# Sensor Placement and Diagnosability

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Abstract. Maintenance and diagnosis of complex systems are common activities in the industrial world. Technological advances have led to a continuously increasing complexity of industrial systems. This complexity, which is due to an increasing number of components reduces in turn the reliability of plants. Therefore, fault diagnosis is becoming a growing field of interest. But fault diagnosis relies on sensors: efficient fault diagnosis procedures require a relevant sensor placement. This paper presents a method for sensor placement based on diagnosability criteria. It makes it possible to determine a sensor placement, which satisfies specifications diagnosability specifications. This method does not require the design of any analytical redundancy relation.

Keywords: fault diagnosis, diagnosability, sensor placement

## 1. INTRODUCTION

Sensor placement decisions depend on expected objectives. For instance, in control theory, the sensor placement is used to provide sufficient information for the control of systems. Criteria deal with observability and controllability of the variables. (Madron and Veverka, 1992) has proposed a sensor placement method which deals with linear system. This method makes use of the Gauss-Jordan elimination to find a minimum set of variables to be measured. This ensures the observability of variables while simultaneously minimizing the cost of sensors. In this theory, the observable variables include the measurable variables plus the unmeasured but deductible variables.

However, in fault diagnosis, the goal of sensor placement should be to satisfy detectability and diagnosability properties. Detectability is the possibility of detecting a fault on a component and diagnosability is the possibility of identifying a fault on a component without this creating ambiguity with any other single fault.

(Travé-Massuyès *et al.*, 2001) has proposed a method based on consecutive additions of sensors, which takes into account diagnosability criteria. The principle of this method is to analyze the physical model of a system from a structural point of view. This structural approach is based on Analytical Redundancy Relations (ARR) (Cassar and Staroswiecki, 1997), which can be obtained from combinations of model constraints using bi-partied graph (Blanke *et al.*, 2003) or elimination rules (Ploix *et al.*, 2005), and on the corresponding signature table(Patton and Chen, 1991). In a signature table, rows and columns represent respectively, the set of analytical redundancy relations and the set of considered faults. However, this method requires an a priori design of all the ARR for a given set of sensors. Unfortunately, up to now, no method has been able to guarantee to provide all the possible ARR.

This paper presents a method which improves the possibility of detecting and localizing faults in systems of which only the structure is known. Thanks to this method, the sensor placement satisfying diagnosability objectives becomes possible without designing ARR a priori. It is an important feature since it is no longer necessary to design all the possible ARR assuming all the variables are measured.

## 2. Problem formulation

A system $\Sigma$ can be described by a tuple $(V_\Sigma, K_\Sigma, C_\Sigma, \Phi_\Sigma)$. $V_\Sigma$ is the set of variables that models observable phenomena related to $\Sigma$. The behaviour is represented by constraints $K_\Sigma = \{\dots, k_i, \dots\}$ that established relationships between variables of $V_\Sigma$. It can be summarized by a structural matrix $\mathcal{M}_\Sigma$, which is an incidence matrix representing the application $\mathcal{M}_\Sigma : V_\Sigma \to K_\Sigma$. $C_\Sigma = \{\dots, c_j, \dots\}$ is a set of independent components constituting $\Sigma$. Each constraint $k_i \in K_\Sigma$ models a component $c_j \in C_\Sigma$ satisfying $c_j = \Phi_\Sigma(k_i)$ where $\Phi_\Sigma : K_\Sigma \to C_\Sigma$[1].
Let us introduce the concept of testable subsystem (TSS) and its relationship with the concept of ARR.

**Definition 1** *A set of constraints is testable if all the constraints can be merged into at least one global constraint that no longer contains variables. The values appearing in the global constraint may correspond either to model parameters or to observations coming from measurements or from controlled variables.* □

**Definition 2** *A testable set of constraints is minimal if it is not possible to keep testability when removing a constraint.* □

The global constraint that can be deduced from a TSS is named ARR.

Let $R_\Sigma = \{\dots, r_k, \dots\}$ be the set of all the testable subsystems (TSS) that can be deduced from $K_\Sigma$ according to (Staroswiecki and Declerck, 1989; Blanke *et al.*, 2003; Ploix *et al.*, 2005). Because of the one-to-one relationships between constraints and components, notions of detectability and discriminability can be extended to constraints.

Let $R$ be a set of TSS coming from $(V_\Sigma, K_\Sigma, C_\Sigma, \Phi_\Sigma)$. A constraint $k \in K_\Sigma$ is non detectable in $R$ if $\forall r_i \in R,\ k \notin r_i$. By extension, the constraints $K \subset K_\Sigma$ are non detectable in $R$ if $\forall k_i \in K$, $k_i$ is non detectable in $R$.

Let $R$ be a set of TSS coming from $(V_\Sigma, K_\Sigma, C_\Sigma, \Phi_\Sigma)$. Two constraints $(k_1, k_2) \in K_\Sigma$ are non discriminable in $R$ if: $\forall r_i \in R,\ k_1 \in r_i \Leftrightarrow k_2 \in r_i$. By extension, the constraints of a set $K \in K_\Sigma$ are non discriminable in $R$ if: $\forall (k_i, k_j) \in K_\Sigma^2$, $k_i$ and $k_j$ are non discriminable

[1] A component may also be modeled by several constraints but, for the sake of simplicity, it has not been considered in this paper.

in $R$ with $k_i \neq k_j$.
Obviously, non detectability implies non discriminability.

Let $R$ be a set of TSS coming from $(V_\Sigma, K_\Sigma, C_\Sigma, \Phi_\Sigma)$. A constraint $k \in K_\Sigma$ is diagnosable in $R$ if: it is detectable and $\forall k_j \in (K_\Sigma \setminus k)$, $(k, k_j)$ are discriminable in $R$. By extension, the constraints $K \in K_\Sigma$ are dignosable in $R$ if: $\forall k_i \in K$, $k_i$ are diagnosable in $R$.

In order to formulate the sensor placement problem, the notion of terminal constraint has to be introduced.

**Definition 3** *A terminal constraint $k_i$ is a constraint that satisfies: $card(V(k_i)) = 1$ where $V(k_i)$ is the set of variables appearing in the constraint $k_i$. A terminal constraint usually models a sensor or an actuator. It is thus a major concept in sensor placement.* □

In fault diagnosis, sensor placement has to satisfy specifications dealing with detectability and diagnosability. Therefore, the components $C_\Sigma$ may be decomposed into several sets:

- the set of components $C_{diag}$ / constraints $K_{diag}$ that has to be diagnosable
- the set of subsets of components $\mathbb{C}_{nondis} = \{\ldots, C_i, \ldots\}$ / constraints $\mathbb{K}_{nondis} = \{\ldots, K_i, \ldots\}$ that has to be non discriminable but detectable for each set $C_i$ or $K_i$.
- the set of components $C_{nondet}$ / constraints $K_{nondet}$ that has to be non detectable

Specifications $C_{diag}$, $\mathbb{C}_{nondis}$ and $C_{nondet}$ of sensor placement problems are meaningful if the two following properties are satisfied:

1. Sets in specifications must not to overlap one each other to make sense: constraint sets have to satisfy: $C_{nondet} \cap C_{diag} = \phi$, $\forall C_i \in \mathbb{C}_{nondis}, C_i \cap C_{nondet} = \phi$, $\forall C_i \in \mathbb{C}_{nondis}, C_i \cap C_{diag} = \phi$ and $\forall (C_i, C_j) \in \mathbb{C}^2_{nondis}$, $C_i \cap C_j = \phi$ if $C_i \neq C_j$ (no overlapping property).
2. The union of all the components appearing in $C_{diag}$, $\mathbb{C}_{nondis}$ and $C_{nondet}$ has to correspond to $C_\Sigma$: $C_\Sigma = C_{diag} \cup C_{nondet} \cup \bigcup_{C_i \in \mathbb{C}_{nondis}} C_i$ (completeness property).

If these properties are satisfied the specifications are qualified as consistent in $C_\Sigma$ . Replacing components by corresponding constraints leads to the same properties for specifications $K_{diag}$, $\mathbb{K}_{nondis}$ and $K_{nondet}$ to be consistent in $K_\Sigma$.

Satisfying the specifications requires information delivered by sensors. Let $\Sigma'$ represent the system $\Sigma$ with the additional sensors. $\Sigma'$ can be described by a tuple $(K_{\Sigma'}, C_{\Sigma'})$ where $C_{\Sigma'}$ represents the components of system $\Sigma$ plus the additional sensors and $K_{\Sigma'}$ represents the constraints of system $\Sigma$ plus the additional terminal constraints which model the sensors.

The sensor placement problem consists in determining the additional terminal constraints in $K_{\Sigma'}$ that lead to the satisfaction of the specification $K_{diag}$, $\mathbb{K}_{nondis}$ and $K_{nondet}$. Because of the relations between constraints and components, the results can be extended to components.

## 3. Preliminary concepts

Before deducing diagnosability properties of constraint sets, some concepts have to be introduced.

### 3.1. Some characteristics of constraint sets

A path $p$ in a subset of constraints $K \subset K_\Sigma$ is a alternate list $(k_1, v_1, k_2, v_2, ..., k_{n-1}, v_{n-1}, k_n)$, satisfying:

1. $\forall k_i \in p, k_i \in K$
2. $k_i \neq k_j$ if $i \neq j$
3. $v_i \in V(k_i) \cap V(k_{i+1})$
4. $v_i \neq v_j$ if $i \neq j$

A path $p$ is qualified as complete in $K$ if it involves all the constraints of $K$. The variables involved in a complete path $p$ are denoted $V(p)$. If there is a complete path between a subset of constraints $K$, $K$ is a constraint set linked by $V(p)$.

A subset of constraints $K \subset K_\Sigma$ is *linked by path* in $K_\Sigma$ if there is at least one complete path $p$ linking $K$ such that $V(p) \cap V(K_\Sigma \setminus K) = 0$. The shape of a structural matrix corresponding to constraints that are linked by path in $K_\Sigma$ is drawn in figure 1.

A set of constraints $K \subset K_\Sigma$ isolated by a path $p$ in $K_\Sigma$ if it is linked by path $p$ and if there is at least one variable $v \in (V_\Sigma \backslash V(p))$ such that $v \in V(K)$ and $\{v\} \cap V(K_\Sigma \backslash K) = 0$. The variable set $V(K) \backslash V(K_\Sigma \backslash K)$ are qualified as *stump* in $K_\Sigma$. The set of all stump variables of a set $K$ into $K_\Sigma$ is denoted $V_S(K_\Sigma, K)$. The shape of a structural matrix corresponding to constraints isolated by path in $K_\Sigma$ is drawn in figure 2.

One constraint $\{k\} \in K_\Sigma$ is named *stump constraint* in $K_\Sigma$ if there is at least one variable $v \in V_\Sigma$ such that $v \in V(k)$ and $\{v\} \cap V(K_\Sigma \backslash \{k\}) = 0$. The variables set $V(k) \backslash V(K_\Sigma \backslash k)$ are also qualified as stump in $K_\Sigma$ with respect to $\{k\}$. The set of all these variables is denoted $V_S(K_\Sigma, \{k\})$. The shape of a structural matrix corresponding to a stump constraint in $K_\Sigma$ is drawn in figure 2.

### 3.2. Value propagation as a theoretical tool

According to the definition, a TSS can be modelled by a subset of paths that starts and ends by terminal constraints. An ARR corresponding to a TSS can be seen in different ways. The most common approach is to consider an ARR as a constraint. Another way is to think an ARR as a complete value propagation w.r.t. variables i.e. a propagation that lead to an information about the consistency of a set of constraints, including terminal constraints that

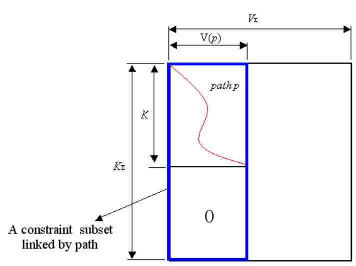


Fig. 1. Structural matrix of a constraint set, which is linked by path

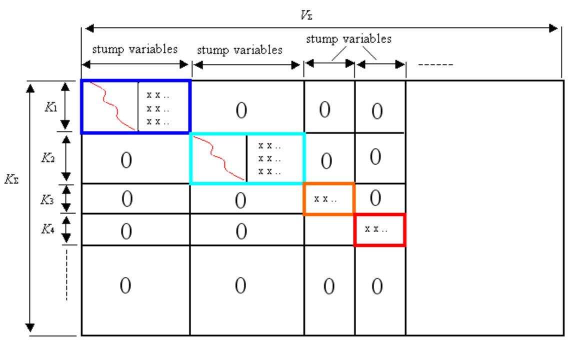


Fig. 2. Structural matrix of non detectable constraints

contains known data. This approach has been adopted as a theoretical tool to develop proofs.

## 4. Constraint set and diagnosability properties

This section aims at setting up a direct link from problem formulation to detectability, discriminabilty and diagnosability properties.

**Lem 1** *Let $K$ be a set of constraints. If additional terminal constraints dealing with each variable in $V(K)$ are added, then all the constraints $K$ are diagnosable.* □

**pf 1** *Consider one constraint $k \in K$. Because it exists additional terminal constraints dealing with each variable in $V(k)$, it exists an TSS containing $k$ and additional terminal constraints but not other constraints in $K\backslash\{k\}$. Therefore, each constraint $k \in K$ is necessary diagnosable.* □

**Lem 2** *A necessary and sufficient condition for a subset of constraints $K \subset K_\Sigma$ to be non detectable is that there exists a partition $P(K)$ of $K$ such as each element $K_i \in P(K)$:*

- *is isolated by a path $p_i$ when there are several constraints in $K_i$*
- *corresponds to a stump constraint when there is only one constraint in $K_i$*

*and there are no additional terminal constraints containing the stump variables in $K_\Sigma$ with respect to all the different $K_i$.* □

Figure 2 points out the shape of a structural matrix of non detectable constraints.

**pf 2** *Two situations may occur depending on the constraint sets $K_i \in P(K)$. If $K_i$ is composed of only one constraint that contains a variable $v$, which is absent from other constraints, it is necessarily non detectable, providing that there is no additional terminal constraint dealing with this variable. Indeed, the* value *of $v$ cannot be propagated and, therefore, no TSS can contain $K_i$. Consider now the case where $K_i$ is composed of several*

*constraints isolated by a path $p_i$. It means that the constraints $K_i$ come always together and that there exists stump variables, which do not belong to the path $p_i$. Let's name these variables $V_i^+$. Because variables of $V_i^+$ are absent of other constraints $K_\Sigma \backslash K_i$, their value cannot be propagated and, providing that there are no additional terminal constraints dealing with these variables, constraints $K_i$ are necessarily non detectable.*
*Conversely, a constraint is non detectable if it does not appear in any TSS. It means that at least one variable cannot be propagated. Except for the obvious case where the constraint is stump in $K_\Sigma$, it exists necessarrily a propagation within a subset of constraints $K \in K_\Sigma; \{k\} \in K$ where the variables $V(K)$ are stump in $K_\Sigma$ with respect to $K$. Therefore, $K$ is necessarily isolated by path.* □

Consider for example a system modelled by the structural matrix drawn in table 1.

Table 1. Structural matrix

| | $v_1$ | $v_2$ | $v_3$ | $v_4$ | $v_5$ | $v_6$ |
|---|---|---|---|---|---|---|
| $k_1$ | 1 | 0 | 0 | 1 | 0 | 0 |
| $k_2$ | 0 | 1 | 1 | 0 | 1 | 0 |
| $k_3$ | 0 | 1 | 1 | 0 | 1 | 0 |
| $k_4$ | 0 | 0 | 0 | 1 | 0 | 1 |
| $k_5$ | 0 | 0 | 0 | 1 | 1 | 1 |

Assume that the set $K = \{k_1, k_2, k_3\}$ is requested to be non detectable. In this example, it exists a partition $P(K) = \{\{k_1\}, \{k_2, k_3\}\}$ such as each element $K_i \in P(K)$ verifies lemma 2. If there are no additional terminal constraints containing $v_1$, $v_2$ and $v_3$, the subset $K$ is non detectable.

**Lem 3** *A sufficient condition for a subset of constraints $K \subset K_\Sigma$ to be non discriminable is that the constraints of $K$ are linked by a path $p$ and that there are no additional terminal constraints containing a variable of $V(p)$.* □

**pf 3** *Firstly, consider the situation where if $K$ is isolated by $p$ in $K_\Sigma$. Then, according to lemma 2, the constraint set $K$ is non detectable and consequently, non discriminable. Secondly, consider situations where $K$ is only linked by path. Two cases may arise: there is only one path $p$ or there are alternative paths $p_i$ satisfying $\forall p_i, V(p) = V(p_i)$. Whatever the case is, the values of these variables can only be deduced by the propagation defined by the path $p$ or possibly by alternative paths $p_i$, providing that there are no additional terminal constraints dealing with the variables $V(p)$. Therefore the constraints of $K$ will always come together in TSS. i.e $\forall(k_i, k_j) \in K^2$, $k_i \in TSS \Leftrightarrow k_j \in TSS$, then $k_i$ and $k_j$ are non discriminable in $TSS$ with $k_i \neq k_j$. Consequently the constraints of $K$ cannot be discriminated.* □

Consider for example the system drawn in table 1.
Assume that $K = \{k_2, k_3\}$ is a constraint subset that should be non discriminable. Because the constraints $k_2$, $k_3$ are linked by the path $p = (k_2, v_2, k_3)$, lemma 3 is satisfied. Therefore, $k_1$ and $k_2$ are non discriminable provided that no additional terminal constraints

contains a variable of $V(p)$.
The following theorem gathers lemmas 1, 2 and 3.

**thm 1** *Let $(V_\Sigma, K_\Sigma)$ be a model and $K_{nondet}$ , $\mathbb{K}_{nondis}$ and $K_{diag}$ be the specifications of a sensor placement problem consistent in $K_\Sigma$. The specifications are fulfilled if:*

1. *it exists a partition $P(K_{nondet})$ such that $\forall K \in P(K_{nondet})$, $K$ is either isolated by a path if there are several constraints in $K$ or, if $K = \{k\}$, $k$ is a stump constraint. The set of all the stump variables is denoted $V_S = \bigcup_{K \in P(K_{nondet})} V_S(K_\Sigma, K)$*
2. *each constraint set $K \in \mathbb{K}_{nondis}$ is linked by a path in $K_\Sigma \backslash K_{nondet}$. The set of all the variables belonging to a path is denoted $V_P = \bigcup_{K \in \mathbb{K}_{nondis}} V(p)$ where $p$ is a linking path in $K$*
3. *there are no additional terminal constraints containing stump variables coming from 1 and variables of the paths used in 2 i.e. $V_S \cup V_P$*
4. *additional terminal constraints are added for all the remaining variable $V_\Sigma \backslash (V_S \cup V_P)$* $\square$

**pf 4** *The proof directly follows up 2, 3 and 1. The first item of theorem 1 correspond to the direct application of lemma 2. Because there are non detectable, the constraints in $K_{nodet}$ have to be removed from $K_\Sigma$ before applying lemma 3. According to lemma 1, if additional terminal constraints are added on remaing variables $V_\Sigma \backslash (V_S \cup V_P)$, the constraint in $K_{diag}$ are diagnosable.* $\square$

Satisfying this theorem guarantees that the specifications are satisfied and conversely, if conditions cannot be satisfied, it means that the specifications cannot be satisfied. However, because lemma 1 provides only a necessary condition for diagnosability, the number of additional terminal constraints is not necessary minimal. It has to be checked afterwards.

The sensor placement problem has been studied without considering components. Let's now take components into account. Components of a system may be divided into three sets: the components on which faults need to be isolated, the components on which faults need to be detected but not necessarily localized and the components on which faults need to be non detectable. Because it has been assumed that each component is modeled by only one constraint, the results obtained for constraints can be extended to components using the application $\Phi_\Sigma : K_\Sigma \rightarrow C_\Sigma$.

## 5. Application to DAMADICS benchmark

Several methods for fault isolation have been benchmarked on a pneumatic servo-motor actuated valve named DAMADICS (Development and Application of Methods for Actuator diagnosis in Industrial Control Systems). (Spanache and Escobet, 2004) has designed a sensor placement method for this problem that optimize the diagnosability level of the system. In this section, the proposed method in this paper, is applied on this benchmark in order to propose a sensor placement that satisfies diagnosability specifications.
The system is defined by the following equations:

$k_1 : X = r_1(P_s, \triangle P)$, $k_2 : F_V = r_2(X, \triangle P)$
$k_3 : CVI = r_3(SP, PV)$, $k_4 : P_s = r_4(X, CVI, P_z)$
$k_5 : PV = r_5(X)$
The corresponding structural matrix is given in table 2.

Table 2. structural matrix of DAMADICS

| | $X$ | $P_s$ | $CVI$ | $PV$ | $F_V$ | $P_z$ | $SP$ | $\triangle P$ |
|---|---|---|---|---|---|---|---|---|
| $k_1$ | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| $k_2$ | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 1 |
| $k_3$ | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 |
| $k_4$ | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 |
| $k_5$ | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |

Let's fix these specifications: $K_{nondet} = \{k_1, k_2\}$, $\mathbb{K}_{nondis} = \{\{k_3, k_4\}\}$ and $K_{diag} = \{k_5\}$.
The set of constraints $K_{nondet} = \{k_1, k_2\}$ is linked by the path $\{k_1, \triangle P, k_2\}$. Because of variable $F_V$, $K_{nondet}$ is isolated by the path $\{k_1, \triangle P, k_2\}$.
The set of constraints $K = \{k_3, k_4\} \in \mathbb{K}_{nondis}$ is linked by the path $\{k_3, CVI, k_5\}$.
According to theorem 1, no terminal constraints containing a variable from $\{\triangle P, F_V, CVI\}$ have to be added i.e. these variables must not be measured.
In order to satisfied the last item of theorem 1, all the variables of the system except $\{\triangle P, F_V, CVI\}$ have to be measured.

The proposed method in (Ploix *et al.*, 2005) has been used to design all the ARR. It has led to this fault signature matrix:

Table 3. Fault Signature Matrix of DAMADICS

| $TSS$ | $k_1$ | $k_2$ | $k_3$ | $k_4$ | $k_5$ | $k_6$ | $k_7$ | $k_8$ | $k_9$ | $k_{10}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $TSS_1$ | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 |
| $TSS_2$ | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| $TSS_3$ | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 0 |
| $TSS_4$ | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 |

According to these results, the constraint set, which cannot be discriminated is: $\{k_3, k_4\}$, the constraints set, which cannot be detected is: $\{k_1, k_2\}$ and the diagnosable constraint set is: $\{k_5\}$. Applying the function $\Phi : K_\Sigma \longrightarrow C_\Sigma$, it is obvious that the components, which cannot be discriminated are: $\{c_3, c_4\}$ and the components, which cannot be detected is: $\{c_1, c_2\}$. The diagnosable component is: $\{c_5\}$.

The results presented in this paper demonstrate clearly that our method facilitates sensor placement which satisfy diagnosability criteria without designing ARR a priori

## 6. Conclusion

A new method of sensor placement has been proposed. It manages specifications dealing with set of constraints that have to be diagnosable, non discriminable or non detectable.

The method applies to any system depicted by constraints, which may only be described by the variables appearing in them. Thanks to this method, sensor placements satisfying diagnosability specifications become possible without designing ARR a priori. It is a very important feature since it is no longer necessary to design all the possible ARR assuming all the variables are measured. An algorithm providing solutions to the sensor placement problem that contain a minimum number of sensors will be provided in the near future.

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