N92-15866

1991

NASA/ASEE Summer Faculty Fellowship

Marshall Space Flight Center
University of Alabama, Huntsville

On the Development of System–Theoretic Tools for the Design of Integrated Health Monitoring and Controls for Rocket Propulsion Systems

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As NASA continues to develop various advanced propulsion technologies for space exploration two factors are becoming increasingly dominant in design specifications: increase operational reliability and decrease operational cost. One approach that has been proposed to meet these challenges is to incorporate into current and future rocket propulsion systems some sort of diagnostic/monitoring capability in the form of a Health Monitoring System (HMS). HMS technology offers the promise of increased operational reliability through its ability to assess system performance, detect and isolate degradations and/or failures, and modify system operation so as to minimize effects on performance. Decreased operational costs are accrued by the use of the HMS technology to help automate inspection and checkout procedures and to help minimize maintenance activities by transitioning from a maintenance-on-routine basis to a maintenance-on-condition basis.

The block diagram shown in Figure 1(a) illustrates a generic interconnection of a rocket engine (E), together with its sensors (S), actuators (A), and controller (C), and a generic HMS. The main functional components of the HMS can be classified according to their level of sophistication as follows [6]:

Safety Monitoring: Assure completion of mission. Simplest level of HMS function. Typically takes the form of a red-line checking algorithm which can initiate engine shutdown. Currently in use on SSME in the form of FASCOS system.

Health Monitoring: Determine condition of engine components during operation and identify any anomalous behaviors. Next higher level of HMS function. Possessing some form of failure/degradation isolation and accomodation capabilities. Currently under development for use on SSME in the form of SAFD [2] and on STME in the form of RECOMS [1].

Condition Monitoring: Determine readiness of engine to perform required mission. Most sophiticated level of HMS Function. May involve use of trending analysis, artificial intelligence, etc. Currently an open research area.

As the descriptions above indicate, the sate-of-the-art in HMS technology is still relatively unsophisticated. Several interesting issues remain as yet unresolved. The purpose of the research reported here is to study, from a systems engineering perspective, the particular issues of analysis and synthesis for generic HMS's such as the one depicted in Figure 1(a). Specific system-theoretic questions of interest include: Can one develop analytical methods for the analysis and synthesis of HMS specifications? Given a set of HMS specifications, can one develop analytical methods for deciding on the selection and placement of sensors to achieve the given specifications? Given a set of HMS specifications and an HMS sensor suite, can one develop analytical methods for characterizing the algorithms needed to process the sensor data in order to achieve the given specifications? To what extent do the design objectives of a HMS conflict/interact with design objectives of a control system?

The research presented here proposes a system-theoretic framework within which questions like those posed above can be studied in a unified manner. In addition, partial answers to the last question posed, i.e., the question of control/HMS conflict/interaction, are given as an indication of the potential utility of the proposed framework. Finally, it is indicated how the proposed framework can be extended to handle some of the other questions raised above.

The specific issue of the impact of control system design objectives on HMS design objectives and vice versa is particularly interesting in that a fundamental objective of control systems is that they be relatively insensitive to small changes in the system being controlled (i.e., the so-called robustness issue) whereas it is precisely the objective of HMS's that they be able to sense changes in system behavior. This conflict can be more concretely illustrated by considering the block diagram given in Figure 2. It shows a plant

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = Pu = \begin{bmatrix} P_1 \\ P_2 \end{bmatrix} u\ .$$

together with a compensator K and diagnostic module D. Subsystem P_1 defines those plant sensors selected for diagnostic purposes, and subsystem P_2 defines those plant sensors selected for control purposes. The exogenous signal f is representative of a sensor failure, i.e., $f = 0$ corresponds to nominal sensor behavior and $f \neq 0$ corresponds to an off-nominal condition in one or more of the sensors defined by P_2. The goal here is to design K to achieve good control performance and to design D so that failures at f can be monitored at

d, the diagnostic module output. Straightforward manipulations yield that the transfer function M_{fd} from f to d is given by:

$$M_{fd} = DP_1K(I - P_2K)^{-1} .$$

This expression clearly indicates that the extent to which the loop gain P_2K is shaped to achieve control objectives has an impact on our ability to monitor failures f at d. Moreover it is clear that K and D cannot be designed independently without possible adverse effects to either control performance or diagnostic performance.

The discussion above indicates that an integrated analysis of HMS and control system design is necessary. For this purpose the configuration shown in Figure 1(b), discussed in [4], will be considered. Here T and T' represent, respectively, the engine system together with its sensors and actuators, and an integrated health monitoring and control system (IHMC). They are partitioned conformably with respect to their inputs/outputs as follows:

$$\begin{bmatrix} z \\ y \end{bmatrix} = T \begin{bmatrix} w \\ u \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} w \\ u \end{bmatrix}, \quad \begin{bmatrix} z' \\ y' \end{bmatrix} = T' \begin{bmatrix} w' \\ u' \end{bmatrix} = \begin{bmatrix} T'_{11} & T'_{12} \\ T'_{21} & T'_{22} \end{bmatrix} \begin{bmatrix} w' \\ u' \end{bmatrix} .$$

Definitions and interpretations of the various signals shown in Figure 1(b) are listed in Table 1. Off-nominal conditions are handled in a manner similar to that shown in Figure 2. Specifically, off-nominal conditions are represented by injecting fictitious input signals at

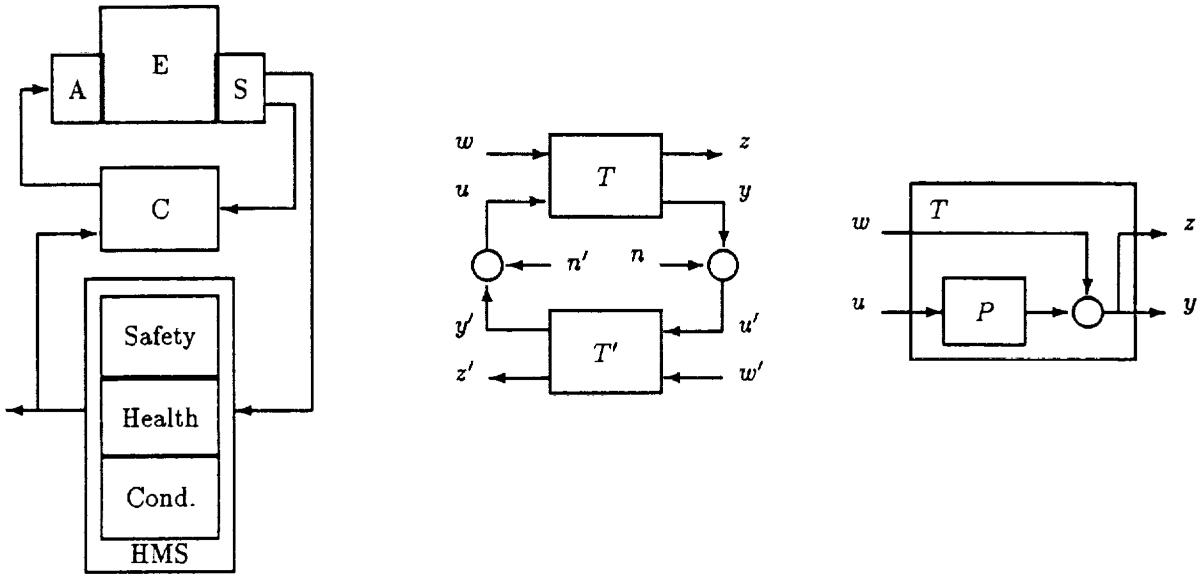
$$n = \eta + f \ , \ n' = \eta' + f' \ , \ w \ .$$

Here f, f' denote, respectively, sensor and actuator failures/degradations, η, η' denote, respectively, sensor and actuator noise, and w denotes internal failures/degradations. Both control and HMS design objectives can be stated in terms of these interpretations as indicated in Table 2.

The motivation for this choice of framework stems from the direct similarity between the generic architecture depicted in Figure 1(a) and the structure of the interconnection shown in Figure 1(b). We note that this similarity has already been suggested in the literature [5] for the case where the block T has the restricted form shown in Figure 1(c). However, this restriction has two severe limitations which make it inadequate for use in the present context: First, the fact that y is directly tied to the plant P output implies that no distinction is made between those sensors used for control and those used for diagnostics. In actual propulsion systems such as the SSME there are always many more sensors available for health monitoring than are used for control. Second, the fact that the exogenous plant input w is restricted to enter at the plant output corresponds reflecting respresentative failure inputs to the plant output, thus adding some degree of conservatism to this configuration. The results given below are extended to encompass the general T block.

Using straightforward transfer function analysis methods the interaction effects between the health monitoring module and the control module can be characterized and quantified. Table 3 summarizes some of the key tradeoffs uncovered using this analysis. For example, the first entry illustrates that sensor noise cannot be simultaneously rejected at the diagnostic output over the same frequency range that sensor faults are to be detected. This, in turn, means that there is a direct tradeoff to be made between sensor noise rejection and achievable diagnostic specifications. Similar arguments can be given for the other entries of Table 3, and although space constraints do not permit their inclusion here they are fully documented in [3] together with a more detailed analysis of the IHMC structure of Figure 1(b).

In addition to directly addressing issues related to interaction of health monitoring and controls modules the framework associated with Figure 1(b) can be used indirectly to obtain information on the problems pertinent to the design of IHMC. As one example, consider the problem of sensor suite selection, i.e., the problem of how to select a group of sensors to achieve a given level of health monitoring and control performance. Based on physical reasoning a candidate set of sensors can be selected thereby defining the entires of T. Once this is accomplished, analysis similar to that above can be used to see how eliminating certain sensors effects the overall IHMC performance. In this way trade studies can be formulated to analyze optimal sensor suite selection.



(a) (b) (c)

Figure 1: Generic Architecture.

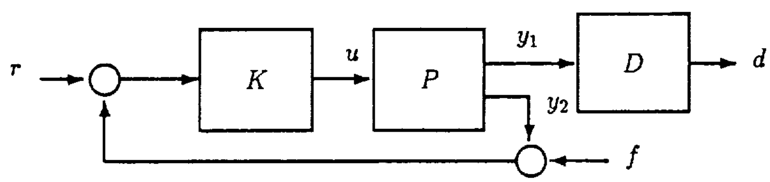


Figure 2: "Unintegrated" Health Monitoring and Control?

Signal	*Interpretation*	*Examples*
z	Engine output variables not sensed for IHMC	Thrust, etc.
y	Engine output variables sensed for IHMC	Pressures, Temperatures, etc.
w	Exogenous engine input variables	Disturbances, internal component failures, etc.
u	Engine input variables actuated by IHMC	Actual valve settings, etc.
z'	IHMC diagnostic output variables	Pressures, Temperatures, etc.
y'	IHMC output variables fed to Engine	Ideal valve settings, etc.
w'	Exogenous IHMC input variables	Controller commands, etc.
u'	IHMC input variables from Engine sensors	Actual sensor values, etc.
n, n'	Exogenous interconnection inputs	Noise, sensor failures, actuator failures, etc.

Table 1: Signal Interpretations for Figure 1(b).

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Control Objectives:
Interconnection should be stable.
Noise/Disturbance Rejection $\Rightarrow$ $M_{\eta y}, M_{\eta' y}, M_{wy} \approx 0$.
Command Tracking $\Rightarrow$ $M_{w'y} \approx I$.
Control Effort $\Rightarrow$ $M_{w'u}, M_{\eta u}, M_{\eta' u}$ sized reasonably.
Satisfy above robustly in the face of modeling errors.
Health Monitoring Objectives:
Noise Rejection $\Rightarrow$ $M_{\eta z'}, M_{\eta' z'} \approx 0$.
Command Rejection $\Rightarrow$ $M_{w' z'} \approx 0$.
Failure/Degradation Tracking $\Rightarrow$ $M_{f z'}, M_{f' z'} \approx I$.
Satisfy above robustly in the face of modeling errors.

Table 2: Control and Health Monitoring Objectives.

Sensor Noise Rejection vs. Sensor Fault Detection:
$M_{\eta z'} = M_{f z'}$
Actuator Noise Rejection vs. Actuator Fault Detection:
$M_{\eta' z'} = M_{f' z'}$
Sensor Fault Detection vs. Actuator Fault Detection vs. Internal Fault Detection:
$M_{f' z'} = M_{f z'} T_{22}$, $M_{w z'} = M_{f z'} T_{21}$

Table 3: Control/Health Monitoring Objective Conflicts/Interactions.