DESIGN OF ROBUST DETECTION FILTER AND FAULT CORRECTION CONTROLLER

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Overview of PhD Thesis

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ABSTRACT

The challenge of nowadays control engineering claims a more and more complex functionality of control systems. Beyond the stability, the robustness and the disturbance rejection properties, controllers need to ensure the requirements of the nominal performance as well. The topic of the dissertation is one of the most exciting research domain in control system engineering, namely Fault Detection and Isolation (FDI). The realtime detection of the malfunctions in the system, either in uncontrolled or in closed-loop is always a difficult and complex problem from point of view engineering. However, the place of the fault can be located, its magnitude and rising time is rather known. Robustness in FDI is an auxiliary attribute which provides a safer detection when in model-based description the model is uncertain or exogenous disturbance corrupts the system.

Using estimated fault information the control rule could be modified. If the detected failure information is available the control algorithm could be changed. The adjustment of the faulty loop is called reconfiguration. Sometimes, the recognized malfunction is used to correct the effect of the failure in the loop. The PhD thesis shows a solution of the joint fault detector - controller scheme with special regards to application problems.

The scope of the dissertation is double. Firstly, the develop of a model-based, computationally thrusted and robust detection algorithm for safety critical systems. On the other hand, the representation of a potential application domain is needful to prove its importance ex., Aircraft Flight Control System (AFCS) design. By the vast increase of air passengers there is a growing need to high fidelity AFCS. The dissertation is impressed by the safety features of the flight controllers, by the recognition of the occurring faults during any kind of airborne manoeuvre.

The dissertation suggests to treat the FDI problem robustly and attaches it with controller for fault corrector reason. The paper could be fruitful and very valuable for engineers dealing with the control of high reliable systems. This model-based approach rends with the classical aspects of the robust detection filters, and by the extension of the model classes the algorithm are applicable for certain kind of nonlinear plants. Finally, the Thesis is recommended for engineers, since aerospace domain is not the only scope and based on all remarks, summary and conclusive parts allows to think it over.

MOTIVATION

Control system is a multidisciplinary science condensing a wide range of many research fields.

Control engineering makes systems stable, takes performance requirements, constraints and uncertainties into account. Various approach permits the interpretation of control systems. From the classical aspects throughout the modern methodologies up to the post-modern description several modus provide the opportunity of controller design. Though, the palette is large enough, engineer needs to decide among the methods. Consequently, the application of controller might be a certain kind of trade-off, or at least a choice.

Not only the primordial control aims are important, but also the more complicated ones. Nevertheless, optimality and robustness are two major characteristics to be considered. The role of the robustness against disturbance or model mismatches is an important factor to be fulfilled during the control synthesis. Although, the design is based on the nominal plant, the controller should work with the real system. Since, it would be rather a failure to think, that nominal model description precisely describes the real system. Usually, modeling is always a certain kind of degeneration of the reality, because nominal model is never as complicated as the real plant it is. Generally, there is loss of information caused by the simplification of the real dynamic during the modelization. Another reason of using nominal plants could be based on the fact, that (mainly postmodern) control rules can be well established to simplified dynamics (linear case). If the nominal model contains a restricted amount of information about the plant, with all a priori data, the controller should provides the stability and other performance outcomes. This is the point where robustness come into consideration. While the control energy is limited the controller, or the states of the system generally are varying between known maximal and minimal bounds, the saturation of the variables could be assimilated in the design process.

The cue of the control strategy is augmented whenever supplementary function are considered. Since, incommoding faults could always perturb the system, obviously the accomodation of these failure terms is always important regarding to the hole structure, mainly in safety related systems. This discipline in control system is called fault tolerant control. The topic of the dissertation was motivated by the robustness and the fault tolerant control.

One component of the fault tolerant control system design is the Fault Detection and Isolation (FDI).Therefore the dissertation is focusing on the progressively developing subject, the fault detection but under exogenous disturbance effect. One of the main contribution of the thesis is the robustness itself. While several methods offer the possibility of FDI and robust control, the present document diverges from the classical deal and suggests the application of robust FDI.

The fault detection could be approached from the controller design, since a wide set of failure recognition is based on detection filter design. In this context the detection filter is an observer. In other words, the dissertation proposes the robust detection filter design by the duality the robust controller design.

A newly emerged area of the model classes is described by the variation of a parameter, the Linear Parameter Varying systems. Evaluating a complicated dynamics in LPV form has many opportunities. This is the reason why the dissertation extends the robust FDI problem to parameter varying case.

The mathematical formulation of disturbance in a dynamic system could be different. The thesis shows the detection under deterministic and stochastic formulation as well. Moreover, all possible a priori information might help the detection performance. Such an a priori knowledge could be the extremal limits of the parameters. With a potential state estimation process the optimal states are given back subjected to equality or inequality constraints. Sometimes the structure of the state space requires to manage constraints during the detection. Sometimes the maximal or minimal values of the failure are important depending on the system.

The detection of faults is never assertive. Diagnosing a system provides information to supervisory level, where further measures could be taken. A part of safety systems needs to be controlled with the toleration of a certain amount of malfunctions. Either with the extended margin of the robust performance, or with the implementation of the detected or estimated faults, the system should functions with a predefined safety level. The last part of the thesis was motivated by a possible application of the previously elaborated robust detection filters. The joint FDI-controller structure is able to handle constraints in the control algorithm.

Finally, a possible application domain of dynamic FDI design and control is clearly precised in the dissertation. It has been dedicated to aircraft dynamics and control for several reason. First of all, because the author had studied flight dynamics. Secondly, because a fellowship program gave the possibility to a research and development cooperation with the Department of Aerospace Engineering in Minneapolis. Moreover, the author had contact with several other international research center (Technion, Université de Haute Alsace) and would like to contribute to the Hungarian aerospace and control science.

Notions and Methods Applied

Fault Detection and Isolation

Reliability, efficiently and availability support a more complex functionality towards to controllers. Moreover the specially safety related applications such as aircraft industry, traffic systems and nuclear power plants, the phenomenon safety (including reliability as well) must be extended and occasionally implemented in the control loop. Obviously, safety critical systems are usually provided with a capability of fault diagnostic issue. Since in these cases the recognition of the occurring malfunction is crucial for the hole system (breakdowns, catastrophes, injuries), a permanent, on-line diagnosis must survey the plant. Of course, when failure appears in the systems the appropriate decision needs to be carried in order to preserve the human life, devices or the outage of the production.

Consequently, the recognition of the fault is not enough. While in safety oriented industries the detected failure information (respectively the reaction of the supervisor) needs to be injected into the system to avoid ex. catastrophes, in not safety critical applications the fault diagnosis is used first of all to increase reliability. The modifications, respected to the occurring faults can be automized. Generally speaking, in closed loops. the control law could be changed so that it takes the malfunction into consideration. The modification of the control algorithm is called reconfiguration. The reconfiguration can be a simple-minded switch between redundancies upto a rather complex reconfiguration logic. Safety dependent systems are highly influenced with fault deterioration, and engineering always should keep the down-time of the system in mind. Another reason of using modern diagnostic methods is to reduce the maintenance costs.

In case of a fault, the system must continue operating when speaking about fault tolerant behavior. After the appearance of the fault, the main goal is to maintain the basic and safety functionality of the plant, even if the system losses some of the redundancies. The logic behind the fault tolerance is unambiguous: the system breakdown is either impossible or rather costly. Nevertheless, the system is able to tolerate a certain level of fault, a predefined number and nature of failures can be permitted. Giving an illustrative example of the aircraft industry, where the safety is the most important issue and failures could not cause air crash. The fault tolerant control always means the presence of a certain kind of redundancy, of reserve. When the system does not work properly, a part of this redundancy might be used. The maximum level of failure, i.e. a threshold of the failures which are still tolerated, needs to be well laid down. The fault detection and isolation is not enough when applying a fault tolerant control system, since measures must be taken in order to avoid system breakdowns. Many fault tolerant manipulation is though as a intelligent system, a higher level of automatization.

On the other hand, failsafe behavior represents another system class, where the malfunction is absolutely not tolerated. The philosophy behind is the operation without fault. If it can not be achieved, the system should change safety level, i.e. the same failsafe rate can not be held.

Redundancies can be classified in two major part. First, hardware/psychical/paralell redundancy is a widespread method of using multiple channels of hardware (sensors,actuators, computers, etc.). When data acquisition devices, measurements are replicated by several, different channels, the supervisory level needs to decide among them. The voting logic is applied to choose amongst hardware redundancies.

Sometimes the assessment cost is extremely limited, or simple there is no room, load enough to apply it. At times, only psychical reserve is not enough to maintain safety rate. Hence, one uses analytical/functional redundancy. Analytical redundancy is based on different methods (different measurements) to provide safety information. In that case no supplementary equipment is required, the only difference is in the algorithms providing safety information. The major part of the analytic redundancies come from the model based fault diagnosis, when the system is represented in a model form. Although, this is not the only way.

Dynamic fault detection algorithm creates a residual, which is the difference signal between the measured and the estimated one. The residual permanently observes the system and if fault appears, it shows up in the residual as well. To create residual, different model based methods exist.

The reader could address to [17] to have an overview description in FDI technique.

However precise, accurate the mathematical model description, disturbances, model mismatches abrupt the system. Only robust fault detection algorithm will be working properly [25],[52].

The fault corrupted description of the linear time-invariant system is given by:

$$\dot{x}(t) = Ax(t) + \begin{bmatrix} B_1 & B_2 \end{bmatrix} \begin{bmatrix} d(t) \\ u(t) \end{bmatrix} + \sum_i L_i m_i(t) \quad (1)$$

$$y(t) = Cx(t) \quad (2)$$

where $\mathcal{X}$, $\mathcal{Y}$, $\mathcal{U}$, $\mathcal{M}_1$ and $\mathcal{B}_1$ are real linear vector space with appropriate dimension, $x(t) \in \mathcal{X}$ is the state vector, $y(t) \in \mathcal{Y}$ is the output vector, $u(t) \in \mathcal{U}$ is the control inputs and $d(t) \in \mathcal{B}_1$ is the disturbance input, $m_i \in \mathcal{M}_1$ are the failure input to the system. The L_i directions are the appropriate failure signatures, modeled as linear additive terms in the dynamical equation. The aim is to accurately isolate and detect the change in fault terms.

Geometric approaches was initiated in the early 70's when Beard developed on the basis of Jones interpretation a new analytical, model based fault detection algorithm. This is called BJDFP. During this solution all possible faulty events are collected in a single residual. Another geometric solution is the FPRG developed in [45], is a way to separately detect failures in the system by multiple residuals. These geometric solution was late on reused and extended by [65],[1]. Unknown input observer theory could be applied to detect a not-known, external input such as **[16]** under the linear form of a state observer:

$$\begin{aligned} \dot{w}(t) &= Fw(t) - Ey(t) + Gu(t) && (3) \\ r(t) &= Mw(t) - Hy(t). && (4) \end{aligned}$$

Abreast the geometric methods, [47] suited a stochastic FDI approach, based on innovation processes, using Kalman filtering and describing the faults by statistical parameters. [66] elaborated the Generalized Likelihood Ratio for FDI technique. The detection of parameter changing applied to fault diagnosis can be found in the early papers of Baseville [2], and later on Nikiforov[3]. One needs to mention the use of the multiple method, when a complete bank of Kalman filter provides the a posteriori probability [12]. The new deal in the statistical approach could be the search for principal components.

Detection filter design can be solved with observer based FDI. So [20] showed the Luenberger observer form for FDI. Among others Frank prepared a summary of the observers to be applied.

The parity approximation is the generation of parity vector as residual, first published by Mironovski (1979) and after proposed by several authors [19], [28], [18]. Recently development of the parity space algorithm can be read in [31, 29, 30].

A part the stochastic algorithms, the FDI can be formulated by the estimation of the model parameters. These techniques are mainly based on system identification proposed in the 80's. Isermann and many others elaborated estimation methods in order to identify unmeasured system parameters [34],[35]. He studied the on-line parameter approaches based on heuristic knowledge, and has many application oriented paper [36].

In [19] suggested a bi-stages methods called two-stages model based FDI. In that case the first step is to make the residual and the second one is the decision-making. Generally speaking, the two stage method became the most worldwide process of FDI.

The system inversion to fault detection purpose is a well known newly developed technique, where by the dynamic inversion of the system the unknown input can be estimated [11, 61]. The robust extension of the inversion is to be worked out.

As already mentioned robustness is necessary to FDI. Either model uncertainty, or disturbance rejection must be taken into account. Robust unknown input observers family was extended by Frank [25] (among others). The unknown input strategy evolve the fault information with the help of the measured inputs and outputs, with the dynamic behavior of the system.

[52] showed the robustness in fault detection via eigenstructure assignment. To be sure parity space approach towards optimality and robustness was proposed by Frank, Gertler, Kunwer. Furthermore, frequency domain design strategies were published by many authors Frank, Patton, Edelmayer et al [22]. On the palette of the FDI design a possible color could be the adaptive threshold method, the uncertainty modeling approaches and the quick or rapid progress FDI techniques.

A more and more developing area of FDI is the nonlinear dynamic FDI system. The nonlinear problem can be originated in linear FDI's. The linear solution is valid only in a restricted area and works properly when there is no big difference between the linear and the nonlinear one. The next step was the beginning of the use of nonlinear observers, bilinear systems from 1995.

One of the most promising field of the FDI might be the Linear Parameter-Varying systems (LPV), respectively the LPV FDI [1].

A special class of linear parameter varying systems where the state matrices depend affinely from the parameter vector $\rho(t) \in \mathcal{P}$, a time dependent vector.

$$\dot{x}(t) = A(\rho)x(t) + \begin{bmatrix} B_1(\rho)B_2(\rho) \end{bmatrix} \begin{bmatrix} d(t) \\ u(t) \end{bmatrix} + \sum_{i=1}^{l} L_i(\rho)m_i(t) \tag{5}$$

$$y(t) = Cx(t), \tag{6}$$

where m_j are the failures modes to be detected and isolated, $d(t)$ is the disturbance vector, $x(t)$ is the state vector, $u(t)$ is the control input. $y(t)$ is the measured output vector.

Among the latest nonlinear paper on can found [68, 67] as well.

In the chapter 3 and 4, the dissertation deals with the extension of the FRPG towards robustness for linear time-invariant and linear parameter varying system as well.

Receding Horizon Control and Application

Model Predictive Control (MPC) strategy provides a reliable and effective control tool when constraints can reside in the multivariable systems. The MPC description is widely applied in the industry. The reader can referred to the MPC literature [24, 7, 5, 4, 16, 42, 43, 53].

The perfect annulation of the fault or disturbance requires the exact disturbance modelling, the ”measurement” of disturbance (in case of feed-forward control). Though it is not possible, the control loop (the feedback part) resets the remaining so-called unmeasured, unknown disturbance, see [42].

A part of the realization of the joint fault detector - controller structure are the reconfigurable systems. The reconfiguration is the modification of the controller structure whenever failure is present [13, 15, 14], **[3]** in adaptive manner. A new deal in the reconfigurable control is the reconfiguration of the closed-loop LPV systems [44, 60]

The application, implementation of the estimated failure in closed-loop for correction purpose is called fault correction control system can be found in the cahpter 6. From a certain point of view it could be thought as a permanent configuration of the control signal, but not the hole control rule. The correction is due to the previously estimated fault or other unmeasured signal. During the fault correction, the effect of the unknown signal is permanently taken into account in the feed-forward loop.

The feed-forward controller, i.e. the usage of the information of measured disturbance, can be simply implied into the manipulated variables. Only the prediction of the future outputs needs to be evaluated properly. [56] has proposed the controller structure using estimated disturbance for Lipschitz nonlinear systems. Nevertheless, the main contribution of the present PhD on fault correction controller domain, is the estimation of the unmeasured signal under constraints. The joint structure can be treated as a permanent correction of the fault effect of the model predictive controller by taking into account the known disturbance in the closed loop system under constraints.

The fault detection filters and fault correction controller theories are applied for aircraft control system design in the Thesis.

The first evolution of flight control theory control started in the early 40’s during Second World War, mainly in Germany, United Kingdom and US. During the period, the research is based on the contributions of Nyquist and Bode. At the time, the output feedback methodologies are using PID structures and root locus by graphical phase margin techniques. The main results in flight control are summarized in [10] and in [58].

In the 50’s, control engineers had lack of MIMO design techniques, because of cross-coupling in aircraft dynamics. The problem became more and more serious while increasing performance.

The solution of the cross-coupling flight channels were initiated from the early 60's by Rudolf Emil Kalman, who developed the state-space based analysis and synthesis techniques as a new basis for modern control theory. Pole placement and optimal LQ design methods appeared in aircraft flight control system design, along the state observer.

In the few next decades, several control algorithm tried to extended the optimal methods towards the robustness with LQ Servo and LQG/LTR applied appeared in this term up to the 80's see ex. Books published in the 90's about aircraft control contains mainly the optimal and modern methods such as [46].

From 90's, the appeared methods are mainly reffered to signal and operator norms minimizations and touching the robustness. A bunch of articles deals with $\mathcal{H}_\infty$ control method applied for VSTOL aircrafts such as [33, 55, 54, 32]. One can also find articles about LPV techniques application [39, 27, 26, 59]. These techniques are recently applied for F-14 [27, 26] and F-16 aircrafts [39].

Besides fighter aircraft applications, the techniques are also used in large airliner and UAV design. The MPC control technique is applied to flight control design, even in formation control [40].

Constrained State Estimation

Based on the model predictive controllers, a growing need induced the experts to formulate the dual counterpart of the receding horizon control algorithm. There was a perpetual need on online, constrained and nonlinear estimation which allies to fault detection since a vast part of the FDI methods are defined as state observers.

Concerning the linear systems, receding horizon estimation is similar to adaptive, limited memory filters (Jazwinski, 1970, [38]).

Unconstrained state estimation with moving horizon has been suggested in the middle of the 70's by Thomas [62], and later on by Kwon, Bruckstein and Kailath in 1983, [41].

The moving horizon state estimation, or receding horizon state estimation was firstly applied in nonlinear initial state estimation in a noise-free case and without constraints, by Jang, Joseph and Mukai in 1986, [37]. After many researcher developed constraint estimation problem such as de Souza, Gevers, Goodwin in 1986 [21]. Bequette [8], showed the correspondance between the receding horizon control and estimation, Biegler [9] published the statistical and numerical description of nonlinear, optimized moving horizon estimation. Muske, Rawlings and Lee [51] pointed the advance of receding horizon approach in recursive manner out. Moreover

Muske and Rawlings in [49], [50] deals with the stability and the duality problems of constrained estimation. Marquardt [48] investigated the scaling possibilities and the constraints of the process. Tyler and Morari [64] worked on general stability aspects of the estimation, and with different application related opportunities. Many application paper was created at the time mainly in chemical area such as [63]. Findeisen [23] dealed with the update algorithms (smoothing and filtering). Bemporad, Morari, Mignone, Tyler [6], [63] used the constrained state estimation even for hibrid systems. Rao summarized and applied the receding horizon estimation, and formulated the problem in stochastic viewpoint, as well [57].

The major focus will be carrying on the usage of the receding horizon estimation for fault detection purpose in the sequel. The RHE was applied not only for state (initial value) estimation, but also for ex. fault detection. Implementing binary state in the description and getting a hybrid system, the mixed logical dynamic form, in the [6] for failure detection purpose. In [63] a bank of MH has been used for the same reason.

DISSERTATION OVERVIEW

The introductory chapters of the dissertation are the Chapter 1 Introduction and Chapter 2 Mathematical Backgrounds. In the Introduction a brief motivation background is given, after a short review of the control systems, state observation and fault detection with the overview of the thesis follows. In order to understand the notation and the basic mathematical background a compact description of the symbolism is presented. Moreover, the Appendix part expound the keywords of the dissertation.

The PhD thesis is organized around three (and for the first slight) different topics.

The first part of the dissertation deals with the robustness of the Fault Detection and Isolation research field for linear time-invariant dynamics and for linear parameter varying systems respectively. The geometric based detection performance can be increased in order to avoid false alarm sign on detector, caused by exogenous disturbance. The robust extension of the geometric detection filter design is on the focus and called Robust Fundamental Problem in Residual Generation (RFPRG). The robustness against external noise, the disturbance rejection of the residual generator can be achieved by $\mathcal{H}_\infty$ filtering when designing the stability of the filter in linear case. The sensitivity and effectiveness of the RFPRG is demonstrated through a possible aerospace-related application domain in Chapter 3. Chapter 4 formulates the robust parameter varying detection problem and propose a solution, the induced $\mathcal{L}_2$ norm minimization on the residual output. The Chapter extends the fault recognition to parameter varying model classes with example.

One part of the fault detection filter rests on state observer design. State observers estimate the states of the dynamic system. The main contribution of the second part of the thesis consists on constraint state estimation in fault detection purpose. The Moving Horizon state estimation can augment the detection performance with equality or inequality using only a ceratin amount of the past data in Chapter 5.

Chapter 6 suggest the closed-loop application of the fault detection system. Nearby the fault detection of the occurring failures, the joint controller-detector structure permits to take residual information into account. The applied controller scheme is able to work under constraints.

Scientific Contributions

Thesis 1 (*Robust Fundamental Problem in Residual Generation, RFPRG*). *Assume the following condition are held:*

1. *the projection of the system (1)-(2). on the factor space of $\mathcal{S}_i$ is detectable, i.e. (M_i, A_{0i}) detectable;*
2. *the input observability, the solvability condition of the fault detection filter is met for undisturbed case $\mathcal{S}_i^* \cap \mathcal{L}_j = \emptyset$;*
3. *$\mathcal{S}_i^* \cap [\mathcal{L}_j \ \mathcal{B}_1] \neq \emptyset$ where $\mathcal{B}_1$ is the image of the disturbance direction.*

*Then a residual generator under the form (3)-(4). exists, and with $\gamma_i > 0$ the $d(t) \in \mathcal{L}_2$ disturbance can be attenuated in $\mathcal{H}_\infty$ sense on residual $r_i(t)$ by the solution of the Modified Filter Algebraic Ricatti Equation **[4,6,9]**.*

The influence of the disturbance can be minimized with the appropriate choice of D_{1i} given by:

$$F_i := A_{0i} + D_{1i} M_i.$$

A_{0i} assures only the decoupling of the failure direction if possible.

The noise, $\|d\|_2 < \infty$ entering the system through the fault direction B_1 can be attenuated to $\|G_{dr_i}\|_\infty < \gamma_i$ by the solution of the Modified Filter Algebraic Ricatti Equation written as:

$$\begin{aligned} A_{0i}Q_i &+ Q_i A_{0i}^T - Q_i\left(\frac{1}{\rho_i} M_i^T M_i - \frac{1}{\gamma_i^2} M_{1i}^T M_{1i}\right) Q_i + \\ &+ P_i B_1 B_1^T P_i^T = 0 \\ D_{1i} &= -\frac{1}{\rho_i} Q_i M_i^T. \end{aligned}$$

Thesis 2 (*Robust Parameter Varying Fundamental Problem in Residual Generation, RpvFPRG*). *Assume the following condition are held:*

1. *the projection of the affine LPV system (5)-(6). on the factor space of $\mathcal{S}_i$ is detectable, i.e. $(M_i, A_{0i}(\rho))$ is detectable;*

2. *the input observability, the solvability condition of the fault detection filter is met for undisturbed case* $\mathcal{S}_i^* \cap \mathcal{L}_j = \emptyset$*;*

3. $\mathcal{S}_i^* \cap [\mathcal{L}_j \; \mathcal{B}_1] \neq \emptyset$ *where* $\mathcal{B}_1$ *is the image of the disturbance direction.*

Then a LPV residual generator under the parameter dependent form (3)-(4). exists, and with $\gamma_i > 0$ *the* $d(t) \in \mathcal{L}_2$ *disturbance can be attenuated in induced* $\mathcal{L}_2$ *norm on residual* $r_i(t)$ *by the solution of Linear Matrix Inequalities at each extremal point of the vertex* ***[5,9,10]****.*

Robust fault detection and isolation filter has been elaborated against exogenous disturbance signal when decoupling is not possible for affine linear parameter varying system by induced $\mathcal{L}_2$ norm minimization.

For affine LPV description the induced $\mathcal{L}_2$ minimization is as follows:

$$\sup_{\rho} \sup_{d} \frac{\left\|\tilde{G}(\rho)_{dr} d\right\|_2}{\|d\|_2} \rightarrow \min_{D_1 \subset \mathcal{D}_{stab}}$$

The effect of the disturbance can be attenuated in induced $\mathcal{L}_2$ norm by solving linear matrix inequalities on the boundary points of the parameter polytope given by:

$$X > 0$$

$$L(X,\gamma) = \begin{bmatrix} F^T(\rho)X_1 + F(\rho)X - M^T M & XPB_1(\rho) & M_1^T \\ PB_1(\rho)X & -\gamma I_m & 0 \\ M_1 & 0 & -\gamma I_m \end{bmatrix} < 0.$$

Thesis 3 (*Receding Horizon Filtering on Residual, RHFR*). *Assume the following condition are fulfilled:*

1. *the projection of the discrete-time equivalent of the system (1)-(2). on the factor space of* $\mathcal{S}_i$ *is detectable, i.e.* (M_i, A_{0i}) *detectable;*

2. *the input observability, the solvability condition of the fault detection filter is met for undisturbed case* $\mathcal{S}_i^* \cap \mathcal{L}_j = \emptyset$

Then by the application of the Moving Horizon State Estimation process, by the minimization of the functional Ψ_k*, equality and inequality constraints can be taken on estimated state, noise or output constraints into consideration in order to diminishes the state error in* l_2 *sense* ***[7,8,11,12,13,14,15]****.*

The capacity and stability of noise filtering of the fault detection and isolation filter based on the concepts of fundamental problem in residual generation can be assured on the factor space of the minimal unobservability subspace containing the image of the fault direction where the poles of the system can be allocated freely.

The Moving Horizon state estimation can be applied in order to achieved constrained state estimation on the above factor space.

The Moving Horizon state estimation consists in the minimization of the functional given by:

$$\min_{(\bar{x}_{k-N-1}, \hat{w}_{k-N-1|k}, \ldots, \hat{w}_{k-1|k})} \Psi_k$$

$$\Psi_k = \hat{w}^T_{k-N-1|k} Q_0^{-1} \hat{w}_{k-N-1|k} + \sum_{j=k-N}^{k-1} \hat{w}^T_{j|k} Q^{-1} \hat{w}_{j|k} +$$
$$+ \sum_{j=k-N}^{k} \hat{v}^T_{j|k} R^{-1} \hat{v}_{j|k} + \Psi_0,$$

subjected to dynamic

$$\hat{x}_{k-N|k} = \bar{x}_{k-N} + \hat{w}_{k-N-1|k}$$
$$\hat{x}_{j+1|k} = A\hat{x}_{j|k} + G\hat{w}_{j|k} + Bu_j$$
$$j = k-N-1, \ldots, k-1$$
$$y_j = C\hat{x}_{j|k} + \hat{v}_{j|k} \quad j = k-N-1,$$

and any supplementary equality, respectively inequality constraints on estimated state, noise and output components by:

$$w_{lower} \leq \hat{w}_{j|k} \leq w_{upper}$$
$$v_{lower} \leq \hat{v}_{j|k} \leq v_{upper}$$
$$x_{lower} \leq \hat{x}_{j|k} \leq x_{upper}.$$

Thesis 4 (*Model Predictive Controller with Fundamental Problem in Residual Generation, MPCFPRG*). *Suppose the following conditions are satisfied:*

1. *the projection of the system (1)-(2). on the factor space of $\mathcal{S}_i$ is detectable, i.e. (M_i, A_{0i}) detectable;*

2. *the input observability, the solvability condition of the unmeasured disturbance filter is met $\mathcal{S}_i^* \cap \mathcal{B}_{1u} = \emptyset$*

3. *the system (1)-(2). is stabilizable, i.e. (A, B_2) is stablilizable.*

Then fault corrector and optimal Model Predictive Controller can be designed using previously defined constraints on performance, manipulated and measured variable, where the detection and estimation of the unmeasured disturbance is provided by a FPRG filter ***[1,2,3]***

If the solvability condition of FPRG is met, the unmeasured disturbance d_k^u can be estimated by the appropriate choice of the residual generator providing estimated disturbance. The prediction can be modified in case of model predictive control strategy in order to precise tracking and stability requirements by:

$$\mathcal{Z}_k = \Psi \hat{x}_{k|k} + \Upsilon u_{k-1} + \Theta \Delta \mathcal{U}_k + \Xi \mathcal{D}_{mk} + \Omega \mathcal{D}_{uk}.$$

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$$\mathcal{D}_{uk} = \begin{bmatrix} \hat{d}_k^u \\ \hat{d}_{k+1|k}^u \\ \hat{d}_{k+2|k}^u \\ \vdots \\ \hat{d}_{k+H_p-1|k}^u \end{bmatrix}$$

$$\Omega = \begin{bmatrix} C_z B_{1u} & 0 & \dots & 0 \\ C_z A B_{1u} & C_z B_{1u} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ C_z A^{H_p-1} B_{1u} & C_z A^{H_p-2} B_{1u} & \dots & C_z B_{1u} \end{bmatrix}.$$

The advantage of the method is in the constraints, namely control input, measured output and other performance hard and soft constraints can be implemented into the controller design during the minimization of the following functional:

$$V_k = \sum_{i=H_w}^{H_p} (\hat{z}_{k+i|k} - r_{k+i})^T Q_i (\hat{z}_{k+i|k} - r_{k+i}) + \sum_{i=0}^{H_u} (\Delta \hat{u}_{k+i|k})^T R_i (\Delta \hat{u}_{k+i|k}).$$

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