Multi-agent dynamic risk modelling for accident risk assessment of runway incursion scenarios

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Mastering the complex ATM system safely

Complexity and performance variability in ATM

- Distributed human operators and technical systems
- Considerable interconnectivity between the agents
- Internal and external uncertainties and disturbances
- Human role is important to cope efficiently with uncertainties and disturbances
TOPAZ safety risk assessment cycle

0 Identify objective

Operational development

1 Determine operation

Decision making

2 Identify hazards

3 Construct scenarios

4 Assess severity

5 Assess frequency

6 Assess risk tolerability

7 Identify safety bottlenecks

Iterate (option)
Active runway crossing operation

**Human operators**
- Pilots aircraft taking-off
- Pilots aircraft taxiing
- Runway controller
- Ground controller

**Visibility conditions**
- Visibility condition 1
  - Unrestricted range
- Visibility condition 2
  - Range of 400 – 1500 m

**Technical systems**
- VHF R/T communication
- Ground radar
- Active stopbar
- ATC alert system
  - Ground radar data
  - Alerts runway controller
- Cockpit alert system
  - GPS ownship data
  - ADS-B linked othership data
  - Alerts pilots
Runway incursion scenario

Aircraft is erroneously taxiing across the runway while an aircraft is taking off

Proceeding on a normal taxiway

Allowed to cross the runway
Timeline example 1 of runway incursion

**AC-TO**
- Start TO
- Start taxi

**AC-TX**
- See conflict
- Brake
- Hold

**PF-TO**
- See conflict
- Start RTO

**PF-TX**
- See conflict
- Brake

**ATCo**
- See conflict
- RT
- Active

**ATC Alert**
- Active
Timeline example 2 of runway incursion

- **AC-TO**: Start TO
- **AC-TX**: Start taxi
- **PF-TO**: See conflict, Start RTO
- **PF-TX**: See conflict, Brake
- **ATCo**: See conflict, RT
- **Active**: ATCo Alert
- **RTO**: Brake
Event sequence-based risk model

Accident is a combination of ordered events and conditions
- failures of systems or humans
- recovery actions of systems or humans
- contextual conditions

Examples: event tree, fault tree, event sequence diagram

Predominantly used in reliability engineering and risk assessment
Problems with event sequence-based risk models

**Fixed event sequences**
- No account for timeline variations

**Event probabilities**
- How to obtain appropriate values?
- How to know interdependencies between?

**No emergent risk results**
- What you see is what you get
- No insights for various contextual conditions
TOPAZ multi-agent dynamic risk modelling of runway incursion scenario

- **Hazard: No frequent visual monitoring**
- **Hazard: Controller reacts late to alert**
- **Hazard: Failure of alert system**
- **FMS taking-off aircraft**
- **PF taking-off aircraft**
- **Taking-off aircraft**
- **FMS taxiing aircraft**
- **PF taxiing aircraft**
- **Taxiing aircraft**
- **R/T System**
- **Runway controller**
- **ASMGCS**

The diagram illustrates the process and potential hazards involved in a runway incursion scenario, with various agents and systems interacting and affecting risk levels.
Submodels in TOPAZ MA-DRM: Multi-agent situation awareness (MASS)

Multi-agent system:

SA of agent $k$ at time $t$ about agent $j$:

$$\sigma_{t,k}^j = \begin{pmatrix}
\text{identity} \\
\text{state} \\
\text{mode} \\
\text{intent}
\end{pmatrix}$$

SA updating processes:

Observation

Communication

Reasoning

Decision rules
Submodels in TOPAZ MA-DRM: System mode / Variability / Context

System mode (SM)

Mode 1 ← Mode 2 ← Mode 3

Dynamic variability (DV)

\[ \dot{x} = f(x, u) \]

\[ y = g(x, u) \]

Stochastic variability (SV)

Contextual condition (CC)
Petri nets

- **Place**
- **Transition**
- **Arc**
- **Token**

Diagram examples of Petri nets with places, transitions, arcs, and tokens.
**Stochastically and Dynamically Coloured Petri Nets (SDCPN)**

- Tokens have Euclidean values
  - Follow SDE while the token resides in its place
- Arcs:
  - Ordinary
  - Inhibitor
  - Enabling
- Transitions:
  - Delay
  - Guard
  - Immediate
- Firing:
  - Euclidean valued tokens
  - According to probability measure
- Hierarchical modelling to enhance *compositional specification* of complex models
Tokens have Euclidean values
  - Follow SDE while the token resides in its place

Arcs:
  - Ordinary
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  - Enabling

Transitions:
  - Delay
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  - Immediate

Firing:
  - Euclidean valued tokens
  - According to probability measure

Hierarchical modelling to enhance compositional specification of complex models
MA-DRM formalization by SDCPNs
- Situation Awareness of Pilots -
MA-DRM formalization by SDCPNs
- Controller Message Transfer -
MA-DRM formalization by SDCPNs
- Flight Control Pilots Taxiing Aircraft -

Diagram:
- Stop Taxiing
- Taxi Off Runway
- Line-up
- Cross Runway
- Taxi Taxiway
- Hold at WP
- Hold at Stopbar
- System Entrance

Network:
- Situation Awareness [Pilots_T]
- IPN FC [Pilots_T]
- Int-FC

Legend:
- G
- I
- SA

Flights control [Pilots_T]
MA-DRM formalization by SDCPNs
- Evolution of Taxiing Aircraft -
Monte Carlo simulations are needed to evaluate the risk implications of a multi-agent DRM

- Large numbers of simulation runs for the stochastic dynamics of the DRM
- Draw samples from the PDFs in the DRM
- Detect safety-relevant data: accidents, incidents, other events, agent variables
Speed-up of MC simulations by risk decomposition

\[ P(\text{collision}) = \sum_{i} P(\text{condition}_i) \cdot P(\text{collision} | \text{condition}_i) \]

Conditions (selected)

- Visibility condition
  - 1 (unrestricted)
  - 2 (400 – 1500 m)

- Availability of runway incursion alert systems
  - None
  - ATC
  - Both aircraft
  - ATC and both aircraft

- Situation awareness of pilot flying taxiing aircraft
  - Proceed taxiway
  - Cross runway
Monte Carlo simulation results for (good) visibility condition 1

Conditional collision risk (per take-off)

Alerts: None ATC A/C ATC+A/C None ATC A/C ATC+A/C
SA PF: Proceed taxiway Cross runway
Monte Carlo simulation results for (reduced) visibility condition 2

Conditional collision risk (per take-off)

Alerts: None ATC A/C ATC+A/C None ATC A/C ATC+A/C
SA PF: Proceed taxiway Cross runway
Monte Carlo simulation results for visibility conditions 1 & 2

<table>
<thead>
<tr>
<th>Alerts</th>
<th>Conditional collision risk (per take-off)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>10^{-6} 1</td>
</tr>
<tr>
<td>ATC</td>
<td>10^{-3} 2</td>
</tr>
<tr>
<td>A/C</td>
<td>10^{-4} 2</td>
</tr>
<tr>
<td>ATC+A/C</td>
<td>10^{-5} 2</td>
</tr>
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<th>Alerts:</th>
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<tr>
<td>Proceed taxiway</td>
<td>None</td>
</tr>
<tr>
<td>Cross runway</td>
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</table>
MC simulation measurements (good visibility)

Unconditional PDFs

PDFs given collision

PF-TX detects by own observation

ATCo warns PF-TX

Front-wheel position of taxiing aircraft w.r.t. runway centre-line (meters)
MC simulation risk sensitivity and uncertainty results (good visibility/ATC alert)

Large effects
- Deciding by pilots when other aircraft is conflicting
- Speed of taxiing aircraft
- Visual monitoring frequency of pilot flying of taxiing aircraft
- Deceleration profile of aircraft in case of collision avoidance
- Time before initiation of braking
- Types of manoeuvres of the taking-off aircraft to avoid a collision
- ...

Negligible effects
- Performance of VHF R/T systems
- Performance of surveillance tracking systems
- Performance of runway incursion alert system
- Variation in take-off weight
- Lift-off velocity
- Engine failure during take-off
- Task scheduling of runway controller
- ...

Large effects

Negligible effects
Comparison of event tree and MA-DRM results (good visibility/ATC alert)

Risk reduction by ATC alert system

Conditional accident probability

Risk reduction by 10.06

Risk reduction by 16
The effectiveness of runway incursion alert systems depends considerably on the type of alert and the operational context.

An event tree-based risk assessment led to a considerably lower risk estimate (good visibility)

- An event tree cannot well account for ATM scenarios with interacting and mutually dependent entities (humans, systems).

The TOPAZ MA-DRM simulations show that the collision risk depends on totality of the performance and interactions of all human operators and technical systems in the operational context considered.

- Collision risk as an emergent property of a complex system.
TOPAZ MA-DRM application areas

- Opposite en-route parallel lanes
- Free flight equipped aircraft
- Wake vortex induced risk
- Converging runways
- Active runway crossings
- Runway occupancy time
- Noise abatement approach
- Galileo

TOPAZ MA-DRM simulation has been chosen as the application method in SESAR WP16.1.3 on dynamic risk modelling