Traffic Manager - Traffic Simulation for Validation of Future ATM Concepts

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TRAFFIC MANAGER
TRAFFIC SIMULATION FOR VALIDATION OF FUTURE ATM CONCEPTS

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ABSTRACT

The National Aerospace Laboratory NLR developed the Traffic Manager (TMX), a desktop air traffic environment simulation tool suitable for a wide range of fast and real-time applications. The main reason for this development was the need for a research simulation tool that could be used in the exploration and validation of new Air Traffic Management (ATM) concepts.

Because the current medium and long-term forecasts predict significant increase in air traffic movements, there is a strong need for new ATM concepts that can deal with this increase in air traffic movements. For this reason both Europe and the United States are investing in the development and validation of future ATM concepts. NLR is participating in many projects concerning these research topics.

Concept validation research often encompasses fast- and real-time simulation studies. Studies that demand flexible, accurate and easy-to-use tools. In particular realistic traffic simulation is essential when it comes to validating new operational concepts. For this purpose the TMX has been developed. TMX has proven to be an ideal tool for various validation and research purposes. It can be used as on-line traffic generator and experiment manager for flight simulators, but also as off-line traffic simulation tool.

This paper discusses the development of this versatile traffic simulation application and the way it grew to new research challenges. Special attention is paid to the various developed interfaces for linking TMX to real-time flight simulators, such as NLR's Research Flight Simulator (RFS) or remote simulators via Distributed Interactive Simulation (DIS), High Level Architecture (HLA) and/or internet protocols. Also an overview is given of some recent ATM studies that made use of TMX.

TMX has earned its "wings" in Free Flight research over the past years. It has been used very successfully in many research projects often concerned with Free Flight. One of the most important reasons for this success is the development philosophy which made it possible to have new research capabilities available in short time. Its flexible set-up and the ability to link it to external simulators make TMX an extremely useful tool for simulating a realistic traffic environment. The combination of the traffic environment simulation with multiple real-time human-in-the-loop simulators is ideal for validating new ATM concepts from an airborne perspective.

Because of the wide range of capabilities of TMX, it also is used in many experiments that don't involve Free Flight research. One of the strongest points of TMX which sets it apart from other traffic simulators, is the capability to simulate in real-time a large number of up to 1000 fully equipped aircraft (including FMS, ASAS, ADS-B) at a time.

INTRODUCTION

After decades of continuous growth of air traffic, the research into the future of the Air Traffic Management (ATM) is one of most relevant topics in aviation industry. Although there is a temporary halt to traffic growth, current medium term forecasts still predict significant increase in traffic movements. For this reason both Europe and the United States are investing in the development and validation of future ATM concepts.

Concept validation research often encompasses fast- and real-time simulation studies. Studies that demand flexible, accurate and easy-to-use tools. In particular realistic traffic simulation is essential when it comes to validating new operational concepts. For this purpose the National Aerospace Laboratory NLR developed the Traffic Manager (TMX), a desktop air traffic environment simulation tool for a wide range of fast and real-time applications. TMX has proven to be an ideal tool for various validation and research purposes.

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It can be used as on-line traffic generator and experiment manager for flight simulators, but also as off-line traffic simulation tool.

Moreover, the origin of TMX lies in the NLR Free Flight research and therefor contains several conflict detection and resolution algorithms for simulating autonomous traffic. Some algorithms take into account the traffic intent, others are based on aircraft state or predefined rules.

This paper discusses the development of this versatile traffic simulation application and the way it grew to new research challenges. Special attention is paid to the various developed interfaces for linking TMX to real-time flight simulators, such as NLR's Research Flight Simulator (RFS) or remote simulators via Distributed Interactive Simulation (DIS), High Level Architecture (HLA) and/or internet protocols. Also an overview is given of some recent ATM studies that made use of TMX.

HISTORY AND DEVELOPMENT OF TMX

Development of TMX started in 1996 initially as an off-line desktop simulation application for an interaction study of multiple aircraft in a Free Flight environment. The focus of this study was to develop and compare different algorithms for conflict resolution.

To make this possible the basic components of TMX were developed. The real heart of TMX is the simulation of multiple aircraft. For this initial study the guidance for each aircraft was implemented as direct routing from origin airport to destination airport with great circle trajectories. Conflict detection is based on extrapolation of both the aircraft state vectors until the maximum look-ahead time, for each pair of aircraft. A number of methods for conflict resolution were implemented[1]: altitude step, cross product of speed vectors, extended Visual Flight Rules (VFR) rules and two different implementations of the Modified Voltage Potential (MVP), one specially to manoeuvre without speed changes. The Conflict Detection & Resolution (CD&R) algorithms form the key components of the Airborne Separation Assurance System (ASAS). In order to keep score and rate the different simulation runs, a number of statistical calculations were implemented. The results of these calculations are recorded to a logging file for later analysis.

After this desktop investigation there was a desire to test the developed conceptual CD&R algorithms in a human-in-the-loop experiment using NLR's motion base real-time simulator, the RFS. For this purpose the baseline of TMX was enhanced to serve as traffic environment simulation for the RFS. In order to use TMX as an on-line traffic simulation, a connection with the real-time simulation of the RFS and its subsystems had to be created.

This connection was implemented using TCP/IP over ethernet. Position and state information of the simulated traffic in TMX is broadcasted over ethernet as to simulate Automatic Dependent Surveillance Broadcast (ADS-B) transmitted data from surrounding traffic. This data is used to generate traffic information on the cockpit displays and show traffic in the computer generated out-of-the-window view. The ASAS is simulated in TMX for all simulated traffic and also for the RFS itself. This means that CD&R information for the RFS is generated by TMX and is broadcasted over ethernet to the cockpit displays and warning systems.

This was the first time TMX was used to simulate the traffic environment and ASAS for the RFS. In the following years TMX was used in numerous experiments. With every new experiment the capabilities of TMX were expanded to suite the needs for more functionality. This often involved adding new functionalities but also refinement or enhancement of existing functionalities. Some of the major added functionalities include:

- Predictive ASAS, indicating the presence of potential conflicts relative to the current aircraft state vector.
- 4D Flight Management System (FMS) guidance, flight plan based trajectories.
- Automatic traffic scenario generation.
- Intent based CD&R, making use of FMS and Mode Control Panel (MCP) data.
- Connections for multiple on-line simulators.
- Hosting of interactive distributed traffic simulation using the internet.
- DIS and HLA interfaces for connection with other simulators.
- ADS-B characteristics simulation.

DEVELOPMENT PHILOSOPHY OF TMX

The main philosophy behind the development of TMX was to fulfil the specific needs for research tools in studies on future ATM concepts, in a rapid prototyping fashion. Or to put it in other famous words: "I feel the need for speed". Each step in the development of TMX is primarily driven by the short-term goals of the next research experiment but with an eye on future opportunities and developments that already can be foreseen.

This philosophy also determines the way TMX is constructed. TMX has a modular structure in which existing modules can grow and mature to meet new functionality needs and new modules can easily be fitted in. A module is not developed to be an all comprehensive version but must meet the goals of today. In a way similar to the "just in time" concept. It's not efficient to develop functionality that will be laying on the shelf and won't be needed for a long time or even ever. Another strong point to this approach is the fact that with every experiment new insights are gained that can affect and even turn around the direction of future developments. This might result in developments made in advance becoming obsolete, which is a waste of invested time.

Through the years many developers have contributed to the development of TMX. A developer doesn't need a complete understanding of all the TMX code. The modular structure makes it possible for a developer to concentrate on the module he's working on. The only knowledge he needs to have of the other TMX modules is to which modules he must interface and what interaction is needed. Besides this the main architecture of TMX is compact and easy to comprehend, as will be shown in a later section describing the architecture.

In the past years this approach has been exercised in the development of TMX with great success. Many research projects depended on the availability of new functionality that only could be provided in time using this approach.

CAPABILITIES OF TMX

Today, after more than seven years of development and use in various international research projects, TMX has grown to one of NLR's key research tools for future ATM concepts. The success of TMX is a result of its wide range of capabilities, which also made it very useful in simulation experiments that don't involve Free Flight. Some of TMX major capabilities are:

- Off-line (fast-time) Traffic Simulation
- On-line (real-time) Traffic Simulation
- Internet Traffic Simulation
- In-flight Traffic Simulation
- Experiment Control Station
- Scenario Generator, Editor and Player
- Data Recording Tool
- Demonstration Tool

The above-mentioned capabilities of TMX will be discussed in more detail in the next subsections.

Off-line Traffic Simulation

The off-line (i.e. stand-alone) traffic simulation mode of TMX allows users to prepare and analyse traffic scenarios from their desktop. The simulation can be run in real-time or in fast-time. As part of the NLR Free Flight research several off-line simulation studies have been conducted using TMX. As already mentioned, TMX started out as a test bench for different CD&R algorithms. Off-line simulations were used to test and compare effectiveness and efficiency of these algorithms. Furthermore in 1998 a Cost-Benefit Study was performed aimed at investigating the conflict resolution manoeuvres using state-based conflict detection and resolution algorithms[2,3]. Another off-line simulation study looked at complex conflict geometries to test the robustness and exception handling of the different CD&R algorithms[4].

Off-line simulation is also used to test traffic scenarios and fine-tune them before they can be used for on-line simulation with a simulator. Testing scenarios with off-line simulation is needed to make sure that the desired traffic densities are reached and no unwanted behaviour or incidents occur. Fine-tuning scenarios is often needed to ensure that the research aircraft (simulator) will encounter the intended number of conflicts. It turns out to be hard to generate conflicts in a Free Flight airspace, especially if no flight plan routing is used.

On-line Traffic Simulation

Besides the off-line capabilities of TMX its big advantage over other traffic simulation tools is its capability to run on-line simulations as well. In an on-line simulation TMX is connected to one or more flight simulators, such as RFS, making it possible for simulators to become part of the traffic simulation. Connected to TMX the RFS enables concept validation of ATM concepts from an airborne perspective[5]. In the on-line set-up TMX simulates the interactive traffic and provides the traffic data to the connected flight simulator. Pilots flying the simulator can perceive the surrounding traffic on the cockpit displays like the Cockpit Display with Traffic Information (CDTI) and in the out-of-the-window view.

Internet Traffic Simulation

A special variant of on-line traffic simulation is one with multiple flight simulators connected to TMX over internet using the DirectPlay® library, which is part of Microsoft® DirectX®. The use of this protocol enables simulation sessions with remote participants that log on to the TMX. In 2000 NLR conducted internet Free Flight experiments involving pilots from Europe, the United States and even Japan[6]. The subject pilots were tasked to fly through a predefined free flight airspace using the NLR desktop simulator FreeSIM. Purpose of the internet experiment was to involve as many real pilots in order to study human interaction effects on the Free Flight operation. For additional incentive, money prices were awarded to the pilots who operated their simulated aircraft best within the safety and economic constraints.

One of the most interesting observations during this so-called web experiment, was that pilots could not distinguish between traffic controlled by humans and by 'bots' (automated pilots), so the pilot models of TMX passed this variation of the Turing-test. This shows that the off-line simulations with only bots are useful for validation.

In-flight Traffic Simulation

TMX can also be used for in-flight simulation to perform flight trails. The state information of the research aircraft is retrieved from the avionics systems and interfaced to TMX. In this manner the research aircraft is connected to TMX in the same way a flight simulator is connected for on-line simulation. TMX can simulate traffic around the research aircraft that can be displayed on experimental cockpit displays making it possible to generate virtual conflicts and let the experimental pilot interact with the simulated traffic. At this moment preparations are under way to use TMX in Free Flight flight trails in both Europe and the US. In Europe the Mediterranean Free Flight (MFF)[7] project will perform flight trails in the Mediterranean area, which are planned to start in 2004. In the US the NASA-led Small Aircraft Transportation System (SATS)[8] program is preparing flight trails to be held this year.

Experiment Control Station

During on-line simulations TMX also serves as experiment control station where the complete traffic simulation can be overseen. The experiment leader can watch the scenarios develop and if necessary control the complete traffic simulation by entering commands. A wide range of commands make it possible to take control over each simulated aircraft and set all kinds of parameters. The behaviour of almost every simulated system can be adjusted by changing its parameter values. Special events such as simulated system failures of the simulator can be introduced. Data logging can be monitored and controlled during the experiment. Remarks or other markers can be added to the loggging files at any time during the simulation runs.

Scenario Generator, Editor and Player

TMX can automatically generate traffic scenarios. To do so the user has to select a number of airports and airspace entries around the experiment area and define average time intervals between scheduled take-offs. Each departing aircraft will randomly receive one of the selected destinations. The trajectory between origin and destination airport can be direct routing or following user defined flight plans between origin and destination. Aircraft that reach their destination or leave the experimental airspace are deleted from the simulation. In this way the scenario generation will fill the airspace randomly with traffic, and after some build-up time will produce a filled airspace with a stable traffic density. This results in very realistic traffic scenarios. It is possible to save the stabilised traffic picture into a start-up traffic scenario file.

TMX can play back one scenario file and simultaneously record to another one. In this manner an existing scenario can be played back, changed by on-line inserting commands, and recorded to a new scenario file. In the simulation experiments the prepared scenarios are played back to reproduce the complete traffic picture.

Data Recording Tool

TMX contains a number of statistical functions to determine the traffic density, fuel consumption, number of conflicts and intrusions. Besides this the position of the research simulator can be tracked and in case it's in a conflict the Closest Point of Approach (CPA) en the resolution vector. All these parameters are time stamped and written to a logging file. Remarks or other markers can be entered on the command line and also will added to the logging file. Research projects may have special needs for recording parameters and this can easily be added to the existing capability.

Demonstration Tool

TMX can run on almost any laptop computer and therefore can be demonstrated almost anywhere running in its off-line mode. It is often used to show examples of scenarios that were used in on-line simulation experiments or show enlightening examples of complex conflict geometries and the way they are solved by the CD&R algorithms.

TMX ARCHITECTURE

The previous section gave an overview of the diversity and flexibility of the TMX. This section will give a look inside TMX and will show its architecture. But first a look at the face of TMX, its Graphical User Interface (GUI).

Graphical User Interface

The GUI of TMX is shown in Figure 1. The TMX software runs on a conventional personal computer running the Windows® (95, 98, 2000) operating system. The GUI consists of both an input and output part. The output part presents all information about the simulated traffic and the execution status of the scenario. Furthermore status indication is provided for connections to other simulations. The input part accepts user inputs entered in a console/command window with a keyboard or selecting functions or objects with a cursor control device.

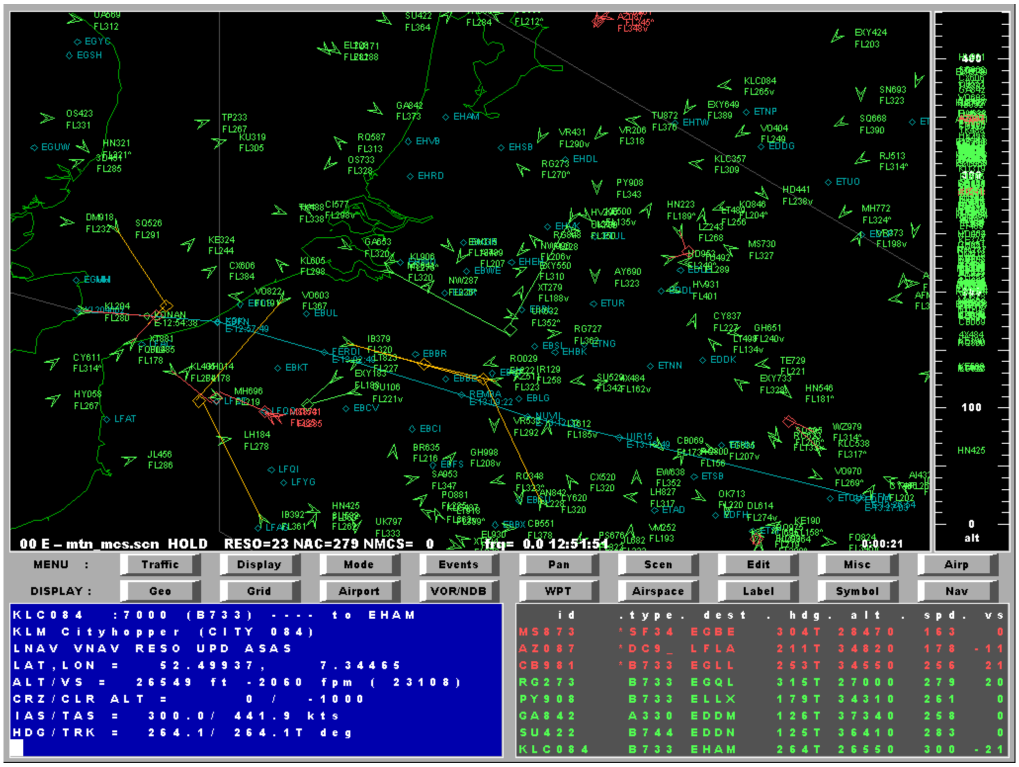

Figure 1 TMX Graphical User Interface

The main screen of TMX consists of:

1. The radar window (main window) displays the simulated traffic in a map perspective with coastlines for geographical orientation and user defined sector and airspace boundaries. Other display features are CPA location in case of a conflict (amber and red lines), aircraft FMS routes (magenta lines), the location of navigational aids, and even the runway layout of some airports.

2. The button bar (below main window) allows the user to bypass command line inputs by using a pointing device. The button bar consists of two rows of buttons. The top row selects a sub set of buttons on the second row. The function of each button and the menu structure of the buttons is completely configurable by the user by means of a data file. The buttons can be used to store often used commands as well as complete macros.

3. The console/command window (lower left-hand corner) allows the user to enter commands with the keyboard at the command line prompt. This console can also be used for the prompting of relevant messages, such as events, errors or warnings.

4. The strip window (lower right-hand corner) displays so-called aircraft strips of one or more selected aircraft and aircraft that are involved in a conflict. The strips display call-sign, origin, destination, altitude, heading, speed and rate of climb.

5. The altitude bar (right of main window) displays the altitude of the traffic on the radar window. When creating a new aircraft this bar can also be used to quickly select the desired aircraft type, altitude and speed by clicking on the bar, instead of using the command line.

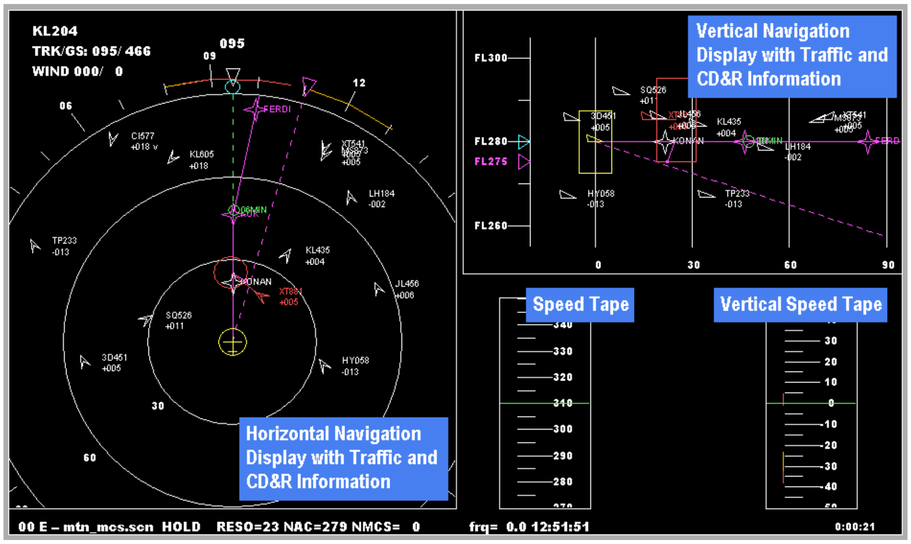

Figure 2 Aircraft Navigation Display

The main radar window can be replaced by an alternative screen showing a simple aircraft navigation display for both the horizontal and vertical situation, as shown in Figure 2. Moreover, tape gauges for the aircraft actual and selected speed and vertical speed are also available. This view can be selected for any aircraft within the traffic simulation. This feature enables a quick view into the cockpit of an aircraft and makes it easy to understand strange conflict geometries and corresponding resolutions. It also is very useful for taking control of an aircraft during on-line simulation.

Architecture Breakdown

TMX is constructed in a modular way. It's not possible to describe the complete architecture of TMX in this paper and therefore only the higher level architecture will be presented. Figure 3 shows the overall top level architecture of TMX with its main components. The heart of TMX is the traffic simulation of multiple aircraft. In order to simulate autonomous (Free Flight) traffic TMX can simulate CD&R functionality for each aircraft. The scenario and simulation control component is needed to initialise and control the traffic simulation and other components within TMX. As already mentioned the GUI is split into an information presentation and a user input part. The remaining modules in the top level breakdown take care of communication with other simulations. A closer look into the architecture is given in Figure 4. In the following subsections the main components will be described in more detail.

Traffic Simulation

For the traffic simulation six-degrees-of-freedom aircraft models are used with auto-flight functionality, 4D FMS guidance functionality and a pilot model. TMX is capable of simulating up to 1000 fully equipped aircraft at a time. The performance data for simulating different type of aircraft is based on the Eurocontrol Base-of-Aircraft Data (BADA)[9].

Aircraft state information for all traffic is available in three levels: true state, perceived state and received ADS-B state. The aircraft simulation delivers the true state of the aircraft. The perceived state of the aircraft will usually differ from the true state because of sensor errors. A sensor model makes it possible to introduce these sensor errors. The perceived state is used for transmitting the aircraft state over ADS-B.

The ADS-B received state differs from the transmitted in update rate. ADS-B messages are transmitted with a selectable update rate. Between two transmits the received ADS-B data is extrapolated based on the last received data. The ADS-B model also contains a probability of lost messages and transponder failures.

ASAS Simulation

Aircraft will detect and resolve conflicts depending on the selected CD&R algorithms in the ASAS module. Many different CD&R algorithms have been developed and can be selected by their CD&R algorithm number. Both state-based and aircraft intent algorithms are available. CD&R characteristics can be set by means of parameters. CD&R and all other simulation parameters can be set in a scenario file and changed on-line by entering new values on the command line.

It is also possible to create a so-called mixed-equipped traffic environment, by simulating both controlled and autonomous aircraft at the same time. The ASAS equipage is an option that can be selected for each aircraft individually.

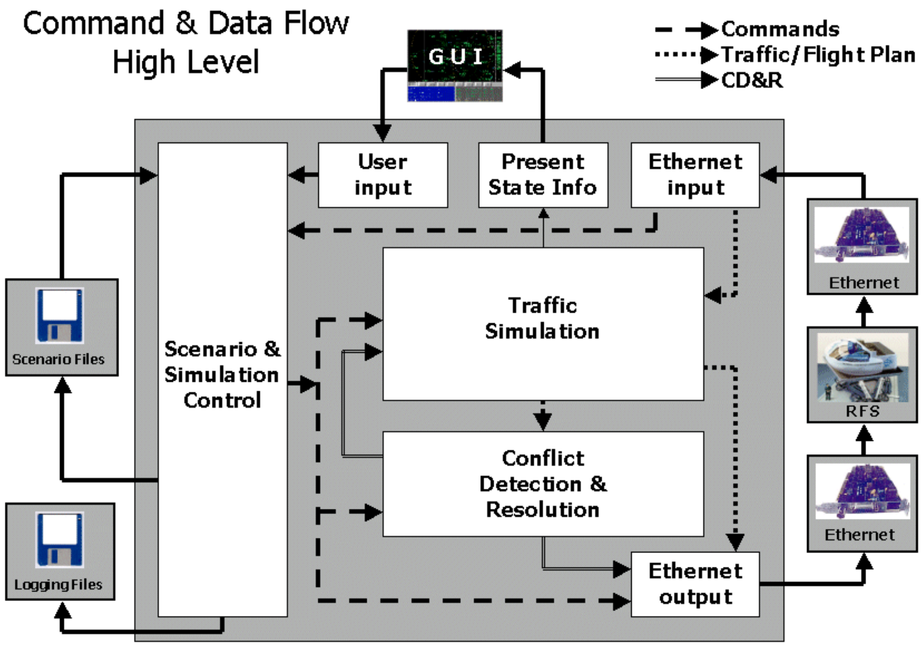

Figure 3 Top Level Architecture TMX

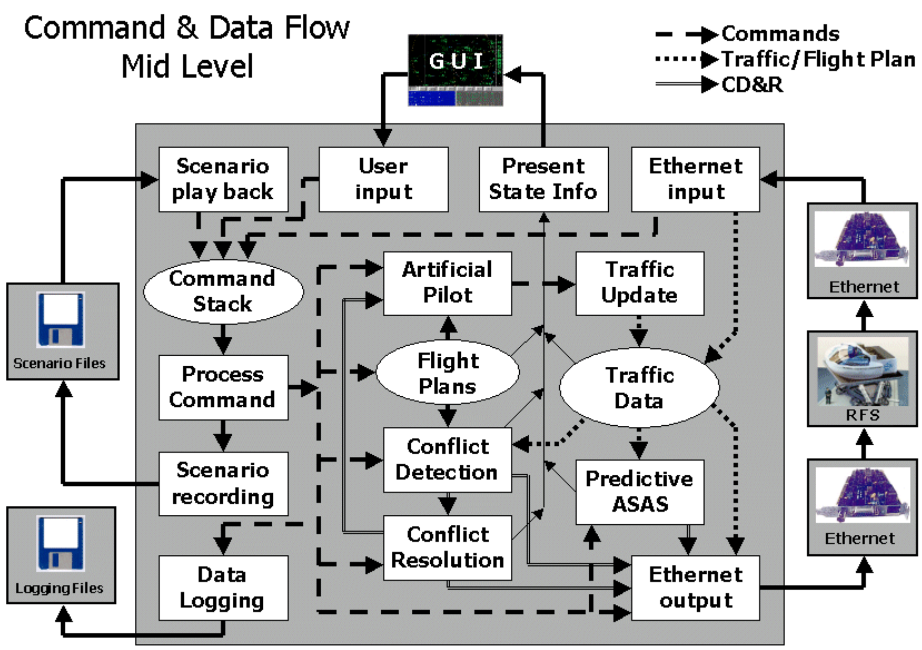

Figure 4 Mid level Architecture TMX

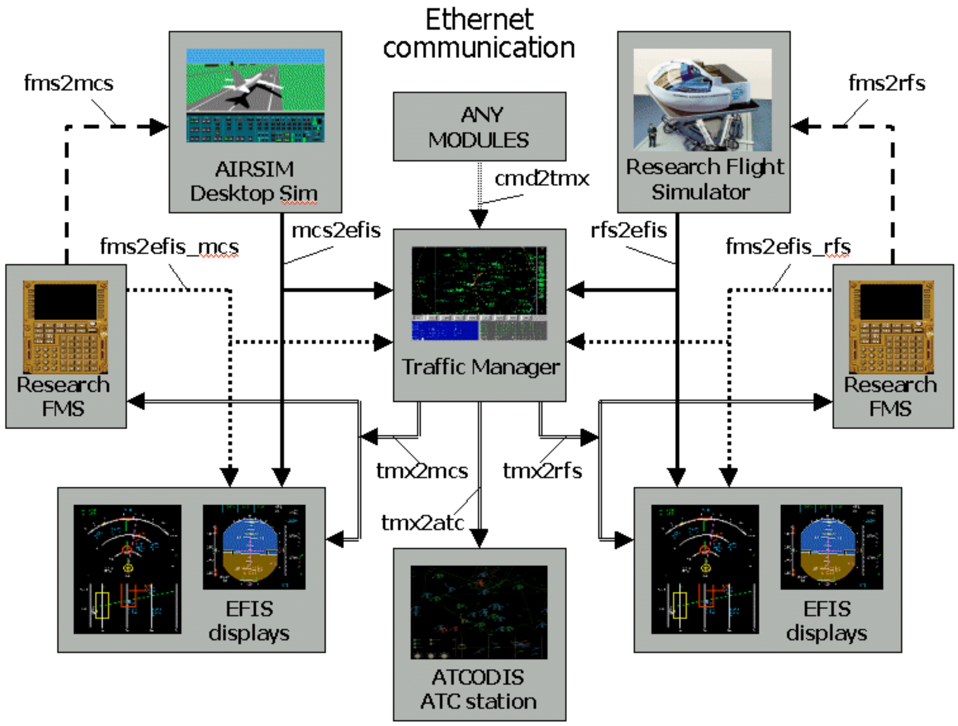

Figure 5 Ethernet Connections with TMX

Besides CD&R, this module also contains conflict prevention in the form of the so-called Predictive ASAS (PASAS). PASAS is used to prevent aircraft from maneuvering into a conflict. It also prevents automated traffic from turning back into the same conflict over and over again after executing a conflict resolution.

Scenario and Simulation Control

TMX is event driven. Its central element is a so-called Command Stack. Every module in the TMX is controlled by one or more commands. The user enters commands via the GUI, or commands are read from a recorded or edited scenario file. The scenario file contains a list of time stamped commands. Each command in the scenario file is put on the Command Stack at the simulation time stated in its timestamp. Commands also can be received through ethernet from any other module in the simulation configuration.

The Command Stack works as a First In First Out (FIFO) buffer. The first command in the stack is passed to the Process Command module. Process Command interprets the command and executes all needed actions and sets appropriate parameters. If scenario recording is activated all executed commands will be time stamped and written to the selected scenario file.

This module also contains the data logging function. As already mentioned TMX contains a number of statistical functions that gather performance numbers about the traffic simulation.

Interfaces to External Simulations

The wide range of interfaces contained in TMX makes it a very versatile traffic simulation tool. Because TMX can be hooked up to almost any simulator and even to flight hardware of a research aircraft, its application for Free Flight research is limitless.

In the first place TMX can be hooked up to any aircraft simulator, from desktop till motion base simulator, if it can provide basic aircraft state information. The connected simulator will become part of the traffic simulation within TMX and can interact with every aircraft in the simulation. Even multiple simulators can be linked directly to TMX. TMX will provide each simulator with ADS-B traffic and CD&R information for the cockpit displays and warning system. If use is made of intent information for CD&R the FMS of the simulator must also be connected to TMX in order to collect flight plan data. This basic direct link between TMX and aircraft simulators is depicted in Figure 5.

It is also possible to connect simulators to TMX using the DIS standard. This may be a number of flight simulators, another traffic simulator or a combination of both. Besides DIS also a High Level Architecture (HLA) interface is available.

Yet another way to connect to TMX is through the internet. TMX can host a web session that allows desktop simulators to log on to the traffic simulation in progress. Each simulator that logs on gets assigned to an aircraft already part of the traffic simulation and will take over control of this aircraft. The simulator will send out its current state information; position, altitude, speed, vertical speed and track. TMX will send the simulator all state information of all surrounding traffic. In this case the CD&R algorithms are contained in the remote simulator. Performance and CD&R information is send to TMX for data logging.

TMX Research Projects

The first research project that made use of TMX was the NLR Free Flight project that started out in 1997[1]. This project was carried out in collaboration with NASA, the FAA and the RLD (Dutch Civil Aviation Authorities). This collaboration in Free Flight research is still continued. One of the results of the close collaboration with NASA is the use of TMX in research projects at NASA as part of the Advanced Air Transport Technology (AATT) program. A description of an example research study can be found in reference 10.

After the first few years of Free Flight research, also a number of European projects were initiated. The Free Flight - Flight Management System (3FMS)[11] project was the first European Free Flight project that made use of TMX. For this project TMX had to be fitted with new CD&R algorithms that take into account the aircraft's intent information. Part of the resolution with intent information was implemented in NLR's Research Flight Management System (RFMS).

The INTENT project[12], as the name implies, addressed also and in more detail the use of intent information for CD&R. The "intent" CD&R algorithms were refined and extended. The new algorithms were developed and tested in TMX but they were extracted from TMX and put into the RFMS for the on-line simulation experiment. This resulted in a FMS with integrated ASAS functionality.

Other projects that made use of TMX are for instance the Mediterranean Free Flight (MFF)[7] project and the More Autonomous Aircraft in the Future Air Traffic Management System (MA-AFAS)[13] project.

Because of the wide range of capabilities of TMX, it also is used in many experiments that don't involve Free Flight research. A number of military projects use TMX as well. More information about Free Flight research at NLR and even a demo version of TMX can be found on the Free Flight web site of the NLR[14].

Conclusion

TMX has earned its "wings" in Free Flight research over the past years. It has been used very successfully in many research projects often concerned with Free Flight. One of the most important reasons for this success is the development philosophy which made it possible to have new research capabilities available in short time. Its flexible set-up and the ability to link it to external simulators make TMX an extremely useful tool for simulating a realistic traffic environment. The combination of the traffic environment simulation with multiple real-time human-in-the-loop simulators is ideal for validating new ATM concepts from an airborne perspective.

Because of the wide range of capabilities of TMX, it also is used in many experiments that don't involve Free Flight research. One of the strongest points of TMX which sets it apart from other traffic simulators, is the capability to simulate in real-time a large number of up to 1000 fully equipped aircraft (including FMS, ASAS, ADS-B) at a time.

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ABBREVIATIONS & ACRONYMS

3FMS	Free Flight - Flight Management System
AATT	Advanced Air Transport Technology
ADS-B	Automatic Dependent Surveillance Broadcast
ASAS	Airborne Separation Assurance System
ATM	Air Traffic Management
BADA	Base-of-Aircraft Data
CD&R	Conflict Detection & Resolution
CDTI	Cockpit Display with Traffic Information
CPA	Closest Point of Approach
DIS	Distributed Interactive Simulation
FAA	Federal Aviation Authority
FIFO	First In First Out
FMS	Flight Management System
FreeSim	Free Flight Desktop Simulation
GUI	Graphical User Interface
HLA	High Level Architecture
IP	Internet Protocol
MCP	Mode Control Panel
MFF	Mediterranean Free Flight
MVP	Modified Voltage Potential
NASA	National Aeronautics and Space Administration
NLR	Nationaal Lucht- en Ruimtevaart-laboratorium (National Aerospace Laboratory)
PASAS	Predictive Airborne Separation Assurance System
RFMS	Research Flight Management System
RFS	Research Flight Simulator
RLD	Rijks Luchtvaart Dienst (Dutch Aviation Authority)
SATS	Small Aircraft Transportation System
TCP	Transmission Control Protocol
TMX	Traffic Manager
VFR	Visual Flight Rules