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Design and flight-testing of non-linear formation control laws

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Abstract

This paper presents the results of a research effort focused on the modeling, identification, control design, simulation, and flight-testing of YF-22 research aircraft models in closed-loop formation. These models were designed, manufactured, and instrumented at West Virginia University (WVU). The first phase of flight tests was performed with the goal of exciting all the aircraft dynamic modes. The recorded flight data were then used for a parameter identification study. The output of this study was a mathematical model of the WVU YF-22 aircraft, which was then used for the design of the formation control laws. The design of the formation control laws is based on an inner/outer loop design with the objective of controlling the forward, lateral, and vertical distances between two aircraft in the formation. The design for the outer loop scheme was based on feedback linearization while a root locus-based approach was used for the design of the inner loop scheme. The paper presents experimental results validating the performance of the formation control laws using a 'virtual leader' configuration.

Keywords: Formation flight; Guidance; UAV; Non-linear control; Non-linear dynamic inversion; Feedback linearization

1. Introduction

Autonomous formation flight is a growing research area within the aerospace flight control community. The benefits of formation flight and development of formation control problems have been well documented (Giulietti, Pollini, & Innocenti, 2000; Pachter, D'Azzo, & Proud, 2001). General behavioral approaches (Anderson & Robbins, 1998; Giulietti, Pollini, & Innocenti, 2001; Stankovic, Stanojevic, & Siliak, 2000), as well as 'leader–follower' formations (Campa, Wan, Napolitano, Seanor, & Fravolini, 2004; Hall, 2000; Lavretsky, 2002; Mengali & Giulietti, 2004; Schumacher & Kumar, 2000) have been investigated in recent years, leading to the introduction of different classes of compensation-type controllers. Additionally, non-linear approaches (Boskovic, Li, & Mehra, 2001, 2002; Kale & Chipperfield, 2005; Oosterom & Babuska, 2006; Yang, Masuko, & Mita, 2004) are also becoming of interest due to their capability of explicitly taking into account non-linearities that are typical of the formation control dynamics.

This paper presents some of the results of a 4-year research project in formation flight control sponsored by the US Air Force Office of Scientific Research (AFOSR), and performed at West Virginia University (WVU), more details on the effort are described in Napolitano (2005), Campa, Seanor, Gu, and Napolitano (2005), Gu et al. (2006). The ultimate goal of the project was the experimental demonstration of formation flight using three YF-22 aircraft models designed, manufactured, and instrumented at WVU (Figs. 1 and 2).

Specifically, in the planned flight configuration, a radio control (R/C) pilot on the ground was required to maintain control of the leader aircraft while one or more follower aircraft was required to maintain a pre-defined position and orientation with respect to the leader.

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Nomenclature

a	linear acceleration (m/s^2)
b	wingspan (m)
$\bar{c}$	mean aerodynamic chord (m)
f	forward distance between 'leader' and 'follower' aircraft (m)
fun	generic function
g	gravitational acceleration (m/s^2)
h	vertical distance between 'leader' and 'follower' aircraft (m)
H	altitude (m)
l	lateral distance between 'leader' and 'follower' aircraft, (m)
m	aircraft mass (kg)
p	roll rate (deg/s)
q	pitch rate (deg/s)
$\bar{q}$	dynamic pressure (PSI)
r	yaw rate (deg/s)
S	wing platform area (m^2)
T	thrust (N)
V	speed (m/s)
x	position of an object along the x-axis (m)
y	position of an object along the y-axis (m)
z	position of an object along the z-axis (m)

Greek letters

α	angle of attack (deg)
β	angle of sideslip (deg)
δ	command input
θ	pitch angle (deg)
ϕ	roll angle (deg)
χ	azimuth angle (deg)
ξ	aircraft state vector
Ω	angular turn rate (rad/s)
ρ	air density (kg/m^3)

Subscripts

A	aileron
d	desired value
e	error between desired and measured variable
f	forward
H	stabilator
i	command input
L	'leader'
l	lateral
R	rudder
s	speed
T	throttle
x	projection along the x-axis
xy	projection along the horizontal plane
y	projection along the y-axis
z	projection along the z-axis

Acronyms

AFOSR	air force office of scientific research
BLS	batch least square
CSDS	control signal distribution system
CPU	central processing unit
DAQ	data acquisition
DIO	digital input/output
ECU	engine control unit
EMI	electromagnetic interference
FCS	flight control system
GPS	global positioning system
GUI	graphical user interface
IDE	integrated drive electronics
IMU	inertial measurement unit
NLDI	non-linear dynamic inversion
MB	mega byte
OBC	on-board computer
PID	parameter identification
PWM	pulse width modulation
R/C	radio controlled
RMS	root mean square
RF	radio frequency
SIO	serial input/output
UAV	unmanned aerial vehicle
VL	virtual leader
WVU	West virginia university

Within (Campa et al., 2004) a compensation-type approach has been proposed for the design of a set of formation control laws based on an outer/inner loop architecture. That design was tested in a Simulink-based formation flight simulation environment; however, it lacked a validation with experimental results. The main contribution of this paper is to present a new design approach where the outer loop formation control scheme relies on the use of a non-linear dynamic inversion (NLDI)-based set of control scheme. The above design is performed using a mathematical model of the WVU YF-22 aircraft, which is obtained through a detailed parameter identification (PID) study.

Furthermore, the overall design is validated experimentally through flight-testing using the 'virtual leader' (VL) configuration. Specifically, the objective of the VL flight-testing phase was to assess the performance of the formation control scheme in terms of capabilities for maintaining a pre-defined position and orientation with respect to a previously recorded flight path.

The paper is organized as follows. First, a detailed description of the test-bed aircraft and the relative avionic payload is provided. Next, the development of the linear and non-linear mathematical models of the WVU YF-22 aircraft through a PID study is described. Following