ADDRESSING INFORMATION OVERLOAD IN THE MONITORING OF COMPLEX PHYSICAL SYSTEMS

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Abstract: The objective of this research is to develop techniques for safe, reliable monitoring of complex, dynamic systems where human resources for sensor interpretation are constrained. The challenge is to avoid information overload and alarm escalation. Our approach is twofold: the current emphasis is on defining context-sensitive sensor ordering criteria to be used as a basis for selecting a subset of the available sensor data for presentation during system operations. The future emphasis will be on developing design analysis tools for assessing and defining monitoring requirements during the design phase.

The Problem

Physical systems which are to be monitored may be partitioned into three classes according to a complexity criterion (see Figure 1):

- Those of few sensor channels and low complexity which can be monitored safely and reliably using a comprehensive strategy (all sensor channels interpreted all of the time).
- Those of many sensor channels and high complexity which can be monitored safely and reliably using a selective strategy (some sensor channels interpreted all of the time).
- Those of very many sensor channels and very high complexity which cannot be monitored safely and reliably using any known or projected strategy.

COMPLEXITY	low few sensors	high many sensors	too high too many sensors
MONITORING STRATEGY	comprehensive	selective (a posteriori)	design analysis (a priori)

Figure 1. Complexity partitions and monitoring strategies.

All NASA space systems to date have been monitored using a comprehensive strategy. This strategy has been effective and appropriate because these space systems have been designed for uncomplicated behavior and have had relatively few, unsophisticated sensors. Experienced operators have been able to interpret sensor data coming down from these platforms without being overtaxed.

However, future space platforms such as the Lunar Outpost, Space Station Freedom, and the Earth Observing System network of satellites will contain upwards of 10,000 sensors. There will be insufficient human resources to continuously interpret all sensor data coming down from these platforms all of the time. Incidents at complex ground-based systems have already revealed the potential for alarm escalation. At the Three Mile Island nuclear facility, a simple fault cascaded through the system rapidly, firing over a thousand alarms in a matter of minutes. Operators were unable to deal with this volume of unfocused information.

In this work, we address the issue of information overload in the monitoring of complex systems by substituting a selective monitoring strategy for the inappropriate comprehensive monitoring strategy. The challenge is to identify context-sensitive sensor importance criteria so that operators are always presented with a non-overwhelming amount of relevant, informative data on the state of the system.

This selective strategy, which we believe will prove both effective and necessary for future space platforms, is nevertheless not a complete solution to the problem of information overload in monitoring. We must avoid a technology race between our ability to build complex systems and our ability to devise safe and reliable monitoring strategies to keep pace with the complexity. The selective monitoring approach as developed thus far is essentially an "after the fact" approach to monitoring complex systems. A complementary approach would involve assessing and defining monitoring requirements during the design phase. Space systems must be designed up front so as to ensure the ability to monitor them safely and reliably. We must avoid building systems which cannot be monitored even selectively.

The organization of this paper is as follows: First we describe our work on developing context-sensitive sensor ordering criteria as a basis for a selective monitoring strategy. Next we report on our progress in evaluating this approach on a NASA spacecraft domain. Then we present our ideas on developing design analysis tools for assessing and defining monitoring requirements. Designing for monitorability will be the next focus for this task.

Sensor Ordering Strategies

Our approach to avoiding information overload in the monitoring of complex physical systems involves defining sensor ordering criteria which assess the importance of sensor data according to context. The sensor orderings generated by the criteria are used as a basis for selecting information to be presented to human operators during system operations. This approach is depicted in Figure 2.

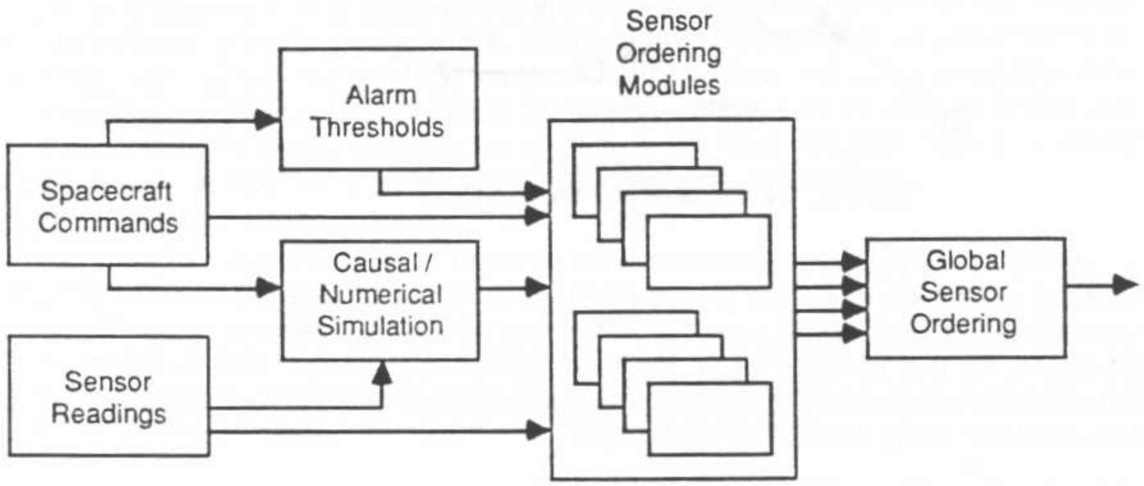

Figure 2. Selective Monitoring Based on Sensor Ordering.

The sensor ordering criteria we have defined thus far are as follows:

Causal Analysis: A causal simulation makes explicit which mechanisms in a system are active and which are inactive (e.g., a closed valve, an open switch). Sensors which report on active mechanisms are deemed more important.

A causal simulation also provides a dependency trace for predicted events. Sensors which report on events which are highly connected in the causal dependency graph are deemed more important. See Figure 3.

Disparity: Sensors which show a high disparity between predicted and actual values are deemed more important.

Alarm Thresholds: Safety thresholds can typically be defined *a priori* for operational limits and nominal ranges for major operating modes. Sensors are ordered according to the degree to which thresholds are exceeded.

Trend Analysis: The pertinent data are proximity to an alarm threshold and rate of change. Sensors are ordered according to the time of expected alarm threshold crossing. Sensors already in alarm are ordered according to the time of expected emergence from alarm state.

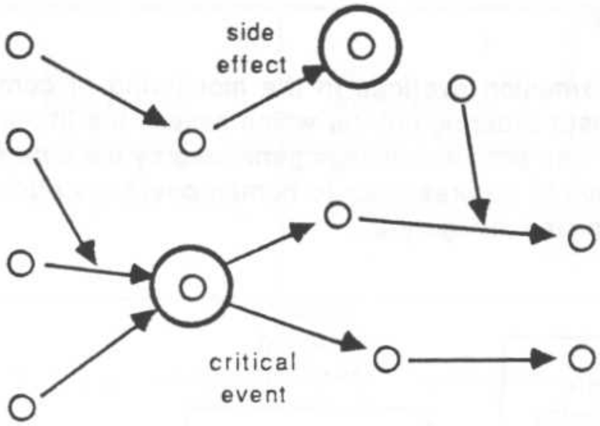

Figure 3. Causal dependency analysis.

Teleological Analysis: Teleological information can be used in several ways: 1) command sequences can be interpreted to predict intended behavior, 2) subsystems can be analyzed according to directness of contribution to purpose; e.g. a heating element directly contributes to the purpose of a thermal control system, 3) sensitivity to departures from designed purpose; the Voyager mission is replete with examples of basic spacecraft capabilities being utilized in novel ways.

Control Points: Sensors which are near to control points where there is the potential for intervention and corrective action are deemed more important.

Damage Potential: Sensors which report on subsystems which are susceptible to rapid, unrecoverable damage are deemed more important.

Redundancy: Sensors which report on subsystems which have no back-up or for which the back-up system is already on-line are deemed more important.

Recency: Recency information can be used in two ways: 1) the relevance of alarm information for which no response is taken is assumed to degrade over time, and 2) in a troubleshooting context where cascading faults are suspected, the earliest recorded alarm is deemed most relevant.

Probability of failure: Sensors which report on subsystems for which there is a history of unreliability are deemed more important.

We are exploring ways to quantify the information content of sensors for each of these importance criteria, being inspired by the precepts of information theory [Shannon 48] in general and by the minimum entropy approach utilized in GDE [de Kleer and Williams 87] in particular.

An open issue is how to combine the outputs of the various sensor ordering strategies into a global sensor ordering. Currently, a simple voting scheme is used which favors those sensors which have a high priority in several orderings, with no further weighting among the orderings.

Methodology

We are using the following methodology to evaluate the sensor ordering criteria both theoretically and empirically: Our domain experts provide us with operations scenarios for the systems we are modeling. These scenarios include command sequences, alarm thresholds, sensor data, and the results of simulation (see Figure 2); they reveal what data are selected out by the sensor ordering criteria. Our task is to assess the sensor ordering criteria for redundancy and synergy and to characterize how well the state of the system is captured by subsets of the available sensor data relative to the state description defined by all the sensor data. Some criteria may show poor performance for identifying alarm situations but may nonetheless provide useful complementary information to those criteria which do report on alarms. Some criteria may be better than others at characterizing the state of the system in the most compact manner. We will evaluate and refine the sensor ordering criteria based on these analyses.

The Domains

Our domain is the thermal control system for the High Precision Scan Platform of the Mariner Mark II spacecraft to be flown for the Comet Rendezvous and Asteroid Flyby (CRAF) mission. A diagram of this platform appears in Figure 4.

The purpose of the thermal control system is to maintain a thermal profile that ensures that each scientific instrument on the platform is within its operational temperature range. Each instrument has both an "on" and an "off" temperature range. The platform is equipped with heating elements for warming, louvers for cooling, and thermal socks for insulating some instruments from space or from each other.

At this writing, we have begun to model another NASA domain: the air recycling and water reclamation components of the ECLSS life support system testbed for Space Station Freedom.

Status

We have implemented the first four sensor ordering strategies described above for the CRAF thermal domain: causal analysis, disparity, alarm thresholds, and trend analysis. Our domain expert has provided us with operations scenarios for the platform which include the results of simulating a numerical model. We have constructed an approach to deriving a causal description from the results of numerical simulation which is outside the scope of this paper. We are currently evaluating the sensor ordering strategies using the methodology described above. Knowledge and data acquisition for the ECLSS life support system testbed has been initiated with personnel at Marshall Space Flight Center in Huntsville, Alabama.

The current SELMON prototype consists of mechanism representations and a causal simulation capability adapted from the JACK causal model generation system [Doyle 88], the implemented sensor ordering modules, and a user interface consisting of strip chart, causal graph, and sensor ordering displays. Earlier results from this project are reported in [Doyle et al 89a, Doyle et al 89b, Fayyad et al 90].

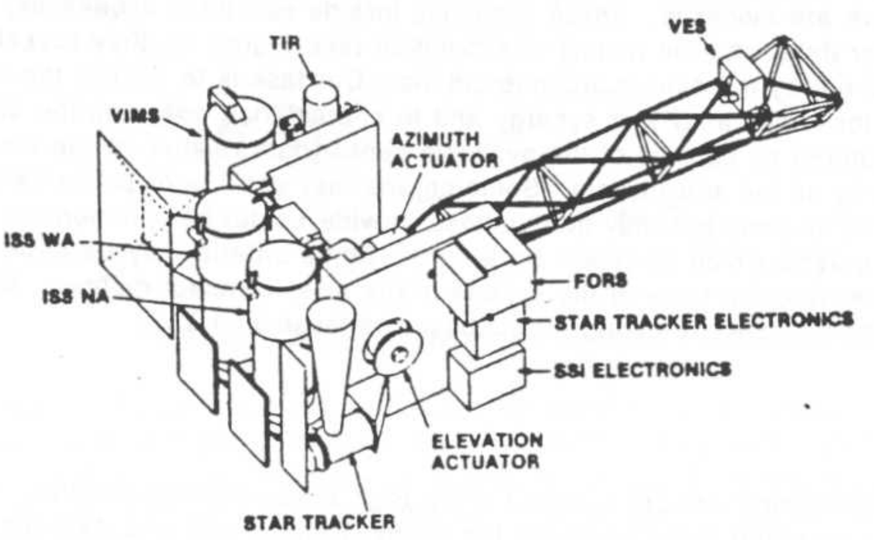

Figure 4. CRAF High Precision Scan Platform.

Design Tools for Assessing Monitoring Requirements

Current plans for this research call for investigation into sensor ordering strategies as a means of avoiding information overload in the monitoring of complex systems. Later, the task will shift to a complementary focus: the development of analysis tools for assessing and defining monitoring requirements during the design phase. One issue is: How many sensors should there be and where should they be placed? At this time, we have the following sketch of an approach to addressing this issue based on a generalization of our approach to sensor selection during monitoring:

- Generate a total envisionment for the device, including known fault behaviors.
- Apply the sensor ordering criteria to all device parameters across the behavior space.
- Place sensors at those locations corresponding to device parameters which are most frequently selected by the sensor ordering criteria across the behavior space of the device.

Relation to Other Work

This research effort introduces the notion of sensor ordering strategies, and unifies issues in design and monitoring [Dvorak and Kuipers 89]. Moreover, the task addresses the ubiquitous scale-up issue for AI systems, which has recently been taken up in the model-based reasoning literature as well [Forbus and Falkenhainer 88].

Acknowledgements

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Daniel Berleant and Usama Fayyad have also made important contributions to this work. We wish to thank Glenn Tsuyuki, our domain expert for the CRAF thermal control system.

References

[Doyle 88] R. J. Doyle, "Hypothesizing Device Mechanisms: Opening Up the Black Box", Technical Report 1047, Artificial Intelligence Laboratory, Massachusetts Institute of Technology, Cambridge, MA, June 1988. Also, submitted to *Artificial Intelligence* as "Constructing Device Models from Observations of Behavior".

[Doyle et al 89a] R. J. Doyle, S. M. Sellers, and D. J. Atkinson, "A Focused, Context-Sensitive Approach to Monitoring", *IJCAI-89*, Detroit, August 1989.

[Doyle et al 89b] R. J. Doyle, D. Berleant, L. P. Falcone, and U. M. Fayyad, "Selective Simulation and Selective Sensor Interpretation in Monitoring, *Computer in Aerospace VII*, American Institute for Aeronautics and Astronautics, Monterey, October 1989.

[Dvorak and Kuipers 89] D. L. Dvorak and B. J. Kuipers, "Model-Based Monitoring of Dynamic Systems", *IJCAI-89*, Detroit, August 1989.

[Fayyad et al 90] U. M. Fayyad, D. Berleant, L. K. Charest, R. J. Doyle, L. P. Falcone, K. Kandt, G. T. Tsuyuki, "Selective Processing in Monitoring: Autumn 89 Report, Report D-7103, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, February 1990.

[Forbus and Falkenhainer 88] K. D. Forbus, and B. Falkenhainer, "Setting Up Large-Scale Qualitative Models", *AAAI-88*, St. Paul, August 1988.

[Shannon 48] C. Shannon, "A Mathematical Theory of Communication", *Bell System Technical Journal*, **27**(3):379-423, 1948.

[de Kleer and Williams 87] J. de Kleer and B. C. Williams, "Diagnosing Multiple Faults", *Artificial Intelligence*, **32**(1):97-130, 1987.