A “closed-loop” approach for complexity maps: principle and applications

Erwan Salaün, Adan Vela, Eric Feron, John-Paul Clarke, Senay Solak†

Georgia Institute of Technology, Atlanta GA
†University of Massachusetts, Amherst MA

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In many enroute regions, air traffic is expected to exceed current capacity limits, as defined by controllers.
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Implications:

- Aircraft may be subject to more conflict avoidance maneuvers
- Requires development of (semi-) automated conflict resolution
- New traffic patterns and new routes are necessary
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⇒ create a complexity map support tool for air traffic manager
Requirements for complexity maps for air traffic management:

- Provide a realistic image of the current and future airspace health
- Be an “easy-to-use” tool
Introduction

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⇒ Our approach:
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⇒ Our approach:
Previous Works on Complexity Maps

Significant volume of research related to estimating air traffic complexity:

- [I.V. Laudeman et al., B. Sridhar et al.]: “dynamic density”
- [D. Delahaye et al.]: Lyapunov exponents map
- [M. Prandini et al.]: probability of presence
- [R. Irvine et al., H.A.P. Blom et al.]: probability of conflict
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Common approach: aircraft position/intent is “known”, no conflict avoidance, short-term time horizon
“Open-loop” vs. “Closed-loop” Approaches

- Common “open-loop” approach

Geometrical configuration → Model and analytical method → Probability of conflict
Aircraft Position / Intent →

⇒ the system runs in closed-loop!
⇒ desired input ≡ flows
⇒ influence of conflict resolution → input ≡ flows
⇒ Is it possible to model? “closed-loop” vs. “open-loop”? 

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[Diagram]

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But in reality

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New “closed-loop” approach
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  Flow characteristics

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  - Geometrical configuration
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  - Flow characteristics

  Model and analytical method

  Probability of conflict

  Conflict avoidance algorithm

  ⇒ influence of conflict resolution
  ⇒ input ≡ flows

  ⇒ Is it possible to model?
  ⇒ “closed-loop” vs. “open-loop”?
Numerous studies focused on the conflict avoidance algorithm itself ($d_{\text{miss}} \geq d$):

- [M. Gariel et al., L. Pallottino et al.] : heading changes
- [J.-P.B. Clarke et al.] : speed & heading changes
- [Z.-H. Mao et al.] : translational shifting (offset method)
Basic Element : Pair-wise Intersection

What is the probability of non conflict $P_{NC}(AC_1^1)$?

Assumptions:
- Flows are independent
- No cross-track errors
- $v_1 = v_2 = v$
- Avoidance algorithm $\equiv$ offset method
- $AC_i^1 \equiv$ last AC from flow $i$
Basic Element: Pair-wise Intersection

The ATM can choose the Encounter and Flow Configuration (E.F.C.)

- **the encounter geometrical configuration**: crossing angle, minimum miss distance
- **the flow characteristics**: the PDF of the inter-arrival distance

- Inter-arrival distance $\Delta d_i$
- PDF of the inter-arrival distance $f_{\Delta D_i}(\Delta d_i)$
Determining $P_{NC}(AC_1^1)$ With a “Closed-loop” Approach

- Aircraft $AC_2^k$ may be subject to lateral displacement $d_2^k$

- $t_2^k$ is the “age” of $AC_2^k \implies$ PDF of $t_2^k$ is known

\[ P_{NC}(AC_1^1) = P(\forall k, AC_2^k \text{ n.i.c. } AC_1^1) \approx \prod_{k=1}^{N_2} (1 - P(AC_2^k \text{ i.c. } AC_1^1)) \]

- $P(AC_2^k \text{ i.c. } AC_1^1) = P(L_n \leq s_2 d_2^k - t_2^k \leq L_p)$, where $(L_n, s_2, L_p) = f(\theta, d)$.

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Determining $P_{NC}(AC^1_1)$ With a “Closed-loop” Approach

Diamond Aircraft $AC^k_2$ may be subject to lateral displacement $d_2^k$

Diamond $t_2^k$ is the “age” of $AC^k_2 \Rightarrow$ PDF of $t_2^k$ is known

$P_{NC}(AC^1_1) = P(\forall k, AC^k_2 \text{ n.i.c. } AC^1_1)$

$\approx \prod_{k=1}^{N_2} (1 - P(AC^k_2 \text{ i.c. } AC^1_1))$

Diamond $P(AC^k_2 \text{ i.c. } AC^1_1) = P(L_n \leq s_2 d_2^k - t_2^k \leq L_p)$, where $(L_n, s_2, L_p) = f(\theta, d)$. To be determined!
This model takes into account
⇒ spatial deviation due to the avoidance maneuver
⇒ dissymmetry of the lateral deviation towards right/left
⇒ \((\alpha_i, \beta_i)\) to be determined as a function of the E.F.C.
Determining $\alpha_i, \beta_i$ as a Function of the E.F.C.

System of 4 equations as a function of the 4 parameters $\alpha_i, \beta_i$.

\[
\begin{align*}
\alpha_1 &= f_1(E.F.C., \alpha_2, \beta_2) \\
(1 - \alpha_1)(1 - \beta_1) &= f_2(E.F.C., \alpha_2, \beta_2) \\
\alpha_2 &= f_3(E.F.C., \alpha_1, \beta_1) \\
(1 - \alpha_2)\beta_2 &= f_4(E.F.C., \alpha_1, \beta_1)
\end{align*}
\]

$\Rightarrow$ for any E.F.C., we can determine in real time $\alpha_i, \beta_i$. 

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Comparison With Simulations

- Algorithm $\equiv$ offset method
- $\theta = 90^\circ$
- $C = (0, 100) \text{ NM}$
- 500 aircraft in each flow
- $v = 450 \text{ kt}$
- $f_{\Delta D_i}(\Delta d_i) \equiv$ exponential distribution
- $\Delta d_{i}^{min} = 5 \text{ NM}$
- $\text{range}(\Delta d_{i}^{m}) = [5.5, 54.5] \text{ NM}$.
Few differences at realistic inter-arrival distances
($\Delta d_i^m \geq 35$NM)
⇒ Few differences at realistic inter-arrival distances ($\Delta d_i^m \geq 35\text{NM}$)

⇒ “Open-loop” approach: similar results
Comparison With Simulations

⇒ Very similar CDF ($P_{NC}$, shape, dissymmetry)
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Validation of the model with the avoidance algorithm
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⇒ Very similar CDF ($P_{NC}$, shape, dissymmetry)

⇒ Validation of the model with the avoidance algorithm

⇒ “Open-loop” approach: no spatial deviation! ⇒ insufficient for multiple intersections
Conclusions

- Validation of the “closed-loop” model
  - Inputs designed for ATM
  - Taking into account the influence of the avoidance algorithm
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- “Open-loop approach” is insufficient for multiple intersections → new conflicts may occur!
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- Illustration with Cleveland center
Acknowledgment

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