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Hardware-in-the-Loop Testing of a Fuel Cell Aircraft Powerplant

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This paper presents the experimental methods and test results of a hardware-in-the-loop simulation of the powerplant for a small-scale fuel-cell-powered unmanned aerial vehicle. In this study, the hardware associated with the powerplant, power train, energy storage, and control systems operates dynamically as a component within a real-time aircraft simulation routine. Control signals, electrical loads, and mechanical loads are applied to the hardware to emulate the conditions of operation of the unmanned aerial vehicle powerplant during flight. Experimental results from hardware-in-the-loop testing of the fuel cell power train are presented with uncertainty analysis and discussion. These results show new aspects of the performance of fuel cell unmanned aerial vehicle powerplants, including the powerplant performance during long-endurance missions, power train subsystem power consumption, and unmodeled fuel cell dynamics. A comparison of the measured powerplant performance to experimental results from the literature shows that the fuel cell powerplant can outperform advanced electrochemical energy storage and internal combustion powerplants at the scale of the hardware-in-the-loop aircraft.

Nomenclature

C_D	=	aircraft coefficient of drag
C_L	=	aircraft coefficient of lift
C_q	=	propeller coefficient of torque
C_{rr}	=	coefficient of rolling resistance
C_T	=	propeller coefficient of thrust
D	=	drag force, N
d	=	propeller diameter, m
E	=	propulsive energy, J
E^O	=	standard potential of the oxygen reduction reaction, 1.229 V
g	=	acceleration due to gravity, m/s^2
h	=	aircraft altitude, m
$h_{desired}$	=	desired aircraft altitude, m
h_{error}	=	error in aircraft altitude, m
I_{sp}	=	specific impulse, s
J	=	propeller advance ratio
L	=	lift force, N
m	=	aircraft mass, kg
m_{power}	=	powerplant mass (including power train, fuel, and tankage), kg
n_{cells}	=	number of cells in the fuel cell stack
P_{H2}	=	hydrogen pressure in the fuel cell anode manifold, Pa
Q	=	propeller and electric motor torque signals, $N \cdot m$
q_{H2}	=	flow rate of hydrogen, kg/s
S_w	=	wing area, m^2
s	=	range, m
T	=	thrust force, N
t	=	endurance, h
t_{cmd}	=	throttle command
t_{PWM}	=	pulse-width-modulated throttle command
v	=	airspeed, m/s
$v_{desired}$	=	desired aircraft velocity, m/s
v_{error}	=	error in aircraft velocity, m/s
W	=	weight force, N
α	=	angle of attack, rad
γ	=	climb path angle, rad
θ_{fc}	=	fuel cell temperature, °C
ρ	=	air density, kg/m^3
ϕ	=	bank angle, rad
ω	=	propeller rotational speed, rad/s
ω_{fans}	=	fuel cell stack fan rotational speed, rad/s

I. Introduction

SMALL-SCALE, electrically powered, unmanned aerial vehicles (UAVs) are currently in use performing a variety of reconnaissance and remote sensing missions. For these missions, electrically powered UAVs are generally preferred to small-scale internal combustion UAVs because of their low cost, reliability in the field, physical robustness, and simple rechargability. A desire for longer endurance than is available from the current generation of commercially available batteries has motivated the development of electrical UAV powerplants with higher specific energy [1,2]. These proposed powerplants incorporate fuel cells [3,4], advanced electrochemical energy storage [5], and hybrid electric systems [6,7]. These advanced powerplant designs often include dynamic subsystems, active controls, and other implementation challenges that will require new development methods and tools.

This paper presents a study of the performance of a fuel-cell-powered UAV using a hardware-in-the-loop (HIL) simulation of the aircraft in flight. HIL simulation is a paradigm of system synthesis, evaluation, and testing; wherein, a dynamic system can be emulated by immersing physical components of some of its subsystems within a closed-loop virtual simulation of the remaining subsystems [8]. HIL testing is currently used for aviation and automotive control system software development [8,9]. For the UAV powerplant application, HIL substitutes portions of the aircraft hardware with

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