On the safety assessment of RPAS safety policy

ERTS

January 30th, 2020

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ONERA

THE FRENCH AEROSPACE LAB

retour sur innovation

Increasing demands for RPAS

Increasing number of operational concepts involving Remotely Piloted Aircraft Systems (RPASs)

- Urban logistic (CDiscount, La Poste, . . .)
- Infrastructure inspection (SNCF, RTE, . . .)
- Rescue mission (Helper drone, . . .)

Safety issues

Integrating Unmanned Aerial Vehicles in airspace raises safety issues:

Ground Risk Collision with infrastructure or on-ground population

Air Risk Air collision with inhabited aerial traffic

Plan

How are these risks managed?

Underlying assumptions

Classical aviation:

1. Aircraft is inhabited
   $\Rightarrow$ ensuring flight safety $=$ ensuring aircraft integrity
2. Pilot is on-board
   $\Rightarrow$ numerous safety actions involve the pilot

UAV:

1. UAV is uninhabited
   $\Rightarrow$ ensuring flight safety $\neq$ ensuring UAV integrity
2. Pilot is remote
   $\Rightarrow$ safety actions taken by the remote pilot and the drone

Leads to different risk management
Must be considered during the safety assessment

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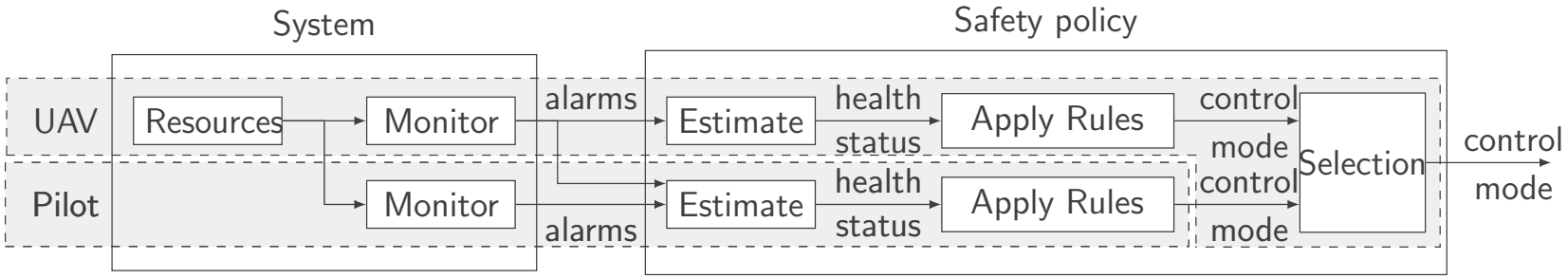
How hazardous situations are handled in an RPAS?

Safety policy by the example

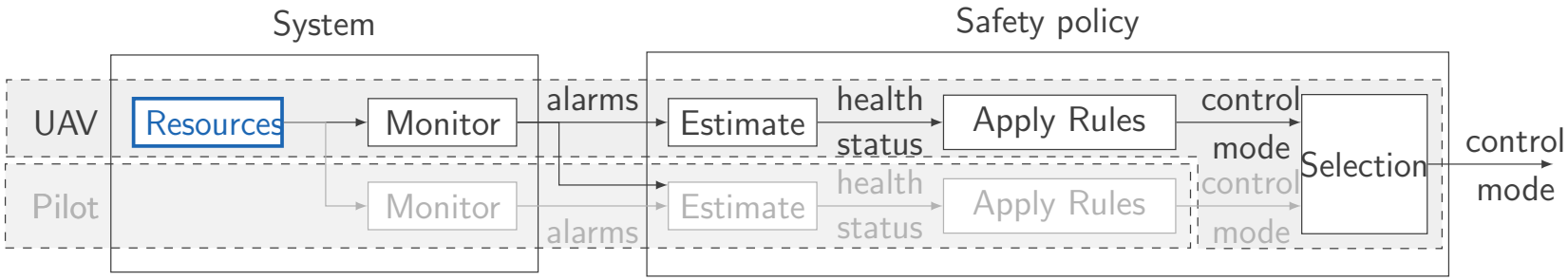


Mission Inspect infrastructures located in pre-defined and controlled evolution zone

Hazard Flyaway or crash outside of the evolution zone

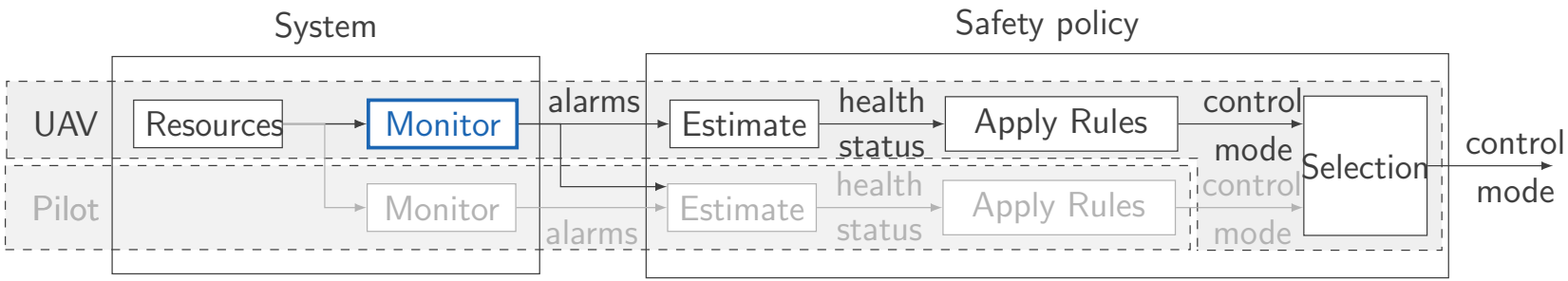
Modes Autonomous (A)
Return to home (H)
Descending spiral (S)

Safety policy by the example



Resource h_1 and h_2 needed by A, h_p needed by H

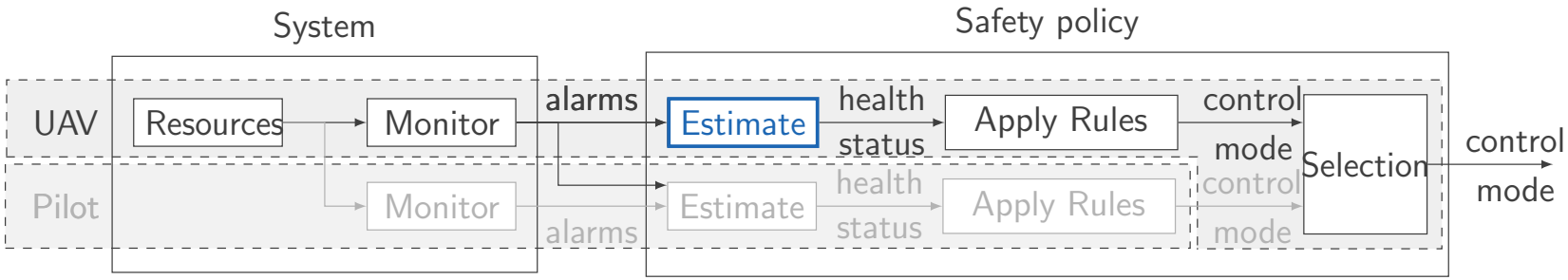
Safety policy by the example



Resource h_1 and h_2 needed by A, h_p needed by H

Monitor a_1 (resp. a_2) powered by h_p monitoring h_1 (resp. h_2)

Safety policy by the example



Resource h_1 and h_2 needed by A, h_p needed by H

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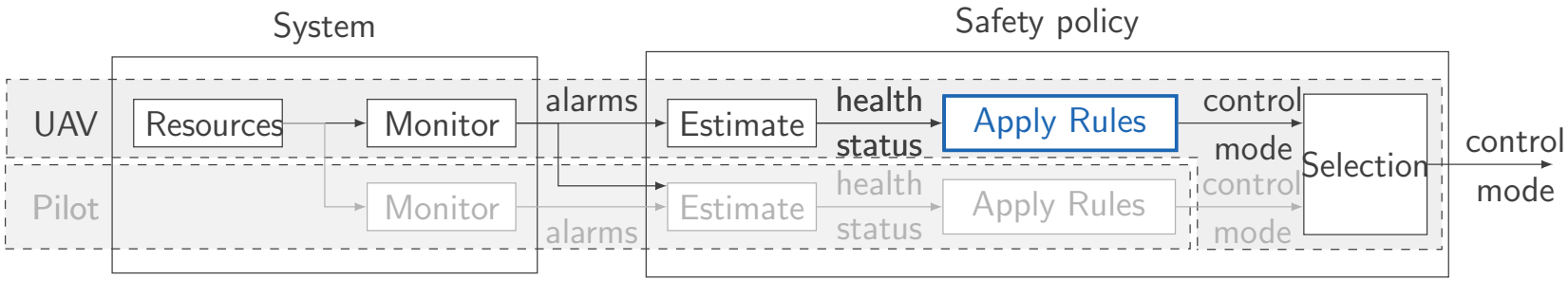
Estimate if a_1 (resp. a_2) then $\overline{h_1}$ (resp. $\overline{h_2}$)

Safety policy by the example



Resource h_1 and h_2 needed by A, h_p needed by H

Monitor a_1 (resp. a_2) powered by h_p monitoring h_1 (resp. h_2)

Estimate if a_1 (resp. a_2) then $\overline{h_1}$ (resp. $\overline{h_2}$)

Apply if $\overline{h_1}$ or $\overline{h_2}$ initiate H
if $\overline{h_p}$ initiate S

Challenges of safety assessment

Dynamism Policy is performed according to the successive estimation of the health status.

- addressed using modelling language for dynamic systems (ALTARICA[APGR99], [PPR16], ...)

Decision UAV on-board monitoring provides partial obervability $\Rightarrow$ possible health status estimation issues

1. selection of unsuitable mode
2. hazardous situations (flyaway, uncontrolled crash, ...)

Problem reformulation

- knowing the alarms (*i.e.* observations) received by the UAV and the pilot
- knowing the possible failures of on-board components (*i.e.* system model)
- a safety policy:
  1. selects a preferred health status among the possible ones
  2. provides a control mode out of this health status

Safety assessment identify when the policy is not able to select a safe mode

$\Downarrow$

Estimation problem identify mis-estimations (policy) leading to an unsafe mode selection

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Contribution

1. formal framework to model the safety policy as a preference-based estimator
   - **Modular** split system model, estimation preferences and mode selection
   - **Generic** no assumptions over the kind of UAV (fixed wing, quad-copter, ...)
2. formal encoding of hazardous events
   $\Rightarrow$ use existing solver to identify hazardous failure combinations

Why considering a preference-based estimation problem?

Estimation problem by the example

Modes Autonomous(A),
Return to home (H)
Descending spiral (S)

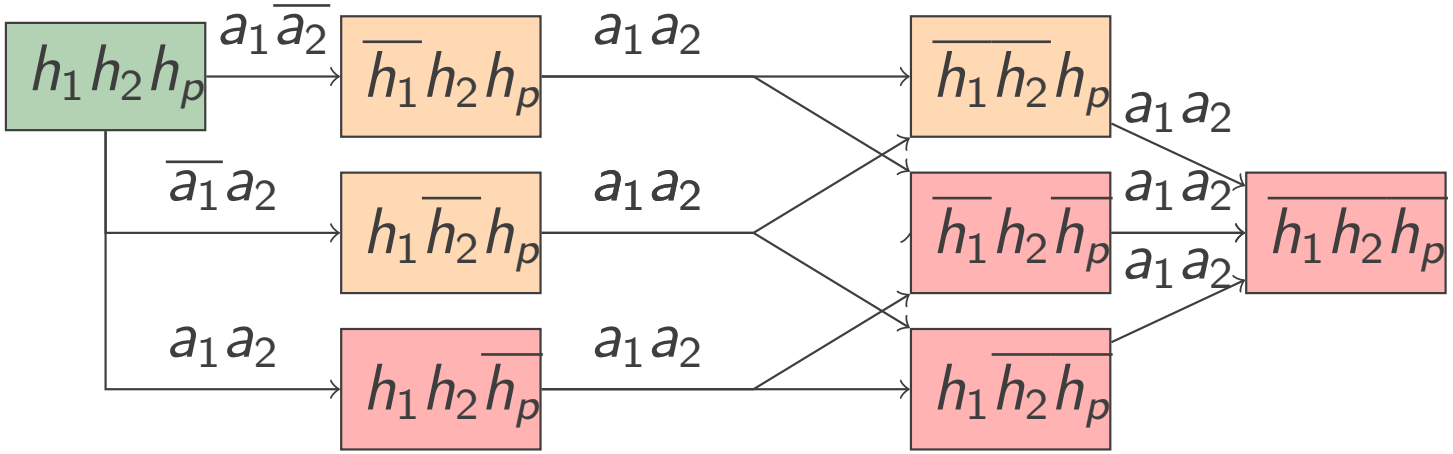
Resource h_1 and h_2 needed by A, h_p needed by H

Monitor a_1 (resp. a_2) powered by h_p monitoring h_1 (resp. h_2)

Assumptions

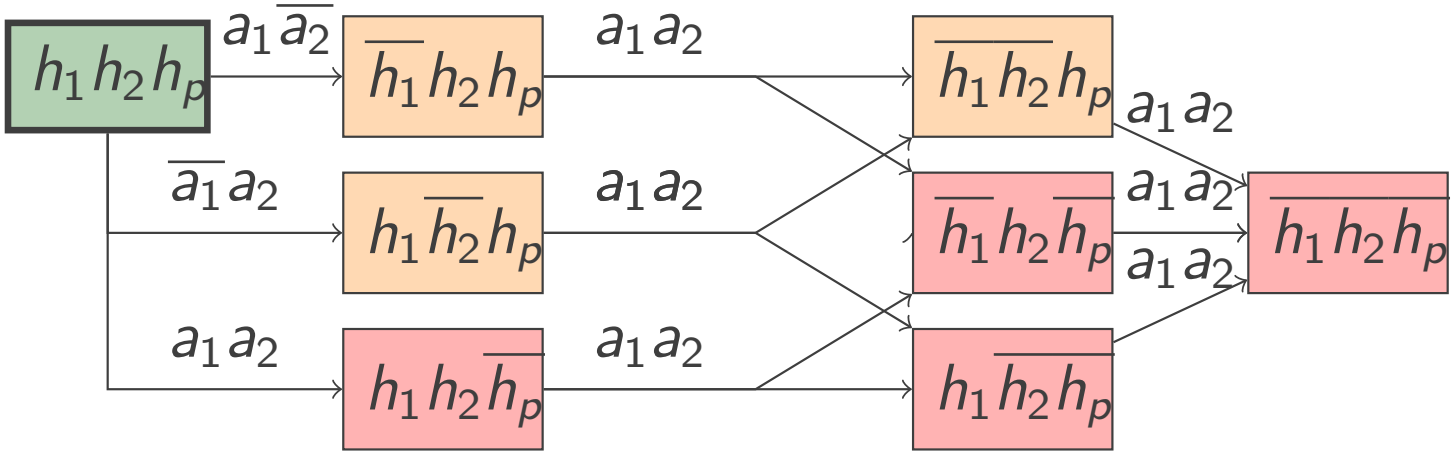
1. permanent failures
2. interleaving
3. only loss failure mode for resources

Estimation problem by the example



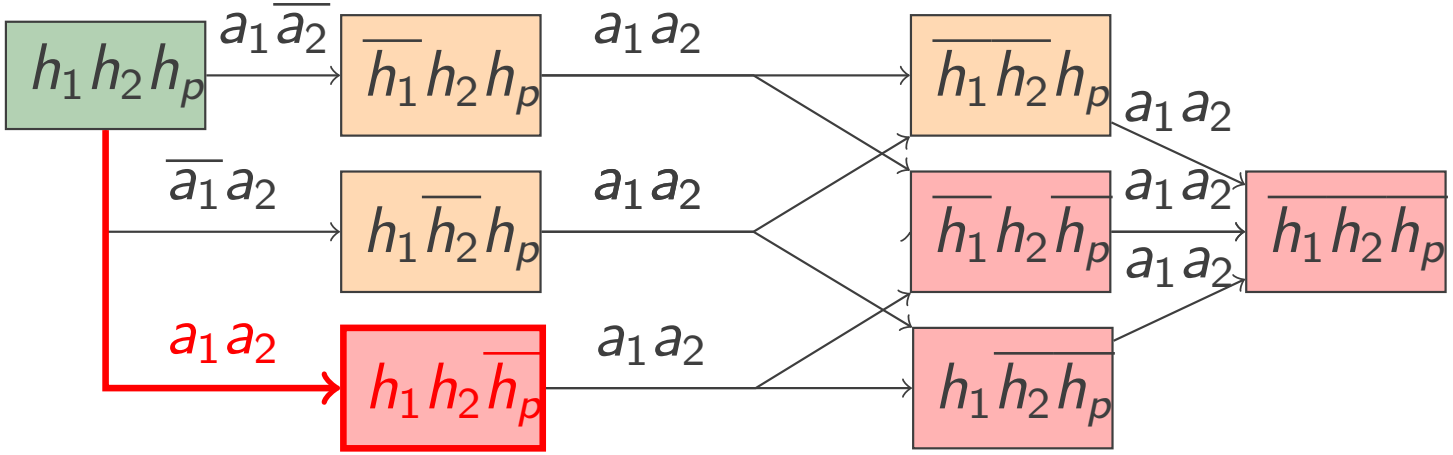
Observation	Real	Estimated

Estimation problem by the example



Observation	Real	Estimated
$\overline{a_1 a_2}$		$h_1 h_2 h_p$

Estimation problem by the example

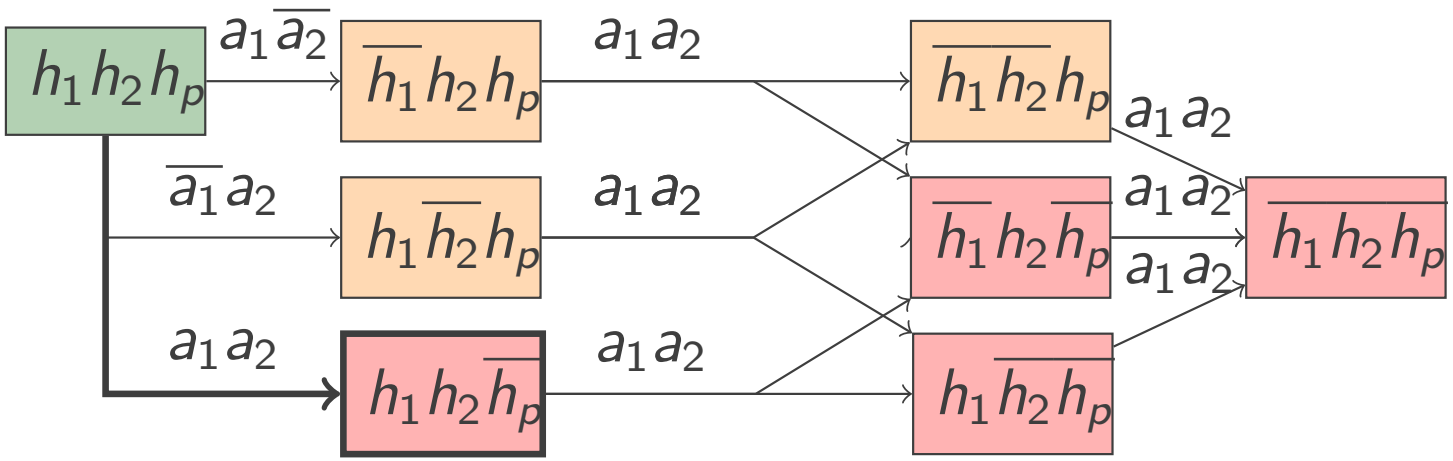


Observation	Real	Estimated
$\overline{a_1 a_2}$		$h_1 h_2 h_p$
$a_1 a_2$		$h_1 h_2 \overline{h_p}$?

if a_1 (resp. a_2) then h_1 (resp. h_2) failed

Cannot select mode

Estimation problem by the example



Observation	Real	Estimated
$\overline{a_1 a_2}$	$h_1 h_2 h_p$	
$a_1 a_2$	$h_1 h_2 \overline{h_p}$	$h_1 h_2 \overline{h_p}$

if a_1 (resp. a_2) prefers $\overline{h_1}$ (resp. $\overline{h_2}$)
if a_1, a_2 both triggered now and not previously prefers $\overline{h_p}$

Preference-based estimation

Modelling of estimation problem with preference provided in [PPR16]:

System model (Δ) Possible behaviours (state transitions) of the system, encoded as a set of PTLTL constraints

Example (Hard constraint)

An alarm is set either when the monitored resource fails or the power supply of the alarm fails. $a_1 \Leftrightarrow \overline{h_1} \vee \overline{h_p}$

Preference (Γ) Ordered conditional preferences (when several possible values)

Example (Preference)

$\overline{h_p}$ is preferred when a_1, a_2 both triggered now and not previously $\overline{h_p} \leftrightsquigarrow \neg Y(a_1) \wedge \neg Y(a_2) \wedge a_1 \wedge a_2$

How do we encode a safety policy using this formalism?

Encoding the safety policy: Main idea

Resource model(Δ_R) Failure model of on-board components

- possible failures of the on-board components
- requested resources for each mode
- assumptions over failure occurrence

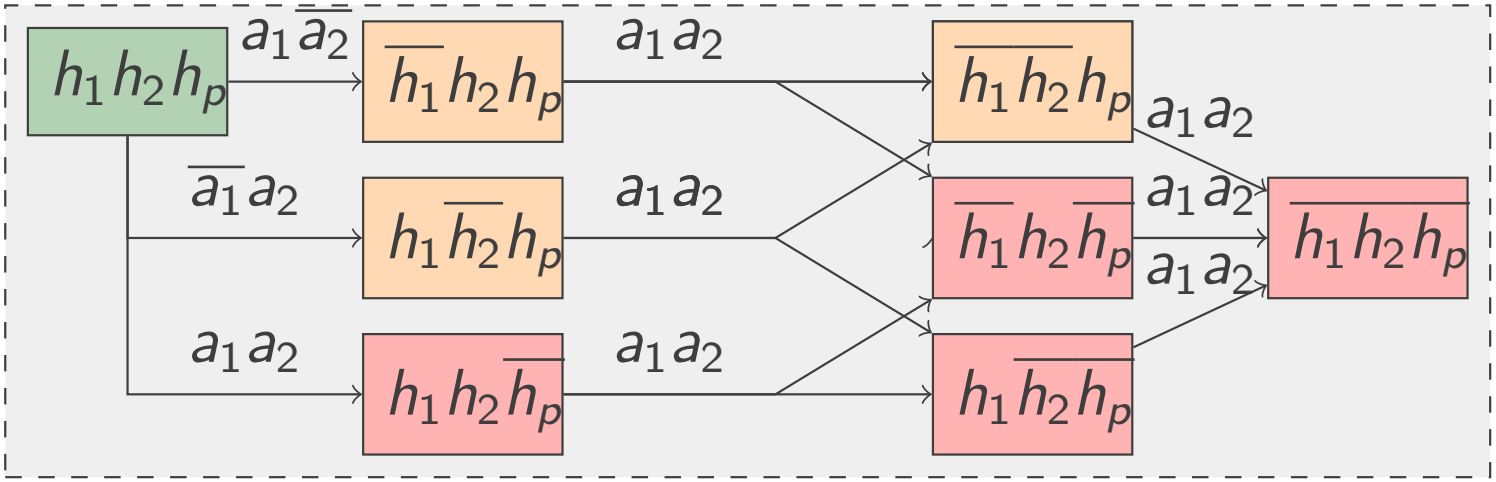
Alarm model(Δ_A) Failure model of alarms

- possible failures of the alarms
- monitoring capabilities of alarms

Resource preferences (Γ_R) preferred failures considering alarms

Mode preferences (Γ_M) preferred modes considering estimated available resources

Encoding the safety policy: Example



1. if a_1 (resp. a_2) prefers $\overline{h_1}$ (resp. $\overline{h_2}$)
2. if a_1, a_2 both triggered now and not previously prefers $\overline{h_p}$

Γ

Framework features

- Structure to encode failure modes, resources, alarms and mode dependencies
- Library of generic constraints to encode:
  - failure assumptions (permanent failures, exclusive failures, interleaving, ...)
  - alarm behaviours (active low/high alarms,...)
  - failure preference (common cause, non monitored components, ...)
  - mode selection (exclusivity, pilot/UAV priority,...)

An example of framework usage

Active low alarm a with:

- monitoring r with a set of detectable failure modes F
- a false negative failure mode fn,
- requesting a set N of resources is modelled by:

$$\overline{a} \Leftrightarrow \left(fn \vee \left(\bigwedge_{f \in F} \overline{f} \wedge \bigwedge_{\substack{r \in N, \\ f' \in r.fm}} \overline{f'} \right) \right)$$

Example (Active low alarm)

An active low alarm *alpi* (powered by *pow*) over a component *pi* is modelled by

$$\overline{alpi} \Leftrightarrow \left(alpi.fn \vee \left(\overline{pi.LS} \wedge \overline{pow.LS} \right) \right)$$

How to identify hazardous failure combinations?

Safety assessment as bounded reachability

Hazardous situations

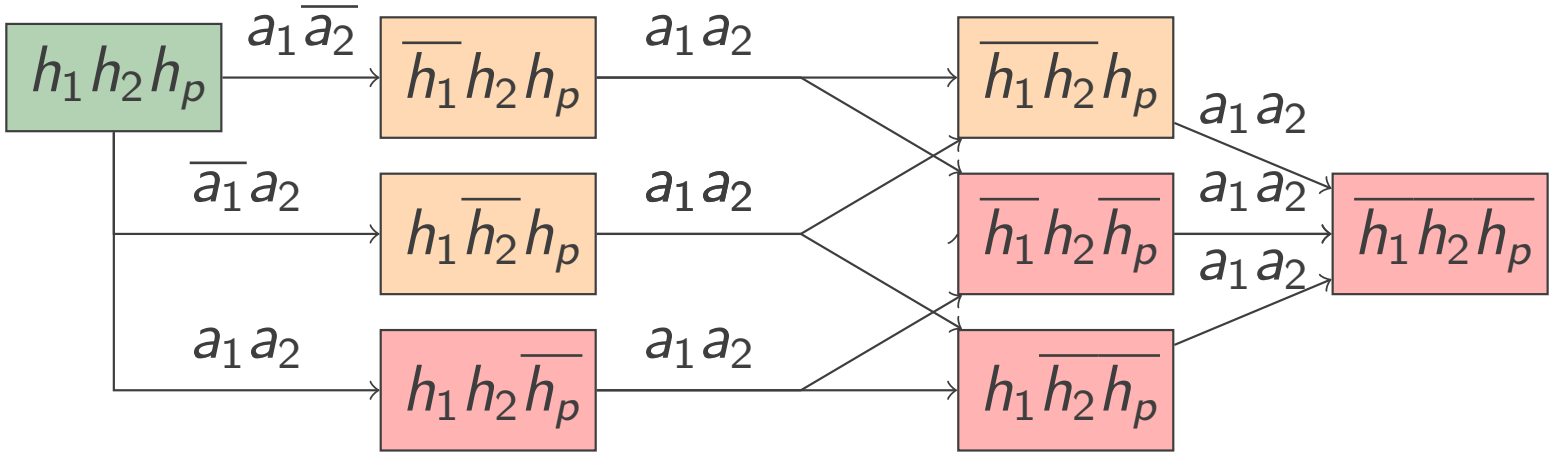
1. combination of failures (of bounded size) leading to unsafe mode selection
2. mis-estimation of the health status
3. addressable through automated bounded reachability analysis

Definition (Reachability analysis)

Safety assessment performed with $\text{REACHABLE}_{\Delta,\Gamma}(\phi_R,\phi_E,n)$ that enumerates pairs (S_R, S_E) and $(e_i)_{[1,n]}$ where:

- S_R satisfies Δ and S_E satisfies both Δ and Γ;
- at the last time step, S_R satisfies ϕ_R and S_E satisfies ϕ_E
- e_i the failure event(s) on the transition $S_{R_{i-1}} \rightarrow S_{R_i}$

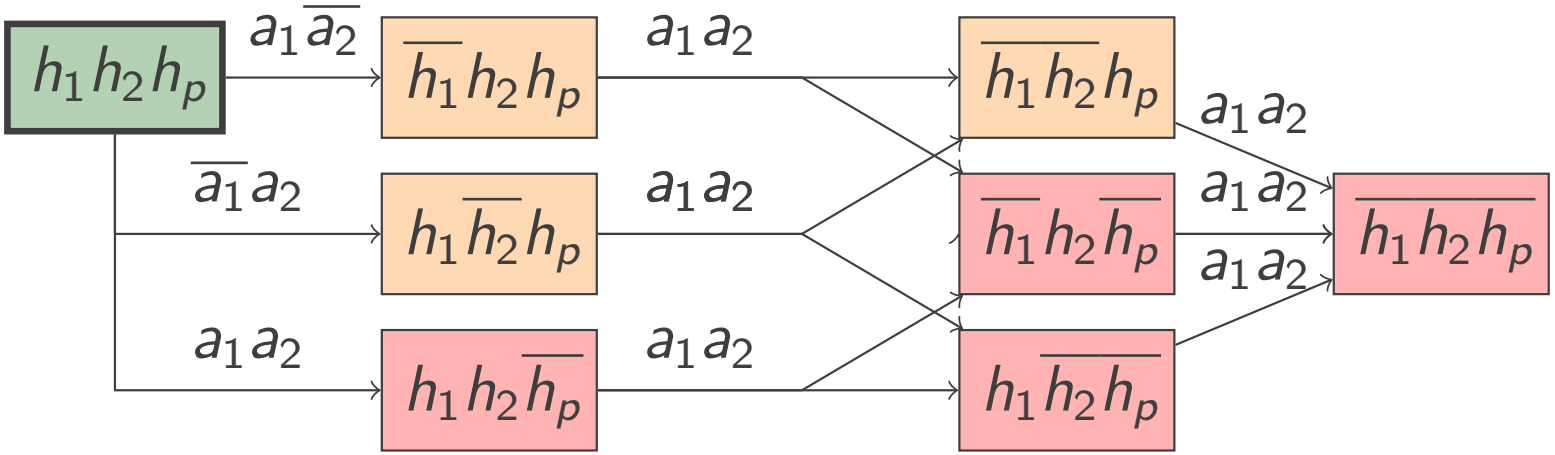
An example of reachability assessment



Observation	Event	Real	Estimated

Is there a failure sequence leading to a flyaway?

An example of reachability assessment



Observation	Event	Real	Estimated
$\overline{a_1 a_2}$	$\emptyset$	$h_1 h_2 h_p$	

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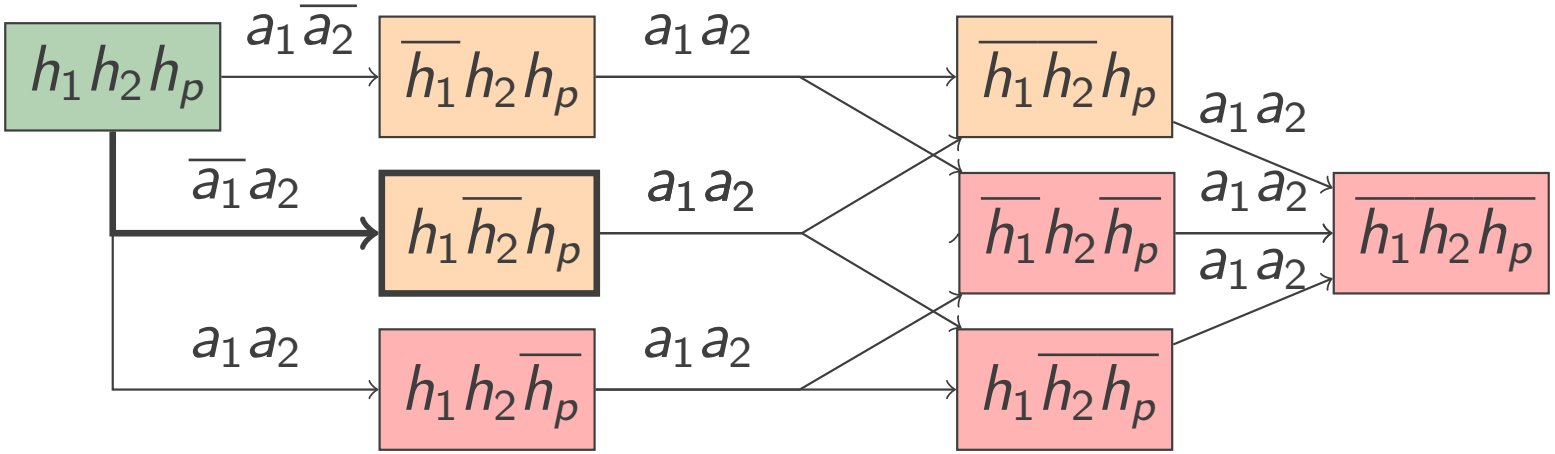

Observation	Event	Real	Estimated
$\overline{a_1 a_2}$	$\emptyset$	$h_1 h_2 h_p$	
$\overline{a_1} a_2$	$h_2.f$	$h_1 \overline{h_2} h_p$	

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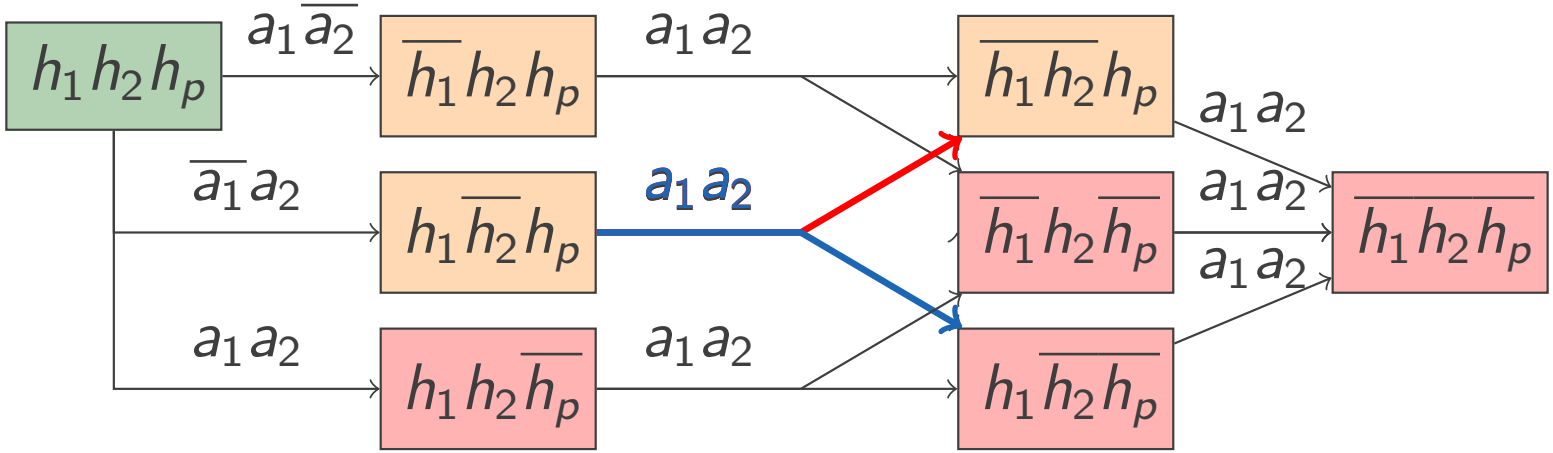

Observation	Event	Real	Estimated
$\overline{a_1 a_2}$	$\emptyset$	$h_1 h_2 h_p$	
$\overline{a_1} a_2$	$h_2.f$	$h_1 \overline{h_2} h_p$	
$a_1 a_2$	$h_p.f$	$h_1 \overline{h_2 h_p}$	$\overline{h_1 h_2 h_p}$

Is there a failure sequence leading to a flyaway? Yes

Evaluation of the framework

Evaluation of SCALA implementation on a toy example:

Order	Failures		Comments
1	$piLaw.LS$ $piLaw.ES$		Undetectable steering control failure
	$guLaw.LS$ $guLaw.ES$		Undectable guidance control failure
2	$a_{pi}.FN$	$pi.LS$	Steering sensors failure and
⋮	⋮	⋮	⋮

Table: Excerpt of safety assessment of the RPAS for the Fly-Away

Conclusion

Proposed a generic framework providing:

- Formal way to encode safety policy
- Library of generic constraints to encode classical assumptions
- Tailorable to various UAV architectures, control modes and monitoring capabilities
- Automatic safety assessment through reachability analysis

Limitations & Future works

Experimental validation

- Performed on a toy example
  $\Rightarrow$ need to be assessed on realistic use case to assess scalability
- Limited modelling of the pilot
  $\Rightarrow$ extend the library

Assessment performance

- Reduce computation time with restriction of the computation to minimal scenarios
- Consider other assessment methods *i.e.* deadends assessment.

Thank you

Any question?

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