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Design of Distributed Engine Control Systems for Stability Under Communication Packet Dropouts

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In this paper, we address the issue of the stability of distributed engine control systems under communication constraints and, in particular, for packet dropouts. We propose a control design procedure, labeled decentralized distributed full-authority digital engine control and based on a two-level decentralized control framework. We show that the packet dropping margin, which is a measure of stability robustness under packet dropouts, is largely dependent on the closed-loop controller structure and that, in particular, a block-diagonal structure is more desirable. Thus, we design a controller in a decentralized framework to improve the packet dropping margin. The effect of different mathematical partitioning on the packet dropping margin is studied. The proposed methodology is applied to an F100 gas turbine engine model, which clearly demonstrates the usefulness of decentralization in improving the stability of distributed control under packet dropouts.

Nomenclature

$K_2(\cdot)$	=	spectral condition number of a matrix
μ	=	$\lambda^+_{\max}$, where λ^+ are eigenvalues with a positive real part
ξ	=	independent and identically distributed Bernoulli random process
$\rho(\cdot)$	=	spectral radius of a matrix
$\otimes$	=	Kronecker product
$\|\cdot\|_2$	=	spectral norm of a matrix
$(\cdot)^{\#}$	=	Moore–Penrose inverse of a matrix

I. Introduction

IN RECENT years, increasingly sophisticated electronics have been added to the engine control system for addressing the needs of increased performance, wider operability, and reduced life-cycle cost. Future engines are expected to have a higher engine thrust-to-weight ratio, low engine fuel consumption, and low overall engine cost [1]. Research is being carried out to make aircraft propulsion systems more intelligent, reliable, self-diagnostic, self-prognostic, self-optimizing, and mission adaptable while also reducing engine acquisition and maintenance costs. This has driven the need for a new, advanced control system. Accordingly, a working group was formed to study and develop a new distributed engine control (DEC) [2,3]. The advantages of a decentralized control scheme for a gas turbine engine are also well discussed in literature [4–6]. In this paper, we extend the decentralized scheme to distributed control and propose a new framework, labeled decentralized distributed full-authority digital engine control (D^2FADEC). Toward this direction, we address the issue of stability under packet dropouts and review the concept of the packet dropout margin (PDM), which is a measure of stability robustness under packet dropouts [7]. Hu and Yan [7] designed a controller based on a centralized framework to improve the PDM. In this paper, we show that PDM is dependent on a closed-loop system matrix structure and demonstrate that controllers designed based on a decentralized framework further improve the PDM with the same nominal performance as the centralized controller. The paper is organized as follows. In Sec. II, we briefly summarize the distributed engine control systems literature along with a discussion on communications constraints in networked control systems (NCS). In Sec. III, we address the issue of packet dropouts in networked control systems and review the concept of PDM introduced by Hu and Yan [7]. In section IV, a mathematical formulation is developed to show that controllers designed in a decentralized framework improve the PDM significantly compared with centralized framework controllers. In addition, the effect of mathematical partitioning on PDM is studied. In Sec. V, we propose a new framework based on decentralization for distributed engine control systems, labeled D^2FADEC. Finally, Sec. VI offers concluding remarks.

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II. Distributed Engine Control Systems

A. Full-Authority Digital Engine Control Based on Distributed Engine Control Architecture

In distributed engine control, the functions of full-authority digital engine control (FADEC) are distributed at the component level. Each sensor/actuator is to be replaced by a smart sensor/actuator. These smart modules include local processing capability to allow modular signal acquisition and conditioning and diagnostics and health management functionality. A dual-channel digital serial communication network is used to connect these smart modules with the FADEC. Figure 1 shows the schematic of the FADEC based on distributed control architecture.

The reduction of engine control system weight, modularity, obsolescence reduction, scalability, and reduction in operational and maintenance costs are some of the perceived benefits of DEC [8,9]. The distributed control approach is inherently more powerful, flexible, and scalable than a centralized control approach. However, there are major technical challenges to the realization of DEC, including high-temperature electronics, selection of appropriate communication architecture, and partitioning of the centralized controller to name a few. As the performance of the DEC will be dependent on the performance of the communication network, the

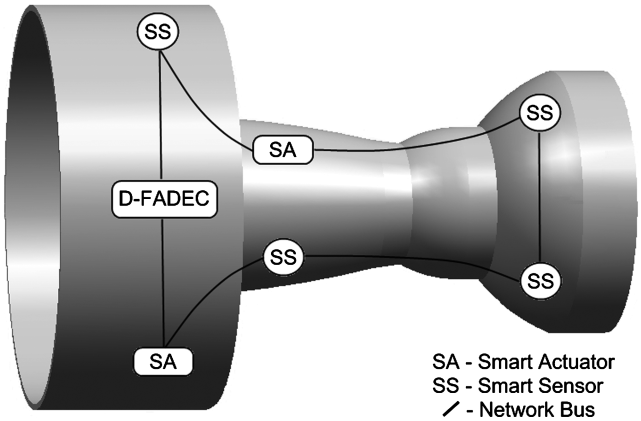

Fig. 1 FADEC based on distributed architecture.

appropriate selection of communication architecture is very important.

To reduce the development time and cost, use of commercial off-the-shelf communication architecture is preferred. Hence, we first select the communication architecture desired for the distributed system and then partition the controller, given the communication constraints, to improve system's performance under these constraints.

B. Selection of Communication Architectures

For a safety-critical distributed control system (DCS), there is a clear preference for time-triggered protocols over event-driven protocols. Time-triggered protocols offer a high level of reliability with fault tolerance. These architectures ensure that the maximum bus loading stays at prescribed levels and also provide efficiency, determinism, and partitioning. Some of the existing off-the-shelf open system communication standards are MIL-STD-1553, SAFEbus, FlexRay, CAN, SPIDER, TTTech Time-Triggered Architecture (TTA), and IEEE 1394b/Firewire. Honeywell SAFEbus is used in the Boeing 777 Airplane Information Management System, Time Triggered Protocol-C (TTP/C) of TTA is used in the environmental control systems in the Boeing 787 Dreamliner as well as the cabin pressure control systems in the Airbus 380, and IEEE 1394b is under development for use in the Joint Strike Fighter. Out of these architectures, TTP/C has clear advantages over the others [10–12]. Some of the requirements of communication architecture for DCS are that it should support fault detection, isolation, and recovery and health monitoring; be highly modular, with high reliability; be easy to maintain; and, finally, have a low overall cost. All these requirements are best met by TTP/C. TTP/C is specially designed for safety-critical, hard real-time distributed control. Along with a high transmission rate, TTP/C has high data efficiency, error detection with short latency, a fault-tolerant clock synchronization service, and distributed redundancy management. This architecture can tolerate multiple faults and a high degree of temporal predictability. TTP/C provides support for a fiber optic physical layer as well as for an electrical physical layer. In the next section, we review some of the features of the communication architecture that are relevant to DEC.

C. Networked Control Systems

Distributed engine control systems can be viewed as an NCS with distributed sensors and actuators. Here, the control loops are closed through a real-time communication network. There are various factors introduced as a result of the addition of the communication network. They include network-induced time delay, packet dropouts, and bandwidth constraints, which have to be considered for ensuring the desired functionality of the NCS [13–16].

1. Network-Induced Time Delay

Time delays occur in a networked control system due to the addition of a network. This delay can destabilize a system designed without considering the delay or can degrade the system performance. Networked-induced delay can be further subdivided into sensor-to-controller delay, controller-to-actuator delay, and the computational delay in the controller. In the selected TTP/C architecture, the use of clock synchronization, transmission window timing, and group membership ensure that the time delays are constant and bounded [17].

2. Constraint on Channel Bandwidth

The capacity of the communication network to carry a finite amount of information per unit amount of time is known as channel bandwidth. The current available TTP/C hardware supports 25 Mbit/s synchronous and 5 Mbit/s asynchronous transmissions. The actual available bandwidth is determined by the physical layer of the network. We consider the use of a fiber optic physical layer that would enable data transmission at high speeds with immunity to electromagnetic interference.

3. Packet Dropouts

Packet collisions or node failures can result in the loss of information packets, which is known as packet dropouts. In a time-triggered protocol, a time division multiple access (TDMA) mechanism ensures that each node can transmit data only during the predetermined time slot, thereby reducing the likelihood of packet dropouts due to packet collisions. However, the network is still subject to node failures. When a node failure occurs, instead of repeating retransmission attempts, it is advantageous to drop the old packet and transmit a new one.

The membership mechanism of TTP is capable of detecting any kind of communication fault that is not already detected and handled by other means. These communication faults include transmission and reception faults. If a node fails to transmit, which is typically due to noise during the transmission, it is removed from the membership list and not allowed to transmit data. Immediate retransmission for this node is not allowed, and it can retry transmission in the next round [17]. Also, if the packet fails the cyclic redundancy check, the packet is dropped and the transmitting node is required to wait for its next TDMA cycle to transmit another message. *Hence, for communication architectures implemented using TTP/C, it is important to consider the stability and performance of the system under packet dropouts*. In this paper, we analyze the effect of packet dropouts on the stability of the system considering the single-packet transmission of plant inputs and outputs.

III. Stability of Networked Control Systems Under Packet Dropouts

Packet dropouts in a communication network can be modeled as either an independent and identically distributed (iid) Bernoulli random process or a Markov chain. Hu and Yan studied the effect of packet dropping in [7]. The packet dropouts in a communication network were modeled as an iid Bernoulli process, and the stability of a discrete-time NCS with static state feedback was studied. A formula for calculating the PDM, an upper bound on the packet dropping probability (PDP), which guarantees system stability, was derived. The stability of networked control systems under packet dropouts is briefly summarized below.

Consider a networked control system as shown in Fig. 2. The network is assumed to be modeled by

$$\hat{x}(k) = \xi(k)x(k) \tag{1}$$

where $\xi(k)$ is the iid Bernoulli random process. $\xi(k)$ can be either 0 or 1 at any time instant k. A value of 0 indicates that the packet is lost during transmission, whereas a value of 1 indicates the successful transmission of packet. The probability of $\xi(k) = 0$ is termed as the PDP and is a measure of the reliability of the network.

Now, when the packet is dropped, $\xi(k) = 0$, that is, $\hat{x}(k) = 0$. If the packet is transmitted successfully, $\xi(k) = 1$ and $\hat{x}(k) = x(k)$.

Stability Condition for NCS: The networked plant with a PDP equal to the constant α is mean-square stabilized by the controller if and only if the following condition holds [18]:

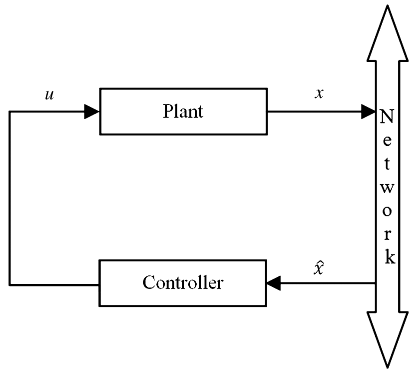

Fig. 2 NCS with packet dropouts.

$$\rho[\alpha A \otimes A + (1-\alpha)\hat{A} \otimes \hat{A}] < 1 \tag{2}$$

where $\otimes$ is the Kronecker product and $\rho(\cdot)$ is the spectral radius of the matrix and $\hat{A} = A - BK$.

Hu and Yan introduced a term known as the PDM, which is defined as the largest positive bound $\alpha_{\max}$ such that the system is mean-square stable for any PDP less than $\alpha_{\max}$. A formula for calculating PDM is as follows [7]:

If the NCS is nominally stable, then,

$$\text{PDM} = 1/\mu(V) \tag{3}$$

where

$$V = \begin{bmatrix} (S \otimes \tilde{S} + \tilde{S} \otimes S)(I - S \otimes S)^{-1} & \tilde{S} \otimes \tilde{S} \\ (I - S \otimes S)^{-1} & 0 \end{bmatrix}$$
$$S = \hat{A} \otimes \hat{A}, \qquad \tilde{S} = A \otimes A - \hat{A} \otimes \hat{A} \tag{4}$$

The lower bound for the PDM, which is dependent on the $K_2(\hat{A})$, is given by the following equation:

$$\text{PDM} \geq \frac{1 - \rho^2(\hat{A})}{K_2^2(\hat{A})\|A\|_2^2 - \rho^2(\hat{A})} \tag{5}$$

From this equation, it is observed that the PDM is inversely proportional to $K_2(\hat{A})$. Hence, to maximize the PDM, Hu and Yan proposed using a robust pole placement technique, which minimizes $K_2(\hat{A})$ using an ODE-based algorithm [7].

IV. Decentralized Controller Design for Packet Dropping Margin Improvement

The aforementioned algorithm is computationally expensive; hence, it is important to find a method to increase the PDM using a less computationally expensive method. In this paper, we offer a solution to improve the PDM by exploiting the structural properties of block-diagonal matrices in comparison with nonblock-diagonal matrices. In particular, we recall the following theorem that explicitly gives a relation between the structure and condition number of the matrix.

Theorem: Let A_T and A_D be a block-triangular and block-diagonal matrix, respectively, given by

$$A_T = \begin{bmatrix} A_{11} & A_{12} \\ 0 & A_{22} \end{bmatrix}, \qquad A_D = \begin{bmatrix} A_{11} & 0 \\ 0 & A_{22} \end{bmatrix}$$

Then,

$$K_2(A_D) \leq K_2(A_T)$$

Proof: We know that the condition number is given as

$$K_2(\cdot) = \sigma_{\max}(\cdot)/\sigma_{\min}(\cdot)$$

And, from Theorem I given in [19],

$$\sigma_{\max}(A_D) \leq \sigma_{\max}(A_T) \qquad \sigma_{\min}(A_D) \geq \sigma_{\min}(A_T)$$

Hence,

$$K_2(A_D) \leq K_2(A_T)$$

Example 1: Consider a linear state-space system in a discrete-time framework with the following system matrices:

$$A = \begin{bmatrix} 1.2 & -0.3 & 0.6 & -0.1 \\ 0.4 & 0.1 & -0.4 & 0.9 \\ -0.5 & 1.5 & 0.3 & 0.4 \\ 0.6 & -0.3 & 0.7 & -0.9 \end{bmatrix}$$
$$B = \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & -0.4 & 0 & 0 \\ 0 & 0 & 0.7 & 0 \\ 0 & 0 & 0 & 0.5 \end{bmatrix}$$

Suppose the desired nominal closed loops are −0.052, −0.4131, 0.758, and 0.897. The closed-loop matrix $\hat{A}$, with the eigenvalues given, can be obtained using gain matrix K_T and K_D as shown, where $\hat{A}_T$ is the closed-loop system matrix with controller K_T and $\hat{A}_D$ is the closed-loop system matrix with gain K_D.

$$K_T = \begin{bmatrix} 1.0889 & -0.7087 & 0.4826 & -0.4188 \\ 0.3548 & -1.2373 & -1.7418 & 1.1895 \\ 0.7143 & -2.1429 & -0.0540 & 0.4446 \\ -1.2 & 0.6 & -0.1944 & 2.2434 \end{bmatrix}$$
$$K_D = \begin{bmatrix} 1.0889 & -0.7087 & 0.6 & -0.1 \\ 0.3548 & -1.2373 & -1 & 2.25 \\ 0.7143 & -2.1429 & -0.054 & 0.4446 \\ -1.2 & 0.6 & -0.1944 & 2.2434 \end{bmatrix}$$
$$\hat{A}_T = \begin{bmatrix} 0.1111 & 0.4087 & 0.1174 & 0.3188 \\ 0.2581 & 0.5949 & 0.2967 & 0.424 \\ 0 & 0 & 0.2622 & 0.7112 \\ 0 & 0 & 0.6028 & 0.2217 \end{bmatrix}$$
$$\hat{A}_D = \begin{bmatrix} 0.1111 & 0.4087 & 0 & 0 \\ 0.2581 & 0.5949 & 0 & 0 \\ 0 & 0 & 0.2622 & 0.7112 \\ 0 & 0 & 0.6028 & 0.2217 \end{bmatrix}$$

Note that $\hat{A}_T$ is a block-triangular matrix, whereas $\hat{A}_D$ is a block-diagonal matrix, both with the same eigenvalues. It is observed that $K_2(\hat{A}_T) = 24.0274$ and $K_2(\hat{A}_D) = 17.7659$, which, in turn, gives

$$\text{PDM}_T = 0.0832 \qquad \text{PDM}_D = 0.5313$$

Thus, as declared in Theorem I, the block-diagonal structure results in a lower condition number and also produces a higher PDM. Hence, we observe that the PDM is largely dependent on the structure of the closed-loop matrix and that, by having a block-diagonal closed-loop matrix, we can increase the PDM significantly. Encouraged and motivated by this observation, in what follows, we propose a decentralized controller scheme that generates a block-diagonal closed-loop matrix, thereby improving the PDM. Furthermore, we study the effect of partitioning in the decentralized scheme on the PDM. This is illustrated with an application in engine control.

A. Controller Design Procedure for Interconnected Systems for Stability Robustness Under Packet Dropouts

Consider a linear system consisting of N interconnected subsystems:

$$\mathbf{S}: \dot{x}_{(k+1)} = Ax_k + Bu_k \qquad y_{(k+1)} = Cx_k \tag{6}$$

For simplicity, we ignore the subscripts and partition the system as

$$\mathbf{S}\colon \dot{x}_i = A_i x_i + B_i u_i + \mathbf{\Sigma}_{j=1}^{N}(A_{ij}x_j + B_{ij}u_j)$$
$$y_i = C_i x_i + \sum_{j=1}^{N} C_{ij}x_j \qquad i \in N \tag{7}$$

where $x_i \in \mathbb{R}^{n_i}$, $u_i \in \mathbb{R}^{m_i}$, and $y_i \in \mathbb{R}^{l_i}$ are the state, input, and output of subsystems $\boldsymbol{S_i}$.

A more compact notation for this system is given as [20]

$$\mathbf{S}: \dot{x} = A_D x + B_D u + A_C x + B_C u \qquad y = C_D x + C_C x \qquad i \in N \tag{8}$$

where

$$A_D = \mathrm{diag}\{A_{D1}, A_{D2}, \ldots, A_{Dn}\}$$
$$B_D = \mathrm{diag}\{B_{D1}, B_{D2}, \ldots, B_{Dm}\}$$
$$C_D = \mathrm{diag}\{C_{D1}, C_{D2}, \ldots, C_{Dl}\}$$

and the coupling block matrices are

$$A_C = (A_{ij}), \qquad B_C = (B_{ij}), \qquad C_C = (C_{ij})$$

The control law for the system is given as

$$u = -Ky \tag{9}$$

The two-level controller is given as

$$u = u^l + u^g$$

The gain K can be decomposed into local and global controller gains as follows:

$$K = K_D + K_C$$

Assuming full state feedback ($C_D = C_C = I$), the closed-loop system becomes

$$\hat{\boldsymbol{S}}\colon \dot{x} = (A_D - B_D K_D - B_C K_D)x + (A_C - B_C K_C - B_D K_C)x$$
$$\hat{\boldsymbol{S}}\colon \dot{x} = \hat{A}_D x + \hat{A}_C x \tag{10}$$

where

$$\hat{A}_D = (A_D - B_D K_D - B_C K_D) \qquad \hat{A}_C = (A_C - B_C K_C - B_D K_C)$$

1. Designing the Local Controller, K_D

Now we consider the selection of local controller gains to exponentially stabilize the overall system to a prescribed degree. For the local controller design, we ignore the interactions between the subsystems, that is, $A_C = 0$. The local controller gain can be found by implementing any controller design method, such as a pole placement controller design or an optimal controller design.

2. Designing the Global Controller, K_C

We select global gain matrix K_C such that $\hat{A}_C \triangleq 0$, which corresponds to reducing the effect of the interconnections [21]. This can be done by selecting

$$K_C = B^{\#} A_C \tag{11}$$

If matrix B is a square, nonsingular matrix, then the interactions are completely nullified and $\hat{A}_C = 0$. If B is a rectangular matrix, then $\hat{A}_C \cong 0$ as B^{-1} does not exist and we have to ensure that the closed-loop system remains stable. For this, we consider $\hat{A}_C$ an unstructured perturbation matrix and use the results obtained in [22] to determine the system stability. This stability condition is given by

$$\sigma_{\max}(\hat{A}_C) < -\sigma_{\max}(\hat{A}_D) + \left([\sigma_{\max}(\hat{A}_D)]^2 + \frac{\sigma_{\min}(Q)}{\sigma_{\max}(P)}\right)^{1/2} \tag{12}$$

where $Q = I$, and P is solution of the discrete-time Lyapunov equation solved for $\hat{A}_D$.

Consider the architecture as shown in Fig. 3. It shows a system with two subsystems in which the local and global controllers are connected to the subsystems using the communication network. Two types of systems are now studied: one in which each subsystem has independent control ($B_C = 0$), and one in which each control input affects two or more subsystems ($B_C \neq 0$).

Case I: $B_C = 0$

When $B_C = 0$, the closed-loop system reduces to

$$\hat{s}\colon \dot{x} = (A_D - B_D K_D)x + (A_C - B_D K_C)x \tag{13}$$

This can be written in a compact form as

$$\hat{\mathbf{S}}\colon \dot{x} = \hat{A}_D x + \hat{A}_C x$$

To reduce the effect of interactions, matrix $\hat{A}_C$ is made zero by the following selection of K_C:

$$K_C = B_D^{\#} A_C \tag{14}$$

Example 2: To compare the decentralized and centralized controllers from the PDM point of view, an example available in the literature [23] is studied.

$$A = \begin{bmatrix} 1.2 & 0.1 & -0.3 \\ 0.5 & -0.2 & -0.3 \\ -2.5 & 1.8 & 0 \end{bmatrix} \qquad B = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0.5 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The desired nominal closed loops are -0.7053 and $0.4777 \pm 0.4535i$.

An algorithm proposed by Hu and Yan [23] was used to find a feedback gain that maximizes the PDM. This gain yields a PDM of 0.3449 and $K_2(\hat{A}) = 1.0709$.

We now build a decentralized controller using the proposed method, which yields

$$K_D = \begin{bmatrix} 0.7223 & 0.5535 & 0 \\ 0.0930 & -1.3554 & 0 \\ 0 & 0 & 0.7053 \end{bmatrix}$$
$$K_C = \begin{bmatrix} 0 & 0 & -0.3 \\ 0 & 0 & -0.6 \\ -2.5 & 1.8 & 0 \end{bmatrix}$$

This gain yields $\mathrm{PDM}_{DS} = 0.39$ and $K_2(\hat{A}) = 1.0708$.

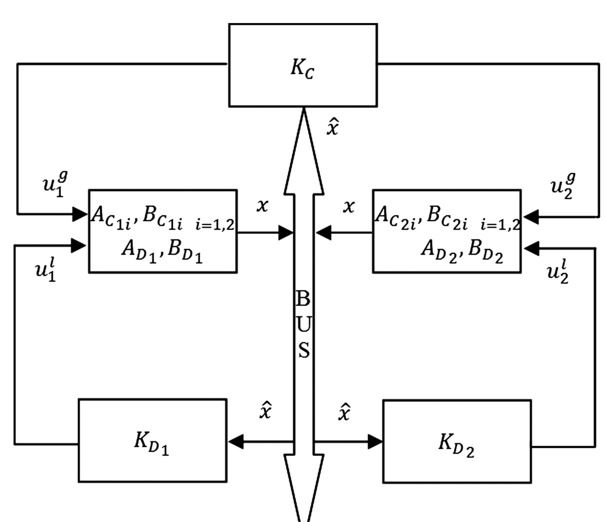

Fig. 3 D²FADEC with distributed local and global controllers.

Note that a significant improvement in the PDM for the same nominal closed-loop poles is observed, which confirms our previous assertion that the PDM is dependent on the structure of $\hat{A}$. We also observe that $K_2(\hat{A})$, obtained with the use of a controller in a decentralized framework, is lower than $K_2(\hat{A})$, obtained by the Hu and Yan algorithm. As we no longer have to solve the minimization problem, the computational effort and time are significantly reduced. Hence, the use of our proposed decentralized controller gives a lower $K_2(\hat{A})$ with a higher PDM and less computational effort.

Case II: $B_C \neq 0$

For this case, the closed-loop system becomes

$$\hat{\boldsymbol{S}}\colon \dot{x} = (A_D - B_D K_D)x + (A_C - B_C K_D - B_C K_C - B_D K_C)x$$
$$\dot{x} = (A_D - B_D K_D)x + (\widetilde{A_C} - B K_C)x \tag{15}$$

where $\widetilde{A_C} = A_C - B_C K_D$ or, in compact form,

$$\hat{\boldsymbol{S}}\colon \dot{x} = \hat{A}_D x + \hat{A}_C x$$

To reduce the effect of interactions, we make $\hat{A}_C \cong 0$ by selecting

$$K_C = B^{\#}\widetilde{A_C} \tag{16}$$

Example 3: We now study the effect of packet dropouts for an F100 engine model under a decentralized framework. The model is obtained from [24]. The continuous time model is converted into a discrete-time model with sampling time of 0.01 s.

Let the networked plant be

$$A = \begin{bmatrix} 0.9598 & 0.0365 & -4.6317 & 0.0608 & 0.0482 & -0.0332 \\ 0.0003 & 0.9708 & -0.5745 & 0.0012 & 0.0199 & 0.1221 \\ 0.0003 & 0.0001 & 0.9556 & 0.0000 & 0.0014 & 0.0010 \\ 0.0085 & -0.0204 & -2.5621 & 0.6065 & -0.0057 & -0.0920 \\ 0.0004 & -0.0009 & -0.1158 & -0.0156 & 0.9799 & -0.0042 \\ 0.0000 & 0.0000 & -0.0059 & 0.0000 & 0.0001 & 0.9934 \end{bmatrix}$$

$$B = \begin{bmatrix} 0.0108 & 1.6642 & -0.9764 & 0.0851 \\ 0.0091 & -0.3464 & -0.0142 & -0.5932 \\ -0.0001 & -0.7790 & 0.0116 & 0.0036 \\ 0.0444 & 0.2358 & -0.1646 & 0.3287 \\ 0.0020 & 0.0103 & -0.0074 & 0.0148 \\ 0.0001 & -0.0008 & -0.0003 & 0.0007 \end{bmatrix}$$

$$C = I_{6\times 6} \qquad D = 0$$

This networked plant was decomposed into two subsystems and the effect of mathematical partitioning on the PDM was studied. The local controller gain, K_D, was obtained using a pole placement technique for the desired closed-loop poles, $0.02 \pm 0.5i$, 0.2, 0.7, 0.9801 and 0.9936. The global controller, K_C, was calculated using Eq. (16).

Table 1 Dependence of the PDM on the system partitioning

Type of partitioning	PDM	$K_2(\hat{A})$
Centralized architecture	0.1955	4.9792
$A_1^{2\times 2}, B_1^{2\times 1}, A_2^{4\times 4}, B_2^{4\times 3}$	0.0117	5.476e + 4
$A_1^{2\times 2}, B_1^{2\times 2}, A_2^{4\times 4}, B_2^{4\times 2}$	1.0386	4.9759
$A_1^{2\times 2}, B_1^{2\times 3}, A_2^{4\times 4}, B_2^{4\times 1}$	1.0394	2.083e + 4
$A_1^{3\times 3}, B_1^{3\times 1}, A_2^{3\times 3}, B_2^{3\times 3}$	1.114e − 7	2.52e + 10
$A_1^{3\times 3}, B_1^{3\times 2}, A_2^{3\times 3}, B_2^{3\times 2}$	0.3204	4.9717
$A_1^{3\times 3}, B_1^{3\times 3}, A_2^{3\times 3}, B_2^{3\times 1}$	1.0338	4.9688
$A_1^{4\times 4}, B_1^{4\times 1}, A_2^{2\times 2}, B_2^{2\times 3}$	3.727e − 8	3.537e + 9
$A_1^{4\times 4}, B_1^{4\times 2}, A_2^{2\times 2}, B_2^{2\times 2}$	0.3285	77.4584
$A_1^{4\times 4}, B_1^{4\times 3}, A_2^{2\times 2}, B_2^{2\times 1}$	0.3835	35.7265

From Table 1, it is observed that the centralized controller gave a PDM of 0.1955. We also observe that the PDM depends on the system partitioning and that, by selecting a suitable system partition, we can obtain a large PDM. For example 3, we select a partition given as $A_1^{2\times 2}$, $B_1^{2\times 2}$, $A_2^{4\times 4}$, and $B_2^{4\times 4}$, because it gives the largest PDM with a small $K_2(\hat{A})$. As the PDM, which is the bound on the PDP, is more than 1, it ensures system stability for all values of the PDP less than 1.

V. Decentralized Distributed Full-Authority Engine Control

It has been shown that the use of a decentralized control structure not only improves the performance of a gas turbine engine, but also reduces the number of controller design operating points [5]. Also, the controller is made more robust and the system remains stable in the presence of soft and/or hard failures. Controllers based on the decentralized framework allow us to consider the interactions between the subsystems and, at the same time, optimize subsystem performance. This approach provides improved component fault prognostics and tolerance while reducing the processing complexity.

In addition, for distributed engine control systems, it can now be said that a decentralized controller design as presented in this paper will also impart stability robustness with respect to packet dropouts. Hence, for distributed engine control systems, the contribution of this paper (decentralized controller design) enhances the applicability significantly.

VI. Conclusions

Advanced future propulsion control demands for intelligent, fault-tolerant systems necessitate new control system development. The benefits of distributed control systems are beginning to be recognized in the engine community. In this paper, the use of TTP/C as a communication architecture is highlighted. D^{2}FADEC is proposed and a mathematical model consisting of a two-level controller structure is analyzed for performance under packet dropouts. It is shown that the PDM is dependent on the structure of the closed-loop matrix; reducing the effect of interactions can therefore result in a significant improvement of the PDM. We also demonstrate that the PDM is less dependent on the condition number and more dependent on the subsystem interactions. An F100 engine model, available in the literature, is used to show that, by selecting a suitable mathematical partitioning, we can obtain a large PDM, given that the system has prescribed nominal closed-loop poles. The same results can be extended to the case in which the control input is also subject to packet dropouts.

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