In this issue, "25 Years Ago" revisits the article "Intelligent Hierarchical Thrust Vector Control for a Space Shuttle" by Keith Redmill, Umit Özgüner, Jeffrey Musgrave, and Walter Merrill in *IEEE Control Systems Magazine*, vol. 14, no. 3, pp. 13–23, 1994. Below is an excerpt from the article.

**A statistical model from reliability theory is used to estimate overall engine damage accumulation and failure risk.**

We present the design of a thrust vector controller for a space shuttle vehicle with multiple engines. This controller will maintain vehicle trajectory and thrust vector while minimizing risk and damage to each engine and to the propulsion system as a whole by independently controlling the thrust magnitude and exhaust cone gimbal angles of each engine. A statistical model from reliability theory is used to estimate overall engine damage accumulation and failure risk. An intelligent control system framework, which functionally decomposes the control task into a formal hierarchical structure composed of nominally independent task coordinators, is used to design and analyze the control structure for the entire propulsion system. One subtask that appears repeatedly within the hierarchy is that of distributing the required control actions among multiple engines or actuators dynamically in response to changing damage, risk, and status information. We identify this as the "control relegation

*Digital Object Identifier 10.1109/MCS.2019.2900813*
*Date of publication: 17 May 2019*



*Digital Object Identifier 10.1109/MCS.2019.2900814*

**We have seen that hierarchical structures in systems and dynamics can be matched to task hierarchies.**

problem" and solve it using linear quadratic optimal control techniques with variable weighting matrices. The individual controllers, when integrated into the formal structure, achieve the control objectives while minimizing mission risk and component stress and maximizing operating efficiency.

## SPACE SHUTTLE PROPULSION SYSTEM REQUIREMENTS

As described in the recent report of the Task Force on Intelligent Control, intelligent control techniques are used to address the control of large, interconnected dynamic systems with complex overlapping goals and constraints. We claim that such systems can be dealt with in an organized methodology that involves

1) identification of conceptual and structural hierarchies
2) modeling and analyzing subsystem dynamics and interactions
3) performing a formal goal-task decomposition
4) establishing specific, standard control problems corresponding to the task decomposition
5) completing the controller design by solving the standard control problems (4) and other required tasks (3).

In this article, we consider a space shuttle propulsion system as an illustrative example of the above design sequence. As in all design studies dealing with large, complex dynamic systems, the process involves the understanding of many subsystems, many goals, and many techniques.

Current studies in reusable rocket engine control design are driven by the need to improve the utility and flexibility of the vehicle-engine system, to improve its reliability and performance, and to increase vehicle availability through reduced maintenance [1]. Furthermore, experience with the space shuttle main engine has demonstrated the need to utilize more sophisticated planning and optimization to address engine durability issues and component problems induced by large vibrations, rapid thermal transients, acoustics, and other mechanisms associated with high performance engines.

Meeting these requirements will require an intelligent vehicle control system.

## BENEFITS OF INTELLIGENT PROPULSION SYSTEM CONTROL

One of the major attributes of so-called intelligent control systems is their utility in addressing the control of large, coupled dynamical systems with multiple, complex, interrelated operating requirements. The understanding of goals, the creation of hierarchies, and the identification of tasks, all with due consideration of fault tolerance, resource allocation, and sensor data fusion, are at the core of intelligent control. However, another important portion of intelligent control is the identification of control subproblems, which can be solved using standard control techniques and their integration into the overall intelligent control scheme.

This article has presented the problem of intelligent control for a space shuttle vehicle powered by reusable rocket engines. An intelligent control framework that decomposes the vehicle and its mission into a hierarchical system was discussed. Possible solutions to several implementation issues, including control action relegation, damage estimation, and risk management, were discussed. Finally, all of these ideas were illustrated by the design and simulation of a space shuttle vehicle thrust vector coordinator.

Although the work reported here is ongoing, several conclusions can be drawn. The main conclusion is that the methodologies collected here under the title of "intelligent control" can be applied to problems that involve large coupled dynamics and interrelated goals. We have seen that hierarchical structures in systems and dynamics can be matched to task hierarchies. We have also demonstrated that a formal goal-task decomposition provides both an additional insight and structure to the control problem and a suitable framework for controller implementation. Finally, we have illustrated these ideas on a nontrivial problem.

## REFERENCE

[1] C. Lorenzo and W. Merrill, "An intelligent control system for rocket engines: Need, vision, and issues," *IEEE Control Syst. Mag.*, vol. 11, pp. 42–46, Jan. 1991.