ROBUST ACTUATOR CONTROLLER FOR ACTIVE-TRUSS-BASED MORPHING WING

BY

DIFAN TANG

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Contents

Abstract

The active-truss-based morphing wing (ATBMW) is a new type of smart structure, which is more efficient than airfoils with conventional control surfaces. However, the sophisticated ATBMW framework and large numbers of actuators make it difficult to obtain the overall structural dynamics for controller design and inconvenient to tune actuators on board. Our research therefore aims to develop an actuator-level control scheme to simplify the process of controller implementation on ATBMWs so that the above problems regarding controller design and on-board tuning can be bypassed.

The proposed control scheme is based on the concept of unknown-input estimation and compensation in a servomechanism. A new unknown-input estimator (UIE) is developed and integrated with a Linear-Quadratic-Gaussian (LQG) controller to provide enhanced compensation of uncertainties. By doing so, the resultant controller can be designed and tuned simply using the dynamics of the actuator, without the necessity to know the dynamics of the entire wing structure. Existing techniques for estimating unknown inputs to a system require at least one or more of the following: detailed knowledge on unknown inputs, derivatives of measured outputs, inversion of plant dynamics, constrained state observer design, parameter optimisation (global optimum not guaranteed), or complicated designs. The new UIE developed in this thesis is exempted from the aforementioned limitations and features a simple structure and straightforward design.

To validate the proposed UIE-integrated LQG controller, an ATBMW prototype with 5 linear actuators is built. For comparison, a PID controller is introduced in both simulations and experiments. Both types of controllers are designed using two sets of models obtained via system identification: one set represents actuator dynamics only, while the other set includes wing structural dynamics.

In simulation study, system sensitivity and stability robustness are firstly investigated against parameters associated with the UIE component, with guidelines for designing the proposed UIE-integrated LQG controller validated. The mechanism of unknown-input compensation is then demonstrated by dividing unknown inputs into exogenous disturbances and internal uncertainties and examining the two situations separately.

Compared with a standard LQG controller, the UIE-integrated LQG controller shows enhanced capability in rejecting unknown inputs. Lastly, the UIE-integrated LQG controller is implemented on all the 5 actuators in the presence of only internal uncertainties, and compared with the PID controller. Superior performance of the UIE-integrated LQG controller over the PID algorithm is observed in simulations.

In experimental study, wind tunnel tests were conducted to further validate the efficacy of the UIE-integrated LQG controller under both aerodynamic loads and modelling errors. The performance of the UIE-integrated LQG controller designed according to actuator dynamics is closely comparable to that of its congener based on wing structural dynamics, and both outperform the PID controller.

In conclusion, the new UIE is capable of effective estimation of unknown inputs. The UIE-integrated LQG controller has an enhanced capacity to compensate a wide class of unknown inputs including exogenous disturbances and internal uncertainties, and meanwhile the ease of design is maintained. The most significant merit of applying the proposed controller on an ATBMW is that the implementation of actuator controllers is considerably simplified despite the complexity of the ATBMW framework. The controller can be based on actuator dynamics only, and can be tuned on individual actuators before the actuators are assembled on the wing. Therefore, the process of controller implementation is free from structural coupling constraints, and there is no need to obtain wing structural dynamics for controller design and to further tune actuators on board.

Beyond the merits mentioned above, the proposed controller has broader significance in the following two aspects. Firstly, it provides a unified solution to simplifying actuator controller implementation on ATBMWs despite the variations and complexity of ATBMW structures, and is thus significant to successful realisations of a wide range of promising ATBMW concepts; Secondly, the enhanced capacity of disturbance rejection is crucial to aerodynamic improvements achieved by ATBMWs as it ensures reliable performance of wing morphing in the presence of unmeasured and unpredictable exogenous loads.

Declarations

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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DIFAN TANG

Date

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List of Tables

List of Figures

List of Acronyms

ATBMW	active-truss-based morphing wing
DOB	disturbance observer
LQ	linear-quadratic
LQG	Linear-Quadratic-Gaussian
MIMO	Multi-Input Multi-Output
PID	proportional-integral-derivative
PIO	proportional-integral observer
SISO	Single-Input Single-Output
SMA	shape memory alloy
UIDO	unknown-input-decoupled observer
UIE	unknown-input estimator
UIO	unknown-input observer

Nomenclature

Latin Letters	Definition	Unit
a	Average cross section area of a strut	m^2
$\boldsymbol{A}$	System matrix (continuous-time domain)	
a_w	Planform area of an airfoil	m^2
b	Coefficient (general)	
$\boldsymbol{B}$	Input matrix (continuous-time domain)	
c	Coefficient (general)	
$\boldsymbol{C}$	Output matrix (continuous-time domain)	
C_L	Lift coefficient	
d	Unknown/disturbance input (general)	
$\boldsymbol{D}$	Direct transmission term (continuous-time domain)	
d_e	Unknown/disturbance input (equivalent)	
e	Error	
E	Young's modulus	N/m^2
f	Force (in local Cartesian coordinate system)	N
F	Force (in global Cartesian coordinate system)	N
F_L	Lift force	N
g	Order of derivatives	
G	Transfer function (general)	
H	Transfer function (feedback controller)	
i	The i^{th} quantity	
$\boldsymbol{I}$	Identity matrix	
j	Imaginary operator	
J	Performance index	
k	The k^{th} quantity	
K	Controller gain (scalar)	
$\boldsymbol{K}$	Controller gain (matrix)	

Latin Letters	Definition	Unit
l	Length of a strut	m
$\boldsymbol{L}$	State observer gain matrix	
m	Denominator order of a transfer function	
M	Transfer function (un-modelled dynamics)	
n	Number (general)	
N	Filter coefficient (for the derivative term of PID)	
p	Numerator order of a transfer function	
P	Transfer function (actual plant)	
P_n	Transfer function (nominal plant)	
q	Nodal displacement along the axial direction of a strut	m
$\boldsymbol{Q}$	Weighting matrix	
r	Reference input	
R	Weighing scalar	
$\boldsymbol{R}$	Weighing matrix	
s	Complex variable	
S	Sensitivity function	
t	Time (general)	s
$\boldsymbol{T}$	Transformation matrix	
t_s	Sampling interval	s
u	Control input	
U	Nodal displacement (in global Cartesian coordinate system)	m
V	Volume of a strut	m^3
v_a	Air velocity	m/s
w	Process noise	
$\boldsymbol{W}$	General matrix	
x	System state	
y	System output	
z	Variable of z-transform	
$\boldsymbol{Z}$	General matrix	

Greek Letters	Definition	Unit
α	Deviation	
β	Stability robustness index	
γ	General scalar	
$\boldsymbol{\Gamma}$	Stiffness matrix (in global Cartesian coordinate system)	N/m
δ	Impulse function	
Δ	Ratio of tracking deviation	%
ε	Strain	
$\boldsymbol{\zeta}$	General matrix	
η	System state (intermediate variable)	
θ	Angle	rad
$\boldsymbol{\Theta}$	Transformation matrix	
$\boldsymbol{\kappa}$	Stiffness matrix (in local Cartesian coordinate system)	N/m
κ	Generalised stiffness of a single strut	N/m
$\boldsymbol{\mu}$	Matrix of nonlinear functions	
ξ	Residual unknown input/disturbance	
ρ	Density of air	kg/m^3
σ	Stress	N/m^2
τ	Time constant	s
υ	Residuals	
$\boldsymbol{\Phi}$	General Matrix	
$\boldsymbol{\psi}$	Transformation matrix	
ω	Frequency	rad/s
ω_c	Cutoff frequency of a low-pass filter	rad/s

Superscripts	Definition	Unit
(i)	The i^{th} quantity	
(k)	The k^{th} quantity	
(e)	The e^{th} element	

Subscripts	Definition	Unit
0	Before change (initial state)	
a	Actuator related	
act	Actual	
c	Nominal controller related	
d	Unknown input/disturbance related	
D	Derivative	
dac	Disturbance-accommodating-controller	
des	Desired	
e	External	
f	Filter related	
i	The i^{th} quantity	
I	Integral	
k	The k^{th} quantity	
L	State observer related	
P	Proportional	
t	After change (final state)	
v	Intermediate variable related	
w	Internal model related	
z	Discrete-time domain related	