Active Fault Detection in Dynamic Systems

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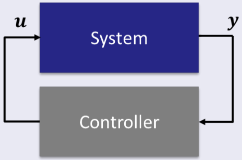
2014 IEEE Symposium Series on Computational Intelligence
(Doctoral Consortium)

Outline

Introduction

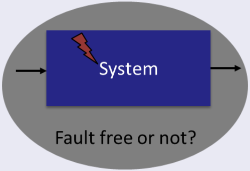
Cybernetics

- **Cybernetics** originates in Greek word "steersman" which refers to steering, governance and navigation. This field studies control and communication in systems.
- **Automatic control** is a control without human interaction.
- **Optimal control** finds a control policy such that a design criterion is optimized (min, max).



Introduction

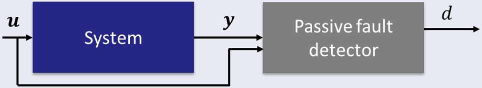
Fault detection and diagnosis



- **Fault detection and diagnosis** is an important subfield of control engineering.
- **Tasks** include determination of kind, size, location and time of detection.
- **Fault detection and diagnosis** can be done passively or actively.

Introduction

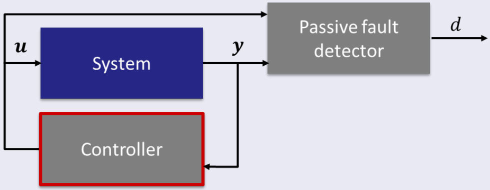
Passive fault detection



- **Passive fault detector** uses the input and output data $[\mathbf{u},\ \mathbf{y}]$ to generate a decision d about faults in the system, no input signal improving the quality of detection is generated.
- Passive approach is widely used mainly because of its simplicity.

Introduction

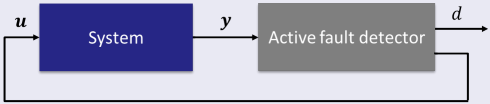
Passive fault detection and control



- **Controller** is designed separately and independently of the passive fault detector.
- **Passive fault detector and controller** generates decisions about faults and controls the system.

Introduction

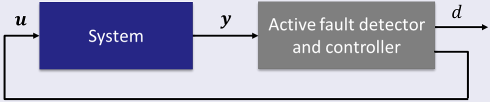
Active fault detection



- **Active fault detector** uses the output data **y** to generate a decision *d* and an input signal **u** that **probes** the system to ensure improved quality of detection.
- The active approach can greatly improve a quality of decision.
- However, the probing signal can disturb the system in an inappropriate manner from the other point of view.

Introduction

Active fault detection and control



- **Controller** is designed together with the detector.
- **Active fault detector and controller** uses the output data **y** to generate a decision *d* and an input signal **u** which **probes and controls** the system.
- The active approach can greatly improve a quality of decision and keep the system output close to a desired reference.

Introduction

Application

- The active fault detection and control can be used to detect fluid leaks as well as to control automatically chemical processes in a chemical plant.
- Another application can be found in smart building control, aviation, automotive, etc.

Problem formulation

System description

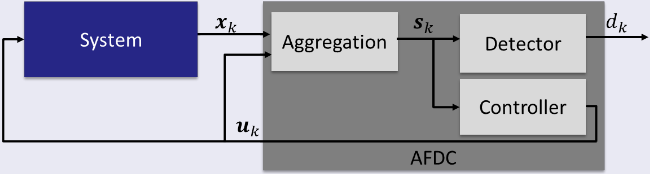
The multiple-model approach is considered (one model fault-free, other faulty, $\mu_k \in \mathcal{M} = \{1,2,\ldots,N\}$ is unknown model index).
A system with the perfect state information is described by time-invariant model

$$\mathbf{s}_{k+1} = \phi(\mathbf{s}_k, \mathbf{u}_k, \mathbf{x}_{k+1}), \quad (1)$$

$\mathbf{s}_k = [\mathbf{x}_k, \ \mathbf{b}_k]^T \in \mathcal{S}$ is a hyper-state (perfect state information),
$\mathbf{x}_k \in \mathbb{R}^{n_x}$ is a common state (x_{k+1} defined by $p(x_{k+1}|\mathbf{s}_k, \mathbf{u}_k)$),
$\mathbf{b}_k = [b_{k,1},\ldots,b_{k,i},\ldots,b_{k,N-1}]^T \in \mathcal{B}$ is a belief state of system models, $b_{k,i} = P(\mu_k = i|\mathbf{x}_0^k, \mathbf{u}_0^{k-1})$, ϕ is a nonlinear vector function,
$\mathbf{u}_k \in \mathcal{U} = \{\bar{\mathbf{u}}^1, \ldots, \bar{\mathbf{u}}^M\} \subset \mathbb{R}^{n_u}$ is an admissible control,
$P_{i,j} = P(\mu_{k+1} = j|\mu_k = i)$, $\mathbf{x}_0$, and $P(\mu_0)$ are known.

Problem formulation

Active fault detector and controller (AFDC)



Two actions: **decision** $d_k \in \mathcal{M}$ and **control** $\mathbf{u}_k \in \mathcal{U}$,

$$\begin{bmatrix} d_k \\ \mathbf{u}_k \end{bmatrix} = \begin{bmatrix} \sigma(\mathbf{s}_k) \\ \gamma(\mathbf{s}_k) \end{bmatrix} = \bar{\boldsymbol{\rho}}(\mathbf{s}_k), \tag{2}$$

$\bar{\boldsymbol{\rho}} : \mathcal{S} \mapsto \mathcal{M} \times \mathcal{U}$ is an unknown policy, $\sigma : \mathcal{S} \mapsto \mathcal{M}$ is a detector, $\gamma : \mathcal{S} \mapsto \mathcal{U}$ is a controller.

Problem formulation

Optimality criterion

An optimality criterion is given by

$$\bar{J}(\bar{\boldsymbol{\rho}}, \mathbf{s}_0) = \lim_{F \to \infty} \mathrm{E}\left\{ \sum_{k=0}^{F} \lambda^k \bar{L}(d_k, \mathbf{s}_k, \mathbf{u}_k) | \mathbf{s}_0 \right\}, \tag{3}$$

where $\bar{L}(d_k, \mathbf{s}_k, \mathbf{u}_k) = \alpha \bar{L}^{\mathrm{d}}(d_k, \mathbf{s}_k) + (1-\alpha)\bar{L}^{\mathrm{c}}(\mathbf{s}_k, \mathbf{u}_k)$ is a cost function (CF), $\alpha \in [0;1]$ is a weighting factor,
$\bar{L}^{\mathrm{d}}(d_k, \mathbf{s}_k) = \mathrm{E}\{L^{\mathrm{d}}(\mu_k, d_k) | d_k, \mathbf{x}_0^k, \mathbf{u}_0^{k-1}\}$, is a detection CF ($L^{\mathrm{d}} : \mathcal{M} \times \mathcal{M} \mapsto \mathbb{R}^+$ is the original detection CF),
$\bar{L}^{\mathrm{c}}(\mathbf{s}_k, \mathbf{u}_k) = L^{\mathrm{c}}([\mathbf{s}_{k,1}, \ldots, \mathbf{s}_{k,n_x}]^{\mathrm{T}}, \mathbf{u}_k)$ is a control CF ($L^{\mathrm{c}} : \mathbb{R}^{n_x} \times \mathcal{U} \mapsto \mathbb{R}^+$ is the original control CF).
It is assumed that L^{d}, L^{c}, and L are bounded making the criterion (3) well defined for any policy $\bar{\boldsymbol{\rho}}$.

Optimal active fault detector and controller

Design

The goal is to find Bellman function V^* that solves the following Bellman functional equation

$$V^*(\mathbf{s}_k) = \min_{d_k \in \mathcal{M}, \mathbf{u}_k \in \mathcal{U}} \mathrm{E}\left\{ \bar{L}(d_k, \mathbf{s}_k, \mathbf{u}_k) + \lambda V^*(\mathbf{s}_{k+1}) | d_k, \mathbf{s}_k, \mathbf{u}_k \right\}. \quad (4)$$

Optimal detector σ^* and optimal controller γ^* are given as

$$d_k^* = \sigma^*(\mathbf{s}_k) = \arg\min_{d_k \in \mathcal{M}} \alpha \bar{L}^{\mathrm{d}}(\mathbf{s}_k, d_k), \quad (5)$$

$$\mathbf{u}_k^* = \gamma^*(\mathbf{s}_k) = \arg\min_{\mathbf{u}_k \in \mathcal{U}} \mathrm{E}\left\{ (1-\alpha)\bar{L}^{\mathrm{c}}(\mathbf{s}_k, \mathbf{u}_k) + \lambda V^*(\mathbf{s}_{k+1}) | \mathbf{s}_k, \mathbf{u}_k \right\}. \quad (6)$$

The Bellman function V^* is computed offline by solving (4), then the AFDC is implemented online by means of (5) and (6).

Optimal active fault detector and controller

Problem

- The analytical solution to the Bellman equation is impossible to find in this case.

Questions and motivation

- How can a suitable approximation of the Bellman function V^* considering accuracy and computational demands be found?
- A suitable approximation can improve the quality of fault detection and control.
- The formulated problem of the AFDC is very challenging.

Key points

Why IEEE SSCI 2014 Doctoral Consortium (DC)?

The DC provides an opportunity to discuss the following key points of my Doctoral Thesis:

- development of methods for the Bellman function approximation,
- broadening of the AFDC theory,
- expansion of the AFDC applications.
- Finally, my aim is to spread awareness about the AFDC.

Results so far: AFD

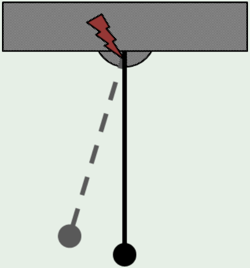
Results so far: AFD

- An **active fault detector (AFD)** for a nonlinear discrete-time stochastic systems over an infinite time horizon was formulated and a suboptimal solution based on a Value Iteration and a Policy Iteration algorithms was proposed (*22nd Mediterranean Conference on Control and Automation, Palermo, June 2014*).
  - The hyper-state space was quantized by a uniform grid.
  - The Bellman function was approximated by a piecewise constant function $\bar{V}$ found by the Value Iteration and the Policy Iteration algorithm, respectively.
  - The expectation in the Bellman equation was approximated by the Unscented transform (nonlinear system).

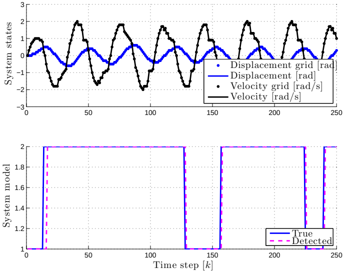
Results so far: AFD

Pendulum

- A numerical example of a **pendulum** is considered.
- A goal is to detect an intermittent fault in the rolling bearings.



Results so far: AFD



- Typical state trajectories and system detection for the time horizon of 250 steps.

- The pendulum is systematically excited to improve the quality of detection.
- The actual model is correctly detected with a delay of approximately 2 steps.

Results so far: AFDC

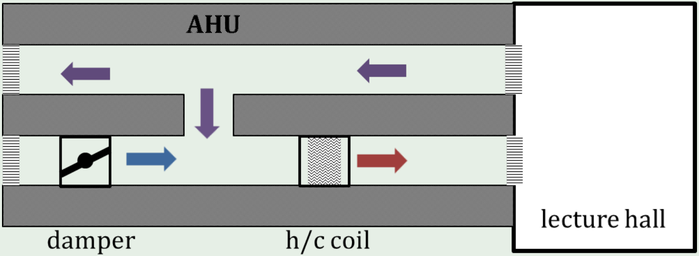
Results so far: AFDC

- An **active fault detector and controller (AFDC)** for a nonlinear discrete-time stochastic systems over an infinite time horizon was designed and a suboptimal active fault detector and controller was applied in the numerical example of an air handling unit (*11th European Workshop on Advanced Control and Diagnosis, Berlin, Nov. 2014*).
  - A compromise between detection and control can be made.

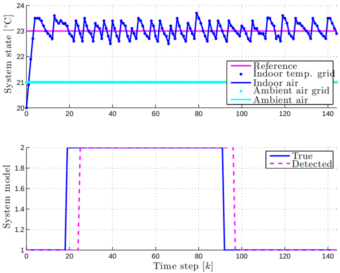
Results so far: AFDC

Air handling unit

- A numerical example of an **air handling unit** (AHU) is shown.
- A goal is to detect a stuck damper in the AHU and to control the indoor air temperature in a lecture hall.



Results so far: AFDC



- Typical state trajectories and system detection for the time horizon of 12 hours.

- The indoor air temperature follows the reference with oscillations caused by a discrete amount of power delivered during the sampling period $T_\mathrm{s} = 300$ [s] (one step).
- The actual model is correctly detected with a delay of approximately 5 steps.

Results so far

Results so far

- Currently a paper on an adaptive Generalized Policy Iteration (GPI) algorithm was submitted to *SafeProcess'15, Paris*.
- There are two steps: policy evaluation and policy improvement. The policy evaluation can be performed exactly (computationally demanding) or iteratively by j steps. The presented adaptive GPI determines how to set the number j so that a specified accuracy of the evaluation is satisfied.
- The numerical example includes 468741 system states and a sparsity is utilized.

Conclusion

Related work

- This formulation is original in the field of AFDC.
- An extensive literature on solving the Bellman equation approximately exists (D. P. Bertsekas, L. Bușoniu, F. L. Lewis, W. B. Powell, R. S. Sutton, and others).

Future work

- There are some ideas for the future work:
  - to study current literature,
  - to focus on some other recent types of approximators besides grid based,
  - to apply some methods of artificial intelligence and control,
  - to familiarize with Partially observable Markov decision process (POMDP) which might bring new perspectives how to solve the problem.

Conclusion

Conclusion

- The AFDC is a new but important part of fault detection.
- The AFDC allows a detector and controller to be designed jointly.
- The AFDC formulated as an optimization problem and solved via Dynamic Programming is very challenging with a space for further research.
- The future applications with AFDC could help to increase efficiency and reduce costs.

Acknowledgments

Acknowledgments

- My research is supported by the European Regional Development Fund (ERDF), project NTIS New Technologies for the Information Society, European Centre of Excellence, CZ.1.05/1.1.00/02.0090.
- I am grateful to my supervisor prof. Miroslav Šimandl and Ivo Punčochář for leading my doctoral studies.
- I am very grateful to IEEE SSCI 2014 Doctoral Consortium for the Financial Support.
- Many thanks to DC Committee for an e-mail support before the conference.

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