Air Traffic Flow Management using multi-agent system

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Outline

- World Air Traffic Control
- Some developed projects
- Project Proposals
- Conclusion
Part I - World Air Traffic Control

Basic Concepts
Basic Concepts

- **Runway**
  - Main runway of an airport
  - Landing and Takeoff

- **Single Runway**
  - most basic runway
  - Low traffic
  - 99 operations VFR (visual flight rules)
  - 42 to 53 operations IFR (instrument flight rules)
Basic Concepts

- Parallel runways
  - More complex scenarios
  - They are named according to the degree of closeness
  - 64-128 operations IFR
Basic Concepts

- **Taxiway**
  - used to maneuver the aircraft
  - to connect runway, parking and hangar
Basic Concepts

- Air traffic control
  - Prevent collisions between aircraft
  - Maintain an orderly and expeditious flow of air traffic
  - Provide suggestions and information
  - Warn of accidents

- Tower of control – TWR
  - Near the track
  - maneuvers, takeoff, landing or overflight
Basic Concepts

- **Air Traffic Controller - ATCO**
  - Responsible for coordinating aircraft - Air or Ground

- **Workload for professionals (Majumdar & Ochieng, 2012).**
  - Safety
  - Delay

- **The increased workload:**
  - Status of the airspace
  - Equipment condition (design, reliability and accuracy)
  - The current state (age, experience)

- **Excessive increase in the workload:**
  - Amount of information exchanged
  - Cause physical and mental exhaustion
Basic Concepts

- Flight Profile
  - Preflight: pilot receives the flight plan, “check list”, go to runway
  - Takeoff: receives permission to take off
  - Departure: the pilot is instructed by the ATC, climbs to a cruising altitude.
  - En Route: The aircraft travels through one or more center airspaces and nears the destination airport.
**Basic Concepts**

- **Flight Profile**
  - **Descent:** The pilot descends and maneuvers the aircraft to the destination airport.
  - **Approach:** The pilot aligns the aircraft with the designated landing runway.
  - **Landing:** The aircraft lands on the designated runway, taxis to the destination gate and parks at the terminal.
Part II - World Air Traffic Control

Organisation of ATM
Basic Concepts

- **American model**
  - **Federal Aviation Administration - FAA**
    - Regulating civil aviation to promote **safety**
    - Encouraging and developing civil aeronautics, including **new aviation technology**
    - Developing and operating a **system of air traffic control** and navigation for both civil and military aircraft
    - Researching and developing the **National Airspace System** and civil aeronautics
    - Developing and carrying out programs to control aircraft noise and other environmental effects of civil aviation
    - Regulating U.S. commercial space transportation
Basic Concepts

- Air Route Traffic Control Center (ARTCC)
  - 21 zones
  - "Centers"
  - IFR
    - provide Air Traffic Service
    - en route
  - It includes all sorts of different types of aircraft
    - privately owned single engine aircraft, commuter airlines, military jets and commercial airlines
  - Safe Separation Standards
    - Laterally -- 5 miles
    - Vertically
      - 1,000 feet (below 29,000 feet)
      - 2,000 feet (at 29,000 feet or above)
  - ZFW – 350 controllers
Basic Concepts

- Terminal Radar Approach Control (TRACON)
  - departure, descent and approach phases of the flight
  - One TRACON can handle the air traffic for several different airports in its sector.
  - Types of traffic controllers
    - high altitude descent controller
    - low altitude descent controller
    - approach controller - 50 milhas
    - feeder controller
  - 185 TRACONs
Basic Concepts

- **Brazilian model**
  - **DECEA (Control Department Airspace)**
    - Military
    - main objectives are to plan, manage and control related activities the control of the airspace
    - protection of the flight
    - the search and rescue service
    - Telecommunications of Air Force Command
  - **CINDACTA**
    - Controlled Airspace
  - **Destacamentos de Telecomunicações e Controle do Espaço Aéreo (DTCEA)**
    - CINDACTA I – 18 units
    - CINDACTA II – 15 units
    - CINDACTA III – 10 units
    - CINDACTA IV – 27 units
Basic Concepts

- Controlled Airspace
  - ATZ - Aerodrome Traffic Zones
    - Airport
  - CTR - Traffic Control Zone
  - TMA - Terminal Control Area
  - Approach Control Center - app
Basic Concepts

- **CTA - Control Area**
  - lower airways
  - lower vertical limit: 500 ft
  - upper limit: FL 245 - 7,500 m
  - side limit: 16NM – narrow – 54NM

- **UTA - Superior Control Area**
  - upper airways
  - lower vertical limit: FL 245
  - upper limit: unlimited
  - side limit: 43NM – narrow – 216NM
Basic Concepts

- Comparison of Air Traffic Management-Related Operational Performance: U.S./Europe
  - European air traffic control is currently fragmented
  - Each country provide your air traffic control
  - Respecting the territorial boundaries

- European system are operated by:
  - similar technology
  - operational concepts

- USA
  - US system is operated by one single service provider
  - same tools and equipment
Basic Concepts

- **Comparison of Air Traffic Management-Related Operational Performance: U.S./Europe**

- **Single European Sky (SES)**
  - **Reduction** this fragmentation
  - **Efficiency** and **interoperability** of the ATM system in Europe were improved

- 2-3 billion dollars

![Figure 5-4: Breakdown of en-route ATFM delay by cause (2015)](image1)

![Figure 5-5: Breakdown of airport arrival ATFM delay by cause (2015)](image2)
Part I - Some developed projects

Scenery, Difficulties and Tools
Research Scope and Motivation

- **Expectations for the future**
  - Demand of Service for Airlines
  - 2.8% Growth per year (2030)
  - 500-1500 new flights

- **Enormous strain on the aviation system**
  - Congestion phenomena are persistent
  - Additional operational cost
    - European: €1.25 billion (2011)
    - American: $5.9 billion (2009)
Research Scope and Motivation

- **Air traffic flow management (ATFM)**
  - has become crucial
  - Prevent local demand-capacity imbalances
    - Adjusting the flows of aircraft on a national or regional basis.

- **Mismanagement**
  - What is the effect of this?

  ![Diagram showing the effects of ATM management and mismanagement on Safety, Aerial Capacity, Cost, and Delay.]
Research Scope and Motivation

- **Difficulties**
  - Hard to predict traffic flow changes
  - Dynamic System
  - Restrictive measures applied in unpredictable situations
    - Based on the original flight plan
    - current scenario of the system
    - ignores current capacity of airports and aviation sectors
Tools

- Simulation Platform
  - Over 30 years of existence
  - Graphic and physical engine
  - Vast amount of vehicles
    - land air and sea vehicle
  - System missions
  - Fault Injection

- SimConnect (API)
  - external applications
Part III - Some developed projects

Air Traffic Control using Microsoft Flight Simulator X
Air Traffic Controller

- Responsible for coordinating aircraft - Air or Ground
- The increased workload:
  - Status of the airspace
  - Equipment condition (design, reliability and accuracy)
  - The current state (age, experience)

- Excessive increase in the workload:
  - Amount of information exchanged
  - Cause physical and mental exhaustion

- Conflict Detection and Resolution Systems
  - Centralized, Decentralized and Hybrid

- Taxiways management
Centralized Approach

- **Agent ATC**
  - Monitoring aircraft
  - Detect and apply solutions to air conflicts
    - Propose multiple secondary routes
    - Some attributes

- **AgentAirPlane**
  - Control the aircraft and execute orders
Centralized Approach

- **Advantages**
  - Provides a better view of the airspace
  - Identifies problematic areas

- **Disadvantages**
  - Catastrophic failure

- **Simulation**
  - Agent ATC has a “Radar”
  - Spheres of radius R and 2R
    (Valkanas et al., 2009) and (Pechoucek et al., 2006)
Centralized Approach

- AgentATC
- Monitoring of the airspace
- Create new Routes
  - Critical time
- Check new Collisions
- Apply Solutions

Diagram:

1. Monitor Traffic
2. Collision detected?
3. U(x1,x2,x3,...,xn) >= 0.75?
   - Yes
     - Generate alternative routes and calculate utilities
     - New collision generated?
       - Yes
         - Execute maneuver
       - No
         - Conflict resolved?
           - Yes
             - Stop
           - No
             - [Loop]
   - No
     - [Loop]
Decentralized Approach

- AgentAirPlane
  - Monitoring the airspace around it
  - In case of air conflicts
    - Its Starts a negotiation process

- Agent ATC
  - Does not interfer during the negotiation
Decentralized Approach

- **Advantages**
  - Autonomy and independence of Aircraft
  - Increasing airspace capacity
  - Decrease workload

- **Disadvantages**
  - Lower airspace monitoring capability
  - Lack of a redundant system
Decentralized Approach

- AgentAirPlane
- Monitoring of the airspace
- Negotiation between Airplane
- Apply Solutions

[Diagram: Flowchart showing the process of monitoring traffic, detecting collisions, generating alternative routes, and resolving conflicts.]
Hybrid Approach

- Combine both techniques
- AgentAirPlane
- Monitoring of the airspace
- Negotiation between Airplanes
- Consult the ATC agent
- Apply Solutions
Utility Functions

- Multi-Attribute Utility Theory (MAUT)
  - Decision-making processes

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Worst</th>
<th>Best</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heading variation (HV)</td>
<td>$\geq 25$ degrees</td>
<td>0 degrees</td>
</tr>
<tr>
<td>Speed Variation (SV)</td>
<td>$\geq 30%$ of actual speed</td>
<td>Speed doesn't change</td>
</tr>
<tr>
<td>Traffic density of the new route (TD)</td>
<td>Half the testing aircrafts</td>
<td>0</td>
</tr>
</tbody>
</table>

- Ratio 6/1/3 for HV, SV and TD respectively

\[
U(x_1, x_2, x_3, \ldots, x_n) = \sum_{i=0}^{n} K_i U_i(x_i)
\]
Experimental Settings

- **Nº of AirCraft**: 2x
  - Cessna skyhawk (128 Knos)
  - Beech baron 58 (151 Knos)

- **Test Zone**
  - 49 km² (a circle with a radius of 3945m)

- **Red Zone**
  - Radius = 1800 m

- **Blue Zone**
  - Radius = 3600 m
Experimental Settings

- The collision is considered
  - less than 30m

- The aircraft will not be excluded
  - fixed number of aircraft during the simulation

- Real Time (10 hours)
Results

- With larger number of aircrafts
  - 8 and 10 agents
  - 65% more detected conflicts
Results

- With larger number of aircrafts
  - 229% more collisions
Results

- Minimum safety requirement - 12.25 km² per aircraft
- Multi-agent systems can be a potential technique
- Future work - Changing dynamics of the weights
Part IV - Some developed projects

A Comparative Study of Meta-Heuristics for the Aircraft Landing Scheduling Problem
The Landing Problem

- The Air Traffic Controller (ATCO) is responsible for creating a schedule of plane landings.
  - Separation Times
  - Time window
  - Plane’s cruise speed
- Little tactical planning is currently done
- “First coming, first serving” (FCFS)
The Landing Problem

- Aircraft Landing Scheduling (ALS): Sequencing and scheduling of aircraft which are landing into the available runways at the airport.

- Objective of the ALP is to minimize the total delay

- There are costs associated with landing

- Important problems in Air Traffic Control (ATC)

- Rate landing and takeoff
Requirements for Aircraft Separation

- To assure safety during landing and takeoff
- wake turbulence

<table>
<thead>
<tr>
<th>Last landing</th>
<th>Next aircraft on the queue</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heavy</td>
</tr>
<tr>
<td>Heavy</td>
<td>1.0</td>
</tr>
<tr>
<td>Large</td>
<td>1.0</td>
</tr>
<tr>
<td>Small</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Neighborhood Function and Cost Calculation

- New solution from changes between adjacent pairs of planes

- **Cost Calculation**
  - ETA (Estimated Time of Arrival) - STA (Station Time of Arrival)

\[
\begin{align*}
\text{(1)} & \quad \sum_{i=1}^{n-1} f(A_i + A_{i+1}) \\
\text{(2)} & \quad f(A_i + A_{i+1}) \begin{cases} 
\text{STA} = \text{STA} - \text{ETA}, \text{if ETA} < \text{STA} \\
0, \text{if ETA} = \text{STA}
\end{cases}
\end{align*}
\]
Analysis of Meta-Heuristics

- **Tabu Search**
- **Simulated Annealing**

**Experiment 1.**
- Number of aircraft = 10 and 40
- Best result neighbor function on TS
- *Tabu list sizes of 2 to 20, with increments of 2.*

**Experiment 2.**
- Number of aircraft = 10, 20, 30 and 40
- We ran = 1000
Performace Analysis - Experiment 1.

- $m=18$ gives the lower costs
- Cost approximately 5% less than the average
- Tabu list size with a ratio of 0.45 for each aircraft

![Figure 3. Neighbor solutions set](image)
Performace Analysis - Experiment 1.

- **mixed** approach had the best performance
  - cost of 19.48
  - standard deviation of 1.25

- The **Lower Cost** approach obtained the worst performance
  - cost of 32.37
  - standard deviation of 13.72

- The random approach obtained intermediate values
  - cost of 27.41
  - standard deviation of 4.78
Performace Analysis - Experiment 2.

- SA achieved better results

  - **TS**
    - 9%, n=20
    - 15%, n=30
    - 55%, n=40

  - **FCFS**
    - 12%, n=10
    - 19%, n=20
    - 15%, n=30
    - 5%, n=40

![Algorithm comparison graph](image_url)

Figure 4. Solution cost (average/standard deviation) vs different problem sizes
Part V - Some developed projects

A collaborative approach to management air traffic flow using multi-agent systems
The Proposal

- Develop a multi-agent system able to work mainly tactical planning ATFM
  - strategic planning; - 24h
  - pre-tactical planning; - 24 hours and 06 hours
  - tactical operations – 6 hours and during the flight

- Propose solutions that optimize air traffic flow in catastrophic situations
  - Sectors capacity management
  - Negotiation between airports
  - Deviations routes
4 types of agents are envisioned

- **Airport Agent**
  - Interests of an airport or coalitions
  - Negotiate air traffic flow demands

- **Airlines Agent**
  - Minimize delays

- **ATC Agent**
  - Management of services
  - Ensure the operational viability

- **Sector Agent**
  - Management of the national or regional
  - Join in the negotiation in special situations
Architecture

- The ATC Agent starts the negotiation
  - Intervention

- The Airport Agent changes proposals
  - Negotiation with Airline Agent

- The ATC checks the viability of proposal

- New Schedule is created
Infrastructure and Agents

- Construction of airports and jetways
  - Route network
  - services of ATC
    - Approach and Taxiway
  - ATC network

- Construction of internal agent modules
  - knowledge base
  - Kernel
  - Connection

- Construction of secondary agents
Part I - Project Proposals

Aircraft Formation
Aircraft Formation

- Construction of aircraft formation
  - Various geometric shapes

- Coordination between aircraft
  - Team Leader
  - choice of new leader
  - Group division

- Message exchange

- May be used to
  - To search and rescue
  - To combat
  - By Airspace Organization
Part II - Project Proposals

ATC network - Jetways
ATC network

- Route network - Graph
- Convert database information to XML
- Improvements in the simulation environment
  - Control Panel
- Air network View Screen
  - Google maps
Part III - Project Proposals

Load test in the simulator
Load test in the simulator

- Create a set of test scenarios
- Performance in different types of simulation tools
- Check the maximum capacity of aircraft in the virtual machine
- Propose an overload mechanism in simulation
- Delay between communication and maneuver
Conclusion
Conclusions

- Modern aviation needs constant technological updates
  - Congestion phenomena are persistent
- There are numerous challenges
- Use your tools
- Thank you for flying with us
Thank you.
Suggestions are welcome.

Álvaro Câmara
Porto, 20th April 2015