Fault-Tolerant Supervisory Control

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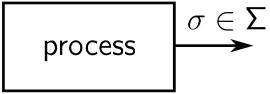
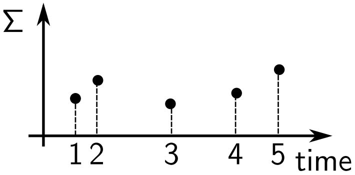
1. Supervisory Control
   - Discrete-Event Systems
   - Closed-Loop Configuration
   - Controller Synthesis
2. Fault-Tolerant Control
   - Naive Approach
   - Active Fault-Tolerant Control
   - Post-Fault Recovery
   - Fault-Hiding Approach

A discrete-event system is a model of a process
... with a particular focus the ocurrence of events

- finite set Σ of symbols $\sigma \in \Sigma$ (alphabet)
- only event ordering is regarded relevant (logic time)
- within finite time a finite sequence $s \in \Sigma^*$ is generated
- set $L \subseteq \Sigma^*$ of sequences that can be generated





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- only event ordering is regarded relevant (logic time)
- within finite time a finite sequence $s \in \Sigma^*$ is generated
- set $L \subseteq \Sigma^*$ of sequences that can be generated
- write $\mathrm{pre}\, L$ to emphasise that $L = \mathrm{pre}\, L$ (local behaviour)

prefix operator $\mathrm{pre}\, L := \{s | \exists\, t : st \in L\}$

A closed language $\mathrm{pre}\, L \subseteq \Sigma^*$ is a discrete-event system.

Literature: Ramadge and Wonham 1989

A natural domain of interpretation for models with liveness properties are ω-languages, i.e., sets of inf. strings $w \in \Sigma^\omega$.

In the absence of deadlocks, use

$$\lim \operatorname{pre} L := \{ w \in \Sigma^\omega \mid \operatorname{pre} w \subseteq \operatorname{pre} L \}$$

to model the process w.r.t. infinite time.

If, in addition, there are no livelocks, choose L s.t. $L = M \cap \operatorname{pre} L$ and consider

$$\lim L := \{ w \in \Sigma^\omega \mid \|(\operatorname{pre} w \cap L)\| = \infty \},$$

to model the process w.r.t. infinite time.

Properties

- safety – bad things never happen

  with $\operatorname{pre} E \subseteq \Sigma^*$, require

  $$\operatorname{pre} L \subseteq \operatorname{pre} E$$

- liveness – good things do happen

  free of deadlocks

  $$(\forall\, s \in \operatorname{pre} L)(\exists\, \sigma \in \Sigma)[\, s\sigma \in \operatorname{pre} L\,]$$

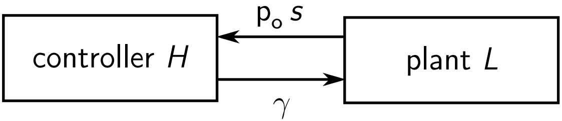
  free of livelocks wrt $M \subseteq \Sigma^*$

  $$(\forall\, s \in \operatorname{pre} L)(\exists\, t \in \Sigma^*)[\, st \in M \cap \operatorname{pre} L\,]$$

For systems with liveness properties:

A language $L \subseteq \Sigma^*$ is a discrete-event system.

With the common partitioning $\Sigma = \Sigma_c \dot\cup \Sigma_{uc} = \Sigma_o \dot\cup \Sigma_{uo}$ regarding controllable and observable events, consider a plant $L \subseteq \Sigma^*$.



- At any time, the controller is provided $p_o\, s \in \Sigma_o^*$ where $s \in \Sigma^*$ is the sequence generated so far;
- in return, the controller applies a control pattern γ of enabled events, where $\Sigma_{uc} \subseteq \gamma$;
- liveness properties of the plant shall be retained.

natural projection $p_o\, \Sigma^* \to \Sigma_o^*$ to remove any symbols not from Σ_o.

Literature: Ramadge and Wonham 1987, Lin and Wonham 1988

Def. A controller $H \subseteq \Sigma^*$ is *admissible w.r.t. the plant* $L \subseteq \Sigma^*$, if

[H0] $H = \mathrm{pre}\, H$

[H1] $H\Sigma_{\mathrm{uc}} \subseteq H$,

[H2] $H = \mathrm{p_o^{-1}}\, \mathrm{p_o}\, H$,

[H3] $(\mathrm{pre}\, L) \cap (\mathrm{pre}\, H)$ does not deadlock, and

[H4] $(\mathrm{pre}\, L) \cap (\mathrm{pre}\, H) = \mathrm{pre}\,(L \cap H)\,.$

Then, $K := L \cap H$ represents the cosed-loop behaviour. $\square$

Thm. Consider tha case $\Sigma_c \subseteq \Sigma_o$. For a plant $L \subseteq \Sigma^*$ and an admissible controller $H \subseteq \Sigma^*$ let $K = L \cap H$. Then

[K0] K is relatively prefix-closed w.r.t. L,

[K1] K is controllable w.r.t. L,

[K2] K prefix-normal w.r.t. L, and

[K3] K does not deadlock.

Vice versa, if K satisfies [K0]-[K3], then there exists an admissible controller H such that $K = L \cap H$. $\square$

Literature: Lin and Wonham 1988, Kumar et al 1992, Moor et al 2012

Control Problem. Given (L, E) with plant $L \subseteq \Sigma^*$ and a specification $E \subseteq \Sigma^*$ construct an admissible controller $H \subseteq \Sigma^*$ such that

$$K := L \cap H \subseteq E.$$

Solution. All properties properties are retained under arbitraty union. Thus

$$K^{\uparrow} = \sup\{K \subseteq L \cap E \mid K \text{ satisfies [K0]–[K3]}\}$$

itself satisfies [K0]–[K3] and is used to extract a minimal restrictive controller.

Note. E can be substituted by a closed language without affecting solutions – it is effectivly a safety specification.

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Interpretation by corresponding $\omega-$ *languages*

- in general, E can not be substituted by a closed language
- if E is (rel.) closed, same solution procedures as with $*$-languages (Ramadge 1989, Kumar et al 1993, Moor et at 2012)
- if E is not (rel.) closed it imposes liveness properties — completely different story
- solution procedure for $\Sigma_o = \Sigma$ by Thistle and Wonham 1994
- solution procedure for $\Sigma_o \neq \Sigma$ and closed L by Thistle and Lamouchi 2009

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    Post-Fault Recovery

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Fault-Tolerant Control

- a fault is a sudden change of behaviour
- passive approach: have a single controller that can handle pre-fault and post-fault behaviour (robust control)
- active approach: detect the fault and switch to another controller (adaptive control)
- core challenge: switching of plant and controller dynamics

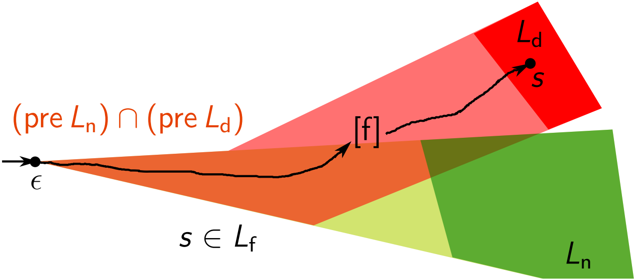
... for continuous systems. However, for discrete-event systems ...

Sudden change of behaviour and switching in the control scheme are the very nature of discrete-event systems. Hence, fault-tolerant control can be synthesised by the same methods as nominal control [??]

Naive approach to fault-tolerant control:

- nominal plant $L_\mathrm{n} \subseteq \Sigma_\mathrm{n}$
- fault event $\mathrm{f} \not\in \Sigma_\mathrm{n}$, uncontrollable and unobservable
- degraded post-fault behaviour $L_\mathrm{d} \subseteq \Sigma_\mathrm{f}^*$ with $\Sigma_\mathrm{f} = \Sigma_\mathrm{n} \dot\cup \{\mathrm{f}\}$ and

$$(\mathrm{pre}\, L_\mathrm{d}) \cap \Sigma_\mathrm{n}^* \subseteq \mathrm{pre}\, L_\mathrm{n} \quad \text{and} \quad L_\mathrm{d} \cap \Sigma_\mathrm{n}^* = \emptyset$$



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- *fault-accommodating model* $L_\mathsf{f} = L_\mathsf{n} \cup L_\mathsf{d}$ where

$$\mathrm{pre}\, L_\mathsf{f} = (\,\mathrm{pre}\, L_\mathsf{n}\,) \cup (\,\Sigma_\mathsf{n}^* \mathsf{f} \Sigma_\mathsf{f}^* \cap \mathrm{pre}\, L_\mathsf{d})$$
$$L_\mathsf{f} = L_\mathsf{n} \cup (\,\Sigma_\mathsf{n}^* \mathsf{f} \Sigma_\mathsf{f}^* \cap L_\mathsf{d}\,)$$

- likewise, the specification $E_\mathsf{f} = E_\mathsf{n} \cup E_\mathsf{d}$ to accommodate for degraded post-fault performance E_d

Naive approach to fault-tolerant control (cnt.)

- invoke synthesis procedure for $(L_\mathsf{f}, E_\mathsf{f})$ to obtain a minimal restrictive admissible fault-tolerant controller H_f.
- note: diagnosibility required only relative to specifications
- option: re-interpretation H_f as active fault-tolerant control

switch on first escape from $H_\mathbf{n}$:

$$T := \{s \in \Sigma_\mathbf{f}^* \,|\, \exists\, \sigma : s\sigma \in H_\mathsf{f} \not\leftrightarrow s\sigma \in \mathsf{p}_\mathbf{f}^{-1}\, H_\mathbf{n}\}$$

$$H_\mathbf{d} := \{s\sigma \in H_\mathsf{f} \,|\, (\mathrm{pre}\, s) \cap T \neq \emptyset\} \cup \{\epsilon\}$$

$$H_\mathsf{f} = ((\mathsf{p}_\mathbf{f}^{-1}\, H_\mathbf{n}) \cap (\Sigma_\mathbf{f}^* - T\Sigma_\mathsf{f}\Sigma_\mathbf{f}^*)) \cup H_\mathbf{d}$$

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- note: in general, $H_\mathsf{f} \cap \Sigma_\mathsf{n}^*$ is not admissible w.r.t. L_n

> this requires two more closed-loop properties for the synthesis of H_f:
> [K4] $K \cap \Sigma_\mathsf{n}^*$ does not deadlock
> [K5] $\mathrm{pre}\,(K \cap \Sigma_\mathsf{n}^*) = (\mathrm{pre}\,K) \cap \Sigma_\mathsf{n}^*$

Literature: Wittmann et al 2012

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- note: in general, $H_\mathrm{f} \cap \Sigma_\mathrm{n}^*$ is not admissible w.r.t. L_n
- option: compute a minimal restrictive nominal controller H_n that solves $(L_\mathrm{n}, E_\mathrm{n})$ and test whether $L_\mathrm{f} \cap H_\mathrm{f} \cap \Sigma_\mathrm{n}^* = L_\mathrm{n} \cap H_\mathrm{n}$

we have $L_\mathrm{f} \cap H_\mathrm{f} \cap \Sigma_\mathrm{n}^* \subseteq E_\mathrm{f} \cap \Sigma_\mathrm{n}^* = E_\mathrm{n}$ for free, and, if $H_\mathrm{f} \cap \Sigma_\mathrm{n}^*$ is admissible w.r.t. L_n,

$L_\mathrm{f} \cap H_\mathrm{f} \cap \Sigma_\mathrm{n}^* \subseteq L_\mathrm{n} \cap H_\mathrm{n}$

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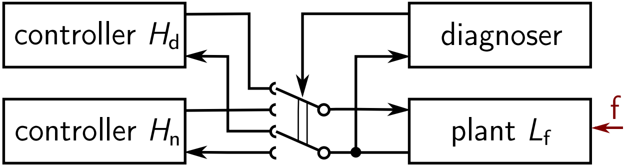
- option: explicit diagnosis by controllable event $\mathrm{F} \in \Sigma_\mathrm{n}$ with plant $\mathrm{p}_\mathrm{F}^{-1}\, L_\mathrm{f}$ and specification $(\mathrm{p}_\mathrm{F}^{-1}\, E_\mathrm{f}) \cap \mathrm{pre}\,(\Sigma_\mathrm{n}^* \mathrm{f} \Sigma_\mathrm{f}^* \mathrm{F} \Sigma_\mathrm{f}^*)$

need to interpret F as forcible event

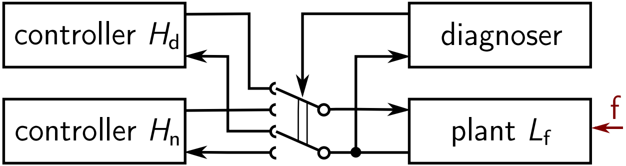
Literature: Wittmann et al 2012

Active fault-tolerant control



- require the fault to be diagnosible, denote $T \subseteq L_d$ the strings corresponding to f-certain diagnoser states
- require/test that the post-fault behaviour satisfies a safety specification (safe diagnosibility)
- design H_d to take over H_n when the plant first enters T
- note: nominal pre-fault behaviour is guaranteed
- option: synthesise H_d online once the fault has been detected

Active fault-tolerant control



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Diagnosis of DES (Sampath et al 1995)

diagnoser: observer automaton with dedicated state labels

f-certain state: state in which the fault must have occured.

diagnosibility: require the plant to evolve to an f-certain state after a bounded number of transitions.

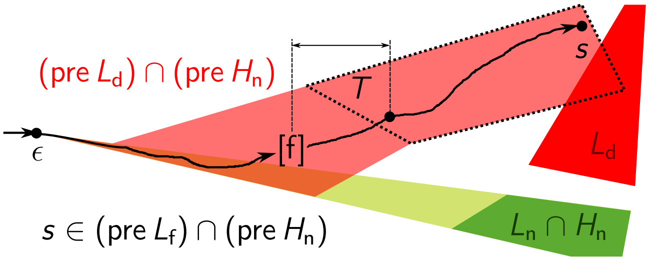
Literature: Paoli et al 2005, 2008, 2011

- diagnosibility ensures that every string after f evolves into T

$$T = \{ s \in (\mathrm{pre}\, L_\mathrm{d}) \cap (\mathrm{pre}\, H_\mathrm{n}) \,|\, (\mathrm{p}_\mathrm{o}^{-1}\, \mathrm{p}_\mathrm{o}\, s) \cap (\mathrm{pre}\, L_\mathrm{f}) \subseteq \Sigma_\mathrm{n}^* \mathrm{f} \Sigma_\mathrm{f}^* \}$$

- safe diagnosibility ensures that

$$[(\mathrm{pre}\, L_\mathrm{d}) \cap (\mathrm{pre}\, H_\mathrm{n})] - T\Sigma_\mathrm{f}^* \subseteq E_\mathrm{d}$$



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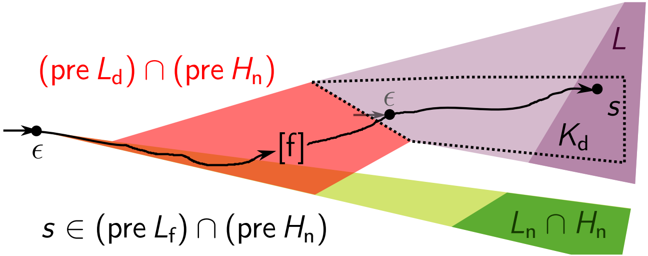
- synthesise H_d for the post-fault detection plant

$$L = \{s | \exists\, t : ts \in L_\mathrm{d} | (\mathrm{pre}\, s) \cap T = s \in H_\mathrm{n}\}$$



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- synthesise H_d for the post-fault detection plant

$$L = \{s | \exists\, t : ts \in L_\mathrm{d} | (\mathrm{pre}\, s) \cap T = s \in H_\mathrm{n}\}$$

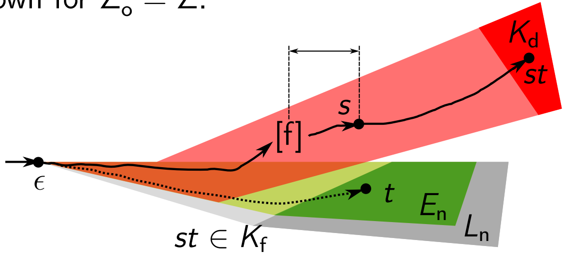
- re-interpret within naive approach:
  - synthesise H_f with $\mathrm{pre}\, \{s\sigma \in T | s \notin T\} \subseteq E_\mathrm{d}$
  - test for $L_\mathrm{f} \cap H_\mathrm{f} \cap \Sigma_\mathrm{n}^* = L_\mathrm{n} \cap H_\mathrm{n}$
  - extract H_d from H_f
  - mimique re-initialisation

Post-Fault Recovery: nominal safety specification

- add a formal closed-loop requirement to [K0]-[K3] for the synthesis of H_f

[K6] $\qquad E_\mathrm{n} \Leftarrow K_\mathrm{f}/(\Sigma_\mathrm{n}^*\mathrm{f})$

- although [K6] is not retained under union, synthesis procedures are known for $\Sigma_\mathrm{o} = \Sigma$.



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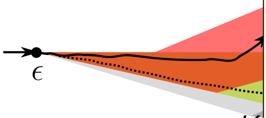


$st \in K_f$

> Language Convergence (Kumar et al 1993)
>
> K is said to *finitely converge* to E if there exists a uniform bound k such that every $s \in K$ can be decomposed
>
> $$s = vw,\ w \in E, \text{ and } |v| \le k.$$
>
> This is written $E \Leftarrow K$.
>
> Without the uniform bound, the condition becomes equivalent to
>
> $$K \subseteq \Sigma^* E,$$
>
> which quite weak.
>
> Alternative approach: refer to the respective ω-languages and require
>
> $$\lim K \subseteq \lim(\Sigma^* E)$$
>
> for not-uniform bounded convergence.

Post-Fault Recovery: liveness

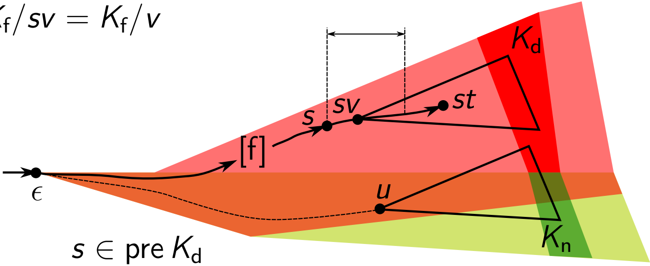
- a closed loop $K_f = K_n \cup K_d$ is *fault toleant* if

  [K7] there exists a uniform bound k such that for every s, t, $|t| \geq k$ with

  $$s \in (\text{pre } K_f) - (\text{pre } K_n) \text{ and } st \in \text{pre } K_f$$

  there exists $u \in \text{pre } K_n$, $v \in \text{pre } t$, $|v| \leq k$ with

  $$K_f/sv = K_f/v$$



$s \in \text{pre } K_d$

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  $$K_\mathsf{f}/sv = K_\mathsf{f}/v$$

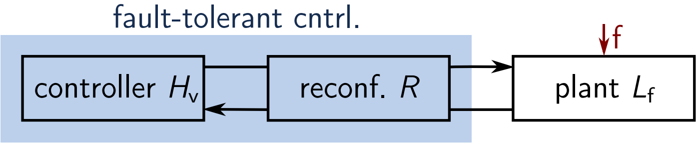
- synthesis problem: given $L_\mathsf{f} = L_\mathsf{n} \cup L_\mathsf{d}$ and E_f, compute an admissible controller H_f such that the closed loop satisfies [K7].

- the property is not retained under union; synthesis procedure exists for $\Sigma_\mathsf{o} = \Sigma$

Literature: Wen et al 2008, 2014

Fault Hiding

Given $L_\mathrm{f} = L_\mathrm{n} \cup L_\mathrm{d}$, $E_\mathrm{f} = E_\mathrm{n} \cup E_\mathrm{d}$, and a solution H_n to $(L_\mathrm{n}, E_\mathrm{n})$



- disconnect nominal controller, i.e., $H_\mathrm{v} = h(H_\mathrm{n}) \subseteq \Sigma_\mathrm{v}^*$ with $\Sigma_\mathrm{v} \cap \Sigma_\mathrm{f} = \emptyset$, h bijective and applied per event.
- synthesise reconfiguration dynamics $R \subseteq (\Sigma_\mathrm{v} \cup \Sigma_\mathrm{o})^*$ to re-connect
- do so by interpreting $H_\mathrm{v} \parallel L_\mathrm{f}$ as plant and use std. procedures on adapted language inclusion specification

Fault Hiding

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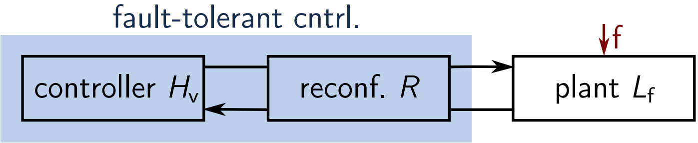

- when using a minimal restrictive solution $H_\mathrm{v}^\uparrow$ for the design, and if the closed loop K satisfies in addition to [K0]-[K3]

  [K8] $$(\forall\, s \in \mathrm{pre}\, K\,)[\ ((\mathrm{p_v}\, s) \ \cap\ h(\Sigma_\mathrm{uc})\ \cap\ (\mathrm{pre}\, h(L_\mathrm{n})) \neq \emptyset$$
  $$\Rightarrow\ \ s(\Sigma - h(\Sigma_\mathrm{c}))^* h(\Sigma_\mathrm{uc})\ \cap\ (\mathrm{pre}\, K) \neq \emptyset\ ]$$

  then R is admissible to any nominal controller that solves $(L_\mathrm{n}, E_\mathrm{n})$.

- [K8] is retained under union, synthesis procedures are known.

- note: nominal controller does not need to be known

Literature: Wittmann et al 2013

Summary

Fault-tolerant supervisory control is addressed by the recent literature in various ways, including passive and active approaches, post-fault recovery and fault-hiding.

Conclusions

- switching is addressed by the common modelling framework — any method for fault-tolerant supervisory control should be interpretable within this framework
- additional features of individual approaches amount to additional closed-loop properties — and novel synthesis problems
- insisting in uniform bounds for diagnosibility and language convergence may be too strict for particular applications — discussion in terms of ω-languages may turn out beneficial

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[**more references are given in the paper**]

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