Red Bull Air Race

Planung und Sicherheitsanalysen
für Luftrennen

R. Leitner - IABG mbH

München, 2014-07-09
Contents

- Red Bull Air Race World Series
- Problem Description and Motivation
- Race Track Elements
- Software Structural Layout and Graphical User Interface
- Track Generation and Simulation Model
- Safety Assessment and Abu Dhabi Track
- Conclusion
Red Bull Air Race World Series

- Spectacular public sporting event like Formula-1
- Pilots have to pass a race course at minimum time
- Low-Level flying conditions
- Aerobatic Maneuvers
- Race Locations: Large cities around the world
- Safety is a paramount Issue
- Transparent Track Planning Process is required

IABG used MATLAB and Simulink to tackle this challenge
Red Bull Air Race World Series 2014: Abu Dhabi
Red Bull Air Race World Series 2014: Abu Dhabi
Red Bull Air Race World Series 2014: Abu Dhabi
Problem Description and Motivation

- Critical Boundary Conditions
  - Race Locations inside major cities
  - Large Number of Spectators
  - High Velocities and Load Factors
  - Low-Level Flight
  - Collision of A/C with pylons possible

SafEty is a paramount issue!

- Permissions for the race have to be negotiated with local municipal and aviation authorities

Comprehensible and transparent track planning process is required!

- Until 2007/2008 Track Design Process based only on the experience of the track designer and computer based drawing programs
Race Track is defined by two main components:

- **Race Gates**
  - Inflatable Pylons made of special fabric
  - Defining the race course by sequence and direction in which they have to be passed
  - Aerobatic maneuvers can be associated to gate

- **Race Zones**
  - Definition of specially designated areas in the race course
  - Highlighting of certain landmarks
## Race Track Elements: Gates

<table>
<thead>
<tr>
<th>Gate</th>
<th>Name</th>
<th>Associated Maneuvers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Level Gate</td>
<td>Pass with wings level</td>
</tr>
<tr>
<td></td>
<td>Knife-Edge Gate</td>
<td>Pass with +/- 90° bank</td>
</tr>
<tr>
<td></td>
<td>Quadro</td>
<td>Pass with +/- 90° bank</td>
</tr>
<tr>
<td></td>
<td>Chicane</td>
<td>Pass in a predefined direction</td>
</tr>
<tr>
<td></td>
<td>Buoy</td>
<td>Pass in a direct, shortest way</td>
</tr>
</tbody>
</table>
Race Track Elements: Zones

- Spectator Area
- Safe Zone
- Construction
- Race Box
- No Fly Zone
- Entry / Exit Corridor
Race Elements: Maneuvers

- Additional element to be taken into account while analyzing the race track
  - Half Cuban 8
  - Quad Gate Repositioning Maneuver
- Used to realign the aircraft with the race track

- Knife-Edge Maneuver
- Pull Maximum g

- Increases requirements to the pilots' capabilities
- Enhances level of spectacularity
- Top-of-the-Line Aerobatics

Inverted Dive
Push-Over
Pull-Up
Level Flight
Half Cuban 8
Software Structural Layout

MATLAB - Simulink – Stateflow - Matlab Compiler – MATLAB/Simulink Coder
Mapping Toolbox - Image Processing Toolbox
Graphical User Interface

- Environment
- Gate Elements
- Race Sequence Setup
- Simulation Control Interface
- Gate Properties
- Track Design Area
Track Generation and Simulation Model

**Stateflow**
- Maneuver Pilot
  - Trajectory Following
  - Maneuver Execution

**MATLAB**
- Reference Trajectory

**Simulink**
- Flight Control System
  - Trajectory CMD/CTRL
  - Path CMD/CTRL
  - Load Factor CMD/CTRL

**Simulink**
- Simulation Model
  - Kinematic/Dynamic

**Maneuver Pilot** can access all loops of the controller:
- Load factor commands
- Path angle rates
- Path angles
- Roll rates or bank angle

**DIRECT CMD**

**LF CMD**
Kinematic Simulation Model

Translational Dynamics → Nonlinear Point Mass Model

- Translation: Three degree of freedom (3-DOF) equations of motion

\[
\begin{align*}
\dot{V} &= g \cdot n_x - g \cdot \sin \gamma \\
\dot{\chi} &= \frac{g \cdot (n_y \cos \mu + n_z \sin \mu)}{V \cos \gamma} \\
\dot{\gamma} &= \frac{g \cdot (n_z \cos \mu - n_y \sin \mu)}{V} - \frac{g}{V} \cos \gamma
\end{align*}
\]

- Rotation: \( \dot{\mu} = p \)

- Position propagation (local NAV frame):

\[
\begin{align*}
\dot{x} &= u = V \cos \chi \cos \gamma \\
\dot{y} &= v = V \sin \chi \cos \gamma \\
\dot{z} &= w = -V \sin \gamma
\end{align*}
\]

- High fidelity simulation model with Dynamic Inversion Autopilot (see AIAA-2008-6532)

- Simulation model realized in Simulink (RTW RSIM target)

- Stand-alone executable

- Parameter exchange using appropriate interface
Maneuver Pilot

- **Purpose:**
  - Performance of race track flight maneuvers

- **Implementation**
  - State Chart driven automaton using STATEFLOW
  - Maneuvers divided into sub-elements which are driven by start / end conditions

- **Interface:**
  Maneuver pilot can access all controller loops to command
  - load factors
  - path angles / rates
  - roll rates and bank angle
Track Generation

- Spline based track generation under consideration of aircraft limits
- Initial connection between two waypoints using DUBINS algorithm
- Transitions between curved and straight line elements using clothoids (modeling a continuous increase in aircraft bank)
- Discrete track points are connected using 6th order spline ("Spline Overplugging")
  - Continuous description of the waypoint connection
  - Used for generation of commands for the simulation model

\[ p = \sum_{i=0}^{n} a_i k^i \]

- see AIAA 2008-6466
Race Track Simulation

Maneuver Pilot
- Mode
  - Reference Trajectory Following
- Mode
  - Flight Maneuver Execution

Level Gate
Knife-Edge Gate
Coordinated 90° Bank
Chicane
Half-Cuban-Eight
Safety Assessment

- After successful track generation, the resulting trajectories can be evaluated with respect to a variety of safety relevant parameters:
  - Time / Distance to Crowd-Line
  - Time / Distance to Ground
  - Ballistic Extrapolation

- Parameters are calculated to identify areas with a potentially higher risk-level for participants and spectators.
Safety Assessment: Ballistic Extrapolation

- "Ballistic Extrapolation" criteria assumes a zero-atmosphere ballistic flight.

- Allows computation of impact point to QUALITATIVELY judge possible hazardous areas.

- HOWEVER(!), method is based on simplifying assumptions and DOES NOT provide realistic impact data.
Not only distance to crowd, but also direction of speed vectors is essential for identifying problematic elements of the race track.
3D Track of ABU DHABI 2014
Ballistic Extrapolation
Conclusion

- Stand-alone tool for the design and evaluation of air race tracks has been presented

- Sophisticated numerical track generation routines in combination with a high fidelity simulation

- Simulation results can be analyzed concerning safety-aspects

- Results can be used for briefing purposes and for negotiations with local aviation and municipal authorities to obtain permission for the air race

Provide the track designer with all the necessary means to develop and analyse the intended race design at a given location.
Benefits of Mathworks Tool Chain

MATLAB in General

- Easy to use programming language
- Handles large datasets easily
- Toolboxes allow to scale MATLAB to the needs of specific project

Dynamic Modeling/Simulation and Control Design of Dynamics in Simulink

- Graphical user interface
  eases design of dynamic system and allows fast control design
- Hierarchical model with subsystems allow to easily adjust modeling level
- Component based, components are easily reusable in multiple model/projects
- Flexible interfaces for post processing of simulation data
- Simulink models can be easily adjusted to model variants
Thank you for your kind attention! Any Questions?