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

INFORMS 2009, San Diego

Introduction

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

Introduction

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

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

Introduction

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

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

$\Rightarrow$ *create* ***a complexity map support tool*** *for air traffic manager*

Introduction

Requirements for complexity maps for air traffic management :

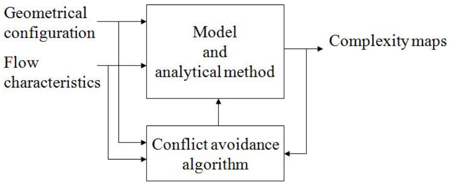
- Provide a realistic image of the current and future airspace health
- Be an “easy-to-use” tool

Introduction

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

⇒ Our approach :

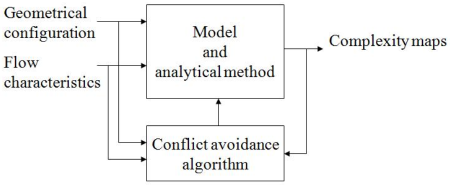


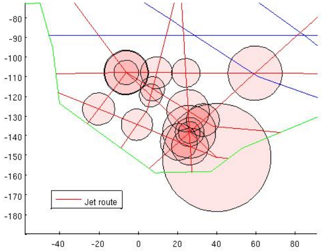
Introduction

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

$\Rightarrow$ Our approach :





Previous Works on Complexity Maps

Significant volume of research related to estimating air traffic complexity :

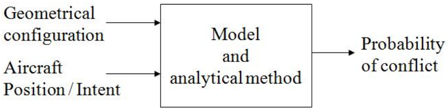
- [*I.V. Laudeman et al., B. Sridhar et al.*] : "dynamic density"
- [*D. Delahaye et al.*] : Lyapunov exponents map
- [*M. Prandini et al.*] : probability of presence
- [*R. Irvine et al., H.A.P. Blom et al.*] : **probability of conflict**

Previous Works on Complexity Maps

Significant volume of research related to estimating air traffic complexity :

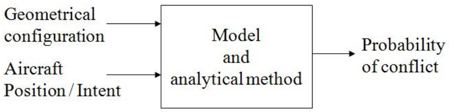
- [*I.V. Laudeman et al., B. Sridhar et al.*] : “dynamic density”
- [*D. Delahaye et al.*] : Lyapunov exponents map
- [*M. Prandini et al.*] : probability of presence
- [*R. Irvine et al., H.A.P. Blom et al.*] : **probability of conflict**

Common approach : aircraft position/intent is “known”, no conflict avoidance, short-term time horizon



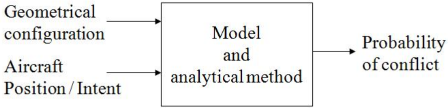
“Open-loop” vs. “Closed-loop” Approaches

- Common “open-loop” approach



“Open-loop” vs. “Closed-loop” Approaches

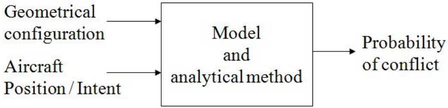
- Common “open-loop” approach



But in reality

"Open-loop" vs. "Closed-loop" Approaches

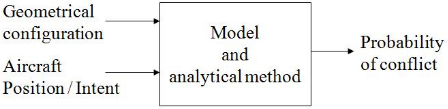
- Common "open-loop" approach



But in reality
$\Rightarrow$ the system runs in closed-loop !
$\Rightarrow$ desired input $\equiv$ flows

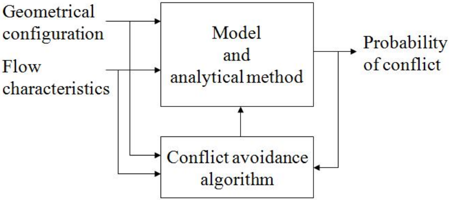
“Open-loop” vs. “Closed-loop” Approaches

- Common “open-loop” approach



But in reality
$\Rightarrow$ the system runs in closed-loop !
$\Rightarrow$ desired input $\equiv$ flows

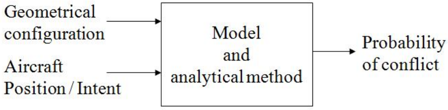
- New “closed-loop” approach



$\Rightarrow$ influence of conflict resolution
$\Rightarrow$ input $\equiv$ flows

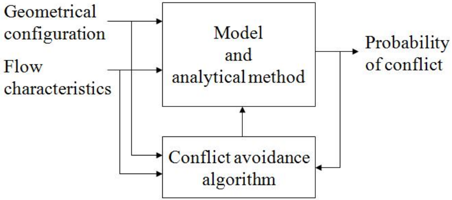
“Open-loop” vs. “Closed-loop” Approaches

- Common “open-loop” approach



But in reality
⇒ the system runs in closed-loop !
⇒ desired input ≡ flows

- New “closed-loop” approach



⇒ influence of conflict resolution
⇒ input ≡ flows

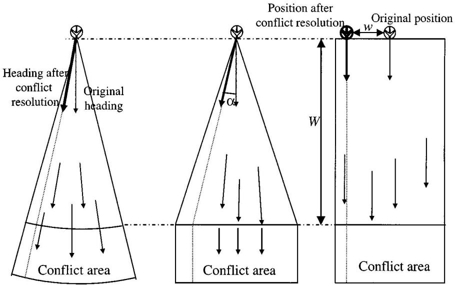
⇒ Is it possible to model ?

⇒ “closed-loop” vs. “open-loop ” ?

Automated Conflict Resolution

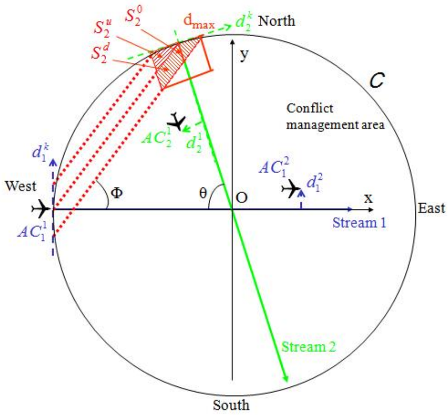
Numerous studies focused on the conflict avoidance algorithm itself ($d_{miss} \geq d$) :

- [*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 :

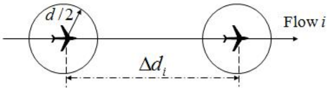
- Flows are independent
- No cross-track errors
- $v_1 = v_2 = v$
- Avoidance algorithm ≡ offset method
- AC_i^1 ≡ last AC from flow i

Basic Element : Pair-wise Intersection

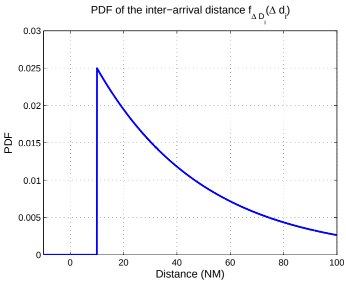
The ATM can choose the Encounter and Flow Configuration (E.F.C.)

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

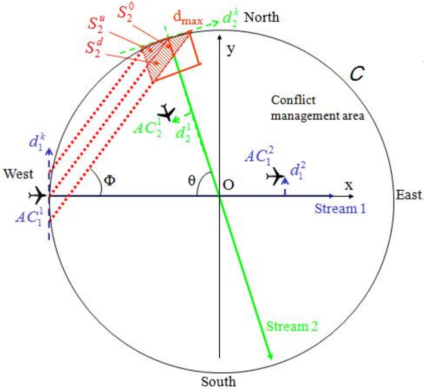
• inter-arrival distance Δd_i



• PDF of the inter-arrival distance $f_{\Delta D_i}(\Delta d_i)$



Determining $P_{NC}(AC_1^1)$ With a "Closed-loop" Approach



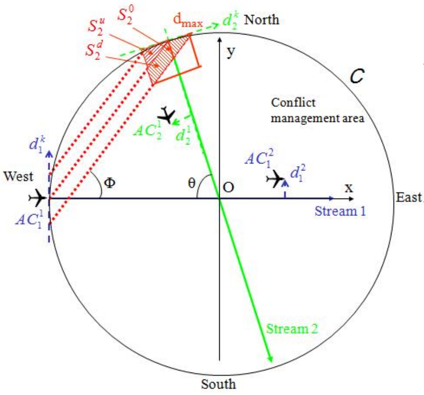
◇ Aircraft AC_2^k may be subject to lateral displacement d_2^k

◇ t_2^k is the "age" of $AC_2^k \Rightarrow$ 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 $(L_n, s_2, L_p) = f(\theta, d)$.

Determining $P_{NC}(AC_1^1)$ With a "Closed-loop" Approach



◇ Aircraft AC_2^k may be subject to lateral displacement d_2^k

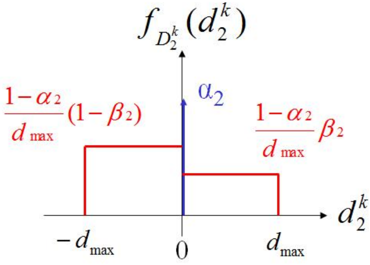
◇ t_2^k is the "age" of $AC_2^k \Rightarrow$ PDF of t_2^k is known

◇ $P_{NC}(AC_1^1) = P(\forall k, AC_2^k \text{ n.i.c. } AC_1^1)$

$$\approx \prod_{k=1}^{N_2} (1 - P(AC_2^k \text{ i.c. } AC_1^1))$$

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

Model of the PDF of the Lateral Deviation



- ⋄ This model takes into account

⇒ spatial deviation due to the avoidance maneuver

⇒ dissymmetry of the lateral deviation towards right/left

- ⋄ ⇒ (α_i, β_i) to be determined as a function of the E.F.C.

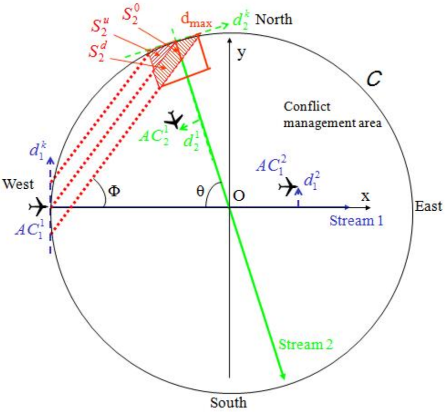
Determining α_i, β_i as a Function of the E.F.C.

System of 4 equations as a function of the 4 parameters α_i, β_i.

$$\begin{cases} \alpha_1 = f_1(E.F.C., \alpha_2, \beta_2) \\ (1-\alpha_1)(1-\beta_1) = f_2(E.F.C., \alpha_2, \beta_2) \\ \alpha_2 = f_3(E.F.C., \alpha_1, \beta_1) \\ (1-\alpha_2)\beta_2 = f_4(E.F.C., \alpha_1, \beta_1) \end{cases}$$

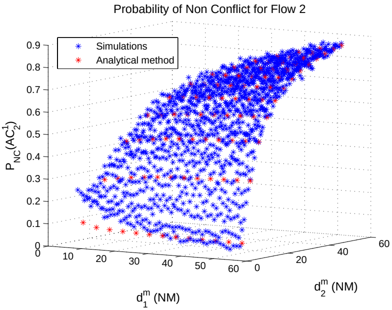
$\Rightarrow$ for any E.F.C., we can determine in real time α_i, β_i.

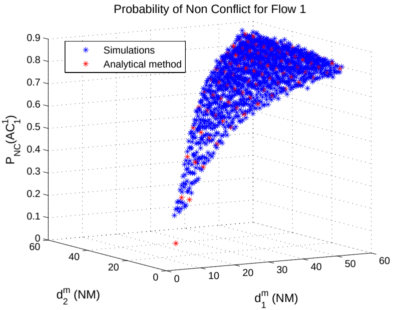
Comparison With Simulations



- Algorithm $\equiv$ offset method
- $\theta = 90°$
- $C = (0, 100)$ NM
- 500 aircraft in each flow
- $v = 450$ kt
- $f_{\Delta D_i}(\Delta d_i) \equiv$ exponential distribution
- $\Delta d_1^{min} = \Delta d_2^{min} = 5$ NM
- range$(\Delta d_i^m) = [5.5, 54.5]$ NM.

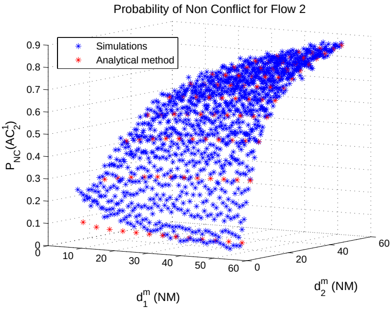
Comparison With Simulations

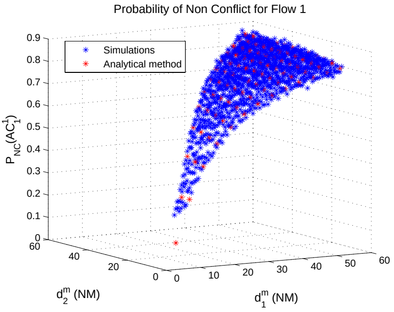




$\Rightarrow$ Few differences at realistic inter-arrival distances ($\Delta d_i^m \geq 35$NM)

Comparison With Simulations

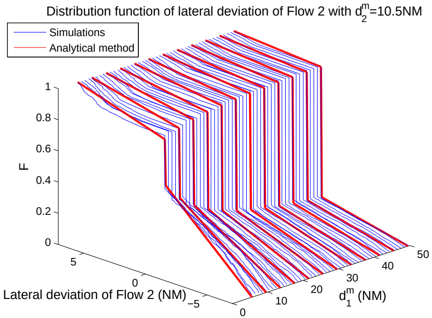




$\Rightarrow$ Few differences at realistic inter-arrival distances ($\Delta d_i^m \geq 35$NM)

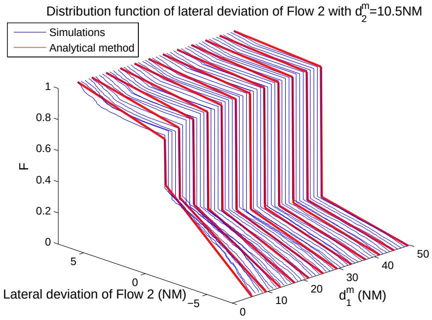
$\Rightarrow$“Open-loop” approach : similar results

Comparison With Simulations



$\Rightarrow$ Very similar CDF (P_{NC}, shape, dissymmetry)

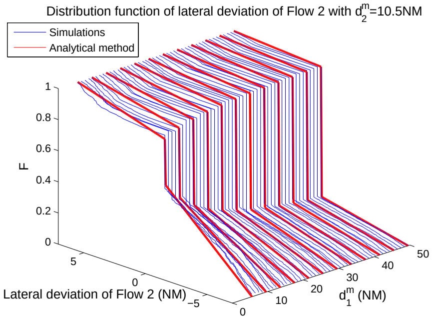
Comparison With Simulations



$\Rightarrow$ Very similar CDF (P_{NC}, shape, dissymmetry)

$\Rightarrow$ Validation of the model with the avoidance algorithm

Comparison With Simulations



⇒ 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

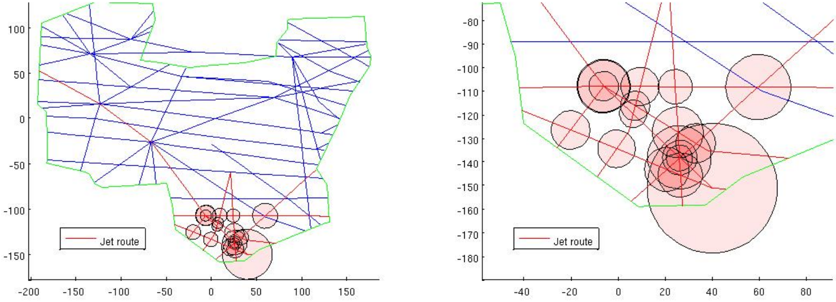
Conclusions

- Validation of the “closed-loop” model
  - Inputs designed for ATM
  - Taking into account the influence of the avoidance algorithm
- “Open-loop approach” is insufficient for multiple intersections $\rightarrow$ new conflicts may occur !

Conclusions

- Validation of the "closed-loop" model
  - Inputs designed for ATM
  - Taking into account the influence of the avoidance algorithm
- "Open-loop approach" is insufficient for multiple intersections → new conflicts may occur !

- Illustration with Cleveland center



Acknowledgment

Special thanks to our sponsors