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SCREENING PLANT DESIGNS AND CONTROL STRUCTURES FOR UNCERTAIN SYSTEMS

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Abstract—Screening tools are developed which provide nonconservative estimates of the achievable performance in the presence of general structured model uncertainty. These tools allow the rational selection among plant designs, or can be applied to provide recommedations on how to modify a plant design to improve the closed loop performance. Many of these tools are applicable to the pairing or partitioning of inputs and outputs of decentralized controllers. It is shown through examples that ignoring or improperly characterizing plant/model mismatch while selecting among plant designs can lead to erroneous results.

1. INTRODUCTION

Ignoring or improperly characterizing plant/model mismatch while selecting among plant designs can lead to erroneous results. This motivates the development of *screening tools* which provide an estimate of achievable performance for a given plant design in the presence of model/plant mismatch. The purpose of this manuscript is to derive screening tools which allow the use of a general structured uncertainty description. By including conditions on the controller structure, these tools can be used for choosing actuators, sensors, and the appropriate *partitions* and *pairings* between inputs and outputs.

2. BACKGROUND

Tools for analyzing the stability and performance of uncertain systems, and the framework of *robust loopshaping*, are summarized.

2.1. Robustness analysis

To account for plant/model mismatch, the true process is represented by a *set of plants*. This set of plants is modeled as unity norm-bounded perturbations Δ_i on the nominal system, where Δ_i is complex for representing unmodeled dynamics or frequency domain performance specifications, and real for representing parametric uncertainty. The perturbations, which may occur at different locations in the system, are collected in the block-diagonal matrix $\Delta = \text{diag}\{\Delta_i\}$ shown in Fig. 1 The *generalized plant* G is calculated by off-the-shelf software (Balas *et al.*, 1992), given the nominal model P, the performance specifications, and the size, nature, and location of the uncertainty. The generalized plant G and the controller K can be combined to give the overall system matrix M. If G is partitioned to be compatible with K, then M is given by the *linear fractional transformation* $M = F_l(G, K) = G_{11} + G_{12}K(I - G_{22}K)^{-1}G_{21}$. The LFT $F_l(G, K)$ is well-defined if and only if the inverse of $I - G_{22}K$ exists.

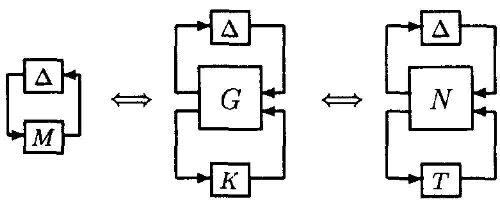

Fig. 1. Equivalent representations of system.

The system is robust to linear time invariant perturbations if and only if the structured singular value $\mu_\Delta[M(j\omega)]$ is less than 1 for all frequencies (Doyle, 1982; Packard and Doyle, 1993). Though exact calculation of μ can be computationally expensive (Braatz *et al.*, 1994), upper and lower bounds for μ can be calculated in polynomial time and are usually close (Young, 1993). Similar necessary and sufficient tests exist for systems with arbitrary nonlinear (NL) (Shamma, 1991), *arbitrarily fast* linear time varying (FLTV) (Shamma, 1991), or *arbitrarily slow* linear time varying perturbations (SLTV) (Poolla and Tikku, 1993). The necessary and sufficient tests for systems with NL, FLTV, or SLTV perturbations can be calculated in polynomial time. Though this manuscript will focus on systems with

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linear time invariant perturbations, the results extend to these other types of perturbations with minor modifications.

2.2. Re-parameterizing the system

It is useful to parameterize the uncertain system in terms of a transfer function of interest T (see Fig. 1). Transfer functions of particular interest include the *block-diagonal sensitivity* $\tilde{S}=(I+\tilde{P}K)^{-1}$ and the *block-diagonal complementary sensitivity* $\tilde{H}=\tilde{P}K(I+\tilde{P}K)^{-1}$, where $\tilde{P}$ is the block-diagonal part of the plant corresponding to the controller structure, $\tilde{P}=\text{diag}\{P_{ii}\}$. The expression for $N^{\tilde{H}}$ and $N^{\tilde{S}}$ [such that $M=F_l(G,K)=F_l(N^{\tilde{H}},\tilde{H})=F_l(N^{\tilde{S}},\tilde{S})$] can be calculated directly from G to be (equations 5.6 and 5.7 of Braatz, 1993)

$$N^{\tilde{H}}=\begin{bmatrix} G_{11} & G_{12}\tilde{P}^{-1} \\ G_{21} & I-P\tilde{P}^{-1} \end{bmatrix}; \quad (1)$$

$$N^{\tilde{S}}=\begin{bmatrix} G_{11}+G_{12}P^{-1}G_{21} & -G_{12}P^{-1} \\ \tilde{P}P^{-1}G_{21} & I-\tilde{P}P^{-1} \end{bmatrix}. \quad (2)$$

2.3. Robust loopshaping framework

Given N^T and the structures of T and Δ, the μ conditions are expressed as norm bounds on T. In the following, let Δ_T represent an arbitrary transfer function with the same structure as T. The following lemma (which corresponds to Theorem 1 of Skogestad and Morari (1988) and Theorem 4.1 of Braatz (1993) provides a sufficient bound on the magnitude of the transfer function T for a μ condition to be achieved.

Lemma 1 (Sufficient Upper Bound). *Let* $M=F_l(N,T)$, *and* k *be a given constant. Define*

$$f(c)\equiv\mu_{\begin{bmatrix}\Delta & \\ & \Delta_T\end{bmatrix}}\left(\begin{bmatrix} N_{11} & N_{12} \\ kc_TN_{21} & kc_TN_{22} \end{bmatrix}\right).$$

Assume $\det(I-N_{22}T)\neq 0$, $f(0)=\mu_\Delta(N_{11})<k$, *and* $f(\infty)>k$. *Let* c_T^{su} *solve* $f(c_T^{su})=k$. *Then* $\mu_\Delta(M)<k$ *if* $\bar{\sigma}(T)<c_T^{su}$.

The bounds given by the above lemma are the tightest bounds possible in that, given $\sigma>c_T^{su}$, there exists a T with $\bar{\sigma}(T)=\sigma$ that does not meet robust performance. Detailed descriptions, derivations, and interpretations of the sufficient upper bound and other necessary bounds and sufficient bounds are provided in Chapter 4 of Braatz (1993).

3. DESIGN CRITERIA

Figure 1 represents the general block diagram for linear systems with uncertainty. The generalized plant G is specified by the plant design, and which actuators and sensors are under consideration. The structure of K is specified by the particular choice of pairings and partitions (the rows and columns of G can always be rearranged so that K is a block-diagonal). The criterion for selecting among *both* plant designs and control structures is the achievable worst-case performance

$$\text{“Is } \inf_{K\in\mathcal{K}_S}\sup_{\omega}\mu_\Delta\{F_l[G(j\omega),K(j\omega)]\}<k?\text{”} \quad (3)$$

where $k=1$ and $\mathcal{K}_S$ is the set of stabilizing controllers with given structure. There is no computable necessary and sufficient test for equation (3). This provides the motivation for developing computable necessary conditions for robust performance. These necessary conditions are used as *screening tools* which may remove candidates from further consideration.

4. SCREENING TOOLS

4.1. Pairing-independent screening tools

In screening among plant designs it is natural to use tools which do not depend on the partitioning or pairing of the control loops. Researchers have developed *pairing-independent screening tools* for the case where the controller is assumed to be designed via robust loopshaping (Lee and Morari, 1993; Braatz, 1993). Here a tight computationally simple screening tool is derived for problems in which integral control is specified.

Theorem 1 (Tool for Integral Controllers). *Consider a system put into the general* $G-K$ *form in Fig. 1, and let* k *be a given constant. Then there exists a stabilizing controller with integral action in all channels that satisfies* $\mu_\Delta[M(j\omega)]<k$ *for all frequencies only if (i)* $\det[P(0)]\neq 0$, *and (ii)* $\nu_I<k$ *where*

$$\nu_I\equiv\mu_\Delta[G_{11}(0)+G_{12}(0)P^{-1}(0)G_{21}(0)]. \quad (4)$$

Furthermore, conditions (i) and (ii) are sufficient for the existence of a stabilizing decentralized proportional-integral controller that satisfies $\mu_\Delta[M(0)]<k$.

Proof: ($\Rightarrow$) Assume that there exists a stabilizing controller K with integral action in all channels [i.e. $K(s)=(1/s)\hat{K}(s)$ with $\hat{K}(s)$ having no transmission zeros at $s=0$, and $\tilde{S}(0)=0$] that satisfies $\mu_\Delta[M(j\omega)]<k$, $\forall\omega$. It is well-known that the existence of a stabilizing integral controller K implies condition (i) (for example, see Theorem 3 of Davison, 1976). Condition (ii) follows because ν_I is equal to $\mu_\Delta[M(0)]$, that is, $\mu_\Delta[M(0)]=\mu_\Delta\{F_l[N^{\tilde{S}}(0),\tilde{S}(0)]\}=\mu_\Delta[F_l(N^{\tilde{S}}(0),0)]=$

$\mu_\Delta[N_{11}^S(0)] = \mu_\Delta[G_{11}(0) + G_{12}(0)P^{-1}(0)G_{21}(0)] = \nu_l$. QED ($\Rightarrow$).

($\Leftarrow$) Condition (i) holds if and only if there exists a decentralized proportional-integral controller K which stabilizes the plant (Guardabassi and Locatelli, 1982). Condition (ii) implies $\mu_\Delta[M(0)] < k$ since $\nu_l = \mu_\Delta[M(0)]$. QED ($\Leftarrow$).

The above screening tool reduces to a well-known condition when the steady-state robustness requirements hold at open loop, that is, $\mu_\Delta[G_{11}(0)] < k$, and the measured variables are equal to the controlled variables plus measurement noise, that is, $G_{22} = -P$ (aside: $G_{22} \neq -P$ in inferential control problems). Under these conditions, it can be shown using the matrix inversion lemma (Lemma 5.7 of Packard, 1988) that conditions (i) and (ii) hold if and only if the determinants of all steady-state plant matrices given by the uncertainty description have the same sign.

4.2. *Pairing-dependent screening tools*

After pairing-independent screening tools have reduced the number of plant designs to a manageable number, it is natural to apply tools which *depend* on the partitioning or pairing of the control loops. Here general screening tools are summarized and *pairing-dependent screening tools* are derived for problems where failure tolerance is a requirement.

4.2.1. General screening tools. A necessary condition that equation (3) is satisfied is for

$$\nu_G \equiv \inf_{K \in \Delta_K} \mu_\Delta[F_l(G, K)] < k \tag{5}$$

to hold for each frequency ω, where Δ_K is the set of all complex matrices with the structure of K (this condition is necessary because $\mathcal{K}_S(j\omega) \subset \Delta_K$). This optimization is nonconvex, and difficult to solve in general. When the controller K in equation (5) is centralized then it can be parameterized by the Youla matrix Q to give $M = F_l(G, K)$ as an affine function of Q. Replacing μ with its upper bound then leads to computable tools which are useful for screening plant designs or control structures (Lee *et al.*, 1995), although these tools are not strictly necessary conditions for equation (5).

4.2.2. Screening tools for failure tolerance. The screening tools thus far measured the suitability of a control structure candidate solely in terms of robust performance. It may be desirable to also consider conditions for which the closed loop system will remain stable as any subset of loops are detuned or taken out of service (put on "manual"). A closed loop system with decentralized controller K is said to exhibit *strong failure tolerance* (SFT) if it remains stable under arbitrary detuning of the block-diagonal complementary sensitivity $\tilde{H}$, that is, for all $\hat{H}$ with the same structure as K which satisfies $\bar{\sigma}[\hat{H}(j\omega] \leq \bar{\sigma}[\tilde{H}(j\omega)]$. A closed loop system which is SFT is stable to arbitrary *failures* in any of the control loops provided that these loops are placed in manual. The following is a tight screening tool for failure tolerant controllers with integral action.

Theorem 2 (Tool for SFT). *Assume* $\det[\tilde{P}(j\omega)] \neq 0, \forall\omega$. *Then there exists a decentralized controller with integral action in all channels which provides strong failure tolerance if and only if (i) P is stable, and*

$$\text{(ii)}\ \mu_{\Delta_{\tilde{H}}}[I - P(0)\tilde{P}^{-1}(0)] < 1. \tag{6}$$

Furthermore, this controller can be chosen to be a decentralized proportional-integral controller.

Proof: The proof basically follows from this Fact: Assume $\det[\tilde{P}(j\omega)] \neq 0, \forall\omega$. Then it immediately follows from the μ-interaction measure theorem (Theorem 6.7 of Braatz, 1993) or Theorem 2.1 of Grosdidier and Morari, 1987) and the definition of μ that a decentralized controller which stabilizes $\tilde{P}$ provides SFT if and only if condition (i) holds and

$$\bar{\sigma}[\tilde{H}(j\omega)] < \mu_{\Delta_{\tilde{H}}}^{-1}[I - P(j\omega)\tilde{P}^{-1}(j\omega)], \forall\omega. \tag{7}$$

($\Rightarrow$) Assume there exists a controller with integral action in all channels which provides SFT. Then the Fact implies condition (i), and evaluating equation (7) at zero frequency (where $\tilde{H} = \tilde{P}K(I + \tilde{P}K)^{-1} = I$) implies condition (ii). QED ($\Rightarrow$).

($\Leftarrow$) The assumption that $\det[\tilde{P}(j\omega)] \neq 0$ at $\omega = 0$ implies that there exists a decentralized proportional-integral controller which stabilizes $\tilde{P}$ (Guardabassi and Locatelli, 1982). Condition (ii) implies that equation (7) will hold at zero frequency and $\det[\tilde{P}(j\omega)] \neq 0, \forall\omega$ implies that the right-hand side of equation (7) is non-zero at all frequencies. Thus this controller can be detuned sufficiently to satisfy equation (7) at all frequencies. Now apply the Fact. QED ($\Leftarrow$).

It is clear from the proof of Theorem 2 that, when there exists a controller which provides an SFT system, the controller can be designed via the μ-interaction measure.

An uncertain system with decentralized controller K is said to exhibit *robust strong failure tolerance* (RSFT) if it remains stable for all $\|\Delta\|_\infty \leq 1/k$ and all $\hat{H}$ with the same structure as K which satisfies $\bar{\sigma}[\hat{H}(j\omega)] \leq \bar{\sigma}(\tilde{H}(j\omega)]$. Screening tools for robust strong failure tolerance are derived via an extension to the μ-interaction measure.

Lemma 2 (Robust Interaction Measure). *Consider a system put into the general $G-K$ form in Fig. 1, and let k be a given constant. Assume (i) G is stable, and (ii) $\det[\tilde{P}(j\omega)] \neq 0$, $\forall\omega$. Then the closed loop system is stable for all $\|\Delta\|_\infty \leq 1/k$ if the decentralized controller K stabilizes the block-diagonal plant $\tilde{P}$ and*

$$\bar{\sigma}[\tilde{H}(j\omega)] < c_{\tilde{H}}^{su}(\omega), \quad (8)$$

where at each frequency $c_{\tilde{H}}^{su}(\omega)$ solves

$$\mu_{\left[\begin{smallmatrix}\Delta & \\ & \Delta_{\tilde{H}}\end{smallmatrix}\right]}\left(\begin{bmatrix} G_{11}(j\omega) & G_{12}(j\omega)\tilde{P}^{-1}(j\omega) \\ kc_{\tilde{H}}^{su}(\omega)G_{21}(j\omega) & kc_{\tilde{H}}^{su}(\omega)[I-P(j\omega)(\tilde{P}^{-1}(j\omega)] \end{bmatrix}\right) = k. \quad (9)$$

Proof: If G is stable, then robust stability is assured if $K(I+PK)^{-1}$ is stable and $\mu_\Delta\{F_l[G(j\omega), K(j\omega)]\} < k$, $\forall\omega$. Because $c_{\tilde{H}}^{su}(\omega)$ is a lower bound to $\mu_{\Delta_{\tilde{H}}}^{-1}[I-P(j\omega)\tilde{P}^{-1}(j\omega)]$, satisfaction of equation (8) implies $\bar{\sigma}[\tilde{H}(j\omega)] < \mu_{\Delta_{\tilde{H}}}^{-1}[I-P(j\omega)\tilde{P}^{-1}(j\omega)]$, which implies nominal stability via Theorem 2.1 of Grosdidier and Morari, 1987 or Theorem 6.7 of Braatz, 1993). Application of Lemma 1 proves the result. QED.

Robust failure tolerant controllers are provided when $\tilde{H}$ is chosen to have independent blocks. Detuning the controller will not affect robust stability provided equation (8) continues to hold. The robust interaction measure (RIM) is *optimal*, that is, it provides the least conservative bound on $\bar{\sigma}(\tilde{H})$ which guarantees robust stability of the overall system. The following is a tight screening tool for RSFT.

Theorem 3 (Tool for RSFT). *Consider a system put into the general $G-K$ form in Fig. 1, let k be a given constant, and assume that $\det[\tilde{P}(j\omega)] \neq 0$, $\forall\omega$. There exists a decentralized controller with integral action in all channels which provides RSFT only if (i) G is stable, and (ii) $\nu_F < k$, where*

$$\nu_F \equiv \mu_{\left[\begin{smallmatrix}\Delta & \\ & \Delta_{\tilde{H}}\end{smallmatrix}\right]}\left(\begin{bmatrix} G_{11}(0) & G_{12}(0)\tilde{P}^{-1}(0) \\ kG_{21}(0) & k[I-P(0)\tilde{P}^{-1}(0)] \end{bmatrix}\right). \quad (10)$$

Furthermore, conditions (i) and (ii) are sufficient for the existence of a decentralized proportional-integral controller that satisfies $\mu_\Delta[M(0)] < k$ and stabilizes the closed loop system with arbitrary detuning of the block-diagonal complementary sensitivity $\tilde{H}$.

Proof: The proof exactly parallels the proof of Theorem 2, but with the RIM from Lemma 2 taking the place of the μ-IM. QED.

It is straightforward to show that Theorems 2 and 3 provide sufficient conditions for *decentralized integral controllability* (Morari and Zafirou, 1989) and its generalization to include plant/model mismatch (Braatz, 1993).

4.3. *Comparisons between screening tools*

4.3.1. Integral vs general. If the input and output weights do not require for the controller to have integral action, then screening candidates based on the general condition (5) would potentially lead to a larger number of potential candidates than would Theorem 1, that is, $\nu_G \leq \nu_I$. The screening tool for controllers with integral action approximates the more computationally complex necessary condition given by equation (5) when the performance weight is sufficiently large. This can be proved rigorously for systems with at least one complex uncertainty block using the fact that μ for such systems is continuous (Packard and Pandey, 1993), and that the conditions are equal when the performance weight includes integrators in all channels (Braatz, 1993).

4.3.2. RSFT vs integral. Candidates which pass the RSFT screening tool given by Theorem 3 will always pass the screening tool for integral controllers given by Theorem 1. The RSFT screening tool allows further screening of candidates, based on failure tolerance and control structure considerations.

4.4. *Inferential control applications*

It is common in applications for the controlled variables to be different from the measured variables. An example is a distillation column where the setpoints are the top and bottom compositions. Composition measurements are unreliable and often too slow for effective control, so temperature measurements are used.

A popular method of controlling these processes is to use the two-step inferential design procedure (Weber and Brosilow, 1972):

(1) an estimator is designed to provide composition estimates using temperature measurements, and
(2) a controller uses these composition estimates for feedback control.

To test for the existence of a robust controller with integral action on the *composition estimates* (instead of integral action on the *measured variables*), the estimator is applied to the plant before application of the screening tools. Examples illustrating this procedure are given elsewhere (Braatz, 1993; Lee and Morari, 1993).

5. EXAMPLE

The steady-state model for a paper machine design is given by $P(0) = I_n + rE_n$, where

$$E_n = \underbrace{\begin{pmatrix} 0 & 1 & -1 & 0 & \cdots & 0 \\ 1 & 0 & 1 & \ddots & \ddots & \vdots \\ -1 & 1 & \ddots & \ddots & \ddots & 0 \\ 0 & \ddots & \ddots & \ddots & 1 & -1 \\ \vdots & \ddots & \ddots & 1 & 0 & 1 \\ 0 & \cdots & 0 & -1 & 1 & 0 \end{pmatrix}}_{n \times n}, \quad (11)$$

I_n is the identity matrix of dimension n, $n = 24$ is the number of actuators and sensors, and the interaction parameter r is imprecisely known, $r \in [0.09, 0.27]$. For these processes, this range of parametric uncertainty is not unreasonably large, and zero steady-state error is a standard performance requirement (Braatz *et al.*, 1992; Laughlin *et al.*, 1993).

The condition mumber of the nominal plant is equal to its minimized condition number (Braatz and Morari, 1994) and is given by $\kappa[P_{\rm nom}(0)] = \kappa(I + 0.18E_{24}) = 4.75$. The nominal RGA $\approx 1.26I$. These well-known controllability measures do not indicate any control difficulties with this paper machine design.

The screening tool given by Theorem 1 accounts for both the magitude and the highly correlated structure of the model uncertainty. The G matrix at zero frequency is determined by elementary algebra to be

$$G(0) = \left[\begin{array}{c|c} 0 & -I \\ \hline 0.09E_{24} & I + 0.18E_{24} \end{array}\right].$$

The perturbation Δ is repeated scalar real, that is, $\Delta = \delta_r I$. Off-the-shelf software gives $\nu_I = 1.2 > 1$; thus there does not exist an integral controller which stabilizes all plants given by the uncertainty description. The RGA and condition number underestimated the control difficulty for this paper machine design. This illustrates that ignoring or improperly characterizing plant/model mismatch while analyzing the controllability of a plant design can lead to incorrect results.

At this point, the design/control engineer may consider either changing the actuator spacing, the slice lip, the machine width, or some other variable in the paper machine design. The screening tools can be plotted as a function of these design variables to provide insight into how to design the paper machine for the purposes of robust control. For illustration, consider the specification of the actuator spacing a with fixed slice lip design and constant machine width $w = 2.4$ m. The actuator spacing a is always chosen so that the machine width w is a multiple of the actuator spacing, that is, $w = na$, where n is the plant dimension. With the slice design fixed, the interactions are expected to diminish as the actuator spacing increases. This effect is approximated by $r = k/a$, where the proportionality constant $k \in [0.009, 0.027]$ characterizes the interaction uncertainty. The controllability index for integral controllers ν_I is shown in Fig. 2 (the solid line) as a function of actuator spacing.

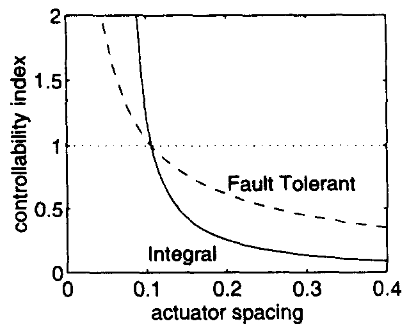

Fig. 2. Paper machine design for controllability.

For decentralized control of this paper machine, the appropriate pairing is that each actuator should be paired to its downsteam sensor. Thus in this case the controllability index for failure tolerant decentralized design ν_F [given by equation (10)] can be used for selecting among plant designs by prechoosing this pairing (ν_F is given by the dashed line in Fig. 2). Both screening tools indicate that the paper machine becomes uniformly more difficult to control as the actuator spacing decreases. For the given slice design and machine width, a controller robust to the interaction uncertainty which provides zero steady-state error cannot be designed for paper machines with actuator spacing less than 0.105 m.

Recall that candidates allowed by the screening tool for fault tolerant integral controllers will always be a subset of the candidates allowed by the screening tool for integral controllers. Figure 2 illustrates that for our machine the candidates allowed by the two screening tools are the *same*, that is, that including decentralized failure tolerance as a performance requirement does not further restrict the number of candidates. Experience with other examples has shown that this is usually not true.

Figure 2 illustrates that ν_I is not always greater than ν_F for a given design. This is because ν_F includes scalings on both the magnitudes of the uncertainty Δ and $\tilde{H}$, whereas only the magnitude of Δ is scaled in ν_I. By scaling only Δ, the maximum amount of uncertainty which may be allowed for a robust integral controller to exist can be determined. These re-scaled controllability indices will uniformly bound each other. These re-scalings were not performed in this manuscript to simplify the presentation in Section 4.

6. BRANCH-AND-BOUND

A centralized controller which includes all the actuators and sensors may be unnecessarily complex and expensive; whereas a control structure candidate with too few actuators and sensors or too restrictive a decentralized structure may perform poorly. Screening tools provide a method to trade off control system complexity with closed loop performance. Owing to the combinatorial nature of the problem, however, the number of candidates is often very large. Braatz (1993) describes a branch-and-bound procedure which substantially eases the computational burden in choosing among control structure candidates.

7. CONCLUSIONS

Screening tools were developed which provide estimates of the achievable performance in the presence of general structured model uncertainty. These tools allow the rational selection among plant designs, or can be applied to provide recommendations on how to modify a plant design to improve the closed loop performance. Many of these tools are applicable to the pairing or partitioning of inputs and outputs of decentralized controllers. The computation of the screening tools derived in this manuscript, though manageable, is numerically more complex than conventional tools such as the RGA or the condition number. However, it was shown through examples that ignoring or improperly characterizing plant/model mismatch while selecting among plant designs can lead to erroneous results.

Once the screening tools have restricted the number of candidates to a manageable number, controllers can be designed and the resulting closed loop systems compared in terms of performance, failure tolerance, ease of implementation, and other practical issues. Robust failure tolerant decentralized controllers can be designed using the RIM bounds of Theorem 8, or using general robust loop-shading bounds (Braatz, 1993).

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