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**STABILITY OF FIBER OPTIC NETWORKED
DECENTRALIZED DISTRIBUTED ENGINE CONTROL
UNDER TIME DELAYS (POSTPRINT)**

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The Ohio State University

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Stability of Fiber Optic Networked Decentralized Distributed Engine Control under Time Delays

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The importance of distributed architecture for turbine engine control is well discussed in literature. Distributed turbine engine control architecture enables the use of new performance optimization methods along with achieving weight reduction. Communication constraints like time delays and packet dropouts can limit the performance of distributed engine control. In this paper, we propose a controller which will stabilize the time delay system based on delay independent condition. The controller under decentralized framework is also studied for stability under both time delays and packet dropouts. The proposed Decentralized Distributed Full Authority Digital Engine Control (D²FADEC) is implemented using Fiber Optics and is validated using a gas turbine engine model.

Nomenclature

FADEC	=	Full Authority Digital Engine Control
D ² FADEC	=	Decentralized Distributed Full Authority Digital Engine Control
DEC	=	Distributed Engine Control
DCS	=	Distributed Control Systems
NCS	=	Networked Control Systems
TDS	=	Time Delay System
PDM	=	Packet Dropping Margin
FDE	=	Functional Differential Equation

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. 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 based on a distributed architecture¹⁻⁴. Distributed Engine Control based on time triggered architecture is extensively studied in literature⁵⁻⁸. The advantages of a decentralized control scheme for a gas turbine engine are also well discussed in literature⁹. This decentralized approach was applied to distributed control and a control design procedure, labeled decentralized distributed full-authority digital engine control (D²FADEC) based on a two-level decentralized control framework¹⁰, was proposed¹¹. It was shown that the packet dropping margin¹², 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. The proposed methodology was applied to an F100 gas turbine engine model¹³, which clearly demonstrates the usefulness of decentralization in improving the stability of distributed control under packet dropouts. In section II, we will briefly review the distributed engine control architecture and communication protocol. The controller design based on delay independent stability condition is given in section III along with a hybrid modeling of the control system.

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II. Distributed Engine Control Systems

FADEC Based on Distributed Engine Control Architecture

Gas turbine engines have played a very important role in establishing air dominance of United States Armed Forces and have also greatly revolutionized air travel. Future engines are expected to have higher engine thrust-to-weight ratio and low engine fuel consumption along with increased performance, wider operability, and reduced life-cycle cost. Research is being carried out to make aircraft propulsions systems more intelligent, reliable, self-diagnostic, self-prognostic, self-optimizing and mission adaptable while also reducing the engine acquisition and maintenance cost. Distributed Engine Control (DEC) is one of the means of achieving this objective. 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 will include local processing capability to allow modular signal acquisition and conditioning and diagnostics and health management functionality. Dual channel digital serial communication network will be used to connect these smart modules with FADEC. Fig. 1 shows the schematic of FADEC based on distributed control architecture.

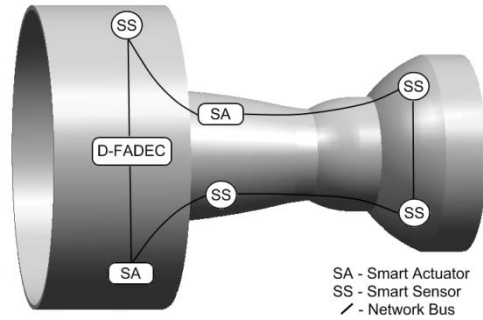


Figure 1. Distributed Engine Control Architecture

Reduction of engine control system weight, modularity, obsolescence reduction, scalability, and reduction in operational and maintenance cost are some of the perceived benefits of DEC. As the performance of the DEC will be dependent on the performance of the communication network, the appropriate selection of communication architecture is very important. Some of the existing off-the-shelf open system communication standards are MIL-STD-1553, SAFEBus, FlexRay, CAN, SPIDER, TTP/C and IEEE 1394b/Firewire. For safety-critical DCS, there is a clear preference for time-triggered protocols over the event-driven protocols. Time-triggered protocols offer high level of reliability with fault-tolerance. One of such time triggered architecture, TTP/C, has clear advantages over the others¹⁴. TTP/C is specially designed for the safety critical, hard real-time distributed control. Along with high transmission rate, TTP/C has high data efficiency, error detection with short latency, a fault-tolerant clock synchronization service, and distributed redundancy management. TTP/C can tolerate multiple faults and high degree of temporal predictability. TTP/C can be implemented using both fiber-optics physical layer as well as an electrical physical layer. Use of fiber optics has certain advantages, for example, immunization to electromagnetic interference, reduction in system weight, higher bandwidth etc.

Fully and partially distributed systems are well discussed in literature. Such systems consist of several local controllers coordinated by a supervisory controller. These local controllers can be used to control or optimize inlet/fan, compressor, combustor or turbine. Such a framework of local and supervisory controllers can be viewed as a decentralized architecture. Hence, we propose the use of Decentralized Distributed Full Authority Digital Engine Control (D²FADEC). Fig. 2 shows the proposed D²FADEC implemented using TTP/C.

As seen in Fig.2, two fiber optic channels are used as physical layer. Smart Sensors or Smart Actuators, which each consists of a Fiber Bus Interface Module (FBIM), a TTP/C Module and a Sensor/Actuator Module, are connected to each of the fiber optic channels. The TTP/C module is shown in Fig. 3

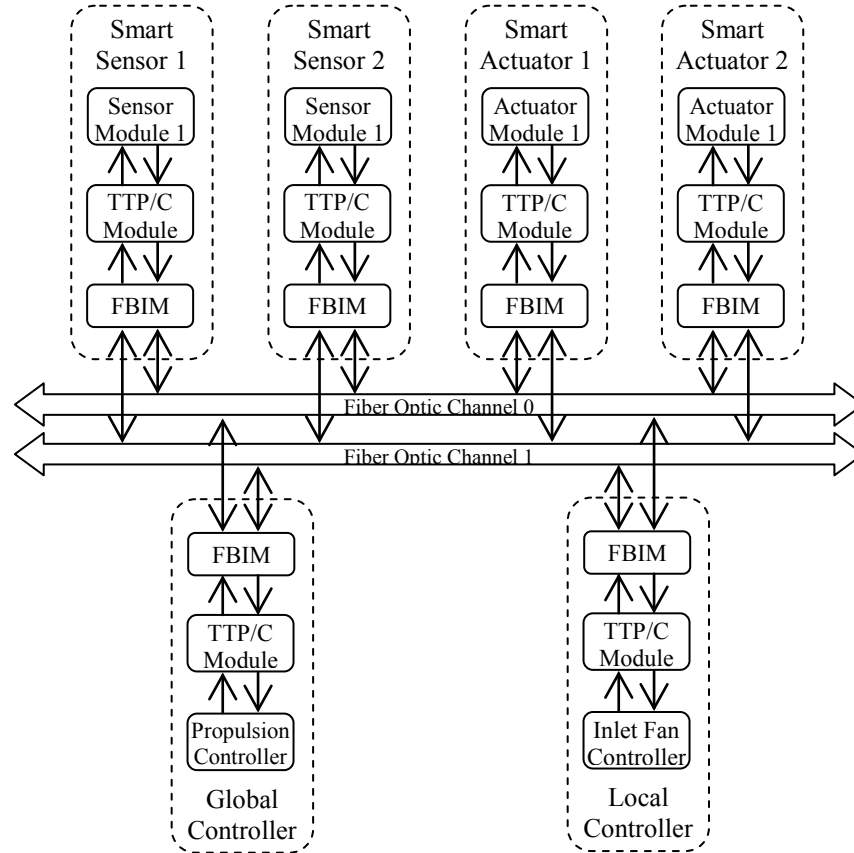


Figure 2. D²FADEC Architecture

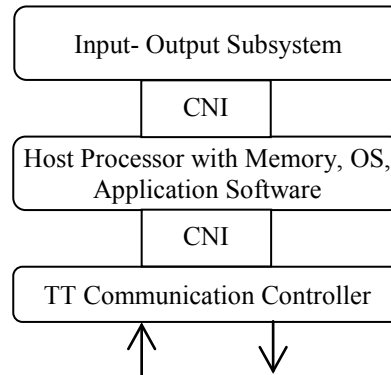


Figure 3: TTP/C Module

The sensor module shown in Fig.2 can consist of only one sensor or an array of sensors. The function of sensor module is to collect the information from array of sensors, perform I/O conditioning and if required, can also perform other functions like health management and diagnostics. TTP/C module then encodes the data using the time triggered protocol. FBIM consist of optical interface that supports, adds, drops, broadcasts and passes optical signals on a bi-directional ring bus with automatic protection. There can be a global supervisory controller, which oversees the control action as well as a group of local controllers, for example, inlet fan controller, compressor controller, etc.

Communication Protocol

As TTP/C is based on Time Division Multiple Access (TDMA) method, each node gets a predetermined time slot to transmit the information. While one node is transmitting the information, all the remaining nodes receive and process the information. TTP/C has an inbuilt mechanism, which verifies if the data packet is received correctly or not. Node faults, faults in fiber optic physical layer or noise can corrupt the data packets. If the data packet is found to be corrupted, the data packet is dropped and the node does not get a retransmission attempt. It has to wait until its next time slot, which is during the next TDMA round, to retransmit a new data packet. Although redundant physical layer avoids packet dropouts due to noise, faulty node can still cause the data packets on both the channels to be corrupted. Hence, packet dropouts are important and need to be studied for system stability. Also, each module in the smart sensors and smart actuators will introduce a time delay. Due to the presence of time-stamps, the delay will be constant, predictable/known and bounded. The controller will have to be designed such that this delay is less than the maximum time delay which can be sustained by the system before becoming unstable. The importance of studying DEC for stability under communications constraints is well explained in Ref. [11,15-16]. For implementing DEC using TTP/C, it is necessary to design the system such that it is robust against time delays and packet dropouts¹¹.

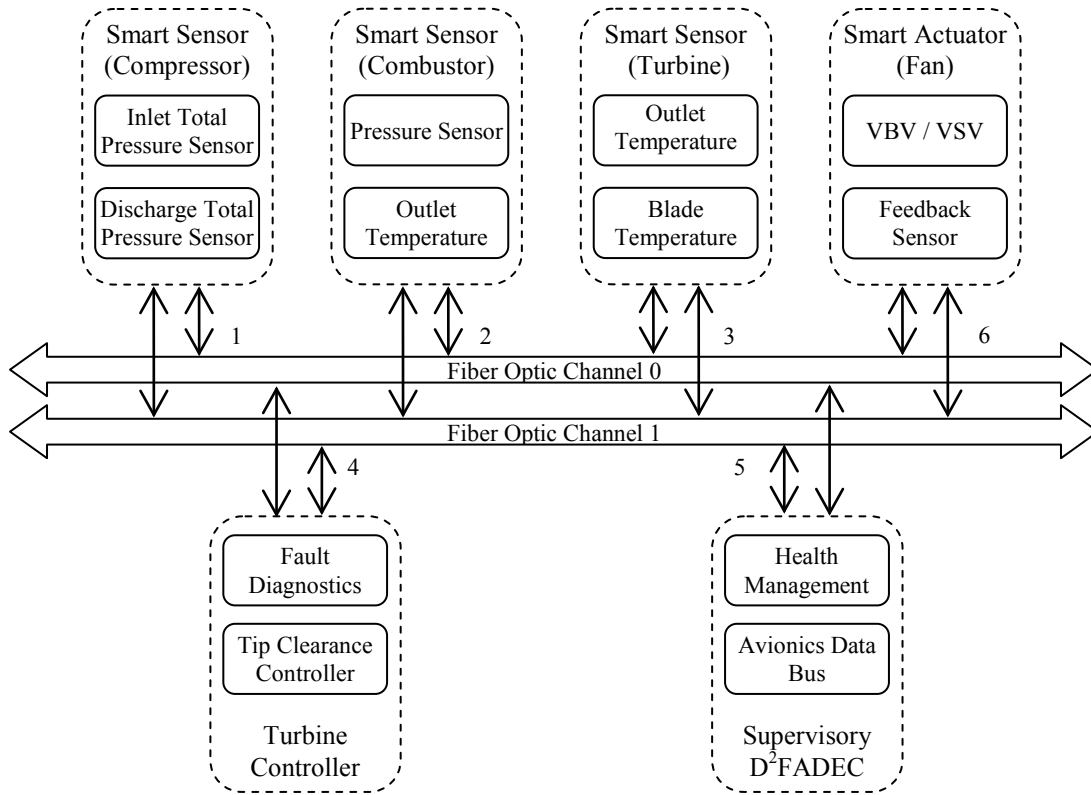


Figure 4: D²FADEC with smart sensors/actuator and Turbine/Supervisory Controllers

Above figure also shows D²FADEC with the sequence of time slots. The first three time slots are reserved for sensor data, fourth for turbine controller, which acts like a local controller and fifth for supervisory FADEC. During this time slot, all the actuator nodes receive the data. However, the actuator nodes may have feedback sensors, which may necessitate the need of reserving time slot for actuator node transmission, during which, the information from actuator feedback sensors will be transmitted to supervisory controller. As D²FADEC consists of several sensor/actuator nodes, the entire state information or output cannot be transmitted using a single packet; instead multiple packet transmission has to be implemented. The sequence of multiple packets received by the controller will be predetermined during the design phase and will remain fixed throughout the operation. For simplicity, we will first assume single packet transmission and perform stability and performance analysis under time delays. Also, we will first verify if the available bandwidth is sufficient for DEC. Application data, i.e. bits required for each

sensor information is 36 bits⁷. Protocol overhead for TTP/C is 32 bits which include 8 bits for frame header and 24 bits for CRC. Hence, assuming that 10 sensors are connected to each node, each node will transmit one data packet of length 50 bytes per round. Assuming 50% efficiency and sampling at 100Hz (10 msec)⁷, 1 Mbits/s is sufficient bandwidth for 25 nodes having 10 sensors each. As the required bandwidth (1 Mbits/s) is far less than the available bandwidth for TTP/C implemented using optical fiber network (5 Mbits/sec), TTP/C can be successfully used for D²FADEC.

III. Stability Analysis under Time Delay

During the mathematical description of a physical process, one assumes that the dynamic behavior of the process depends only on the present states. However, this assumption is not valid when there is an information transfer. In such cases, the dynamic behavior of the process depends on the former states. Such systems are known as Time Delay Systems (TDS). The difference between the former and present states is known as time delay. The physical plant is connected to the controller using a control network which has a finite data transmission capability. Also the controller requires finite time for computation. Hence, three time delays are introduced in the system, which shown in fig. 5.

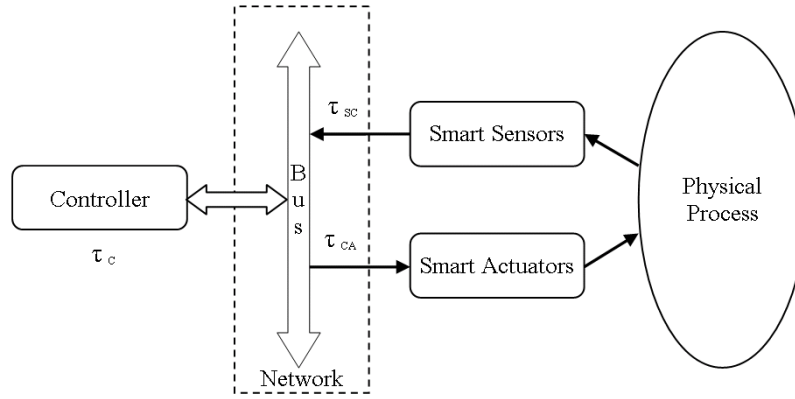


Figure 5: Typical Networked Control Systems with delay process

τ_{SC} = Delay in data transmission between sensor and controller.

τ_C = Delay in controller

τ_{CA} = Delay in data transmission between controller and actuator.

Hence, the total delay which has to be considered is $\tau = \tau_{SC} + \tau_C + \tau_{CA}$

Time delay system is represented mathematically using Functional Differential Equation (FDE) with delay, τ ¹⁷. TDS can be represented as follows.

$$\begin{aligned} \dot{x}(t) &= Ax(t) + A_d x(t - \tau) \\ x(t_0 + \theta) &= \phi(\theta), \theta \in [-\tau, 0] \end{aligned} \quad \boxed{\dot{x}(t) = Ax(t) + A_d x(t - \tau)} \quad (1)$$

The above equation represents an unforced linear FDE with single delay factor. Matrix A_d represents the strength of delayed states on systems dynamics. Stability conditions for TDS are obtained by giving characteristics of the stability regions for linear systems with delayed state in terms of delays. Hence, two stability conditions arise which are as follows

1. Delay Independent Stability

Stability conditions which do not depend on the delay size are known as delay independent stability conditions. Delay independent stability holds for all positive and finite value of delays. Hence, this imparts robustness to the system with respect to time delay.

2. Delay Dependent Stability

Delay dependent stability conditions are those which depend on the delay size. In these conditions, stability is preserved only for some finite value of delay and it is unstable for all other values. Hence, these conditions are less robust than delay independent conditions.

Stability analysis considering both time delays and packet dropouts

It is necessary to study the effect of both packet dropouts and time delays on system stability and performance. Packet dropouts can be either modeled as stochastic process or as a deterministic process. In Ref. [11], packet dropouts were modeled as independent and identically distributed (i.i.d.) process. It was shown that Packet Dropping Margin (PDM), which is a measure of stability robustness under packet dropouts, is largely dependent on the closed loop controller structure; and that in particular block diagonal structure is more desirable. Thus, a controller design method in a decentralized framework was proposed to improve the PDM. One of the main advantages of this technique for handling packet dropouts is that any controller method can be followed as PDM calculation is based entirely on the closed loop systems. However, determining the Packet Dropping Probability (PDP) of TTP/C using fiber optic as physical layer is cumbersome process. Hence, in this research, we will model packet dropouts in a deterministic fashion and obtain the maximum number of consecutive packets which can be dropped without destabilizing the system. If a packet is dropped, the node has to wait for its next time slot in order to retransmit the packet. This enables to represent packet dropouts using time delays, and by designing the system such that the maximum allowable delay bound, is maximized, in turn, makes the system robust for stability under packet dropouts as well as under time delays.

Consider an interconnected system shown as below

$$\dot{x}(t) = Ax(t) + Bu(t) \quad (1)$$

This interconnected system with delay and N subsystems can be further decomposed as

$$\dot{x}_i(t) = A_i x_i(t) + A_i x_i(t - \tau(t)) + B_i u_i + \sum_{j=1}^N (A_{ij} x_j(t - \tau(t))) \quad (2)$$

where $x_i \in \mathbb{R}^{n_i}$ $x_i \in \mathbb{R}^{n_i}$, $u_i \in \mathbb{R}^{m_i}$ are the state and input of subsystems

A more compact notation for the above system is

$$\begin{aligned} \dot{x}(t) &= A_D x(t) + A_C x(t) + B_D u(t) + B_C u(t) \\ \dot{x}(t) &= A_D x(t) + A_{D,d} x(t - \tau(t)) + B_D u(t) + A_C x(t - \tau(t)) \end{aligned} \quad (3)$$

where,

$$\begin{aligned} A_D &= \text{diag}\{A_1, A_1, \dots, A_N\} \\ B_D &= \text{diag}\{B_1, B_1, \dots, B_N\} \\ A_C &= (A_{ij}) \\ B_C &= (B_{ij}) \end{aligned}$$

Delay Independent Stability

A condition for delay independent stability is given in Ref. [18]. We extend this condition and propose a controller which will stabilize the system independent of the delay.

Consider a continuous time controller, with time delay τ

$$u(t) = -Kx(t - \tau) \quad \dot{x}(t) = Ax(t) + Bu(t - \tau(t)) \quad (4)$$

where, τ is the unknown constant delay bound satisfying

$$\begin{aligned} 1 &\leq \tau \leq \tau^0 \\ 1 &\leq \dot{\tau} \leq 0 \leq 1 \end{aligned}$$

Theorem :

The above delayed system is globally asymptotically stable independent of delay if there exists matrices $0 < P = P^T \in \mathbb{R}^{n \times n}$ and $0 < Q = Q^T \in \mathbb{R}^{n \times n}$ satisfying Algebraic Riccati Inequality (ARI)¹⁸

$$PA + A^T P + PBKQ^{-1}(BK)^T P + Q < 0 \quad (5)$$

Let the controller be

$$K = -B^{-1}P^{-1}Q \quad (6)$$

Where, P is obtained from the ARI as shown below

$$PA + A^T P + 2Q < 0 \quad (7)$$

It can be shown that the solution, P of the Algebraic Riccati Equation is also the solution of ARI such that the trace of P is minimized. Hence, we can solve the following Algebraic Riccati Equation and obtain the gain matrix K .

$$PA + A^T P + 2Q = 0 \quad (8)$$

This gain K will always satisfy the above delay independent stability condition. However, the above delay independent controller design, though robust, is more conservative than the delay dependent condition. The controller designed using the above technique will maintain stability of the system against the time delay at the cost of the system performance. Hence, in order to improve the performance, it is necessary to use the delay dependent condition during controller design. Also, in reality, the engine is a continuous time process with discrete D²FADEC. In order to accurately represent the entire system, the system is modeled in hybrid time sense, with continuous process and discrete controller.

Hybrid Modeling

Let us consider a discrete controller

$$u(k) = -Kx(k - \tau) \quad k = 0, 1, 2, \dots \quad (9)$$

As the communication protocol is time triggered protocol, τ , which is the time for one TDMA round, is constant and known. Using sampling at sampling time h and Zero Order Hold (ZOH), a discrete time model can be obtained as follows.

$$\begin{aligned} x(k+1) &= A_D x(k) + A_C x(k) + B_D u(k) + B_C u(k) \\ u(k) &= -Kx(k - \tau) \end{aligned}$$

The closed loop system is given as

$$x(k+1) = A_D x(k) + A_C x(k) - B_D Kx(k - \tau) - B_C Kx(k - \tau)$$

Control gain matrix K can be decomposed as

$$K = K_D + K_C$$

Hence, closed loop equation can be rewritten as-

$$x(k+1) = A_D x(k) + A_C x(k) - B_D K_D x(k - \tau) - B_C K_C x(k - \tau)$$

If “ n ” is the number of consecutive packets which are dropped, or in other words, the faulty node is not able to transmit for “ n ” consecutive rounds, then the closed loop system becomes

$$x(k+1) = A_D x(k) + A_C x(k) - B_D K_D x(k - n\tau) - B_C K_C x(k - n\tau)$$

The time delay $n\tau$ is time variant and can be replaced by $\tau_t(t)$, which is the total time variant delay. It is assumed that $\tau_t(t)$ satisfies

$$0 < \tau \leq \tau_t(t) \leq \tau_{\max} < \infty$$

The control task is to design the controller gain K which will maximize $\tau_{\max}$, preserving the stability and performance of the system. The delay dependent stability condition for hybrid systems given in Ref. [19] was extended under decentralized framework and tested for a F100 engine model available in literature¹³. It was found that the F100 model is delay dependent stable for the proposed D²FADEC architecture.

Conclusion

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. Decentralized Distributed Full Authority Digital Engine Control (D²FADEC) is proposed and a mathematical model consisting of a two-level controller structure is analyzed for performance under packet dropouts and time delays. A controller which stabilizes the time delay system based on delay independent stability condition is proposed. The proposed D²FADEC architecture is implemented using fiber optics and is validated using a gas turbine engine model for stability and performance under both time delays and packet dropouts.

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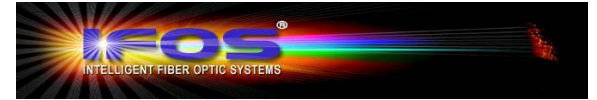
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Joint Propulsion

Conference & Exhibit

August 3, 2009





Stability and Performance Analysis of Turbine Engines under Fiber Optic Networked Distributed Control Architecture

Phase I STTR Project

Agency: Air Force

Firm: Intelligent Fiber Optic Systems Corporation (IFOS)

University: The Ohio State University

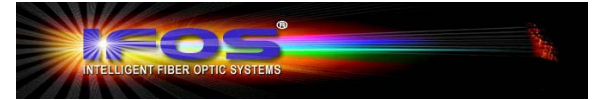
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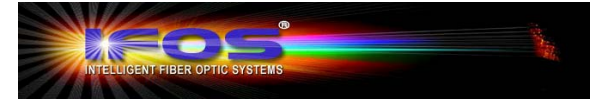
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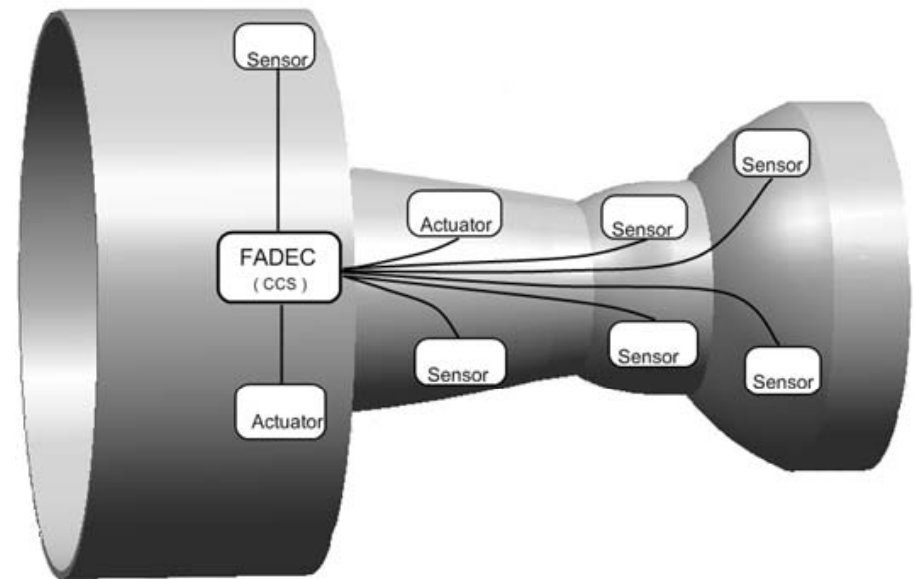


1. Background – Centralized FADEC
2. Motivation – Distributed FADEC
3. DEC as a Networked Control System (NCS)
4. Packet Dropouts
5. Time Delay
6. Conclusions

FADEC based on CCS

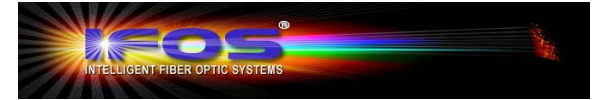


- Full Authority Digital Engine Control (FADEC)
- Centralized control processor.
- Point to point analog communication between sensors and FADEC.
- A/D and D/A circuitry housed in FADEC.
- Dual channel redundancy.
- Heavily shielded FADEC enclosure.

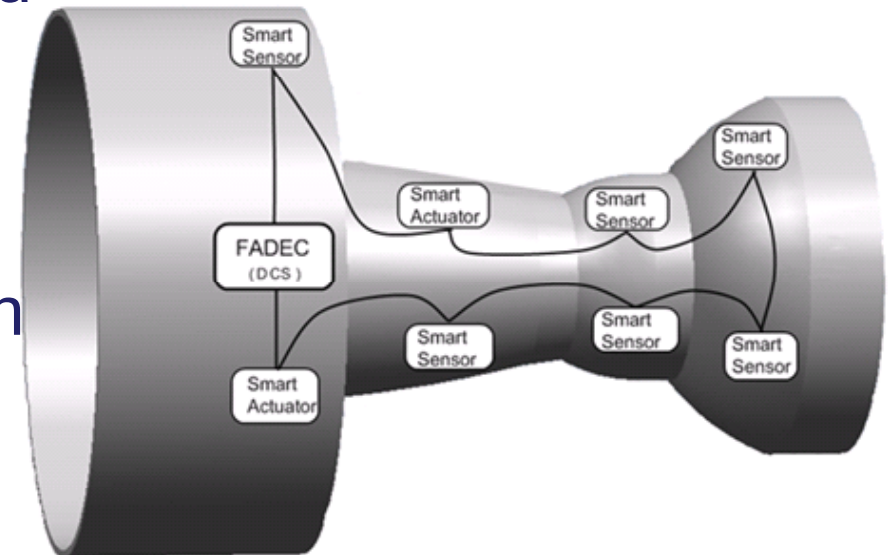


FADEC based on Centralized Architecture

Distributed Engine Control

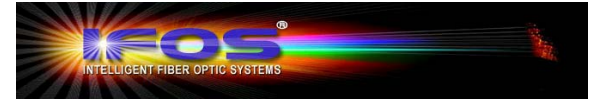


- Each sensor/actuator replaced by smart sensor/actuator.
- Signal processing done by smart modules.
- Information transfer through serial communication.
- Smart modules include processing capability to perform health diagnostics and management functions.



FADEC based on Distributed Architecture

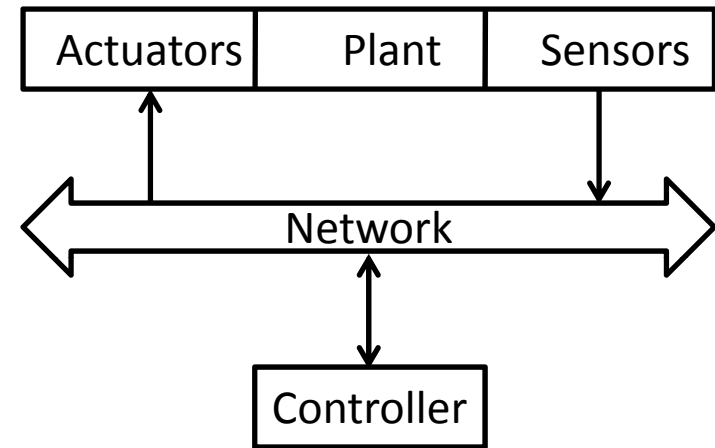
Advantages of DEC



- Weight reduction.
- Cost reduction.
- High Modularity.
- Distribution of computational burden.
- Improved fault diagnostics and prognostics.
- Obsolescence mitigation.
- Use of open system standards.
- Scalability.

Basic elements of NCS

1. Sensors
2. Actuators
3. Communication network
4. Controller

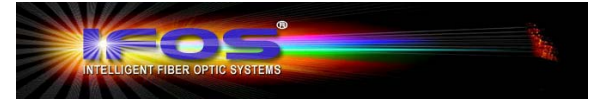


Generic NCS Architecture

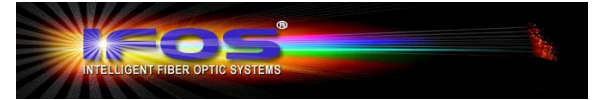
Factors to be considered for analysis of NCS

- Packet Dropout
- Network induced Time Delay
- Channel Bandwidth

Candidate Communication Protocols

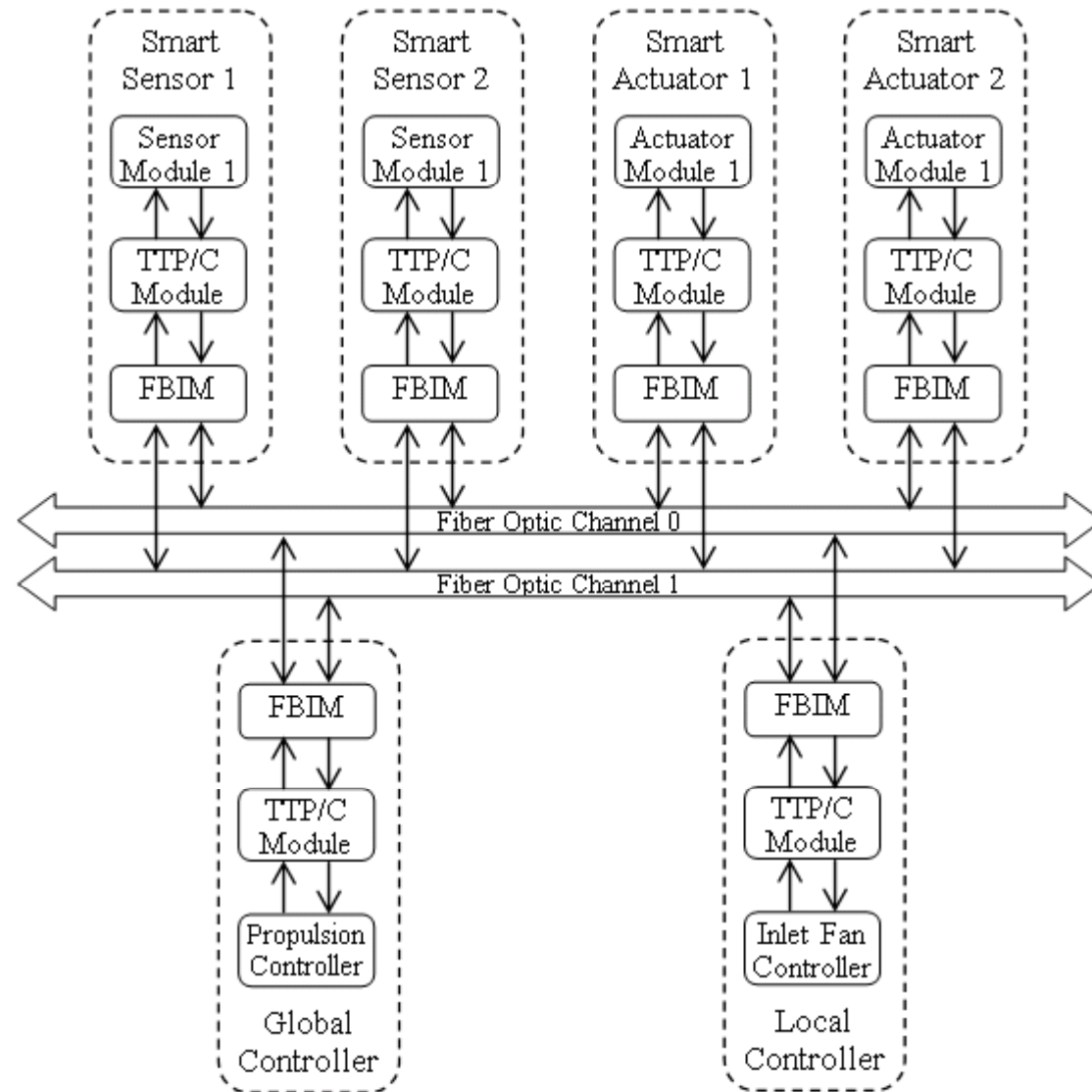


- TTP/C
 - Boeing 787 environmental control systems
- MIL-STD-1553
 - Space Shuttle, ISS
- SAFEbus
 - Boeing 777 Avionics
- IEEE 1394b/Firewire
 - JSF Avionics
- IEEE 1451



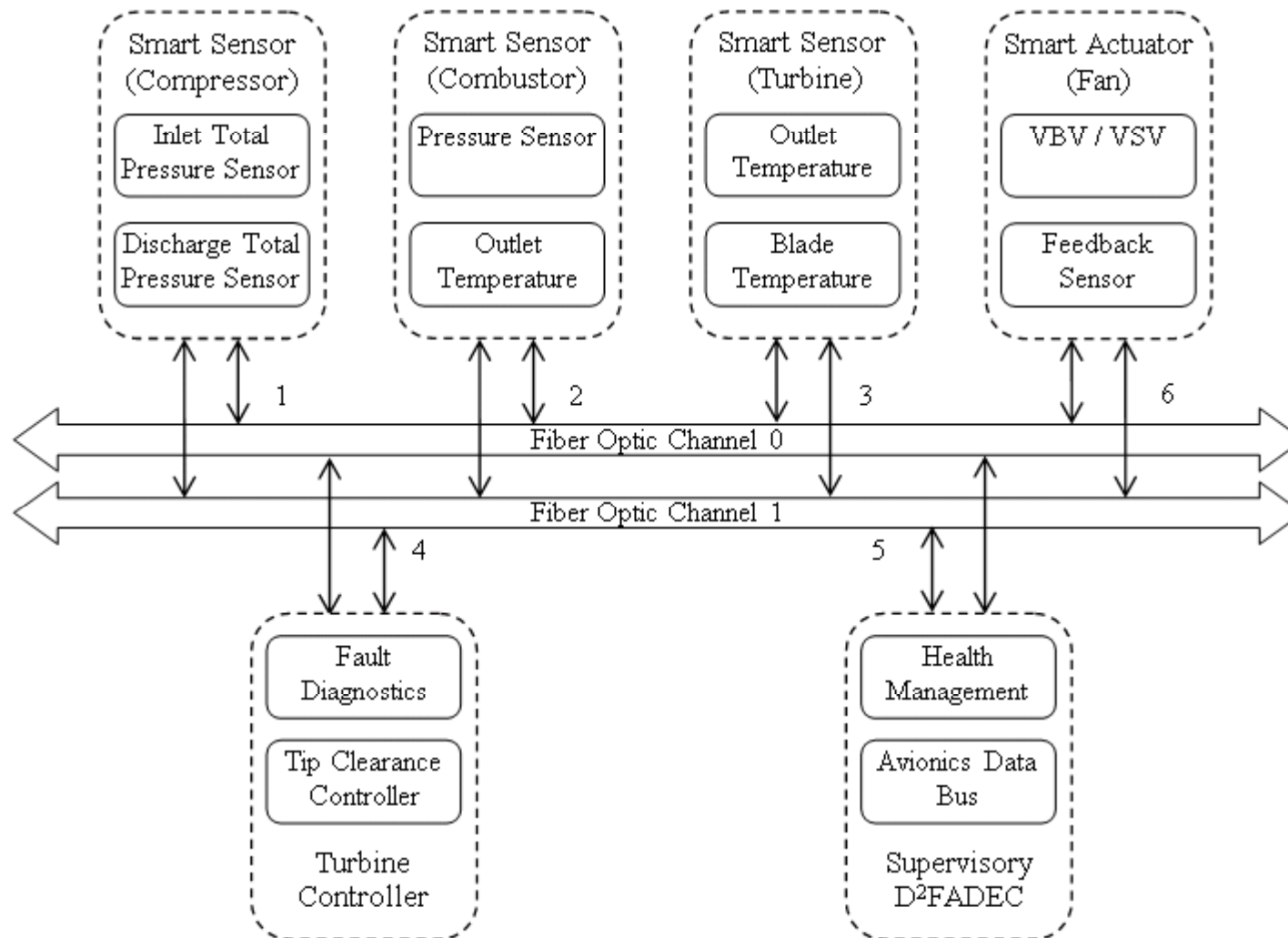
- Physical Layer- Fiber Optics
- Use of Wavelength Division Multiplexing (WDM)
- Reduction in Weight
- Immune to EMI
- High Bandwidth
- Can withstand harsh environment
- Integration with fiber optic sensing technology
 - Temperature
 - Structural Health Measurement

D²FADEC Architecture



D²FADEC with TTP/C Module and Fiber Bus Interface Module (FBIM)

D²FADEC Architecture



D²FADEC with smart sensors/actuator and Turbine/Supervisory Controllers

Number of Nodes	25
Number of smart sensors per node	10
Sampling Time	100 Hz (10 ms)
TTP/C Efficiency	50%

Application Data	36 bits
Protocol Overhead	32 bits
• Frame Header	8 bits
• Cyclic Redundancy Check (CRC)	24 bits

Maximum effective bit rate is 1 Mbits/sec

- Decentralized Distributed Full Authority Digital Engine Control (D²FADEC)
- Stability under Packet Dropouts
 - Stochastic Approach
 - Deterministic Approach
- Stability under Time Delays
 - Delay Independent Conditions
 - Delay Dependent Conditions

$$\text{S: } \dot{x} = Ax + Bu$$

$$y = Cx$$

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

$$\text{S: } \dot{x}_i = A_i x_i + B_i u_i + \sum_{j=1}^N (A_{ij} x_j + B_{ij} u_j)$$

$$y_i = C_i x_i + \sum_{j=1}^N C_{ij} x_j \quad i \in N$$

$$\text{S: } \dot{x} = A_D x + B_D u + A_C x + B_C u$$

$$y = C_D x + C_C x$$

Control Law -

$$u = -Ky$$

$$K = K_D + K_C$$

Closed Loop System -

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

where,

$$\hat{A}_D = (A_D - B_D K_D - B_C K_D)$$

$$\hat{A}_C = (A_C - B_C K_C - B_D K_C)$$

Local Controller

$$u^l = -K_D y$$

Global Controller

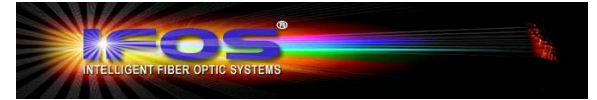
$$K_C = B^\# A_C$$

$$u^g = -K_C y$$

$$u^g = -K_C y$$

where, $B^\#$ is Moore Penrose inverse of B

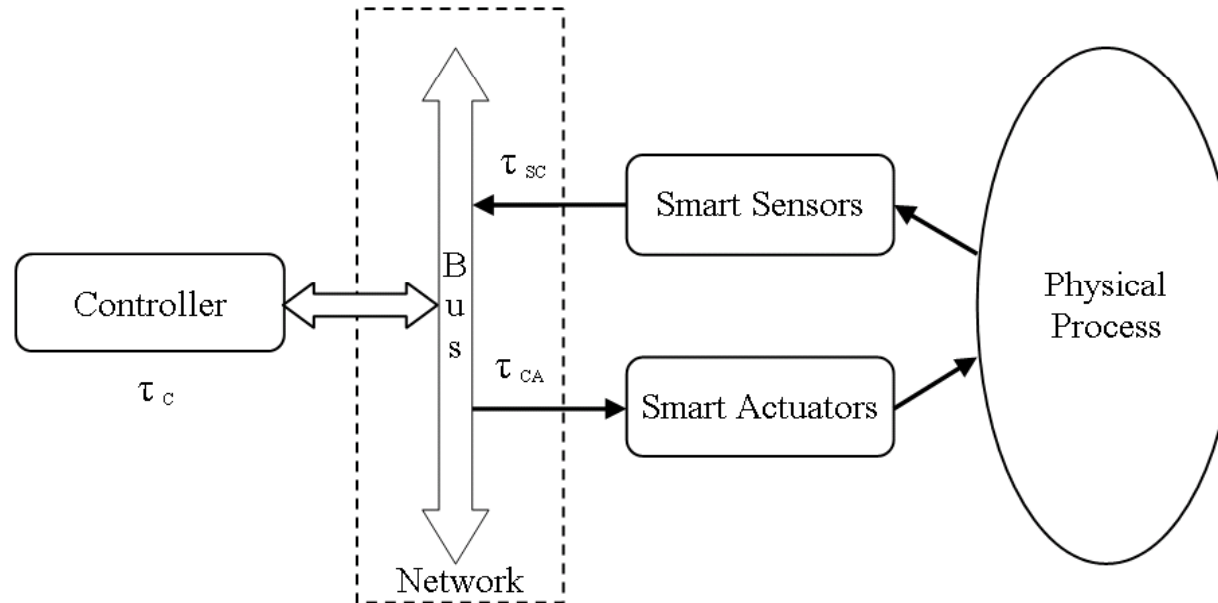
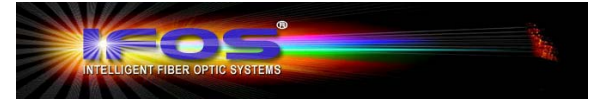
Stochastic Approach for Packet Dropouts



1. Decentralized framework increases PDM.
2. PDM is more dependent on the structure of A_k .
3. PDM depends largely on system partitioning.

- o PDP Packet Dropping Probability
- o PDM Packet Dropping Margin
- o $K_2(A_k)$ Condition number of A_k

Time Delay Systems

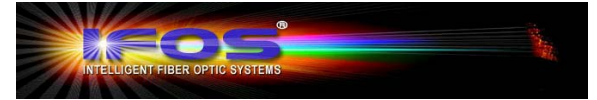


$$\dot{x}(t) = Ax(t) + A_d x(t - \tau) + B_d u(t - \pi)$$

$$x(t_0 + \theta) = \phi(\theta), \theta \in [-\tau, 0]$$

$$u(t_0 + \vartheta) = \varphi(\vartheta), \vartheta \in [-\pi, 0]$$

Types of Delay Conditions



1. Delay Independent Condition
 - Does not depend on delay size
 - More conservative

2. Delay Dependent Condition
 - Does depend on delay size
 - Less conservative

$$\dot{x}(t) = A_D x(t) + B_D u(t)$$

$$u(t) = -K_D x(t - \tau)$$

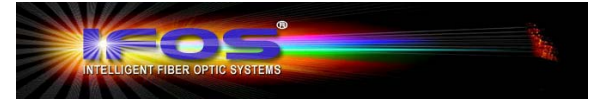
Theorem: The above delayed system is globally asymptotically stable independent of delay if there exists matrices P and Q satisfying Algebraic Riccati Inequality (ARI)

$$PA_D + A_D^T P + PB_D K_D Q^{-1} (B_D K_D)^T P + Q < 0$$

$$0 < P = P^T \in \mathcal{R}^{n \times n}$$

$$0 < Q = Q^T \in \mathcal{R}^{n \times n}$$

Controller Design



Let the Controller be

$$K_D = -B_D^{-1}P^{-1}Q$$

Previous condition reduces to

$$PA_D + A_D^T P + 2Q < 0$$

$$PA_D + A_D^T P + 2Q = 0$$

$$\dot{x}(t) = A_D x(t) + A_C x(t) + B_D u(t) + B_C u(t)$$

$$u(k) = -Kx(k - \tau) \quad k = 0, 1, 2, \dots$$

Closed Loop System-

$$x(k + 1) = A_D x(k) + A_C x(k) - B_D Kx(k - \tau) - B_C Kx(k - \tau)$$

$$x(k + 1) = A_D x(k) + A_C x(k) - B_D K_D x(k - n\tau) - B_C K_C x(k - n\tau)$$

$$0 < \tau \leq \tau_t(t) \leq \tau_{max} < \infty$$

Example



Example- F100 Engine

$K_d =$

19.3146	86.1785	0	0	0	0
0.4515	-0.5485	0	0	0	0
0	0	19.7205	-32.7609	-1.1453	-1.6990
0	0	8.5862	-12.4475	-0.3894	-0.8913

$K_c =$

-22.5857	-75.8787	0.5447	30.1198	1.4156	1.3569
-0.4675	0.5399	-0.2626	0.5600	0.0185	0.0295
-1.0507	-0.0479	-15.3293	33.9951	1.1412	1.7804
-0.0466	-1.4725	-7.5613	12.5488	0.3668	0.6869

$K =$

-45.1713	-151.7574	1.0895	60.2395	2.8312	2.7138
-0.9349	1.0799	-0.5253	1.1199	0.0370	0.0590
-2.1015	-0.0959	-30.6586	67.9902	2.2823	3.5609
-0.0933	-2.9450	-15.1227	25.0976	0.7335	1.3739

Example



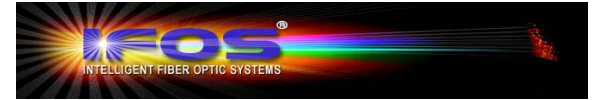
Aclosed =

-0.0003	0.0180	0.0000	-0.0000	-0.0000	-0.0000
-0.0182	0.0003	-0.0000	0.0000	0.0000	0.0000
-0.0000	-0.0000	0.6965	0.4238	0.0161	0.0238
0.0000	-0.0000	-2.1385	-0.6943	-0.0662	-0.0786
-0.0000	-0.0000	-0.0967	-0.0741	0.9772	-0.0035
0.0000	0.0000	-0.0054	-0.0022	-0.0000	0.9934

eigvalues =

-0.0000 + 0.0181i
 -0.0000 - 0.0181i
 -0.0004 + 0.6499i
 -0.0004 - 0.6499i
 0.9935
 0.9801

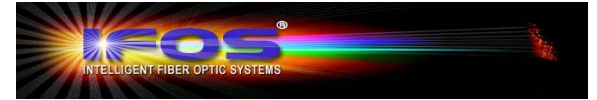
Conclusions



- Development of Fiber Optic Networked Decentralized Distributed Engine Control.
- Study of stability and performance of D²FADEC under both time delays and packet dropouts.
- Development of a delay independent controller.
- Verification of the developed theory using F100 engine model.
- Advantages of

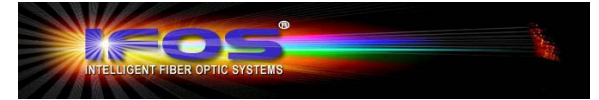
Thank You

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Limitations of FADEC



- Short life
- Not easily upgradeable.
- High overall ownership cost.
- Uses non-standard I/O interface.
- Large impact of obsolescence.
- Large weight penalty.



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