Automatic Air Traffic Control: Application to Approach

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Abstract

With the predicted increase of air traffic along the next years, it is worth the development of tools that can assist the air traffic controllers in order to reduce their workload. This work proposes such a tool, which controls the arrival traffic since the end of cruise till the FAP. This tool intends to guarantee the separation between the aircraft and also to be TMA independent. The objective of an efficient arrival rate of the aircraft to the FAP is also considered. In order assure that this tool can be applied in a real situation, the aircraft's movement was modeled closest possible to the reality, being also considered uncertainty in horizontal and vertical speed. The decision system developed gives path shortening, path extension, holding and altitude change orders. The results obtained show that this tool fulfills the objectives of maintaining separation and working in various TMAs. The arrival rate of the aircraft to the FAP is related with the approach considered for the decision system. The results show that for approaches that have better arrival rates of the aircraft to the FAP, the number of orders assigned to them increase. In most situations, the decision system run in an acceptable period of time.

Keywords: Automatic air traffic control, Approach, Conflict detection and resolution, Uncertainty

1 Introduction

1.1 Motivation

The medium-term forecast, published by Eurocontrol on February 2014 [1], suggests that besides the crisis scenario in Europe, the air traffic level will increase along the next years. With this situation, the quantity of flights demanding to enter in TMA areas (to arrive to a certain destination) will increase. However, there is a limit of traffic that can arrive to the TMA. If that limit is exceeded, the aircraft have to delay their arriving time, causing delays and the increase of fuel consumption and of environmental pollution. The quantity of aircraft that can arrive to a TMA is limited by two factors: airport and sector capacity. The second factor leads that there is a maximum number of aircraft that can be controlled in the TMA. As consequence, it is worth to develop tools and methods that can help in the air traffic controllers task, reducing their workload and so increasing the sector capacity. Such methods and tools are for example Point Merge System [2] and Conflict Detection and Resolution Algorithms [3].

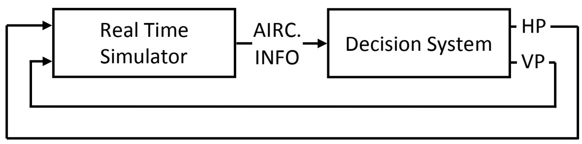
1.2 Work Objectives

This work intends to be an alternative of a software tool that makes the conflict detection and resolution, suggesting a set of orders to apply to the aircraft, given a flight scenario. The flight scenario is composed by a set of aircraft in the arrival phase, being considered and controlled its movement since the final cruise zone till the FAP. This tool was developed to be TMA independent: it must work in all TMAs (or at least most of them). It is also concern of the program to guarantee an ordered and maximum expedite possible arrival of the aircraft to the FAP. Note that, the objectives of guaranteeing safety and being expedite are conflicting, because the more uncertainty is added in the aircraft's movement (to guarantee maximum separation safety), the more unnecessary space is created between aircraft. This unnecessary space penalizes the rate of arrival of aircraft to the FAP. Conciliate these two factors is a challenge.

In order to guarantee this work can be applied in a real situation, real aspects such as the use of real STARs of the TMAs and the use of dynamics and uncertainty in aircraft's movement, were considered. It was also concern that the type of orders given by the software are the same type or they can be easily translated to the type of orders given by the controllers. This is an important feature in order to be possible to implement this tool in a real situation.

2 Real Time Simulator

The simulator developed is composed by two components as shown in figure 1. The first one sim-



HP – Horizontal Path
VP – Vertical Path

Figure 1: Simulator modules

ulates a scenario, the closest possible to the reality, which consists in a set of flights that are in or arriving to the simulation area. The second block represents the decision system, which receives the necessary information from the aircraft and produces the orders to apply to them every ΔT minutes. These orders consist in changes in horizontal or vertical path (due to time restrictions, the speed orders were not considered). This section will describe the first block, being the other described in section 3.

2.1 Aircraft Movement

The horizontal path the aircraft follow is defined through a set of way points. These way points are coordinates (latitude and longitude) of a specific point in space. An example of a horizontal path is shown in figure 2. The respective way point list is

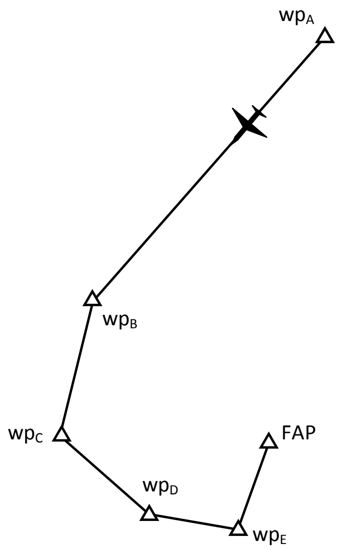


Figure 2: Aircraft horizontal path

$[wp_A, wp_B, wp_C, wp_D, wp_E, FAP]$. Also, when necessary, the execution of a hold may be assigned to the aircraft. In this case, the aircraft goes to a holding fix and executes a pattern as represented in figure 3.

In this simulator the aircraft follow a reference M or CAS, depending if they are above or below the Mach transition altitude, respectively. For each aircraft in simulation it is set its M/CAS schedule which is within a certain interval – $\text{M/CAS}_{\text{min}} \leq \text{M/CAS} \leq \text{M/CAS}_{\text{max}}$. This range of variation not only represents the deviation from the nominal schedules for each aircraft, but also the uncertainty in horizontal speed which is caused by factors such as deviations from ISA atmosphere, wind uncertainty, etc.

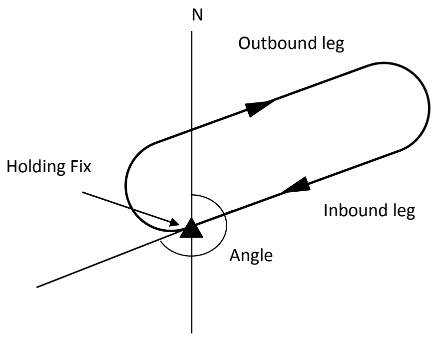


Figure 3: Hold pattern example

Relatively to the vertical path, in this work it is considered that the aircraft remains at the same altitude level, till a certain distance, when it begins a continuous descent to the final altitude. This is done unless the aircraft receives an order to change to another altitude (lower than the current one) in order to maintain separation from other aircraft. The typical altitude profile is represented in figure 4. This descent is executed with a constant

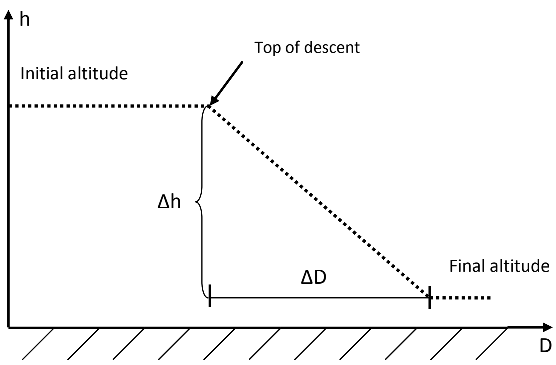


Figure 4: Altitude profile

ROD, which may be also within a certain interval – $\text{ROD}_{\text{min}} \leq \text{ROD} \leq \text{ROD}_{\text{max}}$. As for the horizontal path, in the vertical profile the aircraft has also a list of reference altitudes: $[[h_{ref\ 0}, d_0], [h_{ref\ 1}, d_1]]$. The $h_{ref\ i}$ are the reference altitudes and the d_i the aircraft's Remain Path to the FAP Length – RPFL – till which the correspondent altitude is valid. When it reaches this distance it must begin the descent to the next reference altitude.

2.2 Aircraft Dynamics

In this simulator, the aircraft movement is done based on the dynamical model of [4]. However, the model presented in the referred reference is only valid in a Cartesian coordinate system (x, y, z) or when the curvature of the Earth can be neglected, being not the case of this work. As a result, the first two equations of the model are replaced by a function ($f_{\varphi,\lambda}$), which allows to represent correctly the movement of the aircraft. More details about this function will be given bellow. The resulting model is as follows:

$$\begin{bmatrix} \dot{\varphi}, \dot{\lambda} \\ \dot{h} \\ \dot{v_{TAS}} \\ \dot{\psi} \\ \dot{m} \end{bmatrix} = \begin{bmatrix} \dot{f}_{\varphi,\lambda}(\varphi, \lambda, h, GS_N, GS_E) \\ v_{TAS}\sin(\gamma) + w_D \\ -\frac{C_D S \rho(h)}{2}\frac{{v_{TAS}}^2}{m} - g\sin(\gamma) + \frac{T}{m} \\ \frac{C_L S \rho(h)}{2}\frac{v_{TAS}}{m}\sin(\phi) \\ -\eta T \end{bmatrix} \tag{1}$$

Where:

$$GS_N = v_{TAS}\cos(\psi)\cos(\gamma) + w_N \tag{2}$$

$$GS_E = v_{TAS}\sin(\psi)\cos(\gamma) + w_E \tag{3}$$

The aircraft state variables are latitude (φ), longitude (λ), altitude (h), TAS (v_{TAS}), heading (ψ) and mass (m). The input variables, whose values are determined by the controllers are thrust (T), bank angle (ϕ) and the flight path angle (γ). The wind is represented as w_N (wind North component), w_E (wind East component) and w_D (wind down component), the last one is set to zero in this work. GS_N and GS_E are the ground speed components of North and East, respectively. The remain symbols are drag coefficient (C_D), lift coefficient (C_L), wing area (S), altitude density ($\rho(h)$), gravitational constant ($g = 9.81\text{m/s}^2$) and TSCF (η). Relatively to these parameters, all the details and formulas for their calculation can be found in BADA document [5]. Note that, in this work, all parameters were calculated considering ISA atmosphere.

The discretization of these equations system is done through the Euler's Progressive Method, which for:

$$\dot{x} = f(t, x(t)) \tag{4}$$

yields:

$$x(t_0 + \Delta t) = x(t_0) + f(t_0, x(t_0)) \cdot \Delta t \quad (5)$$

The $f_{\varphi,\lambda}$ function calculates, given a position and GS, the destination latitude ($\varphi_{dest.}$) and longitude ($\lambda_{dest.}$), assuming constant bearing (TC) – movement through a rhumb line. The expressions to perform the function are shown below[1] (all variables in SI):

$$\begin{aligned}
d &= \sqrt{{GS_N}^2 + {GS_E}^2} \cdot \Delta t \\
TC &= \arctan 2(GS_E, GS_N) \\
R &= R_{Earth} + h \\
\alpha &= \frac{d}{R} \\
\varphi_{dest.} &= \varphi_{dep.} + \alpha \cdot \cos(TC) \\
\Delta\varphi' &= \ln\left(\frac{\tan\left(\frac{\pi}{4} + \frac{\varphi_{dest.}}{2}\right)}{\tan\left(\frac{\pi}{4} + \frac{\varphi_{dep.}}{2}\right)}\right) \\
\text{case } \varphi_{dest.} &= \varphi_{dep.} : \\
q &= \cos(\varphi_{dep.}) \\
\text{case } \varphi_{dest.} &\neq \varphi_{dep.} : \\
q &= \frac{\varphi_{dest.} - \varphi_{dep.}}{\Delta\varphi'} \\
\Delta\lambda &= \frac{\alpha \cdot \sin(TC)}{q} \\
\lambda_{dest.} &= (\lambda_{dep.} + \Delta\lambda + \pi) \bmod 2\pi - \pi
\end{aligned} \quad (6)$$

Although in 6 it is added the aircraft's altitude to the Earth radius, in practice it is not necessary since $R_{Earth} \gg h$. The $\Delta\lambda$ is obtained considering the shortest route ($< 180°$).

As referred before, the aircraft inputs (T, ϕ, γ) are determined by controllers, in order to the aircraft perform the desired movement. The variables controlled are M or CAS (by T), aircraft direction and path (by ϕ) and the ROD or altitude (by γ). The type of controllers adopted were proportional or proportional-integral with anti-windup.

[1] The equations were taken from http://www.movable-type.co.uk/scripts/latlong.html, last consulted February 2014

3 Decision System

Every ΔT minutes a "photo" of the simulation area is taken, which gives to decision system the following information about each aircraft: latitude, longitude, altitude, true course and ground speed. With this information and knowing the reference horizontal path and reference altitudes of each aircraft, the orders for each aircraft are produced. As referred before, these orders consist in changes of horizontal and/or vertical profile. Note in a real situation there is a period of time since the information of the aircraft are taken and till they receive the ATC orders. In the tool developed this period of time is taken in consideration and will be referred as "black zone".

3.1 Uncertainty Modeling

As referred in section 2 there is uncertainty in aircraft horizontal and vertical speed, which lead to uncertainty in position along the time. The sources of uncertainty are for example each pilot different speed schedule, deviations from ISA atmosphere (which for the same M/CAS leads to different value of TAS), uncertainty in the wind, delays in maneuvers or ATC orders execution, etc. In horizontal movement it is considered uncertainty in M/CAS and in vertical movement in ROD. The example below demonstrates that from the point view of ATC, all sources of uncertainty for the horizontal speed can be transfered to uncertainty in M/CAS. Consider that at a certain altitude, with ISA atmosphere, the aircraft has a certain CAS_{ref}. For this CAS and pressure it can be written:

$$CAS_{ref} \overset{p_{ISA}}{\Longrightarrow} TAS_{p_{ISA}} \quad (7)$$

If there is a variation of pressure, $p_{ISA} + \Delta p$, this yields:

$$CAS_{ref} \overset{p_{ISA}+\Delta p}{\Longrightarrow} TAS_{p_{ISA}} + \Delta TAS \quad (8)$$

But this ΔTAS is equivalent to a ΔCAS at ISA conditions:

$$CAS_{ref} + \Delta CAS \overset{p_{ISA}}{\Longrightarrow} TAS_{p_{ISA}} + \Delta TAS \quad (9)$$

For each aircraft it is considered that it M/CAS may be within a M/CAS_{min} and a

M/CAS_{max} and it ROD between a ROD_{min} and a ROD_{max}. However, since the ROD has a direct relation with the GS the limits of uncertainty in ROD will vary according with M/CAS. To take into account the uncertainty in the decision system, instances of the aircraft are considered, which each of them represent a possible M/CAS-ROD scenario. These instances must be chosen in such way that assures the uncertainty zone is well represented.

3.2 Orders Assignment

Consider the scenario of figure 5, with the aircraft 6 to be assigned an order. The original way

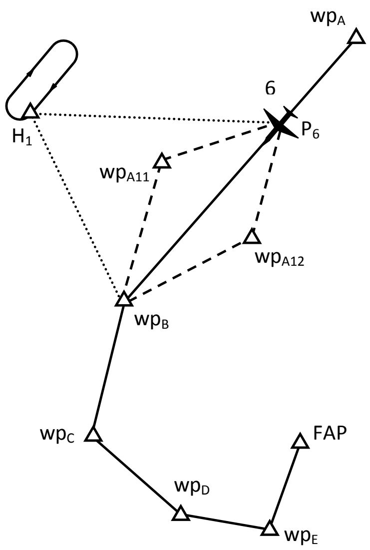


Figure 5: Possible orders to assign to the aircraft 6

point list is [wp_A, wp_B, wp_C, wp_D, wp_E, FAP]. In first place the orders of path shortening are tested. In the example of figure 5, the paths would be tested in the following order:

1. $[P_6, wp_E, FAP]$;

2. $[P_6, wp_D, wp_E, FAP]$;

3. $[P_6, wp_C, wp_D, wp_E, FAP]$.

P_6 is the estimate position of the aircraft when it receives the order, calculated taking into account the black zone. When an aircraft receives an order to change its path the first way point of its way point list (wp_A) is replaced by its estimated position (P_6). Note that, in this process the path [P_6, FAP] is not considered. This is to avoid the arrival of the aircraft to the FAP in a direction much different of its landing direction. Also, in this type of orders, a path which do not allows for the aircraft to be in a certain altitude in its RPFL it is not validated.

If none of the path shorting options are valid, then the aircraft's original path ([wp_A, wp_B, wp_C, wp_D, wp_E, FAP]) is tested. If this is accepted, in practice no order in horizontal path is given to aircraft, since it maintains the same. Otherwise, if this path is also not valid, possible extensions for the current path are tested, as represented in figure 5. If a path extension order cannot be assigned to the aircraft the only remain option is the aircraft to perform a holding during a certain time. An possible path for the aircraft in this case is represented in figure 5: $[P_6, H_1, wp_B, wp_C, wp_D, wp_E, FAP]$. When the aircraft reaches H_1, it executes the holding during a certain period of time.

Besides horizontal orders, the aircraft may also receive altitude change orders. The valid altitudes that the aircraft may change, when receiving an altitude change order, are the ones below its current altitude and till 5000 ft less than it. When assigning an altitude change, the aircraft descents to the available altitude closest to the current one. The vertical profile of an aircraft that receives an altitude change order is as represented in figure 6. Considering the initial list of reference altitudes is

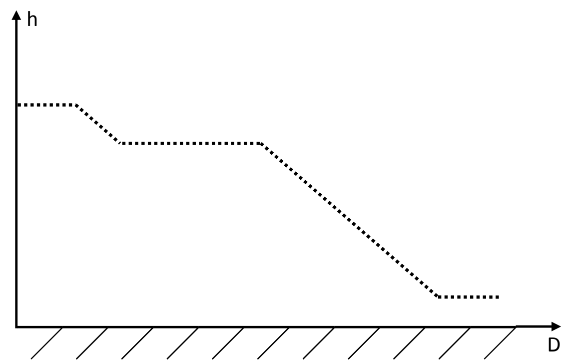


Figure 6: Altitude profile after altitude change order

$[[h_{ref0}, d_0], [h_{ref1}, d_1]]$, to apply the altitude change to the aircraft the decision system changes the list to $[[h_{ref0} - \Delta h, d_0 - \Delta d], [h_{ref1}, d_1]]$. Where Δh is the altitude to loose and since the altitude is lower, the aircraft needs less horizontal space to descent to the next reference altitude, being subtracted Δd space to d_0.

Finally, there is a special type of order implemented in this work, when the orders described above cannot solve he conflict situation. This order is represented in figure 7. The holding is used or

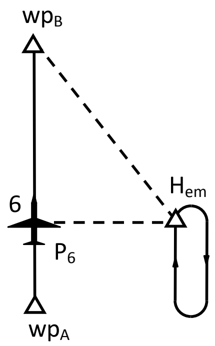


Figure 7: Emergency maneuver

to perform a descent or as a normal holding point, depending on the situation.

3.3 Conflicts Detection and Resolution

In this tool, the conflict detection is done using a queue, which also determines the order of arrival to the FAP (or FAPs, for TMAs with multiple landing runways) of the aircraft. The queue is an important element, because it allows a self-organization of the algorithm in order to it work properly. An example is shown in figure 8.

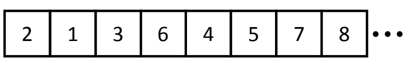


Figure 8: Queue example

In detecting conflicts three zones are considered, which depends on the aircraft flight phase. The first one is since the aircraft enters in the simulation area till it begins the descent to the FAP altitude. This zone comprises most of the aircraft's path, where it maintains a constant altitude in almost of its path in this zone (or all, if no change altitude order is received). Then the second zone begins, which comprises the begin of the aircraft descent till a predefined RPFL (D_{Z3} in figure 9), where the zone 3 starts, ending in the FAP. This predefined RPFL is set 2 times the minimum horizontal separation practiced inside RADAR vectoring area. For the case at which both aircraft are in zone 3 and go to the same FAP, they must be horizontally separated. If they are both in zone 3 and go to different FAPs, they must be vertically separated of each other. In this case, however, the aircraft must reach the final altitude some NM before reaching their FAP, because in this final zone they will not have horizontal separation from the aircraft that go to a different FAP. These zones are represented in figure 9. Note that generally there

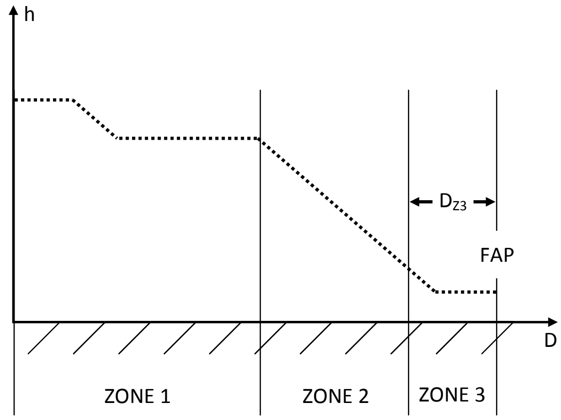


Figure 9: Detecting conflicts zones

may be conflicts between aircraft of different zones, for example an aircraft in zone 2 with other of the zone 3. In all combinations, with exception of the described before (zone 3 with zone 3), the separation can be either horizontal or vertical.

The conflict detection and resolution procedure is systematized in algorithm 1.

4 Simulation Results

Five TMAs were tested: Lisbon (LPPT), Porto (LPPR), Oslo (ENGM), Paris (LFPG) and Frankfurt (EDDF). The results obtained with the tool showed that, it works in all them. In the next

Algorithm 1 Conflict detection and resolution

```
procedure CONFLICT DETECTION AND RESOLUTION PROCEDURE
    while all instances of the aircraft in simulation area do
        for instance i do
            if T_sim > T_horizon then
                if there is queue arrival order violation then
                    return test next horizontal path
            else
                if instance i in zone 3 then
                    if there is conflict then
                        return test next horizontal path
                else if instance i in zone2 then
                    if there is conflict then
                        return test next horizontal path
                else if instance i in zone 1 then
                    if there is conflict then
                        SCAN_ALTITUDES = True
                        (default for this variable is False)
    if SCAN_ALTITUDES = True then
        Detect altitudes to avoid
        if there is available altitude then
            if it is possible to perform the altitude change then
                return altitude change
            else:
                return emergency maneuver
        else:
            if aircraft has assigned a hold then
                return emergency maneuver
            else:
                return test next horizontal path
    else:
        return accept order
```

subsections, the results obtained in Lisbon, considering two arrival scenarios, will be presented. The first one is the arrival of 30 aircraft to the simulation area within one hour and the second one is 41 arrivals also within one hour.

The parameters that will be evaluated in these simulations are the rate of arrival of the aircraft to the FAP, the number of horizontal and vertical orders assigned to the aircraft and the decision system execution time. The rate of arrival to the FAP will be evaluated through a parameter, λ_{FAP}, which represents the time between successive arrivals.

In the simulations, three simulation approaches were considered:

- conventional;
- conservative;
- relaxed.

The conservative approach is the main approach implemented in this work. In this approach the decision system operates normally, being considered all the orders described in section 3.2 and considered the uncertainty of the aircraft's movement along all its path. In the conventional approach the only orders allowed to the aircraft are follow the current path, holding, altitude changes and emergency maneuvers. In this case is also taken into account the uncertainty in all aircraft's path. The relaxed approach allows the execution of all orders implemented, but contrary to the other two approaches, the decision system only takes into account the uncertainty of the movement for aircraft whose RPFL is less than a predefined value.

4.1 Lisbon – 30 Aircraft

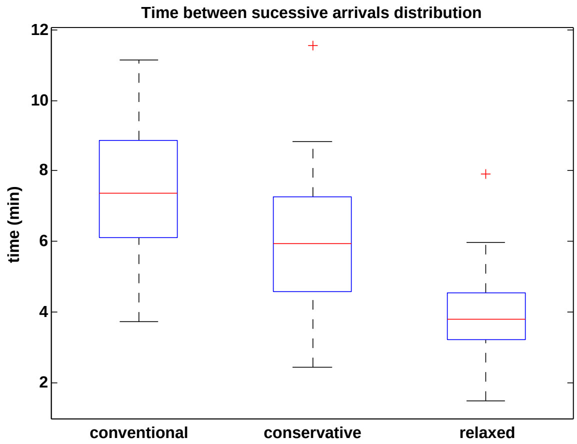


Figure 10: λ_{FAP} distribution

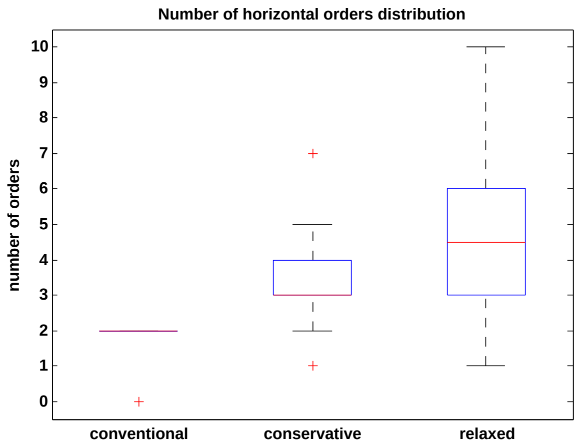


Figure 11: Number of horizontal orders per aircraft distribution

Approach	Number of aircraft
conventional	2
conservative	1
relaxed	1

Table 1: Number of aircraft which received altitude change order

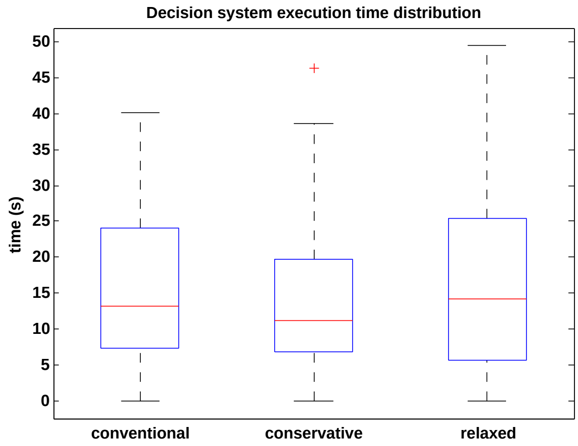


Figure 12: Decision system execution time distribution

4.2 Lisbon – 41 Aircraft

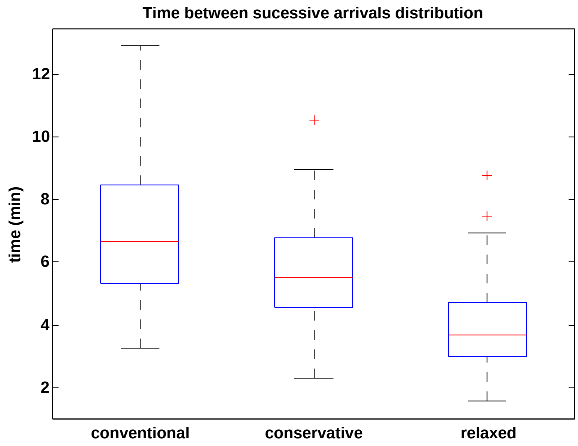


Figure 13: λ_{FAP} distribution

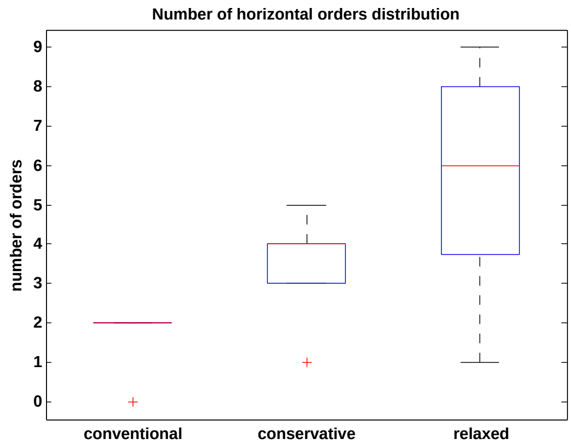


Figure 14: Number of horizontal orders per aircraft distribution

Approach	Number of aircraft
conventional	9
conservative	7
relaxed	5

Table 2: Number of aircraft which received altitude change order

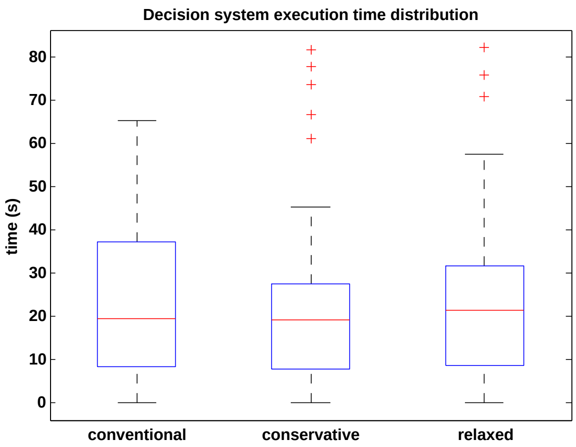


Figure 15: Decision system execution time distribution

In all simulations it is notorious that the λ_{FAP} decreases from the conventional to relaxed approach, but the price to pay to have better λ_{FAP} distributions is the increase of the number of horizontal orders assigned to the aircraft. These results are within the expected. In the case of the conventional approach, it is not allowed to assign path shortening or path extension orders. So the aircraft or follow their original path or, if it is predicted that if they continue to follow the path it will lead to a conflict, they receive order to hold. This implies that or the aircraft do not receive horizontal orders or they will receive only 2 (go to and exit hold). The holding time has to be enough to assure that when the aircraft returns to its path there is no conflicts. Since in this approach the uncertainty is considered along all the path, this will lead to a big penalty in arrival time for each aircraft. The conservative approach allows to the aircraft to recover some time, through the path shortening order and also in this situation there is no need of giving much margin in the aircraft movement, since if there is an initially unexpected conflict it is always possible use the path extension order in order to avoid it. But in this case, even using path shortening orders, it is not possible to recover all the degradation in λ_{FAP} caused by the uncertainty. In the relaxed approach, due to the error that is made in modeling the aircraft movement (when it is not considered uncertainty), there is the need of assign more orders to the aircraft to avoid conflicts. However, since it is not considered the uncertainty in all aircraft's path it allows to mitigate the λ_{FAP} degradation caused by the uncertainty. The number of vertical orders generally decreases a little when it is considered less conservative approaches and it grows with the number of the aircraft in the simulation. This is due to, when the approach is more conservative or the number of aircraft in the simulation is higher, there is more airspace occupancy. As consequence there is more probability of aircraft with the same altitude to cross their paths, increasing the necessary altitude change orders to assign. Considering that the black zone in these simulations was considered to be one minute, looking at the decision system execution time, the results obtained are in the major cases reasonable.

5 Conclusions and Future Work

The objective of this work was to develop a tool that assists in the air traffic controllers task, by suggesting a set of orders to apply to the aircraft in order to maintain the separation between them. This tool operates with arrival traffic in the area close to and in TMA, controlling the aircraft's movement since final cruise till the FAP. This tool intended also to be TMA independent, working in whatever TMA considered. The simulations run based on a simulator, real time simulator, where the aircraft's movement is modeled the closest possible to the reality and also the uncertainty in horizontal and vertical speed is considered. The decision system developed assigns change horizontal or vertical path to the aircraft. In horizontal orders are considered path shortening, maintain the current path, path extension and holding. The vertical order implemented is altitude descent. it was also considered an emergency maneuver when the standard orders cannot solve the conflict situation. The conflict detection is done based on the aircraft queue, which also determines the arrival order of the aircraft to the FAP(s). The Lisbon, Porto, Oslo, Paris and Frankfurt areas were tested with success. The results obtained showed that the orders of path shortening and path extension improve the aircraft's rate of arrival to the FAP. Also, not considering uncertainty in all aircraft's path not only proved to be not problematic in having conflicts, but also improved the aircraft's rate of arrival to FAP. It was notorious that in approaches with better rates of arrival to FAP, the number of horizontal orders assigned to the aircraft increased. The number of vertical orders assigned grew with the airspace occupancy. In most situations the run time of the decision system was below the black zone considered.

For a future continuation of this work, the following improvements/new features are suggested:

1. consider M/CAS orders;
2. improve the aircraft's rate of arrival to FAP;
3. improve the algorithm time execution performance;
4. implement Point Merge procedures in Oslo and Paris (North-West STARs) TMAs;
5. consider cruise and departure aircraft in simulation area;
6. consider situations of emergency landing;
7. take into account the restricted areas, when applicable;
8. add interaction of the tool with the air traffic controllers.

In order to achieve the objective of point 2, it can be considered the improvement of the uncertainty model or finding other techniques in this tool in order to better the arrival rate to the FAP, for example other approaches to relax the decision system. In fact, in this work the relaxed approach was poorly investigated, but a deeper study in this point will allow to explore this tool true potential. Relatively to the point 4, it has to be done maintaining the "TMA independent" feature. Maybe the best approach is to consider in the tool options that the user may choose depending on the TMA in question.

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