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ROBUST FAULT DETECTION USING EIGENSTRUCTURE ASSIGNMENT: A TUTORIAL CONSIDERATION AND SOME NEW RESULTS

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ABSTRACT

The paper presents some new developments in the eigenstructure assignment approach to robust fault detection. By suitable assignment of the eigenstructure of an observer, the residual signal is de-coupled from disturbances. The main contribution of this paper is the novel use of right eigenvector assignment of observers which gives more freedom for achieving disturbance de-coupling. The paper also shows that, when de-coupling conditions are satisfied, the resulting dead-beat design is equivalent to the 1st order parity space structure for residual generation. Two tutorial examples are presented to illustrate the disturbance de-coupling property and the conditions under which either left and right eigenvectors are assignable.

1. INTRODUCTION

The main problem obstructing the progress and improvement in reliability of fault detection schemes is the *robustness problem with respect to uncertainty* which arises, for example, due to process noise, turbulence, parameter variations and modelling error[1-3]. As a general definition, the robustness is the degree to which the fault detection performance is unaffected by (or remains insensitive to) uncertainties of the system. The residual is an indicator signal of faults, and is usually based on a weighted comparison between estimated and measured variables. The residuals are designed in such a manner as to be near zero in normal operation of the process, but with a derivation from zero in the event of a fault. All residual generation methods employ a model of the dynamic system and hence, if there are no uncertainties in the system (the model is accurate and all the disturbances are measurable), fault detection is very straightforward and there is no associated robustness problem. In most practical systems, however, uncertainties are present almost inevitably and may interfere seriously with the fault detection procedure. Robustness is thus a key issue in model-based fault detection techniques.

State observers are often considered for the role of residual generation [4-7]. Our interest lies in the problem of de-coupling the observer estimation from the *structured* type of uncertainty in the following way. Assume that all uncertainties of a system can be summarised as "unknown inputs" (disturbances) with known distribution matrix (so-called structure uncertainties) acting on the system model on which the observer is designed. Patton *et al* first demonstrated the eigenstructure assignment approach to robust detection in 1986 [6] and 1987 [7]. They have shown in continuing work [6-11] that an approach to solving this problem using the assignment of suitable eigenvectors and eigenvalues (eigenstructure assignment) as a way of providing robustness through disturbance de-coupling. By assigning the eigenstructure to a closed-loop system such as an observer, a well-defined residual signal can be completely de-coupled from the disturbances (i.e. unknown inputs). In this way, robust fault detection is achievable. In a similar way, Watanabe & Himmelblau [12], Wünnenberg & Frank [13] and Wünnenberg [14] have used the so-called "unknown input observer" as an approach to the disturbance de-coupling problem. In this latter approach, the state estimate errors are de-coupled from each disturbance. The eigenstructure assignment approach, on the other hand is a method of designing a residual signal which is de-coupled from disturbances. The paper develops further the eigenstructure assignment approach to disturbance de-coupling and hence robust fault detection. Some new ideas are proposed, especially, a new method for the assignment of *right* eigenvectors of an observer to make full use of the design freedom available for de-coupling and good fault detection. Sufficient condition for disturbance de-coupling is given. Connected with this is the philosophy behind the choice of a dead-beat observer structure; the significance of this in terms of the assignability available for de-coupling is given in the paper.

The paper also shows how the eigenstructure assignment problem fits into the context of parity space residual generation methods. In particular, it is shown that when robustness conditions hold true, the dead-beat design is equivalent to the 1st order parity space structure for residual generation. Two tutorial examples is presented to illustrate the approach.

2. PROBLEM SPECIFICATION

To approach the problem from the most general and practical point of view, one must start with a mathematical description of a system that includes all kinds of dynamic input signal that can occur in practice and affect the dynamic behaviour of the system. In principle, either a continuous-time or discrete-time model description can be used. We choose here to use the discrete-time representation:

$$\underline{x}(k+1) = F\underline{x}(k) + G\underline{u}(k) + E\underline{d}(k) + Q\underline{f}_a(k) \qquad (1)$$

$$\underline{y}(k) = C\underline{x}(k) + D\underline{u}(k) + \underline{f}_s(k) \qquad (2)$$

where $\underline{x}(k)$ is the $n\times1$ state vector, F the open-loop system dynamics matrix, $\underline{u}(k)$ the $r\times1$ known input vector with the corresponding input distribution matrix G. The term $E\underline{d}(k)$ characterizes a $q\times1$ *unknown input (disturbance)* vector $\underline{d}(k)$

with known distribution matrix E acting directly onto the system dynamics. $E\underline{d}(k)$ is used to represent uncertainties acting upon the system, the so-called *structured uncertainties*, i.e. although the values of the uncertainty are unknown, its distribution matrix (structure) is known *a priori*. C is the measurement matrix of the system and $\underline{y}(k)$ the m×1 output vector that is assumed to be available for further treatment. The faults that corrupt the measurements, called sensor faults, are described by the vector $\underline{f}_s(k)$. The term $Q\underline{f}_a(k)$ represents the faults acting on the system dynamics, such as actuator or component faults.

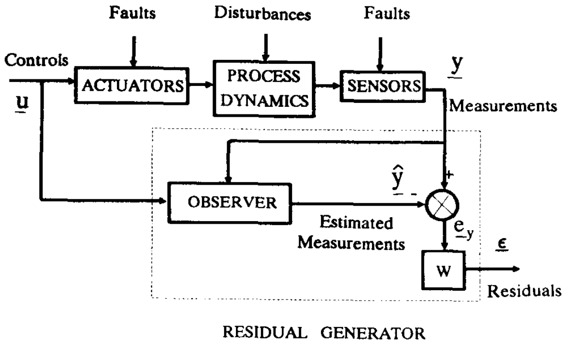

Fig. 1 General structure of observer-based residual generation approach

The principle of the observer-based approach for generating of robust residual is illustrated in Figure 1. The residual generator uses an observer which generates estimates of the system states and measurements, and provides residual signals which are independent of uncertainties. The observer dynamics are described by the following:

$$\hat{\underline{x}}(k+1) = (F - KC)\hat{\underline{x}}(k) + (G - KD)\underline{u}(k) + K\underline{y}(k) \qquad (3)$$

$$\hat{\underline{y}}(k) = C\hat{\underline{x}}(k) + D\underline{u}(k) \qquad (4)$$

where $\hat{\underline{x}}(k)$ is the n×1 state estimation vector and $\hat{\underline{y}}(k)$ the m×1 output estimation vector. The state estimation error ($\underline{e}(k) = \underline{x}(k) - \hat{\underline{x}}(k)$) dynamics are as follows:

$$\underline{e}(k+1) = F_c\underline{e}(k) + E\underline{d}(k) + Q\underline{f}_a(k) - K\underline{f}_s(k) \qquad (5)$$

where $F_c = F - KC$

A p-dimensional residual vector is generated from the difference between the actual and estimated measurements having the form:

$$\underline{\varepsilon}(k) = W\underline{e}_y(k) = W(\underline{y}(k) - \hat{\underline{y}}(k)) \qquad (6)$$

where W is a p×m weighting matrix.

$$\underline{\varepsilon}(k) = WC\underline{e}(k) + W\underline{f}_s(k) = H\underline{e}(k) + W\underline{f}_s(k) \qquad (7)$$

where: $\quad H = WC \qquad (8)$

From equations (5) and (7), we have the complete response of the residual vector is:

$$\underline{\varepsilon}(z) = [W - WC(zI - F_c)^{-1}K]\underline{f}_s(z) + WC(zI - F_c)^{-1}Q\underline{f}_a(z) + WC(zI - F_c)^{-1}E\underline{d}(z) \qquad (9)$$

One can seen that the residual is not zero, even if no faults occur in the system. Indeed, it can be difficult to distinguish the effects of faults from the effects of disturbances acting on the system. The effects of disturbances obscure the performance of fault detection and act as a source of false alarms. Therefore, in order to minimize the false alarm rate, one should design the residual generator such that the residual itself becomes decoupled with respect to disturbances. This is the principle of a *robust residual generator*.

3. GENERAL THEORY FOR DISTURBANCE DECOUPLING DESIGN

In order that the residual $\underline{\varepsilon}$ be independent of uncertainties, it is necessary to null the entries in the transfer function matrix between residuals and disturbances. i.e.

$$G_{rd}(z) = WC[zI - (F - KC)]^{-1}E = 0 \qquad (10)$$

This is a special case of the *output-zeroing* problem which is well known in multivariable control theory [15]. Once E is known, the remaining problem is to choose the matrices K and W to satisfy this equation. The solubility condition for W and K in (10) can be determined in the context of the invariant subspace theory [16,17].

$$H[zI - F_c]^{-1}E = H\{a_1(z)I_n + a_2(z)F_c + \ldots\ldots + a_n(z)F_c^{n-1}\}E$$

$$= [\, a_1(z)I_p \quad a_2(z)I_p \quad \ldots\ldots \quad a_n(z)I_p] \begin{bmatrix} H \\ HF_c \\ \vdots \\ HF_c^{n-1} \end{bmatrix} E$$

$$= H[\, E \quad F_cE \quad \ldots\ldots \quad F_c^{n-1}E] \begin{bmatrix} a_1(z)I_q \\ a_2(z)I_q \\ \vdots \\ a_n(z)I_q \end{bmatrix} \qquad (11)$$

Hence, the equation (10) can be solved by following two approaches:

(1) If the (H , F_c) - invariant subspace (observable subspace) lies in the left zero space of E, the equation (10) holds true.

or

(2) If the (F_c , E)-invariant subspace (controllable subspace) contained in the right zero space of H, the equation (10) holds true.

In section 4, we show that these two goals can be achieved by the assignment of either left eigenvectors or right eigenvectors of the observer.

4. ROBUST RESIDUAL GENERATOR DESIGN BY USING EIGENSTRUCTURE ASSIGNMENT APPROACH

Now, $G_{rd}(z)$ can be expressed in the dyadic form:

$$G_{rd}(z) = \frac{R_1}{z - \beta_1} + \dots\dots\dots + \frac{R_n}{z - \beta_n} \tag{12}$$

here $\quad R_i = H \underline{v}_i \underline{l}_i^T E$

where $\underline{v}_i$ and $\underline{l}_i^T$ are, respectively, the right and left eigenvectors associated with an eigenvalue β_i of F_c. It is well known that, a given left eigenvector $\underline{l}_i^T$ (corresponding to eigenvalue β_i) of F_c is always orthogonal to the right eigenvectors $\underline{v}_j$ corresponding to the remaining (n-1) eigenvalues β_j of F_c, where $\beta_i \neq \beta_j$. In order to get expression (12), all eigenvectors must be appropriately scaled so that $VL^T = L^TV = I_n$, where:

$$V = [\underline{v}_1, \underline{v}_2, \dots, \underline{v}_n]$$

$$L = [\underline{l}_1, \underline{l}_2, \dots, \underline{l}_n]$$

Thus, we note that disturbance de-coupling is possible if and only if $R_i = H \underline{v}_i \underline{l}_i^T E = 0$ for all i = 1 to n. This implies that:

$$\begin{aligned} & R_1 + \dots + R_i + \dots + R_n \\ &= H\underline{v}_1\underline{l}_1^TE + \dots + H\underline{v}_i\underline{l}_i^TE + \dots + H\underline{v}_n\underline{l}_n^TE \\ &= HVL^TE = HE = WCE = 0 \end{aligned} \tag{13}$$

Theorem 1: $WCE = HE = 0$ is a necessary condition for achieving disturbance de-coupling design.

4.1 Disturbance de-coupling design by using left eigenvector assignment

Theorem 2: If (1) $WCE = 0$, and (2) All rows of the matrix $H = WCE$ are left eigenvectors of F_c corresponding to any eigenvalues, equation (10) holds true.

Proof: If the rows of H are p left eigenvectors ($\underline{l}_i^T$, i = 1, 2, ..., p) of F_c, i.e.

$$H = \begin{bmatrix} \underline{l}_1 & \underline{l}_2 & \cdots & \underline{l}_p \end{bmatrix}^T \tag{14}$$

then: $H \underline{v}_i = 0$ and $R_i = 0$ $\quad$ for $i = p+1, \dots, n$

If further we have: $\quad WCE = HE = 0 \quad (15)$

i.e. $\quad \underline{l}_i^TE = 0$ and $R_i = 0$ $\quad$ for all $i = 1, 2, \dots, p$

Thus $\quad G_{rd}(z) = 0$

Then, the residual is completely de-coupled from the disturbance. The first step for the design of a disturbance de-coupled residual generator is to compute the weighting matrix W which must be satisfied to equation (15). The necessary and sufficient condition for solution (15) to exist is rank(CE) < m. The second step is to assign the left eigenvectors of the observer as the rows of H (corresponding to suitable eigenvalues). This can be handled by means of a transformation of the dual control problem. On assignment of the right eigenvectors to the dual control problem these eigenvectors become the left eigenvectors of the observer. The assignment of right eigenvectors for a controller is a well developed technique [18,19]. The assignability condition is that for each β_i, the corresponding left eigenvector $\underline{l}_i^T$ of F_c must belong to the row subspace spanned by rows of matrix $\{C(\beta_i I - F)^{-1}\}$.

4.2 Disturbance de-coupling design by using right eigenvector assignment

If the left eigenvector assignability condition is *not* satisfied, we can consider an alternative approach, that is to assign the right eigenvectors of the observer as columns of matrix E.

Theorem 3: If (1) $WCE = 0$, and (2) All columns of the matrix E are right eigenvectors of F_c corresponding to any eigenvalues, equation (10) holds true.

The assignment of right eigenvectors of the observer (left eigenvector of dual controller) is a relatively new problem, although few other investigators have considered this problem [20]. Here we present the outline of a new assignment method.

Theorem 4: The necessary condition for a vector $\underline{r}_i$ is the right eigenvector of F - KC corresponding to the eigenvalue β_i is:

1^0: $\underline{r}_i$ is the right eigenvector of F corresponding to β_i and $C\underline{r}_i = 0$.

or

2^0 $\underline{r}_i$ is *not* the right eigenvector of F corresponding to β_i and $C\underline{r}_i \neq 0$.

Proof: If $\underline{r}_i$ is the right eigenvector of $F_c = F - KC$ corresponding to a eigenvalue β_i

$$(F - KC)\underline{r}_i = \beta_i \underline{r}_i \tag{16}$$

$$KC\underline{r}_i = (F - \beta_i I)\underline{r}_i \tag{17}$$

The necessary and sufficient condition for solution K of equation (17) to exist is that either condition 1^0 or 2^0 must hold true.

For the case, when a number of right eigenvectors must be assigned, the gain matrix K must satisfy a set of equations like (17). If we want to assign all columns $\underline{e}_i$ (i = 1, ..., q) of E as the right eigenvectors of Fc = F - KC corresponding to eigenvalues β_i, the following equations must be satisfied.

$$KC\underline{e}_i = (F - \beta_i I)\underline{e}_i \qquad \text{for } i = 1, \dots, q \tag{18}$$

i.e. $$KCE = F_\beta \tag{19}$$

where $F_\beta = [\,(F - \beta_1 I)\underline{e}_1 \ldots (F - \beta_i I)\underline{e}_i \ldots (F - \beta_q I)\underline{e}_q\,]$

Now, the right eigenvector assignment problem is to solve the equation (19) and meanwhile to ensure that the observer is stable.

Lemma: The necessary and sufficient condition for solution of equation (19) to exist is:

$$\mathrm{rank}(F_\beta) = \mathrm{rank}(CE)$$

Subject to this condition, the general form of the solution to (19) is:

$$K = F_\beta(CE)^* + K_1[I_m - CE(CE)^*] \qquad (20)$$

where K_1 is a n by m arbitrary design matrix and $(CE)^*$ is the pesudo-inverse of CE. When rank(CE) = q, $(CE)^*$ is given by:

$$(CE)^* = [(CE)^T CE]^{-1}(CE)^T$$

The dynamic matrix of the observer is thus:

$$F - KC = F - F_\beta(CE)^*C - K_1[I_m - CE(CE)^*]C = F_1 - K_1C_1$$

Where

$$F_1 = F - F_\beta(CE)^*C$$
$$C_1 = [I_m - CE(CE)^*]C$$

The necessary and sufficient condition for the observer dynamic matrix F - KC to be stable is that $\{C_1, F_1\}$ is *the dual of a stabilizable pair*. When this condition is satisfied, the assignment problem of the right eigenvectors is to choose the matrix K_1 such that the observer is stable. This problem can be handled by using the traditional pole assignment methods. As $\beta_1, \ldots, \beta_q$ have been assigned as the eigenvalues of $F - KC = F_1 - K_1C_1$, only the maximum (n-q) eigenvalues of $F_1 - KC_1$ can be moved by changing the design matrix K_1.

4.3 Dead-beat design and relationship with the parity space

Here, we consider a dead-beat design, for which the de-coupling can be derived in a very simple manner. Consider the expression:

$$H(zI - F_c)^{-1}E = z^{-1}H(I + F_c z^{-1} + F_c^2 z^{-2} + \ldots + \ldots)E \qquad (21)$$

Choose H and K in such a way that the rows of H are the left eigenvectors of F_c corresponding to zero-valued eigenvalues. From this case, the sufficient de-coupling conditions are:

$$HE = 0 \qquad (22a)$$
$$HF_c = 0 \qquad (22b)$$

Alternatively, the sufficient de-coupling conditions can also be given as:

$$HE = 0 \qquad (23a)$$

$$F_cE = 0 \qquad (23b)$$

If each column of E is a right eigenvector corresponding to a zero-valued eigenvalue of F_c, (23b) holds true.

Because of the assignment of zero-valued eigenvalues, the residuals have dead-beat (minimum-time) transient performance and this feature can be exploited to good use in the aim to provide a high sensitivity to soft faults.

From the observer equations (3), (4) & (6), the z-transform of $\underline{\varepsilon}(k)$ is:

$$\underline{\varepsilon}(z) = [W - H(zI - A_c)^{-1}K]\underline{y}(z) - [WD + H(zI - A_c)^{-1}G_1]\underline{u}(z) \qquad (24)$$

where $G_1 = G - KD$. If the perfect de-coupling conditions (22b) (*not* (23b)) hold true, then $H(zI - A_c)^{-1} = z^{-1}H$, thus the residual vector $\underline{\varepsilon}(z)$ can be re-written as

$$\underline{\varepsilon}(z) = (W - z^{-1}HK)\underline{y}(z) - [WD + z^{-1}HG_1]\underline{u}(z) \qquad (25)$$

i.e
$$\underline{\varepsilon}(k) = [\,W \quad -HK\,]\begin{bmatrix} \underline{y}(k) \\ \underline{y}(k-1) \end{bmatrix} - [\,WD \quad HG_1\,]\begin{bmatrix} \underline{u}(k) \\ \underline{u}(k-1) \end{bmatrix} \qquad (26)$$

It is evident that this is a 1st order parity space relation [21, 22]. In its common form, the parity space approach is an *open-loop concept*, giving rise to residual generation from available measurements and controls [21, 22]. The parity vector (residual) has a finite impulse response. Moreover, it could be designed to be *robust with respect to disturbances*. That is to say, we can design a robust residual generator by using the eigenstructure assignment technique, and by implementing it in the form of the parity space. Note that in the right eigenvector assignment case (condition (23b)), the link with the parity space approach *cannot* be derived.

5. TWO TUTORIAL EXAMPLES

Example 1: Consider the discrete-time system given by, F = diag{0.25, 0.5, 0.375}, $G = [0, 1, 1]^T$, disturbance distribution matrix $E = [\,1 \quad 1 \quad 0\,]^T$, and the measurement matrix

$$C = \begin{bmatrix} 1 & 1 & 0 \\ 0 & 1 & 1 \end{bmatrix}$$

The weighting matrix is W = [-1 , 2] so that WCE = 0, the desired left eigenvector is H = WC = [-1 , 1 , 2] (corresponding to eigenvalue 0) which is assignable (H^T belongs to subspace span$\{-F^TC^T\}$. The remaining two eigenvalues are chosen as {0, 0.1}. Using the eigenstructure assignment technique [9,18,19], the gain matrix is derived as:

$$K = \begin{bmatrix} 0.0165 & -0.3330 \\ 0.4670 & 0.6661 \\ -0.3502 & -0.1246 \end{bmatrix}$$

$H(F - KC) = 0$ and $WCE = 0$, i.e., the de-coupling conditions (22a) & (22b) are satisfied.

$$H(zI - F_c)^{-1}E = 0$$

$$\epsilon(z) = [W - WC(zI - F_c)^{-1}K]\underline{f}_s(z) + WC(zI - F_c)^{-1}Q\underline{f}_a(z)$$
$$= [-1 \;\; 2]\underline{f}_s(z) - [-0.249 \;\; 0.749]z^{-1}\underline{f}_s(z) - z^{-1}f_a(z)$$

Clearly, the disturbance term is not present and the residual is only a function of faults. This means that a robust design has been achieved. And meanwhile, according to equation (26), the residual is:

$$\epsilon(z) = [-1 \;\; 2]\underline{y}(z) - [-0.249 \;\; 0.749]z^{-1}\underline{y}(z) - z^{-1}u(z)$$

This is a 1st order parity space relation.

Example 2: Now consider changing the matrix F to F = diag {0.3, 0.6, 0.9}. In this case, the required left eigenvector of the observer H is *not* assignable (H^T does not belong to subspace span$\{-F^TC^T\}$. We must use the alternative approach of assigning right eigenvectors, as discussed in section 4.2. The eigenvalues are choose as {0, 0, 0.1}. We then assign the right eigenvector of the observer as a single column of E (corresponding to eigenvalue 0), in this case, the resulting gain matrix computed using right eigenvector assignment is:

$$K = \begin{bmatrix} 0.098304 & 0.103392 \\ 0.589304 & -0.596608 \\ -0.8 & 1.6 \end{bmatrix}$$

The z-transform of the corresponding residual signal is:

$$\epsilon(z) = [(-1+1.2z^{-1}-0.27z^{-2}) \;\; (2-2.7z^{-1}+0.81z^{-2})]\underline{f}_s(z)/(1-0.1z^{-1})$$
$$+ [\,3 - 1.8z^{-1}\,]f_a(z)/(1-0.1z^{-1})$$

The disturbance de-coupling has also been achieved, however this residual signal although robust to disturbance is recursive in structure and is not a parity space residual signal.

6. CONCLUDING DISCUSSION

This paper has studied the robust disturbance de-coupling fault detection problem, based on an observer with structured uncertainties acting on the estimation error. The de-coupling approaches making use of either left or right eigenvector assignment have been compared in a tutorial setting. It has also shown that when robustness conditions hold true, the dead-beat design is equivalent to the 1st order parity space relation for residual generation. A new method for direct assignment of the right eigenvectors in the observer design has been presented.

Two tutorial examples have been presented to illustrate the disturbance de-coupling design method. Both of these two examples have structured uncertainties. The method presented can also be used for robust fault detection of a system with unstructured uncertainty. The method has been successfully applied to an example of unstructured uncertainty taken from a jet engine system, in which a structure for the uncertainty is estimated [10, 11], via estimation of an optimal matrix E. As the "best" E is used (although assumed constant), the method can be used to detect incipient faults in a robust way. Later research will concentrate on methods to obtain the optimal approximate structure for general and practical systems with unstructured uncertainties.

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