



An integrated approach for sensor placement in linear dynamic systems

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Abstract

This paper investigates the sensor placement in linear dynamic systems for fault detectability and isolability. A linear system is modelled by a bond graph (BG) that can be associated in a natural way with a set of linear differential-algebraic equations (DAEs). Simultaneously, possible sensor locations are modelled as junctions on the BG. Causal paths capture cause–effect relationships of a linear system and provide a means to analyze what subset of junctions contributes to fault detectability and isolability. Furthermore, this paper exploits DAEs associated with a BG and proves a necessary and sufficient condition of sensor placement to fulfill fault detectability. Based on the fault detectability condition, a necessary condition of sensor placement to achieve two-fault distinguishability is developed in the DAEs model and serves as the basis of formulating the sensor placement problem with regard to a fault set $\mathcal{F}$. For efficiency, a dedicated dynamic programming (DP) algorithm is devised to attain the optimal set of junctions for fault isolability. The two-tank system is employed to illustrate the sensor placement steps in a linear system. The optimal set (s), computed by the proposed sensor placement methodology, is/are validated by deriving primary analytical redundancy relations (ARRs) of the two-tank system.

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1. Introduction

The increasing demand for safety and reliability of engineering systems requires a well-preformed fault detection and isolation (FDI) system to monitor faults and failures. For real-time

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Nomenclature

f^i	the i -th fault
f_i	the i -th flow variable
e_i	the i -th effort variable
$\mathcal{F} = \{f^1, f^2, \dots, f^Q\}$	the set of Q possible faults of concern
$\mathcal{J}$	the set of K junctions
$\mathcal{J}_i$	the subset of $\mathcal{J}$ corresponding to fault f^i
y_k	the k -th sensor variable
$\mathcal{P}$	the set of K sensor variables y_k 's
$\mathcal{P}_i$	the subset of $\mathcal{P}$ related to fault f^i
$\mathbb{Y}$	the set of all pairs of sensor variables with size $(K^2 - K)/2$
$\mathcal{D}$	the distinguishable matrix with size $(Q^2 - Q)/2 \times (K^2 - K)/2$
$\mathcal{Y}$	a set of sensor variables
$\mathcal{Y}^*$	the optimal set of sensor variables
$\mathbb{Y}^*$	the set of all $\mathcal{Y}^*$'s
MISSV	a minimal isolating set of sensor variables
$\mathcal{M}$	the set of all possible MISSVs
s	a binary vector of size $(Q^2 - Q)/2$ to indicate the distinguishability of all pairs of faults, which is called a state
$\mathcal{Y}_s^i$	a subset of $\mathcal{P}$ which has state s and is produced by uniting i pairs $(y_k, y_{k'}) \in \mathbb{Y}$
$\mathbb{Y}_s^i$	the set of all possible $\mathcal{Y}_s^i$'s
$\mathbb{Y}^{DP}[i][s]$	the set of sets $\mathcal{Y}_s^i$'s, each of which has the minimal cardinality and is associated with a state s

monitoring, residuals are extensively used for FDI to indicate the normal state or abnormal state of system operation. Residuals can be generated by comparing a system outputs to those of its reference model. In literature, systematical design of a FDI scheme for a system with sufficient sensors has been intensively studied in [1–11]. However, the issue of sensor placement for FDI has attracted little attention. In the sensor placement issue, of most interest are the number and location of deployed sensors so that FDI can be effectively accomplished.

As the complexity of a physical system increases, modelling of the system becomes difficult. Fortunately, the BG modelling provides an approach to deal with a complex system which possesses large number of subsystems and components [12]. Moreover, the BG provides a systematic and convenient tool to design FDI procedures for complex systems with sensors installed. Finally, the BG offers constitutive relations to build the DAEs model and causal paths to capture cause–effect relationships in a linear system.

Some sensor placement approaches have been reported in literature [13–20]. They pursue the purposes of detectability and/or isolability on two types of models (i.e., the first principle and the data-driven). In [17], sensor location for optimal detection performance on the first principle model was studied. In [15,16], a minimum cost solution was searched out by a pre-specified algorithm to meet fault isolation performance on a data-driven model. In [18–20], a bank of observers was used to structurally analyze fault isolability. In [13,14], the sensor placement approaches exploited fault detectability and isolability on bipartite graphs. The bipartite graph has a drawback that cannot

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