

## Nonlinear Multivariable Flight Control



F-35

Under contracts from NASA and the Air Force Research Laboratory, Honeywell and Lockheed Martin developed and documented a novel approach to flight control design. This multivariable flight control methodology based on nonlinear dynamic inversion was applied to the experimental X-35 military aircraft and the X-38 Crew Return Vehicle program and is now in production for the Lockheed Martin F-35 aircraft.

This work contributed to the advancement of advanced control technology and resulted in the control law being recognized as a design option for flight control development.

### Key Innovations

Nonlinear dynamic inversion control is a systematic generalized approach for flight control. Using general aircraft nonlinear equations of motion and onboard aerodynamic, mass properties, and engine models specific to the vehicle, a relationship between control effectors and desired aircraft motion is formulated. A control combination is designed that provides a predictable response to a commanded trajectory. Control loops shape the response as desired and provide robustness to modeling errors. Once the control law is designed, it can be used on a similar class of vehicle with only an update to the vehicle-specific onboard models.

Specific innovations include:

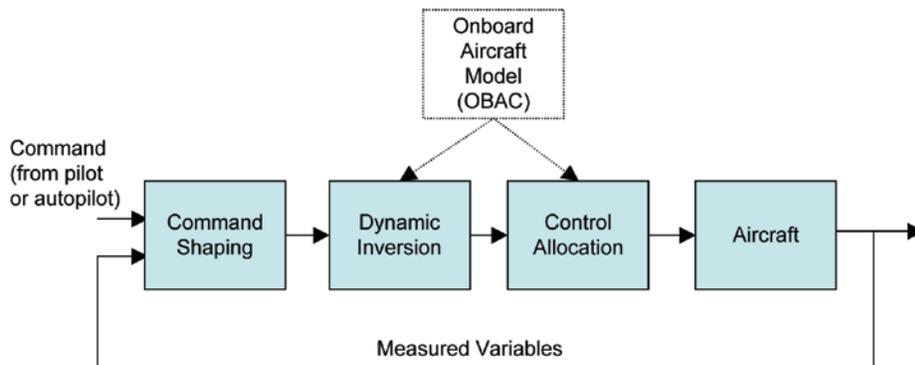
- The dynamic inversion control law
- A control allocation procedure
- An onboard aircraft model (OBAC)

### Previous Practice

Nonlinear dynamic inversion is the first systematic approach to nonlinear flight control. Prior to this development, the control law was typically designed from a set of linear plant models and implemented with a gain-scheduled linear controller. The performance capabilities of the aircraft were not fully realized, and the manually intensive development process was time consuming.

### Onboard Aircraft Model (OBAC)

The NASA/Honeywell/Lockheed Martin flight control approach includes the first use of an aircraft model in the control law. This model is used to derive coefficients for dynamic inversion and control allocation computations. Changes in vehicle structure during design often only require changing the OBAC model for the controller.





F-18

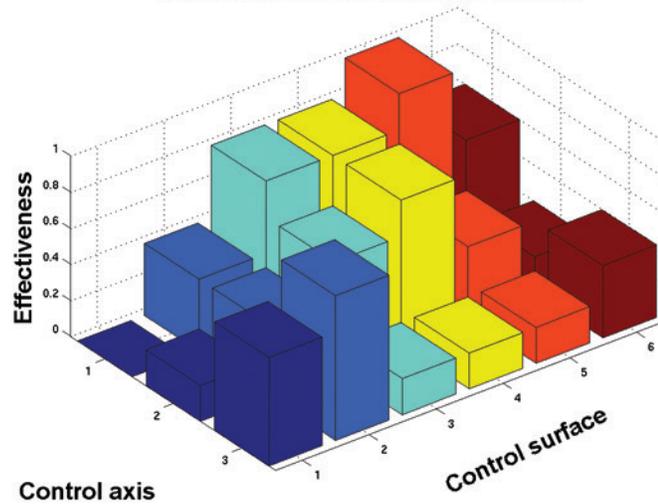


X-38

## Nonlinear Dynamic Inversion

Dynamic inversion “inverts” the aircraft model to identify what roll, pitch, and yaw moments will give the desired aircraft trajectory. Sophisticated numerical algorithms are used to ensure rapid computation and to deal with actuation rate and deflection limits. The inversion is calculated onboard at each control loop iteration during flight.

### Control Effectiveness Model



## Control Allocation

Modern aircraft have redundant actuation capabilities—the same airframe response can be achieved with different combinations of actuators. The problem of determining which actuators to use, and to what extent, at a given instant is referred to as control allocation. The nonlinear dynamic inversion methodology computes an optimal control allocation, taking into account saturation constraints on actuators. The actuators of interest for the applications developed are the control surfaces (ailerons, elevators, rudder) and thrust vectoring (directing the engine thrust). A control effectiveness model is used in the computation (see figure above).

## Program History

The work described in this success story began in the mid-1980s as a theoretical development for an airplane designed for high-angle-of-attack maneuverability. A Honeywell nonlinear dynamic inversion design was selected as the controller for the F-18 research vehicle and implemented in a full hardware-in-the-loop piloted simulation.

In the late 1990s, NASA began the X-38 Space Station Crew Return Vehicle program. The nonlinear dynamic inversion controller was proposed for this program and allowed control updates as the vehicle’s structural design changed by simply updating the OBAC model.

These and other foundational projects led to the collaboration between Honeywell and Lockheed Martin, as well as the implementation of nonlinear dynamic inversion on the X-35 prototype and eventually the production F-35 vehicle, the latest state-of-the-art military aircraft. The controller has provided consistent, predictable control through the transition from conventional flight to hover and has also enabled a 4X to 8X reduction in nonrecurring engineering development cost.

*For more information: Honeywell and Lockheed Martin, Multivariable Control Design Guidelines, Final Report, WL-TR-96-3099, Wright Patterson AFB, Ohio, USA, 1996.*