Abstract:

Functional modelling techniques, such as Multilevel Flow Modelling or the Goal-Tree Success-Tree method, construct models of complex systems, in which the relationship between the structure and physical components of a system, the functions which these components perform and the goals of a system are described. Functional models can be applied in reasoning about goal achievement, construction of expert systems, or evaluation of system designs.

This paper discusses the design of a functional modelling technique for travellers; vehicles such as aircraft, ships, cars, and the space they travel through.

Keywords: Functional modelling, (air-)space use

Introduction

Functional modelling techniques construct models of complex systems, in which the relationship between the structure and physical components of a system, the functions which these components perform and the goals of a system are described. Multilevel Flow Modelling, developed by M. Lind (Lind 1990), is an example of a functional modelling technique. MFM is usually applied to systems that can be characterised by material, energy and information flows within the system, such as power plants, cement mills, chemical installations, etc. Non-industrial applications are also known, for example a model of blood and oxygen supply to the heart. All these systems are characterised by the fact that they provide containment and transportation of
material and energy within the system. MFM is an elegant specialisation of generic functional modelling, and provides a basic set of flow functions that precisely describe the processes common to all these systems.

A set of flow functions is arranged into a flow structure, see Figure 1 for an example. A syntax has been developed for these flow structures. The lines running between the functions indicate causal relations between the functions. Such a specialised notation provides an effective and concise description of the system. General rules about how causally related flow functions influence each other can now be applied.

For a model developed with a more general functional modelling method, such as GTST (Modarres 1993), not only the functions and their behaviour must be identified, but also the ways in which functions interact; information that is coded in the MFM model by the choice of a certain type of flow function and in the layout of the flow structure.

Our interest is the development of functional models for transportation. It would be possible to apply MFM to road traffic. The functions in that case would be provided by the road structure, and the material flowing in the system (being stored, transported, distributed etc. by the functions) would be the cars and trucks.

A less structured use of the infra-structural space is proposed for air traffic in the 21st century. Under the label of “Free Flight” (RTCA 1996), proposals are being made for a more efficient and less regulated use of upper airspace. In this case, the same volume of air that accommodates a Swissair flight going north to south, could five minutes later accommodate a Lufthansa flight going east to west. It can not accommodate both flights at the same time. The volume of air realises (implements) a function. One can see that this function is influenced by the material being transported (the different flights).

In the flow based systems for which MFM was designed, something similar occurs. Consider the storage function in Figure 1 (represented by the hexagonal icon in the middle of the lower structure). It represents the ability of the system to deposit energy in a store, keep it there, and to provide energy to other parts of the system. When the store is completely full, there is no possibility to deposit energy, and when it is empty, there is no possibility to provide energy. The energy, or more accurately how much of it is deposited in the store, affects the storage function.

The mass and energy flows in a power plant are anonymous, and 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 in the system 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.

A component in a power plant provides a limited set of functions. An (unstructured) piece of airspace can provide a much greater variety of functions. It can provide the room for high-capacity north to south travel, intermittent north-south / east-west crossing traffic, or the room for a holding pattern (i.e. storage). Modelling of transport with (discrete) flow functions might be appropriate for highway traffic or air traffic based on flight routes through airways, but not for a flexible use of airspace such as envisioned for “Free Flight”. In the following section a proposal for a “continuous” transport function type is made.
The mechanisms that are currently proposed for the conflict detection and resolution in future air traffic scenarios are based on engineering calculations. Possible conflicts with other aircraft in the vicinity are probed for, one-by-one, by stepwise prediction of future aircraft position and the detection of possible conflicts. It is not our purpose to supplant this rigorous method of conflict detection, but to investigate whether guiding vehicles on the basis of the functions offered by a travel space can provide a smoother traffic flow.

**Function and Use**

Consider a piece of airspace, wide enough for 3 aircraft, one aircraft high and 2 aircraft long. To one traveller, this piece of space provides unlimited manoeuvring and transportation room. When used at maximum capacity, this space is occupied by 6 travellers, that must all have the same velocity and heading. The lone traveller had the whole piece of airspace to its disposal, and the space provided him with many functions. For the 6 travellers, the space permits only travel at one speed in one direction (or at no speed in any direction).

What has happened is that the 6 travellers themselves have changed the functions of the airspace. Consider a traveller in an airspace (Figure 3). Here the separation zones for this traveller have been depicted. On the border of the separation zone, a second traveller’s speed must keep him away from the first traveller.

![Figure 2: Travel space with 6 travellers. The presence of other travellers limits the function offered by the travel space](image)

![Figure 3: Travel space with a single traveller, which has a circular separation zone.](image)
To one traveller, the function provided by the space is amorphous. He can travel the space in any direction and in any speed. However the very act of travelling changes the function of the space. To the second traveller the space is no longer amorphous, it requires him to stay away from certain areas, namely the areas occupied (or probably occupied) by the first traveller, and in other areas his speed must be compatible with the speed of the first traveller.

Functions offered by the space are not discrete, but rather continuous. The space occupied by a traveller can be seen as 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 motion of a traveller and the availability of space to travel in can be seen as functions on the “physical function” level in Rasmussen’s abstraction hierarchy. The traveller’s motion leads to a morphisation of the travelled space. This morphisation is a continuous change in the travel space function, and in the next section the nature of this morphisation is further investigated.

**Characteristics of Morphised Space**

In the previous section it was argued that the travel function offered by space is continuous and that it varies with the location (the coordinates) one considers. Now consider a single traveller in space, at a certain location \( x_1(t) \) and having a certain speed \( x_1(t) \). The speed of the traveller and its location are known with a certain accuracy. Regarding this accuracy, a second traveller must keep a minimum distance \( P_{\text{min}} \) from the first traveller. To facilitate the reasoning, the relative position of the second traveller is introduced, \( x_r(t) = x_2(t) - x_1(t) \), and the relative velocity of the second traveller, \( v_r(t) = v_2(t) - v_1(t) \). The distance \( \rho(t) \) between the two travellers can be calculated as:

\[
\rho(t)^2 = x_r(t) \cdot x_r(t)
\]

Here \( \cdot \) denotes the inner product of two vectors. To find the minimum or maximum distance, one has to differentiate Eq. 1, and find it roots:

\[
\frac{d}{dt} \rho(t)^2 = 2x_r(t) \cdot v_r(t) = 0
\]

One can see that there are three conditions under which a minimum or maximum distance is found:

1. \( x_r(t) = 0 \) for some time \( t \) In this case both travellers have the same (estimated) position, i.e. a collision.
2. \( v_r(t) = 0 \) for some time \( t \) In this case the relative 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 \( P_{\text{min}} \). This case is illustrated in Figure 4.
3. \( x_r(t) \perp v_r(t) \) for some time \( t \). This case describes the minimum or maximum distance at which two travellers pass each other. The distance at that time should be larger than \( P_{\text{min}} \). This case is illustrated in Figure 5.
Figure 4: Illustration showing the *relative* trajectory of two travellers, where the travellers end up in formation, i.e. with relative velocity 0, at $t_1$.

Figure 5: Illustration showing the *relative* trajectory of two travellers, where the travellers pass each other at some time $t_1$.

A simple example can be given for the case that the velocity of the two travellers is constant. In that case the relative velocity of the two travellers should be such that the minimum distance between the travellers, remains larger than $p_{\text{min}}$ this is depicted in Figure 6. The absolute velocity of "our" traveller is then determined by the vector sum of the velocity of the other traveller and...

Figure 6: Permissible *relative* velocity (arced area) for traveller 2, travelling with a constant velocity relative to traveller 1.

Figure 7: Permissible travel speeds for traveller 2.

Travel speeds are limited since the relative velocity with respect respect to traveller 1 must comply with the limits as depicted in Figure 6, and furthermore this traveller has to maintain a minimum speed, and cannot exceed a certain maximum speed For travellers that can accelerate, more complex calculations are necessary. The parameterization of $x(t)$ and the subsequent "shape" of the travel space remains a subject for future research. In a situation with more than two other travellers, additional constraints on the velocity and acceleration of a third traveller are generated.
Basic Morphisation

Travelling space is not only morphised by travellers, but also by (stationary) boundaries of space. Such boundaries occur naturally, consider for example the boundary of air or water with terrain, or they may be artificially created, such as the boundaries of different classes of airspace.

Travelling space can also be morphised by 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 Morphisation as a Control Instrument

If travellers use the morphisation of space as a 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 runways, 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

To enable other travellers to determine the morphology of a travel space, a traveller should somehow publish its position, velocity and if possible acceleration. This can be a passive process, for example when the travellers can see each other (cf. road traffic), or it might be active. For example, for future air traffic control systems the Autonomous Dependent Surveillance Broadcast (ADSB) system will be installed in aircraft. Aircraft equipped with this system will broadcast their position, velocity and possibly other parameters, computed by on-board navigation equipment for the benefit of other aircraft and Air Traffic Control centres.

A second function is that 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.

The third function of a traveller is to travel through the travel space. In terms of functional modelling, this behaviour is useful, and therefore a function, for the traveller itself, to other travellers it is merely behaviour.
Conclusions and Future work

Functional modelling of airspace seems a promising concept for the design of aids in guidance and conflict resolution in “free” travelling space. The main point we try to stress here is that the functions offered by airspace (or any other free n-dimensional space) are no longer amorphous as soon as there are boundaries or other travellers using that space. Visualisation of this temporary morphosity of space could aid pilots in planning a proper, conflict-clean, path for their vehicle. Our plans for future research include simulations of traffic in 3-dimensional space. Each vehicle is controlled by a Traveller agent, and we will investigate whether conflicts can be avoided, and whether a fair use of the space is possible, when each agent determines the functional morphology of the airspace around him and uses that as a basis for his own actions.

Visualisation of the functional morphology is also a point of research. Visualisation of a one dimensional function, such as the train charts in (Tufte 1990), can use the second dimension of a two-dimensional medium (the paper or computer screen) to express time. Flying is a three-dimensional task; visualisation of the (possibly time-varying) morphology in a 2-dimensional display is bound to be difficult, but at least worth a try.

References


