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**ON-LINE AERODYNAMIC
IDENTIFICATION FOR SPACE ACCESS
VEHICLES (PREPRINT)**



**Daniel A. Allwine, Joseph E. Fisher, Jeremy A. Strahler, Ming Wu,
Isaac Rose, Jianwei Guan, and Douglas A. Lawrence**

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**//Signature//*

Michael W. Oppenheimer
Electronics Engineer
Control Design and Analysis Branch
Air Force Research Laboratory
Air Vehicles Directorate

//Signature//

Deborah S. Grismer
Chief
Control Design and Analysis Branch
Air Force Research Laboratory
Air Vehicles Directorate

//Signature//

Brian W. Van Vliet
Chief
Control Sciences Division
Air Force Research Laboratory
Air Vehicles Directorate

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On-Line Aerodynamic Identification for Space Access Vehicles

Daniel A. Allwine, Joseph E. Fisher, Jeremy A. Strahler
Austral Engineering & Software, Inc., Athens, OH, 45701-3208

and

Ming Wu, Isaac Rose, Jianwei Guan, and Douglas A. Lawrence
Ohio University, Athens, Ohio 45701-2979

Abstract

This paper describes the on-going development of a comprehensive integrated guidance and control architecture featuring an on-line aerodynamic identification scheme that produces a global estimate of a damaged vehicle's aerodynamic characteristics. This estimate is used to derive updated constraints reflecting the vehicle's degraded maneuverability that are incorporated into computationally efficient algorithms for on-line trajectory reshaping/retargeting. This paper presents recent progress on a Multiple-Model Adaptive Estimation approach to the global aerodynamic estimation process. The scheme utilizes diagnostic information assumed to be provided by a vehicle health monitor to generate a bank of aerodynamic models in which each model is created by an aerodynamic prediction code for a vehicle configuration reflecting a particular type of damage. The individual models are blended through weights that are adapted on-line using measured data.

Nomenclature

V	=	vehicle speed
M	=	Mach number
χ	=	heading angle
γ	=	flight path angle
α	=	angle-of-attack
β	=	sideslip angle
σ	=	bank angle
L	=	aerodynamic lift force
D	=	aerodynamic drag force
C_L	=	aerodynamic lift coefficient
C_D	=	aerodynamic drag coefficient
ω_B	=	body-axis angular velocity vector
τ_B	=	body-axis moment vector
\bar{q}	=	dynamic pressure
ρ	=	air density
S	=	reference area
s	=	ground-track arc length
W	=	vehicle weight
m	=	vehicle mass
g	=	gravitational acceleration constant

I. Introduction

NEXT-generation hypersonic vehicles will require advanced flight mechanics technology that delivers enhanced adaptability, reconfigurability, and autonomy in order to cope with a wide variety of contingencies. Coordinated adaptation and reconfiguration of the outer-loop guidance laws, inner-loop control laws, and control allocation module has proven to be effective in responding to off-nominal flight conditions and certain failure modes⁹. This alone, however, is incapable of maintaining stability and maneuverability in the face of damage or malfunction so severe as to render the nominal trajectory intrinsically unflyable. This has spurred research activity on the development of guidance algorithms suitable for on-line implementation and therefore able to handle situations in which the nominal trajectory must be reshaped or retargeted on-the-fly^{5,6,11,13-16}.

An important issue arises in that the vehicle's aerodynamic characteristics impact the trajectory design problem in the form of control authority constraints which capture the ability to trim the vehicle with the available effector suite. These constraints depend in a complicated way on the effector limits as well as flight condition and therefore vary over the entire trajectory. As such, the characterization of these constraints requires a substantial portion of the aerodynamic database. This poses a significant challenge for trajectory reshaping/retargeting in that a new *global* aerodynamic database is needed for the damaged vehicle in order to derive updated control authority constraints for the remainder of the trajectory. Since it is not possible to anticipate all possible damage scenarios, the goal is to process available vehicle health information and on-line measurements reflecting only the current flight condition in order to produce a global aerodynamic estimate.

This paper presents recent progress in the development of an integrated guidance and control architecture. Here we focus on an on-line aerodynamic identification scheme that produces a global estimate of a damaged vehicle's aerodynamic characteristics. This estimate is used to derive updated constraints reflecting the vehicle's degraded maneuverability that are incorporated into computationally efficient algorithms for on-line trajectory reshaping/retargeting.. The work described herein, sponsored under an Air Force Small Business Innovation Research (SBIR) Phase II contract, is in progress at the time of this submission. Results presented are of a preliminary nature and will be replaced by more mature counterparts if the paper is accepted.

The remainder of the paper is organized as follows. A high-level overview of the integrated guidance and control (IG&C) architecture is presented in the next section. Section III describes the on-line aerodynamic identification scheme in greater detail. Section IV presents a demonstration of the on-line identification scheme and illustrates its utility in the on-line trajectory generation process. Finally, Section V offers some concluding remarks.

II. Technical Overview

Figure 1 contains a block diagram of the on-line trajectory generation architecture. The Trajectory Generator is the portion of the architecture that will compute feasible trajectories given appropriate knowledge of constraints representing vehicle performance and characteristics. This system employs a novel formulation of the trajectory design problem that unifies path, endpoint, motion, and control authority constraints into a single framework.

The On-Line Identification component represents a unique way of generating an adaptive estimate of the vehicle's global aerodynamic characteristics after unforeseen damage and/or malfunction have occurred. The approach uses information from a Vehicle Health Monitor (VHM) to establish criteria for generating a set of initial global estimates of aerodynamic information derived from an aerodynamic prediction code such as Missile Datcom. On-line measurements of the forces and moments exerted on the vehicle in conjunction with the corresponding motion variables and effector settings are then used to adaptively tune the global database. In addition to an updated global aerodynamic model, local correction information is also generated to improve vehicle control.

The Constraint Estimator uses the output of the On-Line Identification module to control allocation scheme, which is cast as an internal subsystem. The output of the Constraint Estimator essentially represents an estimate of the aerodynamic constraints that are needed for generation of a feasible trajectory by the Trajectory Generator.

The Trajectory Generator and On-Line Identification/Constraint Estimator represent the core technologies currently under development. In addition to those components, the authors will continue the development of enhanced

guidance and control laws that will be used within an X-37 simulation environment to evaluate the trajectory design methodology. Improvements to these designs are underway that take advantage of recent developments in the control of nonlinear Euler-Lagrange systems and in nonlinear control allocation.

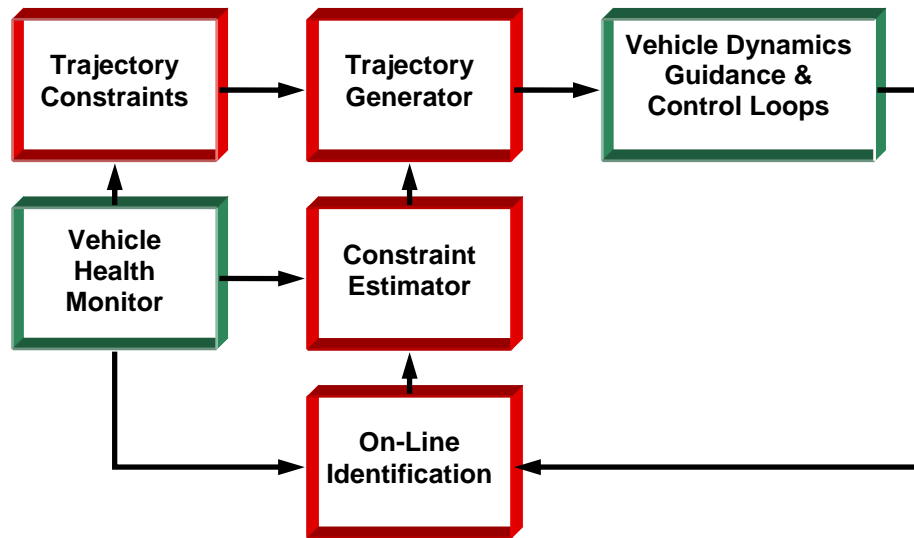


Figure 1: On-Line Trajectory Generation Architecture

III. On-Line Aerodynamic Identification

Embedded in the trajectory design process are constraining relationships cast in terms of the vehicle's aerodynamic characteristics (e.g., lift, drag, etc.) over the entire flight envelope. The on-line trajectory generation design scheme therefore requires reasonably accurate global aerodynamic information. For nominal trajectory designs, this information is known from the data obtained during the vehicle design and development process. However, *a priori* aerodynamic information for a damaged vehicle typically does not exist. For this reason, the ability of the IG&C system to generate a valid trajectory on-line will depend upon its ability to produce reasonably accurate on-line estimates of the vehicle's aerodynamic characteristics after damage and/or failure have occurred. The updated aerodynamic characteristics would then be used to establish new constraints for the trajectory design problem. It should be noted that the constraint estimates addressed here are those that deal with the ability to trim the vehicle. Reformulating constraints on structural loading, heat rate, and other traditional path constraints based on vehicle damage information is considered beyond the scope of this work. In words, the implications are as follows:

1. Trajectory design requires knowledge of control authority constraints on the vehicle over its entire flight regime.
2. Estimating trimmability constraints is equivalent to a trimmability analysis, which is based upon the control allocation problem.
3. Control allocation utilizes an accurate aerodynamic database.

The feedforward/feedback aerodynamic identification architecture is depicted in Figure 2. This system utilizes vehicle damage/malfunction information reported by a Vehicle Health Monitor, global estimates produced by an aerodynamic prediction code such as Missile Datcom, and on-line measurements of the forces and moments exerted on the vehicle and the corresponding motion variables and effector settings to generate an adaptive estimate of the vehicle's global aerodynamic characteristics. This information is combined with a local correction to arrive at an overall aerodynamic model that is used for trajectory design and control.

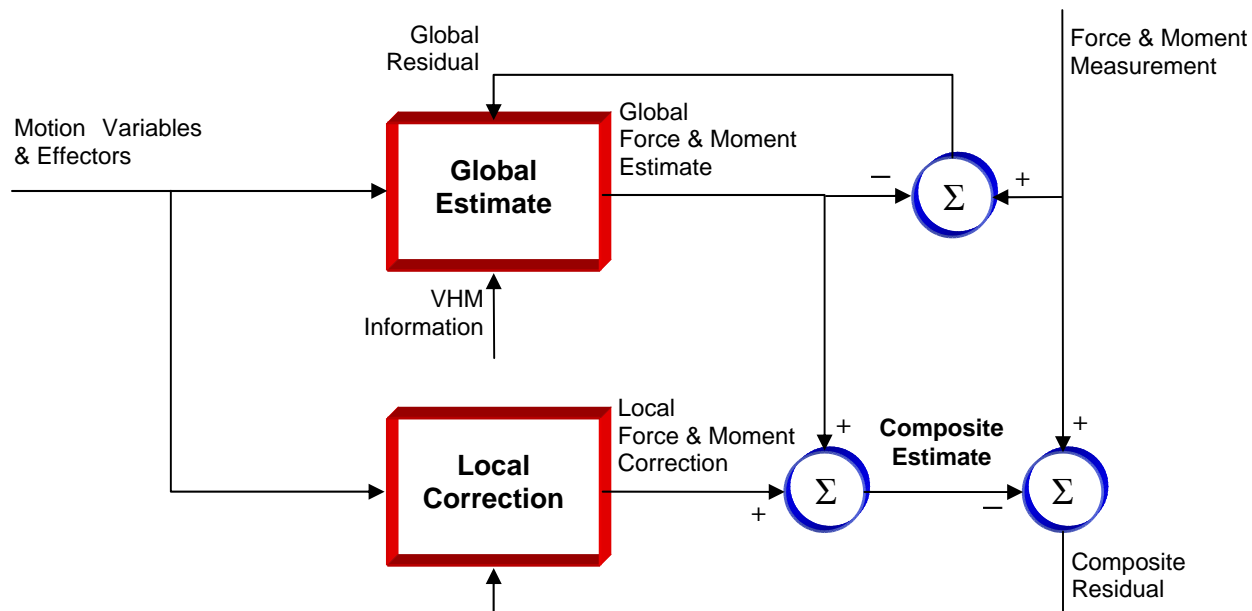


Figure 2: Aerodynamic Identification Architecture

The Global Estimate component will employ a Multiple-Model Adaptive Estimation (MMAE) methodology to exploit the availability of an aerodynamic prediction code in order to overcome the diagnostic limitations of the Vehicle Health Monitor. Specifically, while the Vehicle Health Monitor may be capable of localizing the damage or malfunction (e.g., damage to the left wing) and crudely estimating the extent of the damage (e.g. 25% of the outboard portion of the left wing is missing), it is unlikely that this information alone will suffice for the calculation of an accurate global aerodynamic database necessary for trajectory reshaping/retargeting.

The output of the Global Estimate component will be fed forward to create a residual used by the Local Correction component. The Local Correction component will employ Locally Weighted Learning (LWL)^{1,12,8} to make local corrections to the aerodynamic estimate while not interfering with the Global Estimate component. The improved accuracy afforded by these local corrections will likely yield improved performance by the reconfigurable flight control system as well as benefit trajectory reshaping/retargeting.

In this paper we focus on the Global Estimate block, shown in greater detail in Figure 3, displays the Multiple-Model Adaptive Estimation (MMAE) approach⁷. The underlying idea is as follows. The failure diagnosis provided by the Vehicle Health Monitor is used to populate a set of hypothetical configurations for the damaged vehicle. For example, if the Vehicle Health Monitor estimates that 25% of the outboard portion of the left wing is missing, then hypothetical configurations would involve left wing damage quantified by percentages of missing wing distributed about the 25% estimate provided by the Vehicle Health Monitor.

Each of the models represents an aerodynamic database computed by an aerodynamic prediction code such as Missile Datcom, which is used in the current effort. Each database consists of a set of look-up tables along with the associated interpolation schemes which mathematically can be represented by a function of the general form

$$y = f(x, \lambda)$$

in which the independent variable x corresponds to motion variables including angle-of-attack, Mach number, sideslip angle, altitude, and body rates along with effector settings. The parameter vector λ quantifies the vehicle configuration reflecting the particular damage mode, and the dependent variable y represents the body axis forces

and moments. Given a set of damage configurations represented by parameter vectors $\lambda_1, \lambda_2, \dots, \lambda_N$ chosen based on the Vehicle Health Monitor estimate represented by the parameter vector λ_0 , the MMAE estimate is given by

$$\hat{y} = \hat{f}(x) = \sum_{j=0}^N \theta_j f(x, \lambda_j)$$

in which the scalar model weights $\theta_0, \theta_1, \dots, \theta_N$ are chosen to minimize the least-squares deviation between a set of measurements of the dependent variable and the associated output of the MMAE estimator. As more on-line measurements become available over time, the weights can be adapted via standard recursive least-squared techniques¹.

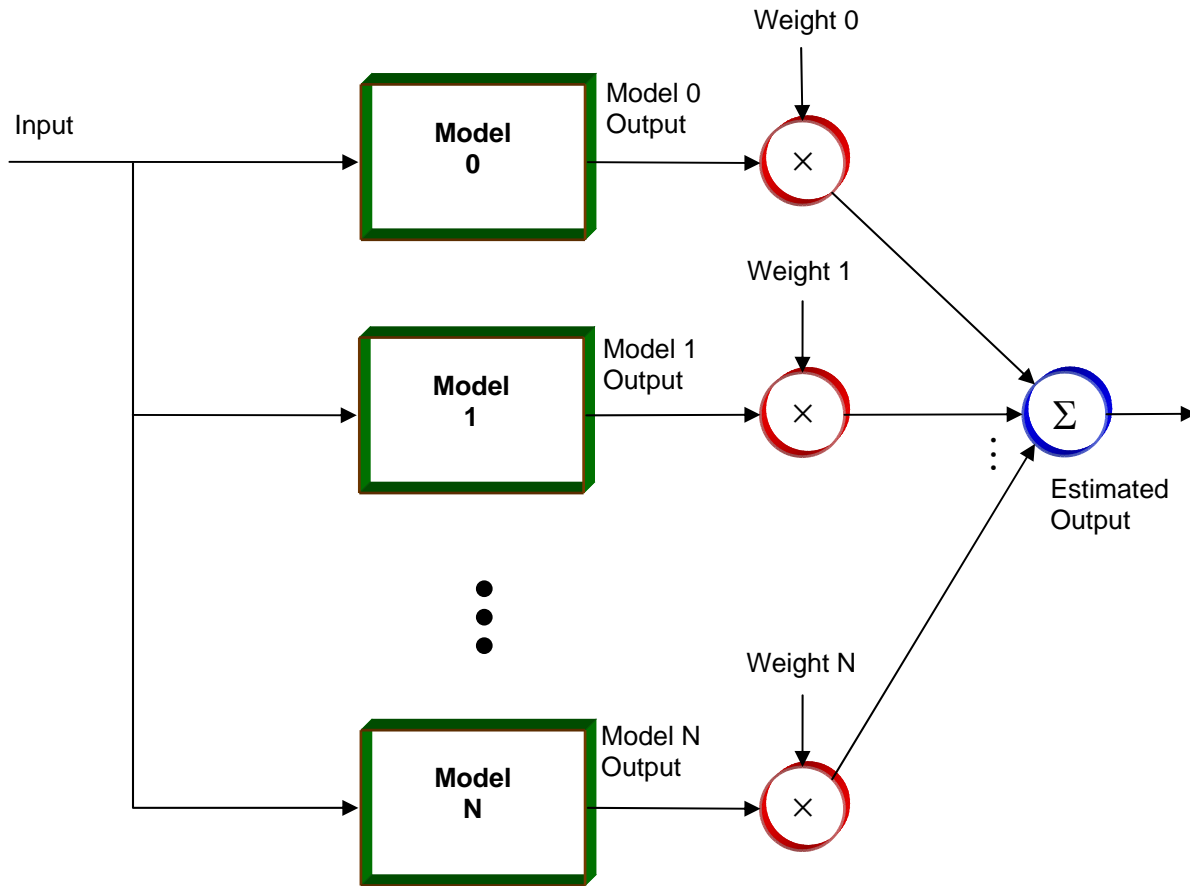


Figure 3: Multiple Model Adaptive Estimation

IV. Demonstration

In this section we demonstrate the performance of the MMAE estimation scheme and illustrate its utility in the trajectory reshaping process. We consider a simulation scenario involving an X-37 entry trajectory with end-point constraints given in Table 1. In addition, we impose path constraints on the trajectory summarized in Table 2.

PARAMETER	INITIAL VALUE	FINAL VALUE
Altitude (ft)	200,000	10,000
Speed (ft/s)	18,900	360
Ground Track x -coordinate (ft)	0	8,400,000
Ground Track y -coordinate (ft)	0	700,000
Heading Angle (degrees)	0	-10

Table 1: X-37 Entry Trajectory End-Point Constraints

PARAMETER	UPPER BOUND
Heat Rate (btu / ft ² s)	70
Dynamic Pressure (lbs/ft ²)	300
Normal Force (gees)	2.5

Table 2: X-37 Entry Trajectory Path Constraints

In our simulation scenario, the vehicle initially flies a nominal entry trajectory designed on the basis of a nominal aerodynamic database produced by Missile Datcom. One hundred seconds into the 20 minute trajectory, the vehicle experiences damage to the left ruddervator modeled as 50% of the surface missing. Based on VHM information indicating that 49% of the left ruddervator is missing, the MMAE architecture is assembled with six aerodynamic models generated by Missile Datcom representing 45%, 47%, 49%, 51%, 53%, and 55% of the left ruddervator missing. Each such model produces three body axis forces and three body axis moments as a function of angle-of-attack, Mach number, sideslip angle, altitude, body axis angular rates, and control surface deflections. Trajectory data is collected at a 100 Hz rate for 20 seconds over which time the model weights are adapted via recursive least squares. It should be noted that the trajectory tracking laws are still under development; hence the trajectory data used in the on-line adaptation process was taken directly from the nominal reference trajectory. For the final version of the paper, the vehicle response with the trajectory tracking loops closed will be used for on-line adaptation. The time history of the model weights over the 20 second adaptation window is shown in Figure 4. With noise-free measurements, recursive least-squares adaptation yields monotonic convergence. It has been noted that noisy data do impact weight convergence, which is a topic of ongoing investigation.

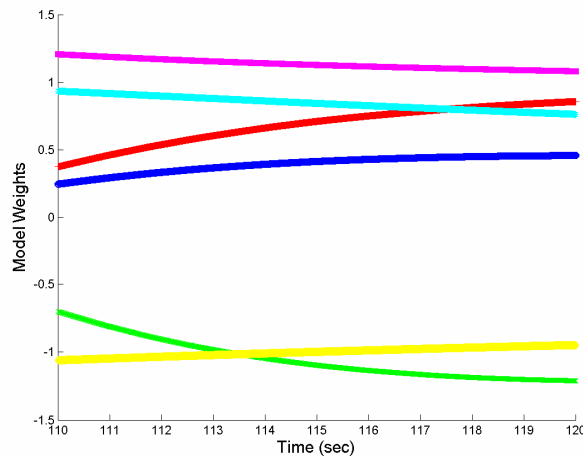


Figure 4: Multiple Model Weight Adaptation

The MMAE estimator consists of the six aerodynamic models with outputs blended according to Figure 3 using the values of the weights obtained at the end of the 20 second adaptation window. Figure 5 through Figure 10 illustrate the accuracy of the MMAE estimator as compared to the Missile Datcom-derived truth model corresponding to 50% of the left ruddervator missing. Corresponding to each of the three body axis forces and the three body axis moments, these figures include a surface plot of the force or moment of the MMAE estimate superimposed on a surface plot of the truth model versus angle-of-attack and Mach number for zero sideslip angle, zero body axis angular rates, zero effector deflections, and an altitude of 100,000 ft. These plots indicate good agreement between the MMAE estimate and the truth model in terms of both absolute error and relative percentage error. Note that the relative error plot for pitching moment is adversely affected by the fact that the true pitching moment is zero or very small over particular portions of the angle-of-attack/Mach number domain.

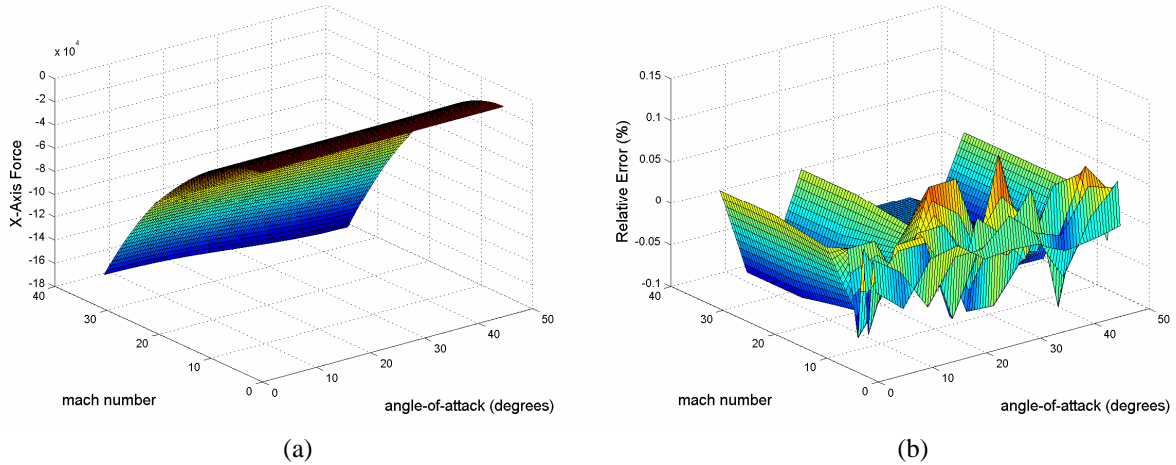


Figure 5: X-Axis Force (a) truth model and MMAE estimate and (b) relative error

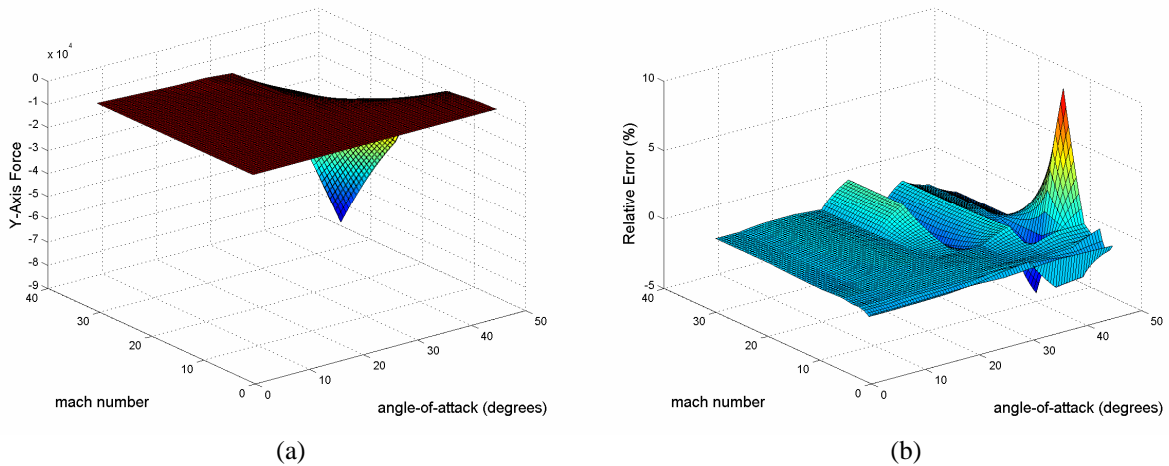
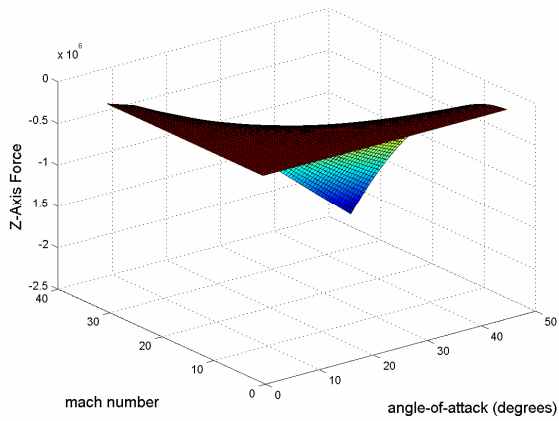
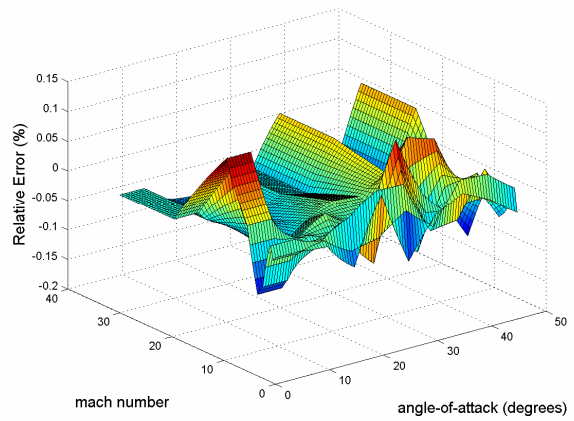


Figure 6: Y-Axis Force (a) truth model and MMAE estimate and (b) relative error

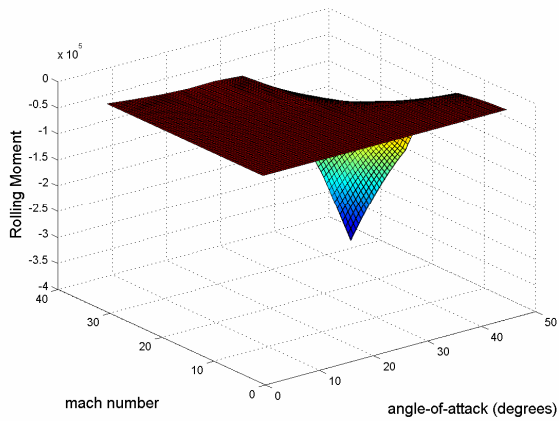


(a)

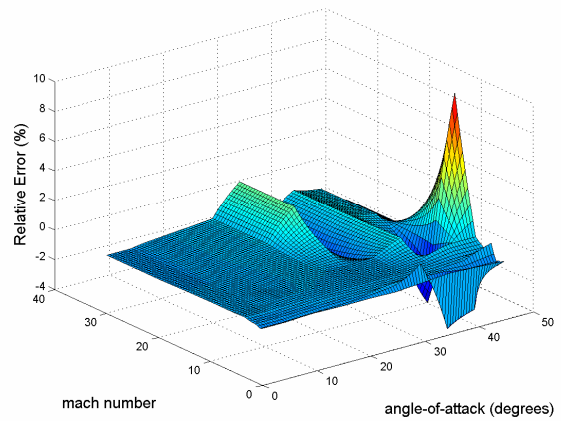


(b)

Figure 7: Z-Axis Force (a) truth model and MMAE estimate and (b) relative error

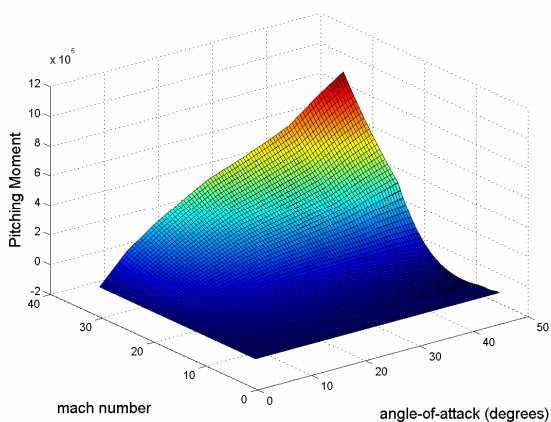


(a)

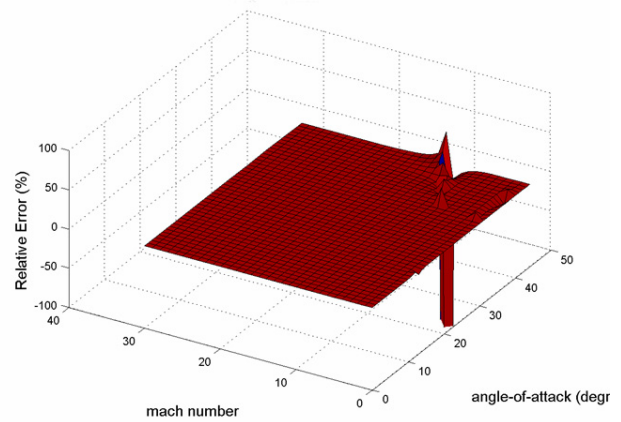


(b)

Figure 8: Rolling Moment (a) truth model and MMAE estimate and (b) relative error



(a)



(b)

Figure 9: Pitching Moment (a) truth model and MMAE estimate and (b) relative error

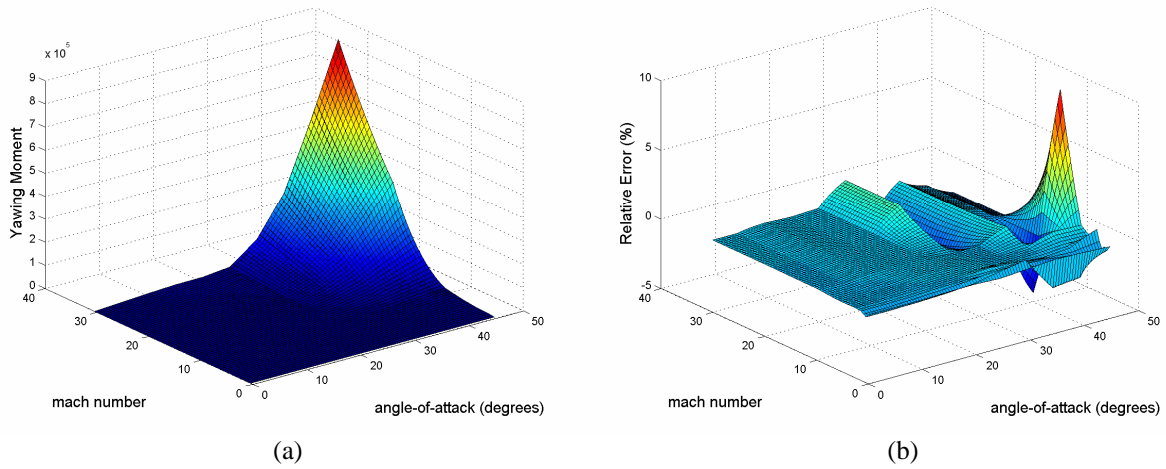


Figure 10: Yawing Moment (a) truth model and MMAE estimate and (b) relative error

Once the MMAE weight adaptation process is complete, the on-line trajectory generator uses the MMAE estimate as an aerodynamic model of the damaged vehicle in order to re-evaluate the possibly diminished vehicle maneuverability and reshape the remainder of the trajectory accordingly. Specifically, the control authority analysis consisting of identifying angle-of-attack/Mach number conditions at which rotational trim cannot be achieved (assuming zero body-rates) is repeated yielding the trim deficiency map shown below in Figure 11. For comparison purposes, the trim deficiency map derived from the MMAE estimate is shown beside the trim deficiency map derived from the truth model of the damaged vehicle. The results are nearly identical, indicating that the damaged vehicle cannot be rotationally trimmed at high Mach number, high angle-of-attack conditions, suggesting that a reshaped trajectory may be required that respects this new constraint that was not present for the nominal vehicle.

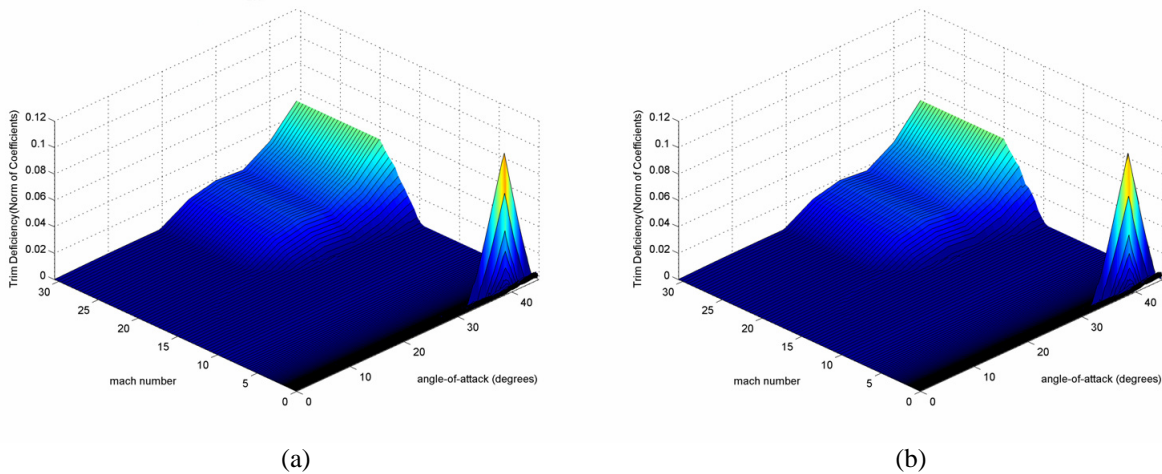


Figure 11: Trim deficiency maps derived from (a) the truth model and (b) the MMAE estimate

To continue with the trajectory reshaping process, the effector settings derived from the control authority analysis are subsequently used together with the MMAE aerodynamic estimate to compute trim lift and drag maps yielding lift and drag force profiles versus angle-of-attack and Mach number that incorporate the impact of effectors set at their required deflections for minimizing trim deficiency. The trim lift and drag profiles are shown below in Figure 12 and Figure 13, respectively, for both the truth model (true failure case) and the vehicle as characterized by the MMAE estimate. With trim lift and drag maps in hand, the on-line trajectory generation algorithm, also developed under this effort, is invoked, now initialized using the vehicle state at 120 seconds. The effect that the vehicle

damage has on the control authority constraints and trim lift and drag characteristics manifests itself in the reshaped trajectories as reflected in the speed vs. altitude and ground track plots shown below in Figure 14 and Figure 15, respectively.

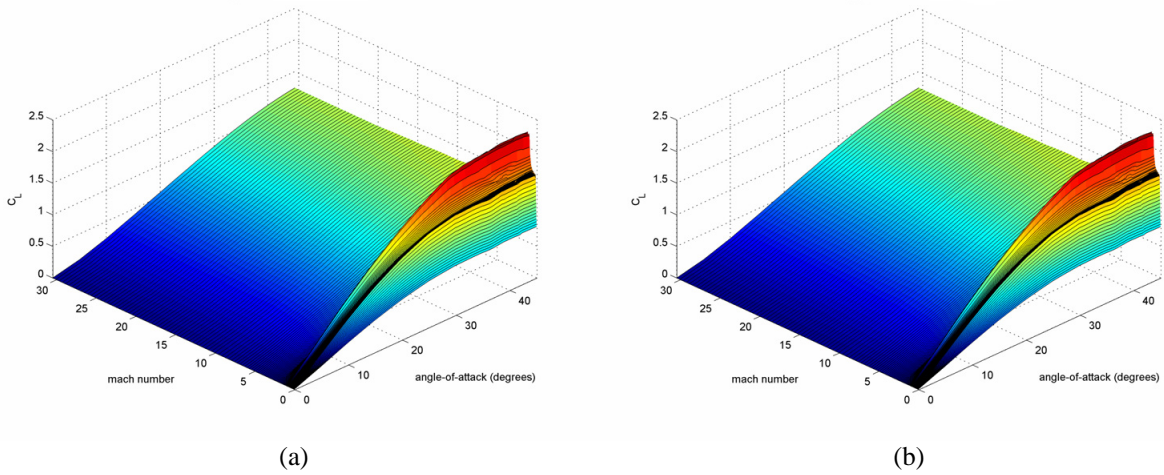


Figure 12: Trim lift map for (a) the truth model and (b) the MMAE estimate

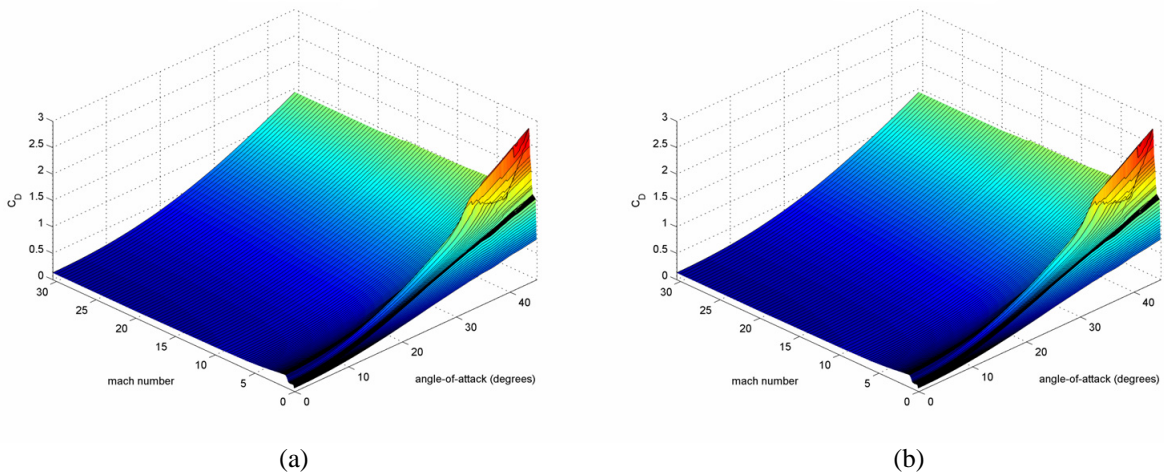


Figure 13: Trim drag map for (a) the truth model and (b) the MMAE estimate

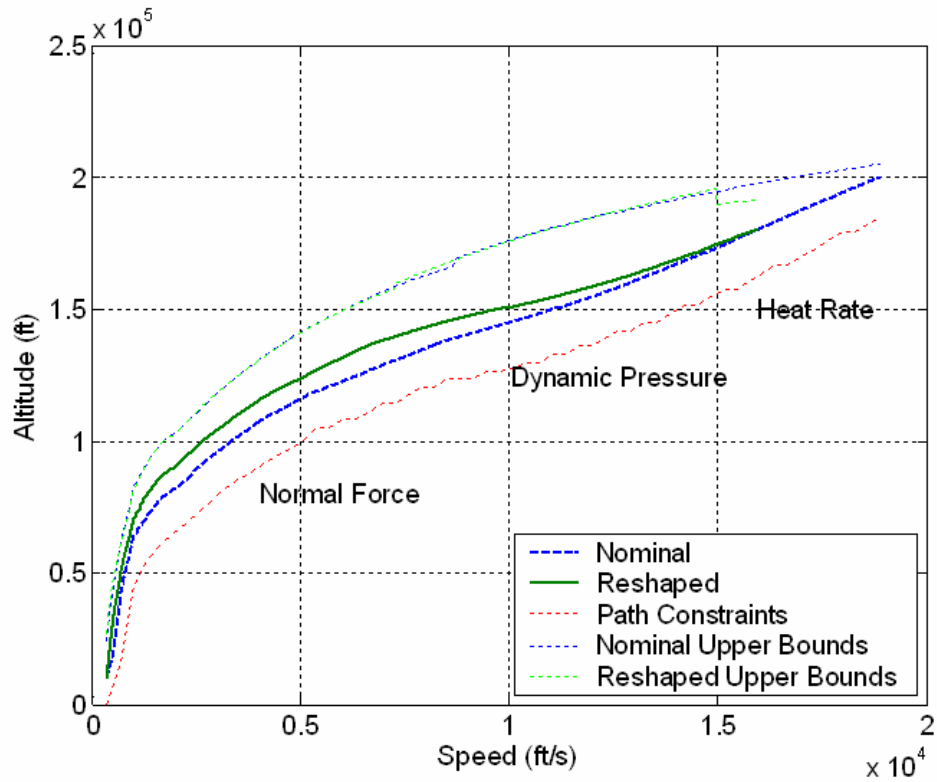


Figure 14: Nominal and reshaped speed vs. altitude profiles

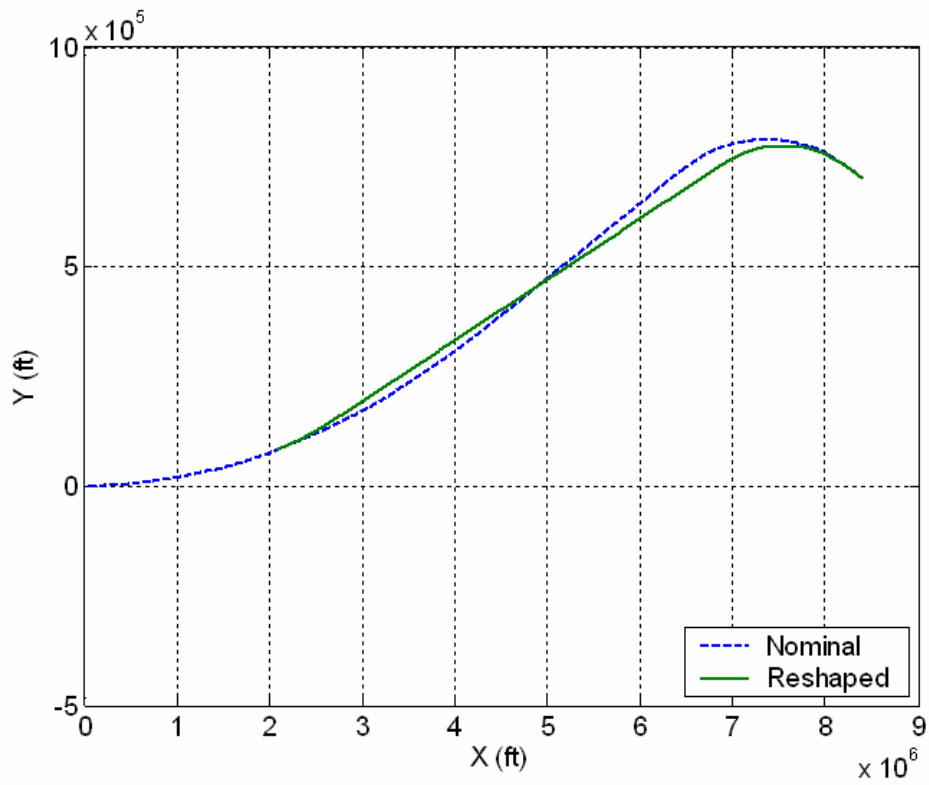


Figure 15: Nominal and reshaped groundtracks

V. Conclusions

This paper has presented an on-line aerodynamic identification scheme that produces a global estimate of a damaged vehicle's aerodynamic characteristics. In order to derive a global estimate from on-line measurements necessarily limited to range a vicinity of the flight condition at the onset of vehicle damage, a Multiple-Model Adaptive Estimation approach has been adopted to exploit the ability to generate global aerodynamic estimates using aerodynamic prediction codes such as Missile Datcom. The underlying idea is to use cursory diagnostic information provided by a Vehicle Health Monitor to populate a bank of aerodynamic models and then use the measurements available on-line to adapt the weights that are used to blend the individual model outputs into a single aerodynamic estimate. The MMAE technique plays a crucial role in the integrated guidance and control architecture that is currently under development. It provides an avenue to quickly reformulate the control authority constraints that reflect the reduced maneuverability of the damaged vehicle, which are then used in the on-line trajectory reshaping/retargeting process.

As noted in the Introduction, the results presented here are of a preliminary nature. Results demonstrating the integrated performance of the on-line identification scheme, on-line trajectory generation capability, and adaptive/reconfigurable guidance and control laws will be available for inclusion in the final manuscript and presentation at the conference should the paper be accepted.

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