FUNCTIONAL MODELLING OF AIRSPACE

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ABSTRACT

For complex installations, such as process plants or energy plants, modelling techniques exist that relate the functions in a system to the goals that have to be achieved. These 'functional modelling' techniques construct models that reveal the knowledge structure that is hidden in the system and can be used to design support systems for the operators.

This article presents such a functional modelling technique for expressing travel possibilities in air traffic. It describes the present approaches to be used in the Airborne Separation Assurance System and the principle of applying functional modelling to this problem. One of the problems is that the properties of the surrounding airspace (in functional terms, its 'behaviour') are complex and changing in time. An efficient representation for this behaviour is researched.

KEYWORDS

Functional Modelling, Air Traffic Control, Airspace, Aircraft Guidance, Conflict Detection & Resolution

INTRODUCTION

In the next fifteen years air traffic is expected to double. This will lead to capacity problems particularly in the vicinity of airports and will also have its effects on safety and efficiency demands and consequently, on the workload of Air Traffic Controllers. In order to be able to cope with these expected problems, new concepts for Air Traffic Management are developed. One of those concepts is the free flight concept, in which aircraft are allowed to determine their own route, thus offering more flexibility (EUROCONTROL, 1997 and Hoekstra et al., 2000). As a result of this greater flexibility an increase of the airspace capacity and the efficiency of flights is foreseen.

The complex system of airways could disappear and could be replaced with the free flight system. With this system, it would become an impossible task for air traffic controllers to separate aircraft all coming from different directions. Therefore separation responsibilities should be (partly) delegated to the cockpit crew. The introduction of new Communication, Navigation and Surveillance (CNS) technologies such as datalink, Global Positioning System (GPS) and Automatic Dependent Surveillance-Broadcast (ADS-B), allows the application of an Airborne Separation Assurance System (ASAS), which will provide the pilots with the necessary information to separate their aircraft from the surrounding traffic.

The airspace, with its structure, the surrounding traffic and the terrain geometry can be viewed as an often complex and changing environment. This environment provides the means to travel, but with restrictions, owing to the presence of other aircraft and the presence of boundaries, artificial or natural. The pilots are faced with the task of trying to accomplish their goal (flying a fast, efficient and safe path towards their destination) in the context of this ever-changing environment.

For complex installations, such as process plants and energy plants, modelling techniques exist that relate the functions in a system to the goals that have to be achieved. These 'functional modelling' techniques, such as Multilevel Flow Modelling (Lind, 1990) and the Goal-Tree Success-Tree method (Modarres, 1993), construct models that reveal the knowledge structure -which functions are performed and how they lead to goal achievement- that is hidden in the system. The models can not only be used to design operator support systems and expert systems, but they can also be used for fault diagnosis or even for the design of an completely new system.

Multilevel Flow Modelling provides structured representations of goals and functions of complex systems in terms of flow. Figure 1 shows an example of a Multilevel Flow Model for the mass flow of a pressurisation cabin. The model is constructed from a basic set of *flow functions* that are arranged into *flow structures*. In the model two of these flow structures can be distinguished, one for the mass flow from the engine compressor through the cabin and another for the energy flow through the engine. The connections between the flow functions express causal relations between the functions. The various flow structures are connected through means-end relations, of which a condition relation is depicted in the example. Once a Multilevel Flow Model of a complex system has been constructed, it provides an explicit and concise representation of the intentional structure of the system. This knowledge structure can be used as a basis for reasoning about the actions that are necessary to achieve the goals of the system or to obtain an intentional mode change of the system (van Paassen & Wieringa, 1999).

Another functional modelling technique is Goal Tree Success Tree (GTST) modelling. This a more general functional modelling method, in which not only the functions and their behaviour must be identified, but also the ways in which the functions interact. In this way GTST is distinct

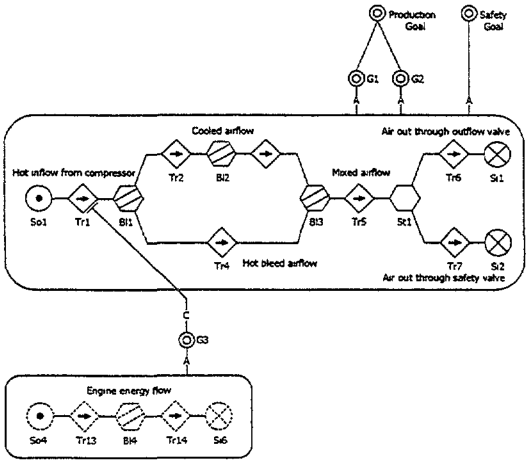

Figure 1. Multilevel Flow Model of a simplified cabin pressurisation system. The model includes two flow structures that describe the mass flow of the system and the energy flow of the aircraft engine. The goal 'Engine running' is a necessary condition to establish the pressurisation.

from Multilevel Flow Modelling, where this information is coded by the choice of a certain type of flow function and in the layout of the flow structure. The application of the GTST method is primarily in the field of fault diagnosis in complex industrial systems.

This paper researches the application of a functional modelling technique to air traffic. It is not possible to apply an existing functional modelling method directly to an environment such as the airspace surrounding an aircraft. A problem is that the properties of the surrounding airspace (in functional terms, its 'behaviour') are complex and changing in time. Therefore it is necessary to develop an entirely new functional modelling concept for airspace, in which this behaviour is represented efficiently. This functional modelling technique could be used to represent the knowledge base of the aircraft environment and provide the cockpit crew with means of selecting an efficient and conflict-lean path towards a destination.

FUNCTIONS OF AIRSPACE

When an aircraft flies in the airspace from one destination to the other, it encounters a continuously changing environment. On the one hand it comes across different airspace boundaries: natural boundaries, e.g. the boundary of air with terrain and the weather, or artificially created boundaries, such as the different classes of airspace (so the environment changes itself). On the other hand the airspace in its vicinity continuously contains different aircraft with different directions and speeds.

In the case that the responsibility for separation is delegated to the cockpit crew, pilots will continuously have to adjust their mental model of the environment, in order to keep situation awareness and resolve potential conflicts with other aircraft. The difficulty in this is that the pilots do not notice all parts of the environment. For instance, the artificially created airspace boundaries are not visible in the air and surrounding aircraft may be out of visual range.

As stated above, ASAS can serve as an aid to overcome these problems. However, the question rises whether with these systems the functionality of the airspace surrounding the aircraft as a means of transportation, is fully exploited.

The airspace can be considered as a complex system, with travellers as the material being transported by it. In contrast to a physical system, the airspace system is composed of components that are often not visible to the users. For example a terminal area is not directly visible, but it can be located by navigation. So, not immediately knowing the components of the airspace system makes it even harder to recognise the functions that these components of the airspace surrounding an aircraft offer. Therefore it is useful to investigate whether there is a possibility to describe the airspace system with a functional model that reveals the functions offered by the system and how these functions can contribute to the achievement of the system goals.

The following proposes a concept for the development of a functional model for airspace as a means of transportation. The objective is to develop a generic description of the functions that a piece of airspace offers travellers, to move around in this piece of airspace. The description will treat the functions available to an aircraft in a uniform manner and so integrates any restrictions imposed upon the aircraft's movements, whether from own limitations, ATC commands, airspace structure or the presence of other travellers. This approach basically differs from Conflict Detection & Resolution (CD&R) approaches, such as Modified Voltage Potential (Eby, 1994), primarily because it tries to uncover the manoeuvring possibilities for an aircraft inside a piece of airspace, whereas CD&R methods only consider limitations imposed on manoeuvring.

Although an unstructured system, such as 'Free Flight Airspace', seems to have less in common with highly structured systems such as power plants that can be functionally described with Multilevel Flow Modelling (MFM), there are more similarities than one would think of at first.

In the first place, a piece of airspace can provide similar functions as can be described with MFM. For example in the case of 'Free Flight Airspace', a volume of air can accommodate different flights in different directions. So in this case the volume of air realises a transport function. Another function realisation occurs in the case that a piece of airspace provides the room for a holding pattern, a so-called stack. Then the volume of air implements a storage function. In case of a restricted area, that particular volume of air functions as a barrier.

In the second place, the function that a piece of airspace provides, is affected by the material (aircraft) being transported, just as with flow based systems for which MFM was designed. As mentioned above, a piece of airspace can accommodate different flights in different directions. However, it can not accommodate all flights at the same time. It can only accommodate more than one flight in the same direction or different directions at different flight levels as long as separation criteria are not violated. So a piece of airspace cannot contain an unlimited number of aircraft. The number is limited by the flights it already contains.

Something similar occurs with a storage function from MFM. A storage function represents the capability of a system to accumulate mass or energy and to provide it to other parts of the system. When the storage is completely full, it has no possibility to accumulate mass or energy any more, and when it is empty, it has no possibility to provide mass or energy to other parts of the system. The mass or energy, or more accurately the amount of it that is accumulated, affects the storage function (van Paassen, 1999).

In the third place, for the system 'Free Flight Airspace', production, safety and economy goals can be distinguished. The production goal of the system is achieved when all travellers in the system reach their destination. One of the safety goals is that at all time conflicts between travellers should be avoided, i.e. separation criteria for the different travellers should not be violated. Several economy goals can be identified. An important economy goal for free flight is to provide the possibility for every airspace user to fly the most efficient route from one destination to the other. Furthermore, the users should be able to define their own path, so-called User Preferred Routes (UPR), in order to give them maximum freedom of movement within the airspace. Other economy goals can be noise reduction in certain airspace areas or fuel use reduction of the aircraft in the system.

Besides the similarities that can be recognised for the 'Free Flight Airspace' system and flow-based systems, also a number of differences exist. Those differences make an existing functional modelling technique such as MFM unsuitable for application to a system with a flexible use of airspace as envisaged for free flight.

In particular the continuously varying function that an (unstructured) piece of airspace can provide, is the cause of this problem. Modelling of transport with (discrete) flow functions, as e.g. in process plants, might be appropriate for highway traffic or air traffic based on flight routes through airways, but not for 'Free Flight Airspace'.

Secondly, the material being transported is not anonymous. The mass and energy flows in a power plant are anonymous, and the achievement of the power plant's goals depends on having the proper amounts of mass and energy at the right places, and flowing at the right rates. In a system with travellers the production goals are achieved if all the travellers reach their destination. The 'material' being treated by the function transportation space is not anonymous, i.e. the KLM flight has to arrive at Schiphol and the British Airways flight has to arrive at Heathrow and not vice versa. (van Paassen, 1999)

Thirdly, Multilevel Flow Modelling uses source functions. These functions represent the property of a system to supply unlimited quantities of mass or energy. In 'Free Flight Airspace' this is not the case. The quantity of material being transported is dependent on the number of flights in the airspace and is certainly not unlimited.

Van Paassen (1999) shows that the functions offered by airspace (or any other n-dimensional space) are no longer amorphous as soon as there are boundaries or other travellers using that space.

Consider a piece of airspace that is one vertical separation level high and that horizontally can contain a maximum of nine aircraft that have a circular separation zone (Figure 2). Note that the separation zone does not correspond with the protected zone that is used for CD&R methods. The radius of the separation zone is only half the radius of the protected zone. Thus two different radii of separation may not intersect.

If one traveller occupies this piece of airspace, it provides him unlimited possibilities of manoeuvring and transportation (Figure 2). However, if it is used at its maximum capacity of nine travellers (Figure 3), the manoeuvring possibilities in the airspace part are restricted to travelling at one speed in one direction (or at no speed in any direction).

In fact, this is only true if the piece of airspace considered is infinitely large and contains its maximum capacity of travellers. Otherwise it depends on the occupation of the airspace surrounding the considered piece of airspace, whether the aircraft must have the same direction and velocity. For instance, if the surrounding airspace is unoccupied, the travellers around the middle aircraft could all have a divergent direction and the same speed as the middle traveller to satisfy the separation criteria. But for the simplicity of the example this will not be considered here. The only purpose is to illustrate that the presence of more than one traveller in a piece of airspace limits the manoeuvring possibilities inside the travel space and consequently changes the functions of the airspace.

To one traveller, the function provided by the travel space is amorphous. He can travel in any desired direction with any desired speed. However, the very act of travelling changes the function of the airspace. As soon as a second traveller enters the part of airspace around the first travel-

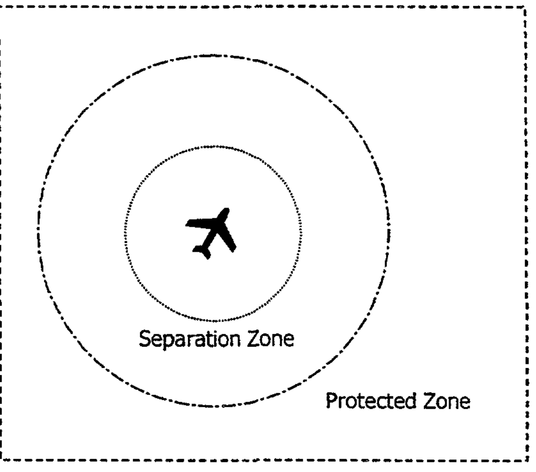

Figure 2. Travel space with a maximum capacity of nine travellers. This travel space offers a single traveller unlimited manoeuvring and transportation possibilities.

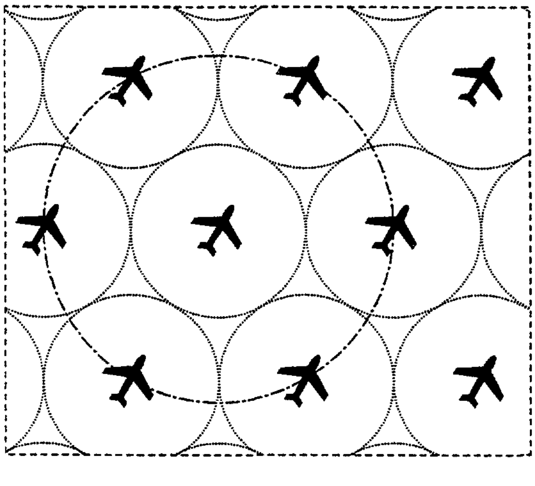

Figure 3. In case of full occupation of the travel space with nine travellers, manoeuvring and transportation is limited to one speed in one direction.

ler, the function provided by the piece of airspace is no longer amorphous. For both the travellers it requires to stay away from certain areas, namely the areas (probably) occupied by the other traveller, and in other areas the speed must be compatible with the speed of the other traveller. This means that on the border of a traveller's protected zone, another traveller's speed and direction must keep him away from the first traveller and the other way around.

Functions offered by the travel space are not discrete, but rather continuous. The space occupied by travellers can be seen as the singularities in this space. Around a traveller space is morphised, in relation to the traveller's position and the certainty of this position, and the traveller's speed and acceleration. The traveller's motion leads to a morphisation of the travelled space. This morphisation is a continuous change in the travel space function and it varies with the location that is considered (van Paassen, 1999).

Consider two travellers in space, one at a location $x_1(t)$ and having a speed $\dot{x}_1(t)$, and another at a location $x_2(t)$ and having a speed $\dot{x}_2(t)$. The locations and speeds of both the travellers are known with a certain accuracy. Regarding this accuracy, both travellers must keep away a minimum separation distance $\rho_{\min}$ from each other. To facilitate the reasoning, the relative position of the second traveller to the first is introduced, $x_r(t) = x_2(t) - x_1(t)$, and the relative velocity of the second traveller, $v_r = \dot{x}_r(t) = \dot{x}_2(t) - \dot{x}_1(t)$. The distance between the two travellers can be calculated as:

$$\rho(t)^2 = x_r(t) \cdot x_r(t), \tag{1}$$

where the dot $\cdot$ denotes the inner product of two vectors. To find the minimum or maximum value of the separation distance ρ, equation (1) has to be differentiated and equated to zero,

$$\frac{d}{dt}\left\{\rho(t)^2\right\} = 2x_r(t) \cdot v_r(t) = 0. \tag{2}$$

There are three conditions for which a minimum or maximum separation distance is found:

- $\boldsymbol{x}_r(t) = \underline{0}$ **for some time** $\boldsymbol{t}$**:** In this case both travellers have the same (estimated) position, i.e. a collision. The condition that the distance between the two travellers should be larger than $\rho_{\min}$, is not satisfied.
- $\boldsymbol{v}_r(t) = \underline{0}$ **for some time** $\boldsymbol{t}$**:** In this case the velocity of both travellers is the same. This might describe the case where one traveller manoeuvres to end up in a formation with the other traveller. The distance at that time should be larger than $\rho_{\min}$.
- $\boldsymbol{x}_r(t) \perp \boldsymbol{v}_r(t)$ **for some time** $\boldsymbol{t}$**:** This case describes the minimum or maximum distance at which the two travellers pass each other. The distance at that time should be larger than $\rho_{\min}$.

A simple case arises when both the travellers have a constant velocity. In that case the relative velocity should be such that the minimum distance between the travellers remains larger than $\rho_{\min}$. This is depicted in figure 4. The absolute velocity of a traveller can then be determined by the vector sum of the velocity of the other traveller and the permissible relative velocity. The velocity is also bounded by the properties of the traveller; an aircraft has a minimum velocity and a maximum velocity. For traveller 2 this would result in the velocity envelope depicted in figure 5.

The travel situation in the airspace is usually not in such way that one aircraft has precedence over another. So, if two aircraft are in the vicinity of each other, constraints on the velocity of both aircraft are generated. Thus also constraints are imposed on the velocity of traveller 1 in the same way as for traveller 2.

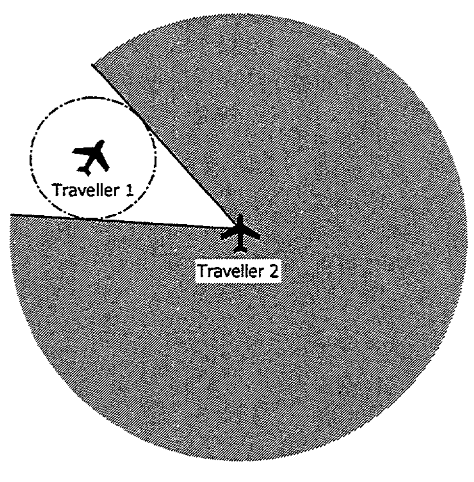

Figure 4. Permissible relative velocity (hatched area) for traveller 2 in case of two travellers with constant velocity.

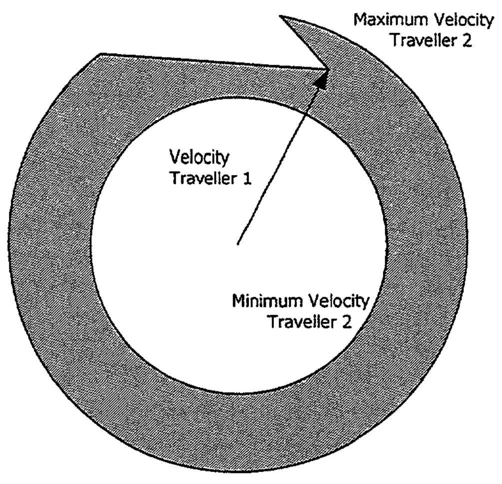

Figure 5. Permissible travel speeds for traveller 2 in case of two travellers with constant velocity. Travel speeds are limited since the relative velocity with respect to traveller 1 must comply with the limits as depicted in Figure 4, and the traveller has to maintain a minimum speed and cannot exceed a certain maximum speed.

Another method for determining the permissible speeds and headings has been developed in earlier research and was implemented in a Predictive ASAS (Hoekstra et al., 2000). Actually, two separate modules, which also utilise relative speed, are used to calculate the speed bands and the heading bands. The speed bands are determined almost in a similar way as described above. The calculation of the heading bands assumes instant heading changes and has been based on target interception by missiles.

The above example illustrates that the travel function that the airspace offers, is morphised by the travellers it contains. However, the resulting morphisation of the travel space is only valid for two travellers with constant velocity in a horizontal plane. For travellers that can accelerate and move vertically, more complex calculations are necessary. The resulting permissible travel velocities and accelerations will not be as straightforward as for travellers with a constant velocity. Furthermore, in a situation with more than two travellers additional constraints on the velocity and acceleration of all travellers are generated. As a consequence the morphisation of the travel space function will be much more complicated.

MORPHISATION OF AIRSPACE

Travelling space is not only morphised by travellers,

as described above, but also by (stationary) boundaries of space. These boundaries occur naturally such as the boundary of air with terrain or water, or they may be artificially created, such as the boundaries of different classes of airspace. Another artificial morphisation of the travelling space is the creation of entry and exit points. For example the approach fixes for the approach to landing of an aircraft or the point where a procedural departure ends.

Artificial morphisations can also be used as a control instrument. If travellers use the morphisation of space as guidance for their travel, then an artificial morphisation of space could help guide the travellers in their use of space. One artificial morphisation for 'free' travellers that is currently in use is the selection of VFR flight levels. Aircraft travelling under Visual Flight Rules (VFR) must take care of their own separation from other aircraft. To help in this, preferred cruise altitudes have been designated for aircraft flying in different directions.

Similar, but perhaps more complicated patterns could be established to guide traffic at complicated or busy crossroads. Artificial morphisation then assures that aircraft follow certain paths or prefer certain altitudes so that conflicts are avoided.

Morphisation in space and time may also be necessary. Consider the transition from a 'Free Flight Airspace' to the controlled approach at an airport. To optimise the utilisation of the runway, landings of aircraft of an equal weight class should be spaced 2 minutes apart. These aircraft may be lined up already at the initial approach fix, and to ensure the spacing in time a pulsating morphisation near the point where the control zone is entered may be imposed by air traffic control.

FUNCTIONS OF TRAVELLERS

In order to obtain a functional description of the airspace, travellers themselves also have to fulfill some functions:

1. Information gathering: A traveller should determine the morphology of the travel space around it, and use that morphology - combined with its travel goal- as guidance for determining its travel direction.
2. Information publishing: To enable other

travellers to determine the morphology of a travel space, a traveller should somehow publish its position, velocity and if possible its acceleration for the benefit of other travellers or Air Traffic Control centres. This process can be passive, e.g. when travellers can see each other, or active, by means of ADS-B, as planned for future air traffic control systems.

3. Transportation: The behaviour of travelling through the airspace is only useful for the traveller itself, and therefore one of its functions. To other travellers it is merely behaviour.

HYPOTHESISED BENEFITS

The purpose of constructing a functional model of a system is to reveal the knowledge structure of a system. The model expresses the system in terms of goals, elementary functions and the relations between these functions and these goals. In fact, it shows how the system functions can achieve the system goals.

In case of constructing a functional model of the airspace the approach will be rather different. The purpose is not to model the airspace as a whole, with all its functions and goals, but merely the airspace around an aircraft. So the system consists of the aircraft together with its direct environment. The goals that have to be achieved are the goals that the traveller in this environment wants to achieve. For instance flying a preferred route, flying with minimum fuel consumption or reaching a destination in a specific time.

The knowledge structure of the airspace provided in this way must serve the traveller in achieving his goals. After a functional model of the airspace has been constructed, reasoning with the model should lead to a clear picture of all travel possibilities that the surrounding airspace offers. The difficulty in constructing such a functional model is that the travel functions offered by the airspace are no longer amorphous as soon as there are boundaries or other travellers using that space, as shown in the above. Furthermore the travel functions are not only morphised but their shape is also continuously changing as the aircraft travels through the airspace.

In order to facilitate the modelling it is preferable to formulate one general expression that can treat all functional properties of the airspace in the same way. It should not matter if the manoeuvring possibilities are limited by airspace boundaries, either natural or artificial, or other aircraft. The expression must be able to handle all cases and combine the limitations to determine the morphology of the airspace surrounding an aircraft. Then this morphology can be used to define the manoeuvring possibilities of the aircraft within a certain area.

Visualisation of this temporary functional morphology of space could aid pilots in planning a proper, conflict-lean, path for their vehicle. Since flying is a three-dimensional task, visualisation of the (possibly time-varying) morphology in a two-dimensional display is bound to be difficult and therefore a point of future research (van Paassen, 1999).

At first sight Functional Modelling (FM) of airspace seems to have a lot in common with existing Conflict Detection & Resolution (CD&R) methods. However, a basic difference is that FM exploits the transport possibilities that a travel space offers, whereas CD&R only determines the limitations. Functional Modelling can be used for guiding of vehicles to provide a smoother traffic flow; CD&R supposes a known flight path and only checks possible conflicts on that track. The need for guidance becomes clear from experiments with CD&R algorithms that were presented in a simulated free flight environment. It was found that the presentation of merely conflicts was seen as a problem by subjects in the experiment. A subsequent modification of the system showed headings that potentially would lead into a conflict (Hoekstra et al., 2000). As FM makes 'visible' all manoeuvring possibilities that a piece of airspace offers, it can be used both to define an efficient path and to avoid conflicts within that area. In addition, the high level of abstraction offered by the model will make it extremely suitable for the design of aids in guidance and conflict resolution in 'Free Flight Airspace'.

POTENTIAL APPLICATIONS

As mentioned above, functional modelling of airspace seems a promising concept for the design of aids in guidance and conflict resolution in 'Free Flight Airspace'. Potential applications for guidance are the line-up at an initial approach fix or the transition to another airspace class, e.g. the transition from 'Free Flight Airspace' to 'Managed Airspace'. In these cases, visualisation of the functional morphisation of the airspace could guide pilots in defining an efficient path for their aircraft to come in line with the other aircraft at the right separation distance and at the right time.

Although a number of conflict resolution methods have been developed, none of them is totally based on concepts of functions and goals. The only goal that can be identified is a safety goal: maintenance of sufficient separation distance with other aircraft. With a functional model the method of approach for designing a resolution method will be much more systematic. Besides the safety goal also other goals could be taken into account. This could lead to an efficient way of resolving conflicts in which the resolution is (more) consistent with the other goals a traveller wants to achieve.

GUIDANCE MODEL

In the foregoing, it is inferred that if the relative speed vector of an aircraft is expected to cross the protected zone of another aircraft at some point of time, an avoidance manoeuvre is required. As an aircraft is not able to change its heading instantaneously, it takes some time to perform the manoeuvre before it can follow its new heading. The time it takes depends on the manoeuvre and airspeed. In the following, manoeuvres are taken into account to use the travel function for guidance.

The basic manoeuvre to change the flight path heading is the true banked or co-ordinated turn: steady curvilinear flight with wings banked and without sideslip (Ruijgrok, 1990). For bank angles smaller than approximately 30°, usually a standard rate turn or Rate-1 turn is performed, where a complete reversal of flight direction (180° turn) takes one minute. Then the radius of turn becomes:

$$R_1 = 60\frac{V}{\pi}. \qquad (3)$$

If the bank angle that is required for a Rate 1 turn,

$$\Phi = \frac{180}{\pi}\arctan\left(\frac{\pi V}{60g}\right), \qquad (4)$$

becomes larger than an angle of 30°, the manoeuvre becomes a co-ordinated turn at bank angle 30° radius:

$$R = \frac{V^2}{g\tan\left(\frac{30\pi}{180}\right)}. \qquad (5)$$

Now a guidance model will be introduced which can guide an aircraft towards its destination, by application of its travel function and some simple decision rules. In the model it is assumed that all aircraft travel at constant airspeeds, which more easily enables calculations with relative speeds. The speed vector of an intruder aircraft is subtracted from the speed vector of the own aircraft. The advantage of calculating with relative speeds is that the position of an intruder aircraft is fixed in the relative airspace. The intruder seems to stand still and the own ship approaches it with relative speed. An additional difficulty is that the manoeuvre is also viewed with relative speed, so the shape of the originally circular turn transforms into an odd curved path.

Other suppositions that are made to simplify the calculations are:

- The model only considers horizontal separation and steady manoeuvres in the horizontal plane;
- The look-ahead time is 8 minutes;
- The maximum heading change is 90° port or starboard;
- Multiple potential conflicts are resolved sequentially in pairs or pairwise: only one intruder aircraft is considered at a time;
- The protected zone of an intruder is circular with a radius of 5 NM.

Since the position of an intruder aircraft is fixed in the relative airspace, it is fairly easy to calculate the headings that are not allowed, due to a potential conflict. These are the relative directions that are tangent to or intersecting the circular protected zone of the intruder (Figure 6). These relative directions are directly related to the absolute heading changes of the own aircraft.

The initial aircraft heading is straight towards its destination. At the moment this heading is not permitted anymore, because of a potential conflict with another aircraft, a new heading has to be chosen. In order not to deviate too much from the direct route it is most likely to choose the smallest heading change possible. This can be either a left or a right turn. If a left turn is chosen the new desired heading will be in a direction starboard of the aircraft, and oppositely if a right turn is chosen the desired heading will move port of the aircraft. As long as the desired heading is blocked, the aircraft has to maintain this new heading, unless a potential conflict with another intruder arises. Then another heading has to be chosen in such a way that the desired heading is most close to this new direction.

Figure 7 depicts on a protractor, which represents the possible turn angles, the blocked headings for the single intruder situation of Figure 6. The desired heading is reflected with a triangle. For simplicity, it is assumed that the current heading (0°) is directly towards the destination, so it corresponds with the desired heading. As the figure shows, the desired heading is not allowed anymore, so a turn has to be performed to change the heading. If a left turn is chosen, both the blocked headings and the desired heading will move to the right. The turn can be ended when the blocked headings are no longer crossing the new heading. As the aircraft approaches the intruder, the area of blocked headings will grow, but will not cross the new heading, if this heading is maintained. As soon as the aircraft passes the intruder the area will start to decrease. After the area has decreased that much that the desired heading is not blocked anymore, it is safe to steer back towards the desired destination. However, if in the meantime the desired heading has changed, the situation has to be assessed again. If the desired heading has moved into the direction of the current heading, it is safe to steer back earlier. If the desired heading has moved away from the current heading further into the heading band, it is required to delay the return manoeuvre until the desired heading is permitted.

Although the above-described method for conflict avoidance is effective, it is not always necessary to stay away from the heading band in such a strict way. If an intruder is remote from the aircraft, it leaves another option: the pilot can steer the aircraft through the heading band until another safe heading is established, without causing a conflict. In a visualisation to the pilots, there will have to be discriminated between both situations, e.g. by using different colours.

In the case of multiple intruders inside the look-ahead time, the heading bands are determined pairwise. This means that first for one intruder the blocked headings are calculated, then for the second, and so on, until all inadmissible headings are determined. In this situation a number of different heading bands appear, which may overlap. Then the problem arises that if there are too many intruders within look-ahead time from the own aircraft, only a little number of admissible headings may remain. As the heading bands successively expand and become smaller, a heading that initially was allowed might suddenly become inadmissible. In order to prevent such a

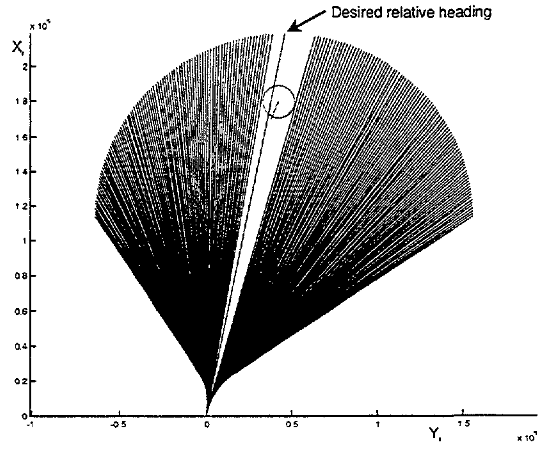

Figure 6. Admissible relative headings for a situation with one intruder depicted in the relative horizontal plane. The desired relative heading intersects the protected zone of the intruder, therefore a heading change required.

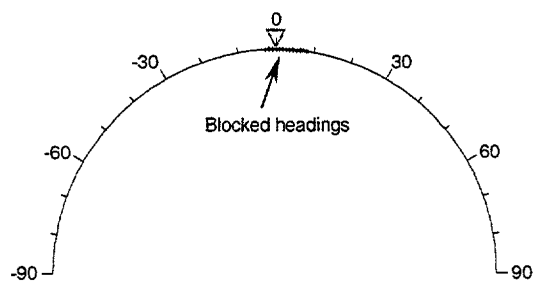

Figure 7. Blocked headings due to the single intrusion case of Figure 6, reflected on a protractor of possible turn angles. The desired heading is depicted with a triangle.

situation, it is recommended to display anticipating cues in a visualisation, such as arrows that indicate the direction in which heading bands grow and decrease. This might also aid pilots in selecting appropriate headings that do not deviate the aircraft too much from the desired heading in time.

CONCLUSIONS

A guidance model that is based on a travel function can safely direct an aircraft through 'Free Flight Airspace' towards its destination. It only requires the application of a few simple decision rules. The guidance model presented in this article takes turn manoeuvres initiating a heading change into account. Therefore the method is still more complex than an 'instant heading change' method such as developed in earlier research (Hoekstra et al., 2000). However, if it is possible to neglect the turn geometry in the model, it will be reduced to an 'instant heading change' guidance model that is based on relative position and speed only. The great advantage of this simplification is that both the admissible speeds and the admissible headings can be calculated simultaneously in a straightforward way. This will make the model even less complex than the forementioned solution, which requires two separate calculations to determine the admissible headings and speeds. In order to justify the simplification of the guidance model, extensive piloted and fast-time simulations and comparison with the 'turn based' model are needed.

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