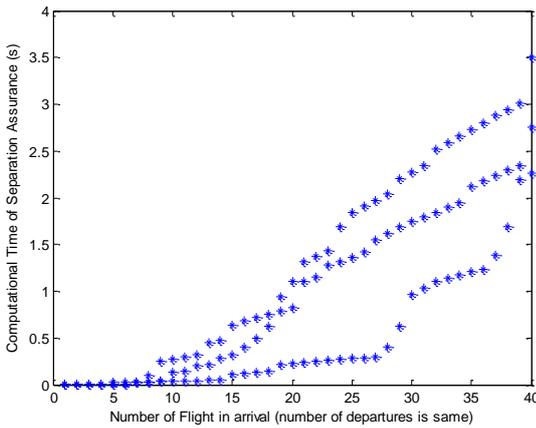


Figure 12. SA for Approach

## VI. IMPLEMENTATIONS AND RESULTS

Implementations are made with ALLFT data from the European Airspace, the ALLFT data depicts the flight trajectories as planned and implemented.

### A. Implementation with ALLFT Data for En route

We used real flight data from 1 March 2011 for implementations. We use two different sets for en route data sets. In first set, data are consists of all flights from 11:00 to 11:15 in Istanbul ACC and second data set are consist of all flights from 11:00 to 13:00. En route controller is responsible from all flights in sector, and vertical limits of ACC are 23500 ft and upper. In first set, 18 flights are appeared at 15 minutes in sector. Two of them will have loss of separation. Result of ACC Controller Algorithm is vector for spacing for one aircraft. In second set, 102 flights appear at 120 minutes in sector. It is seen that thirteen of them will have loss of separation. When separations are checked, it is seen that one aircraft will has loss of separation with maximum two aircrafts at same time. Results of ACC Controller Algorithm are ATC actions for seven aircrafts which have two altitude changes, one direct routing, one reducing of speed and three delaying motion with vector for spacing. Figure 13 and Figure 14

shows all flights with violet in set, and shows intervened flights with yellow.

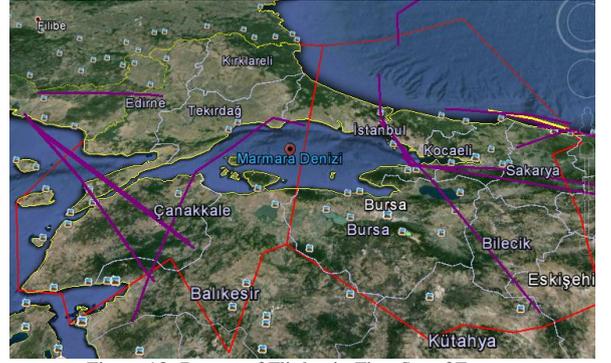


Figure 13. Routes of Flights in First Set of En route

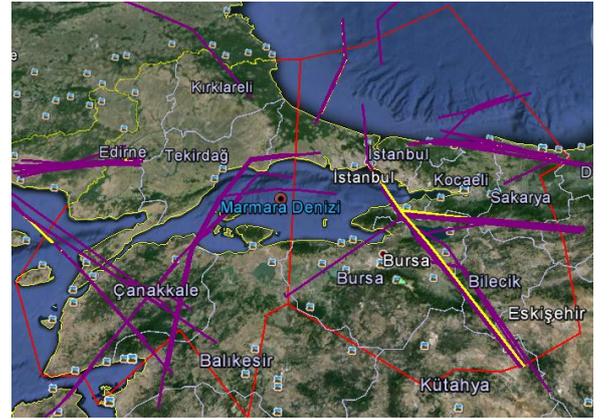


Figure 14. Routes of Flights in Second Set of En route

### B. Implementation with ALLFT Data for Approach

In this implementation, we use two different sets for approach implementations. In first set, we use flights from 18:00 to 20:00 for APP sector which including to Sabiha Gokcen Airport and second set consist of flights from 18:00 to 20:00 for APP sector which including to Ataturk Airport. The vertical limits of APP are 1500ft and 23500ft. In first set, 13 flights appeared in arrival and 19 flights appeared in departure from 18:00 to 20:00. Two of arrival flights and two of departure flights will have loss of separation. One of arrival flights takes an ATC action, which is speed change, after arrival flights are sequenced and one departure flight takes vector for spacing for separation assurance. In second set, 24 flights are appeared in arrival and 31 flights appear in departure from 18:00 to 20:00. Two of arrival flights and six of departure flights will have loss of separation. One of arrival flights takes an ATC action, which is speed change, after arrival flights are sequenced and one of departure flights take reducing of speed action, two of departure flights take vector for spacing action. In this way, all separations are ensured. Figure 15 and Figure 16 shows all departure flights with violet and all arrival flights with blue in set, and shows intervened flights with yellow.



Figure 15 .Routes of Flights to Approach for Sabiha Gokcen Airport

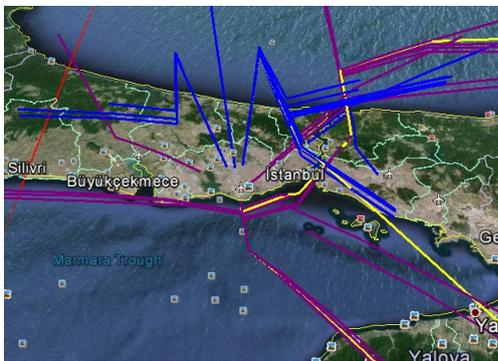


Figure 16. Routes of Flights to Approach for Ataturk Airport

## VII. CONCLUSIONS

In this paper, we have presented two different hybrid system models for the decision process of Air Traffic Controller in en route and approach operation. By using these models, we have designed an automation algorithm for achieving separation assurance. By using real traffic data, we have shown that the algorithm can detect conflicts and recommend solutions at seconds. The workload of controllers can be reduced with proposed automation tools and capacity of current system can be enhanced.

We are currently working to further extend the hybrid systems model and automation feature to flow control at SID and STAR level.

## REFERENCES

- [1] Air Transport Action Group, Revolutionising Air Traffic Management, November 2014
- [2] Joint Planning and Development Office 2004, Next Generation Air Transportation System Integrated Plan: <http://www.jpdo.gov>
- [3] SESAR Master Plan: <http://www.eurocontrol.int/sesar>
- [4] NextGen, Concept of operations for the next generation air transport system, 2007, <http://www.jpdo.gov/library/NextGen v2.0.pdf>
- [5] H. Emami, F. Derakhshan and S. Pashazadeh, A New Prioritization Method for Conflict Detection and Resolution in Air Traffic Management, Journal of Emerging Trends in Computing and Information Sciences, VOL. 3, NO. 7 July 2012

- [6] D. Patchev and A. Tentov, New Concept of Automated Air Traffic Control System, ATACCS'2012, London, UK, 2012
- [7] T. Prevot, T. Callantine, P. Lee, J. Mercer, V. Battiste, E. Palmer and N. Smith, Co-Operative Air Traffic Management: Concept and Transition, AIAA 2005-6045, San Francisco, California, 2005
- [8] H. Erzberger, Transforming the NAS: The Next Generation Air Traffic Control System, NASA/TP-2004-212828, 2004
- [9] A.M. Bayen, P. Grieder and C.J. Tomlin, A Control Theoretic Predictive Model for Sector-based Air Traffic Flow, AIAA 2002-5011, San Francisco, California, 2002
- [10] Andrews, J. W. , Capacity Benefits of the Advanced Airspace Concept (AAC): A Preliminary Investigation. MIT Lincoln Laboratories Report No. 42PM-AATT-0014, Aug. 17 2001
- [11] W. Glover, J. Lygeros, A Stochastic Hybrid Model for Air Traffic Control Simulation, HSCC 2004
- [12] I. Lympelopoulous, A. Lecchini, W. Glover, J. Maciejowski and J. Lygeros, A Stochastic Hybrid Model for ATM processes, Technical Report, Cambridge, vol. AUT07-15, no. CUED/F-INFENG/TR.572, 2007
- [13] Eurocontrol Experimental Centre, User Manual for the Base of Aircraft Data (BADA) Revision 3.9 (2011), [http://www.eurocontrol.int/eec/public/standard\\_page/proj\\_BADA\\_documents\\_39.html](http://www.eurocontrol.int/eec/public/standard_page/proj_BADA_documents_39.html)
- [14] Garcia-Avello, C. and Swierstra, S., "Human Role in ATM: Support for Decision Making", ATM: Support for Decision Making Optimization-Automation, 10 (1), 10-11, AGARD Report 825, Budapest, 1997
- [15] ICAO, Procedures for Air Navigation Services Air Traffic Management Doc.4444; ICAO, Montreal, 2009
- [16] DHMİ, AIP, Ankara, 2013.
- [17] C.G.Cassandra, S.Lafortune, Introduction to Discrete Event Systems, Second Edition, Springer, 2008
- [18] J.H.Hopcroft, R.Motwani, J.D.Ullman, Introduction to Automata Theory Languages and Computation, Second Edition, Pearson Education, 2001