NEXTGEN TRAJECTORY APPROACHES WITH AIR-AIR NEGOTIATION PROTOCOL

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Abstract

Current and future air traffic is requiring new procedures and systems to achieve a greater automation and efficiency of the air traffic operations. On controlled air space and airports, centralized ATC support the real time complexity of air traffic management. But on non-controlled aerodromes, used mainly by general aviation, the absence of ATC support may limit the increase of this type of air traffic. General aviation aircraft fly under VFR and only when weather and visibility conditions are good. Their flight is the closest approach to free flight new concept but without the technological support of avionics to make decisions. An aeronautical radio and a GPS are in most cases their available technologies on board.

This paper proposes an air-air negotiation protocol for general aviation approaching an aerodrome without ATC. The technological requirement of the protocol is the aeronautical radio enhanced with an ACARS avionics. A fast decision making algorithm is proposed to solve landing time requests based on changes in speed and on the use of a same landing procedure. The protocol has been tested for several scenarios involving up to ten aircraft with satisfactory results.

Introduction

Current and future air traffic is requiring new procedures and systems to achieve a greater automation and efficiency of the air traffic operations. Alleviating air traffic management is critical for the Next Generation (NextGen) air transportation system. The current procedures are based on simplistic flight plans, with a sequence of 3D points that the aircraft must follow. Centralized air traffic controllers support the real time complexity of air traffic management providing instructions about route, altitude and speed to the aircraft. Future approaches are 4D trajectory-oriented time-based operations [1, 2] and free flight. [3].

Trajectory-based operations suppose a new concept in the air traffic management procedures. As opposite to the current procedures based on air traffic controller instructions (to provide route, altitude and speed) and simplistic flight plans, trajectory-based operations assume that aircraft will follow 4D trajectories. The idea is to assign to a given aircraft a space & time coordinates, not only in the way points that forms the flight plan but in all the intermediate points between two consecutive waypoints. In this way conflicts can be anticipated and resolved before the flight departure.

The free flight concept is the paradigm of moving responsibilities for aircraft safe navigation from the air traffic controllers to the flight crew. New avionics technologies will support the pilots by integrating traffic information into the flight avionics systems and cockpit displays. The free flight concept for the air traffic management system would enable the flight crew to provide tighter control of the merging and spacing processes. In this approach distributed decision making need to include air-air negotiation protocols.

Automation of arrival operations in terminal areas are particularly difficult due to environment variability inside a delimited air space where multiple aircraft converge. In this context, if a 4D trajectory has been defined for a flight and with the appropriate on board equipment, it is possible to delegate aircraft separation to the flight crew.

The present work proposes an avionics system to resolve conflict separations in landing approaches. Conflict detection and resolution is a critical capacity for free flight. This avionics system includes a negotiation protocol to dynamically decide upon time-based operations. This proposal is based on previous works in the area of Aircraft Separation Assurance System (ASAS) [4] and the preference trajectories paradigm (free flight). We use a previously existing air-air negotiation protocol as a component of the on board automatic system for

978-1-4244-4078-8/09/$25.00 ©2009 IEEE.

supporting pilots with self-spacing flight operation for merging and in-trail separation in terminal areas.

In contrast with the previous work we define an arrival scenario on a non-controlled aerodrome used by general aviation. General aviation usually fly at 18,000 feet (FL180) and below without the benefit of air traffic controller instruction. General aviation aircraft fly under VFR and only when weather and visibility conditions are good. They do not have to file a flight plan or to communicate with air traffic controllers unless they choose to operate close to an airport with a control tower. Under VFR, pilots are responsible for maintaining adequate separation from other aircraft. Their flight is a close approach to free flight but without much avionics technological support to make decisions. An aeronautical radio and a GPS are in most cases the available CNS technologies for general aviation.

We propose the design of an ACARS based avionics system for air-air approach negotiation, as a way to involve general aviation in free flight technologies. A fast decision making algorithm is proposed that includes approach parameters to obtain proposal solutions.

The paper is organized as follows: first a functional description of the operation scenario will be provided, in which the negotiation protocol is projected. Second, the decision algorithm for an optimal solution is formulated. Then two numerical examples are presented in order to show the algorithm implementation. Finally a feasible technological implementation is given and measured. Conclusions and future trends close the paper.

Air-Air Negotiation Protocol

Air-air negotiation protocols have been suggested recently as an extension of capabilities of the current Aircraft Separation Assurance System (ASAS). Current and future air traffic is requiring new procedures and systems to achieve a greater automation on air-traffic operations.

The negotiation protocol presented in this work is based on the proposed air-air negotiation developed by *Canino et al.* [5]. We have adopted some concepts such as some of the operation parameters or merging desires from the aircraft that requests the negotiation and the requirements from the other aircraft.

On The other hand our negotiation protocol has been developed to work in areas without presence of an ATC and it works on a client-server basis instead of taking a Multi-agent approach. We consider that in a negotiation it will always exists an aircraft that requires getting into the landing queue when approaching to a way point, or an aircraft that requires amending its estimated time arrival to the way point. On the other side there will be a group of aircraft that could be affected by those changes and must reply what are their statuses to proceed to the negotiation.

In our protocol, the airplane that starts a negotiation is called *host* airplane. It is the one that initiates the negotiation and requests to negotiate to other aircraft, called *responders*, because they respond to the host request sending their operational parameters: t_{nom}, t_{min}, t_{max}.The first one represents the Estimated Time of Arrival (ETA) whilst t_{min} and t_{max} represent a time range of acceptable solutions if an amendment in t_{nom} is required. See also section *Input parameters.*

Finally the host aircraft proceeds to calculate a suitable set of solutions for the involved aircraft and reports the solution to the responders that must answer whether they accept or not the solution (see Table 1).

Table 1. Aircraft Types and Roles

Aircraft	Roles
host	Calculate new ETAs Confirm / Reject changes
responders	Send their status to the host aircraft Acknowledge / Reject changes

This protocol has been developed thinking in an implementation based on ACARS, so one of the main objectives has been reducing the number of messages required to develop the negotiation. For instance, the host aircraft will send a single broadcast message with all the solutions for the entire group.

Assumptions

General aviation flies usually under Visual Flight Rules (VFR) and most small airplanes take-off and land on aerodromes with no Air Traffic Control (ATC). Different countries publish in their Aeronautical Information Publications (AIP) the general air traffic procedures for the aircraft use of aerodromes (for example see US AIP [6]). Legislation has two main aspects that apply these flights: auto-information reports and departure/approach procedures:

An aircraft, whilst flying in aerodrome traffic where there is no ATC, it must transmit auto-information reports either in the frequency assigned to the aerodrome or in the common frequency (123.500 MHz). On arrival auto-information reports must be sent several times indicating identification, intentions, current position and speed. At least one message has to be sent a) before joining the aerodrome traffic, b) on downwind leg, c) on base leg, d) on final approach, e) on clear of runway and f) on the ramp.

The procedures on a non-controlled aerodrome may have different traffic circuits on ground and on aerodrome, even differentiating between aircraft type (planes, gliders, ULM, helicopters, etc.) But many times aerodrome circuits are not strictly defined or simply do not exist. Internationally it is accepted a more or less standardized landing pattern where the circuit has 5 legs (see Figure 1): Turns must be left hand, the circuit altitude 1,000 ft and the traffic must join when directing the aircraft to the downwind leg.

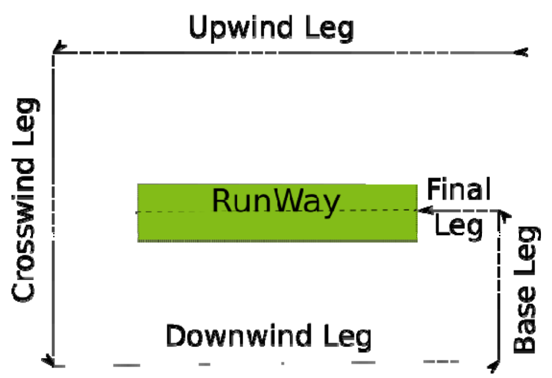

Figure 1. Aerodrome Landing Circuit

There are some exceptions for this last rule. For example it is also accepted to join directly the traffic pattern at the base leg or the final leg if captain is aware of the runway in use by listening to the messages transmitted on the auto information frequency by aircraft already in the aerodrome traffic.

In [7] this circuit has been extended for UAS and previous holding turns have been introduced to wait joining the circuit in case of traffic conflict. A new way point is introduced near the end of the Crosswind leg. It is defined as Crosswind Integration Way Point (CIWP) and we will use it as the point for identifying the landing negotiation in out protocol. A negotiation scenario arises:

- When an aircraft in the proximity of the CIWP desires to schedule its arrival with respect other aircraft in the proximity, or
- When an aircraft already in circuit for the landing requires to modify its nominal time of arrival to the CIWP.

The generic joining procedure rules are:

- Save default separation distances
- Join in accordance with traffic already in the circuit and with other traffic in aerodrome circuits.
- An aircraft may only overtake another one provided that it does not bother or delay the landing

We assume that all involved aircraft are collaborative, this is, all are equipped with the same avionics and execute the same protocol.

State graph

The aircraft are involved in a different way in the protocol depending on their state. We define basically three principal roles: Free (FNE), Host and Responder.

FNE - Free of Negotiation. Aircraft is not involved in any negotiation because it is not yet on the approach and landing procedure. An aircraft in this state does neither need to listen for messages nor to check if there is a negotiation.

Host. Aircraft wants to initiate requests for a negotiation. This aircraft acts as the central decision point of this negotiation.

Resp - Responder. Aircraft is in the way to the CIWP with an approved ETA. Any new negotiation related with this way point has interest to the responder aircraft.

The main state graph is shown in Figure 2.

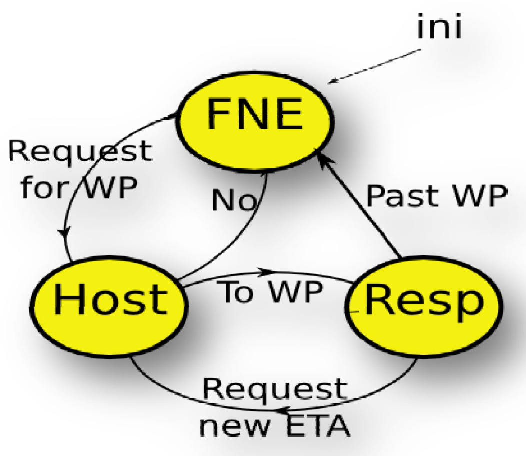

Figure 2. State Graph with Basic Roles

The typical transitions start in the FNE state. When the aircraft wants to start a landing procedure enters to the Host state by sending a broadcast message with its request for the corresponding way point. Host state may transit back to FNE if for any reason its request is not accepted, or otherwise go to Resp. An aircraft can review its assigned ETA at any time during the Resp state and ask for a new one, becoming again Host during this new negotiation. When a responder flies over the way point it is again in FNE, not affected by new requests.

While in Host state an aircraft may be in different sub-states. These are:

HRN - Host Ready for Negotiation: Host requires starting a negotiation due to operation requirements (initial approximation to way point or change of ETA).

HWR – Host Waiting Responders. Host has sent a request message and is waiting for responders. All responders will send back a status message with their ETAs and their operational limitations.

HWA – Host Waiting Last Acknowledge. Host has sent a proposal with new responders ETAs and is waiting acknowledges from responders. Only responders with modifications on their ETA need to acknowledge the changes.

Also the states of a responder aircraft are subdivided into:

RWN – Responder Waiting Negotiation. Responder has obtained a ETA which is accepted by the rest of responders. A new negotiation can be initiated at any time in this state.

RWP – Responder Waiting Proposal. Responder is in a negotiation and has sent a message declaring its timing limitations. It becomes pending to receive a new proposal about its ETA.

RWA – Responder Waiting Acknowledge. Responder is in queue waiting for acknowledgement from previous responder.

RWC – Responder Waiting Confirmation. Responder has sent its acknowledgement and waits for the final result of the negotiation from host.

The state graphs of these sub-states are shown in Figure 3.

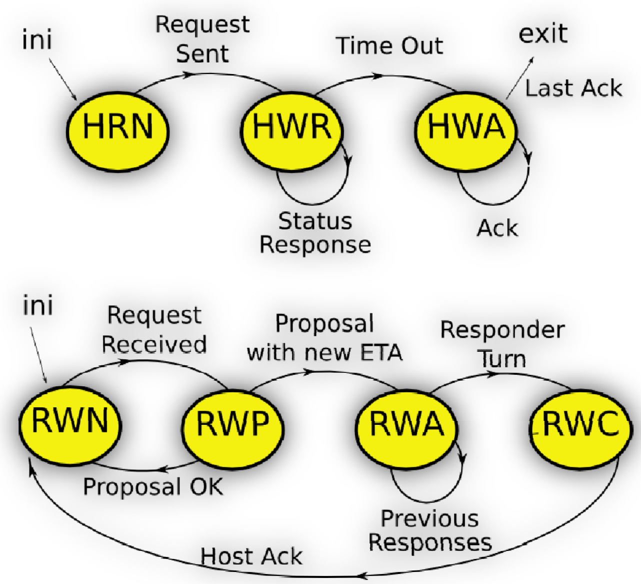

Figure 3. Detailed State Graphs

Protocol Messages

A number of messages go from host to responders and back and trigger changes in states:

Host sends *Request for Negotiation*. This message is sent when an aircraft requires a change of its operational parameters. A negotiation number is proposed to identify further messages within the negotiation. The host aircraft changes from HRN to HWR state and upon message receipt the responders move from RWN to RWP.

Responder sends *Status*. This is a reply to a Request for Negotiation message. Responder broadcast its ETA status and whether the aircraft is committed in another negotiation. The host aircraft waits for these messages. Negotiation finishes if no messages are received or if it detects an alternative negotiation. Responders move from the RWN status to RWP, pending to receive the new ETA proposal.

Host sends *Proposal*. Once all Status messages have arrived to the host, it calculates a proposal and sends it. The Proposal is a broadcast message sent to all the responders. It contains the timing proposal calculated for each involved aircraft that requires a change in the timing. If several aircraft have sent their status to the host but none of them requires changing their ETA, the proposal message would not contain data. In that case the message is not sent and the negotiation finishes. The host aircraft changes its state from HWR to HWA once the proposal message is sent. Aircraft not required to change their proposal will transit directly to RWN, otherwise they transit to RWA.

Responder sends Agree/Disagree Proposal. Responders send their agreement or disagreement to the proposal by sequence, following the sequence dictated by the proposal message. The negotiation is not instantaneous and the responders must calculate if the offset will impact the proposal. The responder changes its state from RWA to RWC once the agreement is sent.

Host sends End of Negotiation OK/Error. In case the negotiation has been accepted by all the responders, the host aircraft sends the OK message to inform the responders that the new schedule is fully accepted: Host and the new aircraft separation is confirmed and used. In case the host detects a single answer with the disagreement message, it finishes the negotiation with an Error message: The ETAs will not be changed for this request and the general schedule returns back to the previous situation. After the End of Negotiation is sent, all the aircraft involved in the negotiation move to RWN.

Aircraft Negotiation Rules

In general these rules apply:

- Minimize the number of aircraft that requires correcting their estimated time of arrival in a negotiation.
- Apply the minimal separation for aircraft in the same trajectory
- Reduce the number of messages sent between aircraft.
- Limit the negotiation time to a maximum of seconds.
- Accept modifications only if all aircraft agree.

Algorithm Formulation

On the transition from HWR to HWA the host aircraft has to calculate an optimal proposal based on the requirements of the responders and its own needs. This section explains the details of such algorithm.

Input Parameters

The algorithm has a single global parameter t_{sep} and then several parameters for each aircraft *(i)*:

- t_{sep} is the minimal time separation between aircrafts. Although aircraft separation usually is expressed as a security distance in first arrival phases, we consider corresponding translation to time unit.
-
- $t_{nom}(i)$: the time scheduled to reach the nearest way point for a given aircraft.
-
- $t_{min}(i)$ and $t_{max}(i)$ represent minimum and maximum time respectively to arrive at the way point for a given aircraft according with its performance and operational requirements.
-
- *Angle(i)* represents the merge track incoming horizontal angle defined by the geographic north, the way point and the aircraft. It is used to determine if the host aircraft shares a trajectory with any other negotiating aircraft with respect to the way point. It is assumed that all the aircraft share the same vertical angle. Note that it is necessary to consider a free flight scenario without 4D well established trajectories. That leads to apply different

rules for two aircraft in the same or in different trajectory approach.

Moreover these input parameters are defined for the host airplane

- t_{des_nom}, t_{des_min}, t_{des_max} represents the nominal, minimum and maximum time required by the host aircraft to arrive the merge point due to operational reasons. Minimum and maximum are the set of acceptable solutions, around $t_{\_des\_nom}$, for the host aircraft.

Output Parameters

The result of the algorithm is the following data defined for each aircraft:

- $t_{sol,}(i)$ are the new set of solutions for the aircraft affected by the negotiation. Finally, after negotiation confirmed, $t_{nom}(i) := t_{sol,}(i)$.

Main Algorithm

The main algorithm is summarized with the steps bellow. The underlined steps are later detailed in this same section.

- Determine if the host airplane requires accelerate, decelerate or simply adapt to the situation.
- Calculate trajectory paths (determine which responders share trajectory with the host airplane).
- Calculate the desired position for the host airplane in the negotiating group.
- <u>Determine aircraft required to accelerate</u>.
    - Determine if the in-path responders will be required to accelerate, affected by the host.
    - Determine non-path responders required to accelerate.
- Determine aircraft required to decelerate.
    - Determine if the in-path responders will be required to decelerate, affected by the host.
    - Determine non-path responders required to decelerate.
- <u>Calculate proposals from the responders required to accelerate</u>.
- Calculate proposals from the responders required to decelerate.
- <u>Merge proposals from accelerating and decelerating aircraft.</u>
- <u>Find the optimal solution for the host aircraft.</u>
- <u>Calculate final solutions</u> for responders.

It can be seen that conceptually the algorithm is working with:

- Nominal times and ranges (input parameter)
- Desires or requirements (input parameter)
- Proposals (internal calculations)
- Final solutions (output parameter, sent to the responders)

Determine Aircraft That Could Be Required to Accelerate

$$Low_{pos} := \textit{major aircraft that } t_{nom} < t_{des}$$
$$High_{pos} := \textit{minor aircraft that } t_{nom} > t_{des}$$
$$host_{pos} := \textit{current host position}$$

Check in-trail aircraft

$$MA \equiv \textit{vector with the accelerating aircraft}$$

```
for i = host_pos to high_pos   step −1
    if (aircraft(i) in_trail with host)
        ind_ac := ind_ac + 1
        add aircraft i into MA
    end
end
```

Check non-path responders

```
for i = Low_pos to 1   step −1
    if (t_des − t_sep · (ind_ac + 1) < t_nom(i)) &(i
                ≠ host)
        ind_ac := ind_ac + 1
        add aircraft i into MA
    else
        break
    end
end
```

ind_{ac} will contain the quantity of aircraft required to accelerate. When considering the decelerating process, ind_{dc} will contain the quantity of aircraft required to decelerate. If not all the responders are required to amend their t_{nom}, then $ind_{ac} + ind_{dc} \neq$ total of responders.

Calculate Proposals from the Responders Required to Accelerate

$MA \equiv vector\ with\ the\ accelerating\ aircraft$
$A := [t_{des\_min}\ \ t_{des\_max}]$
$for\ i = 1\ to\ size(MA)$
  $B := A - t_{step}$
  $A := B \cap [t_{\min}(MA(i))\ \ t_{max}(MA(i))]$
end
$if\ A \neq 0$
  $proposal_{ac} = A + (t_{sep} \cdot size(MA))$
end

$proposal_{ac}$ is a time range valid the host aircraft and suitable to the accelerating aircrafts. If there is no suitable solution, $proposal_{ac} = [0\ \ 0]$. At this point it is still unknown which is the suitable solution for responders. That will be calculated in the step "Calculate final solutions for responders

Merge Proposals from Accelerating and Decelerating Aircraft

$if\ ind_{ac} = 0\ \ \&\ ind_{dc} = 0$
  $result = [t_{des\_min}\ \ t_{des\_max}]$
end
$if\ ind_{ac} \neq 0\ \ \&\ ind_{dc} = 0$
  $result := proposal_{ac}$
end
$if\ ind_{ac} = 0\ \ \&\ ind_{dc} \neq 0$
  $result := proposal_{dc}$
end
$if\ ind_{ac} \neq 0\ \ \&\ ind_{dc} \neq 0$
  $result := proposal_{ac} \cap proposal_{dc}$
end

Find the Optimal Solution

$Divide\ result\ in\ small\ quantums$

$for\ i = 1\ \ to\ maximum\ number\ of\ quantums$
  $for\ j = 1\ to\ size(MA)$
    $k :=\ MA(j)$
    $if\ k + 1 = host$
      $a = min(result) +\ (i - 1)t_{step}$
    $else$
      $a = min(t_{nom}(k + 1), min(result) +\ (i - 1)t_{step})$
    end
    $if\ t_{nom}(k) > a - t_{sep}$
      $t_{nom}(k) := a - t_{sep}$
      $affected := affected + 1$
    end
  end
  $for\ j = 1\ to\ size(MD)$
    $k :=\ MD(j)$
    $if\ k - 1 = host$
      $f = min(result) +\ (i - 1)t_{step}$
    $else$
      $f = max(t_{nom}(k - 1), min(result) +\ (i - 1)t_{step})$
    end
    $if\ t_{nom}(k) < f + t_{sep}$
      $t_{nom}(k) := f + t_{sep}$
      $affected := affected + 1$
    end
  end
  $if\ affected < optimal\_affected$
    $optimal\_affected := affected$
    $t_{sol} := min(result) +\ (i - 1)t_{step}$
  end
end

Calculate Final Solutions for Responders

$for\ i = 1\ to\ size(MA)$
  $za = min(t_{nom}(\ aircraft(MA(i) + 1), t\_nom(host))$
  $if\ t_{nom}(MA(i)) \geq za - t_{step}$
    $t_{nom}(MA(i)) := za - t_{step}$
  end
end

Examples

The protocol has been tested using a similar test bed than in [5]. We assume a merge point of a landing procedure, a minimum separation t_{sep} = 30 seconds, and 8 aircraft involved in an air-air negotiation for landing. For simplicity aircraft are identified by a number from 1 to 8. Figure 4 shows the situation graphically.

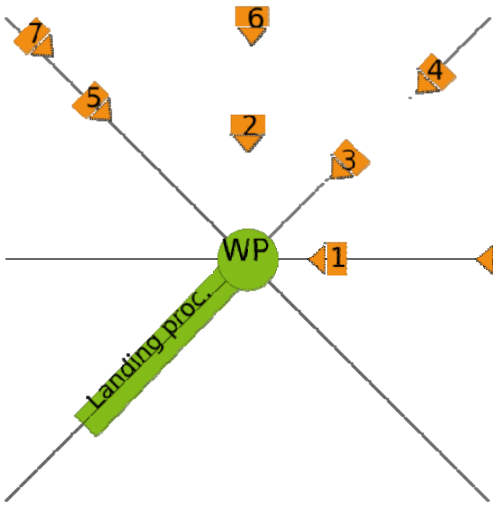

Figure 4. Aircraft Situation

Situation 1

First we show a typical situation of a new incoming aircraft: The host aircraft is the number 8 and just reaches an area close to a way point with other already scheduled aircraft. There are seven responders and their timings and other parameters are shown in Tables 2 and 3.

Table 2. Operational Values

Airc	t_{nom}	t_{min}	t_{max}	ang
1	60	60	90	90
2	100	95	110	0
3	130	110	162	45
4	160	150	186	45
5	190	133	215	315
6	220	154	286	0
7	250	175	325	315
8	270	196	279	90

Table 3. Desires Related to the Host

Airc	t_{des}	t_{des_min}	t_{des_max}
8	270	265	281

In this scenario aircraft 8 reaches the way point area and desires to maintain its current ETA. It starts a negotiation to determine the feasibility.

Firstly it is determined that the new t_{nom} for aircraft 8 will be sorted as the latest one. If required, responders will only be able to accelerate. Then angles are checked, and it is determined that the next aircraft in the same trajectory is far from the new position (the separation between aircraft 1 and 8 is greater than t_{sep}), so no in-path aircraft are considered.

Then we proceed to the *Determine aircraft that could be required to accelerate* routine. Initially ind_{ac} = 0 and MA is empty. Calculations start in aircraft 7 $(Low_{pos} = 7)$. The *if* condition inside the *Check non-path responders* process is satisfied because $t_{des} = 270$, $t_{sep} = 30$ and $t_{nom}(7) = 2$, thus $270 - 30 < 250$. Moreover, aircraft 7 is not the host aircraft. So aircraft 7 is added to the vector that will contain all the pre-selected aircraft that will be used in the calculations.

The same occurs with the next accelerating aircraft. For aircraft 6, $t_{des} - 2 \cdot t_{sep} < t_{nom}(6)$ and so is added to the MA vector. The same can be obtained for aircraft 5 to 2. But for aircraft 1, $t_{des} - 7 \cdot t_{sep} = 270 - 210 \geq t_{nom}(1) = 60$. As the condition is not valid for aircraft 1, it ends the loop. The result is that aircraft 7 to 2 are in the array vector.

Then it is calculated the proposals valid from the responders. Firstly it is considered vector $A = [265\ \ 281]$. After that the process enters the loop. For the first loop, it is subtracted t_{sep} to obtain B, giving as a result $[235\ \ 251]$. Then $A = B \cap [t_{min}(7)\ t_{max}(7)] = [235\ \ 251]$. For the second loop (aircraft 6), $B = [205\ \ 221]\ and\ A = B \cap [t_{min}(6)\ t_{max}(6)] = [205\ 221]$.
The process continues until aircraft 2. Values for vectors are: $B = [90\ \ 101]$ and $A = B \cap [t_{min}(2)\ t_{max}(2)] = [95\ \ 101]$. Finally proposal for the host aircraft is calculated as $A + \left(t_{sep} \cdot size(MA)\right) = [275\ \ 280]$.

This is the valid range of proposals for the accelerating aircraft. As there are no decelerating aircraft it is not necessary to intersect the accelerating range with the decelerating range.

After all these calculations it is obtained that the proposal range has values between 275 and 281. Then all the possible values are checked, in order to obtain what is the value that involves fewer position changes. It turns out that if the new t_{nom} is in the range $[280\ \ 281]$, it is not required to change any responder and the only aircraft required to change the t_{nom} is the host. So the host will finish the process requesting the pilot to change its own t_{nom}.

Situation 2

In this case the host aircraft is number 7 and reaches an area close to the way point at a higher speed than the last responder number 8. The aircraft is in a hurry, so moreover it wants to accelerate. The aircraft situation is the same as in Figure 4 but with different timings for aircrafts 5 to 8 as shown in Tables 4 and 5.

Table 4. New Operational Values

Airc	t_{nom}	t_{min}	t_{max}	ang
1	60	60	90	90
2	100	95	110	0
3	130	110	162	45
4	160	150	186	45
6	220	154	286	0
5	330	250	380	315
7	340	265	410	315
8	400	300	465	90

Table 5. Desires Related to the Host 7

Airc	t_{des}	t_{des_min}	t_{des_max}
7	331	320	335

Firstly it is determined that there are not any aircraft forced to decelerate and that the aircraft that could be required to accelerate is only aircraft 5. Then the proposal is calculated as:

$$B = [290\ \ 305],$$
$$A = B \cap [t_{\min}(5)\ \ t_{max}(5)] = [290\ \ 305].$$

The proposal range is $A + t_{sep} = [320\ \ 335]$, and in all the cases there are two airplanes affected. Finally t_{sol} = 335 is chosen because it is the one that requires fewer speed change for the host aircraft.

Negotiation Protocol over ACARS

The negotiation protocol can be implemented over a number of communication technologies envisioned for future aeronautical CNS technologies like VDL mode 2 and mode 4 or CLPC [8,9]. In this paper we propose the use of ACARS, an old communication technology with low performance but with a solid extension on aircraft because of its low cost.

ACARS [10] is the Aircraft Communication Addressing and Reporting System developed by ARINC on 1978. ACARS is a standard approved by AEEC and adopted by many national airspace authorities like FAA. Today ACARS is constantly used by many airlines for fast operational flight management, for automatic health monitoring of their aircraft, for air traffic surveillance and also for meteorological reporting. Its success is due to the simplicity of adopting it and extending it for new usages. ACARS relays on the voice radio, available on all aircraft, to create a data communication channel over it.

ACARS Messages

In this work we propose to extend ACARS with 7 new message types to implement the air-air negotiation protocol: SNDR, SNDS, PROP, ACKP, ERRP, EONG and EOER:

SNDR Host sends request for negotiation.

SNDS Responder sends Status.

PROP Host sends Proposal.

ACKP Responder agrees Proposal.

ERRP Responder disagrees Proposal.

EONG End of Negotiation.

EOER End of Negotiation with Error.

The first message, SNDR, initiates a new negotiation. Then SNDS are the automatic responses of all involved aircraft, named responders. The host resolves the conflict and informs using the PROP message. The rest are acknowledges or not for the proposition of the host and the end of negotiation confirmation message.

All seven messages follow ARINC 618 and 620 specifications [11, 12] and have the following common format:

- Start of Heading 1 byte
- Mode 1 byte
- Aircraft Address 7 bytes
- Positive Technical Acknowledge 1 byte
- Label (Message Identification) 2 bytes
- Uplink/Downlink Identification 1 byte
- Start of text 1 byte
- Text up to 220 bytes
- Suffix (end of Text) 1 byte
- Block Check Sequence 2 bytes
- Block Check Sequence 1 byte

It can be seen that all the messages will be 18 bytes plus a variable length for text up to 220 bytes depending upon the message type. Table 6 shows the details on the size of the text field for each message type. The number of bytes depends on the parameters of each message.

Table 6. Message Size and Parameters

Message Type	Text Bytes	Parameters
SNDR	9	Way Point Negotiation Number
SNDS	20	Host aircraft t_{nom} t_{min} t_{max} angle Alternative negotiation flg
PROP	3+10n	Negotiation number Up to 20 groups of: • Responder aircraft • t_{sol}
ACKP	2	Negotiation number
ERRP	2	Negotiation number
EONG	2	Negotiation number
EOER	2	Negotiation number

Identifications are sized 7 bytes. This includes Way point, Host and Responder identifications.

Negotiation Number is sized 2 bytes, and it is compacted as based 32. So the range of possible values is 32^2=1024.

Timings and angle are sized 3 bytes numeric. Timings will take values from 0 to 999 (seconds). It is assumed that 16 minutes is sufficient to define a range area around the way point. Angles values range from 0 to 359 degrees.

Message Considerations

SNDR, PROP, EONG and EOER are broadcast messages sent from the host aircraft to the rest of aircraft.

Responders must answer the SNDR message sending their status in the SNDS message. The number of responders is an unknown; if more than one responder is present, several SNDS messages will be received by the host aircraft. A timeout is required to detect the end of the SNDS phase.

To prevent all the responders sending a SNDS at the same time, the protocol considers a delay proportional to t_{nom}/t_{sep} (eg: if t_{sep} = 30s, two responders at t_{nom} = 120s and 210s will try to send their SNDS at 120/30 ms and 210/30 ms).

Not many collisions are expected in the SNDS phase and, if any, the ACARS access to media data transmission mode based on CSMA will manage them. If the channel is sensed busy, then ACARS schedules the transmission some time later according to a uniform random distribution.

ACKP and/or ERRP messages are sent sequentially by all responders. In order to reduce the possibilities of collision, the responders will send them sequentially, starting the aircraft with the lowest ETA and finishing with the one with greatest ETA, as suggested in the PROP message.

Figure 5 shows the overall negotiation time as a function of the number of responders. In includes the mean value of the SNDS phase.

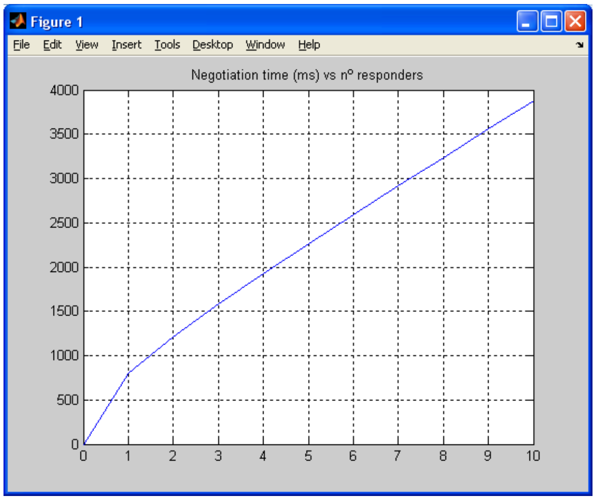

Figure 5. Total Negotiation Time for ACARS

In our previous examples, where 7 aircraft were involved in a negotiation, the estimated time for each negotiation is 2.9 seconds.

Conclusions

This paper presents a protocol for air-air negotiation of a landing procedure, based on a previous work valid for IFR situations that was focused to define an state diagram suitable in situations where an Air Traffic Control exists. We have introduced some changes oriented to general aviation, as a support for a VFR pilot who wants to land in a non-controlled aerodrome. It is specifically oriented to reduce the amount of messages shared between aircraft in order to support existing communication systems.

The protocol is initiated by the aircraft that makes a new request to a set of other aircrafts which have already agreed a landing ordering and timing. This aircraft is responsible of centralizing all the information and of calculating a satisfactory solution with minimal changes. The protocol assumes no ATC support.

For an affordable adaptation of the protocol to general aviation we propose to implement the protocol over ACARS. The number of messages and the time for their transmission is defined and calculated. Measurements show that if we want to establish a limit of 3 seconds as the maximum time for a negotiation, the number of aircraft involved in a landing procedure with this air-air protocol should be limited to 7. Otherwise a more modern communication technology like VDL2 should be used to implement the protocol.

Future work includes considering different separation times for aircraft. This is straight forward using the algorithm formulation presented. Also the implementation with newer CNS technologies can be testes. Finally, the participation of non collaborative aircraft should be considered for a realistic scenario.

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Acknowledgements

This work has been funded partially by Ministry of Education of Spain under contract number MEC TIN2007-63927 and by EUROCONTROL under contract 08-120916-C.

28th Digital Avionics Systems Conference
October 25-29, 2009