Acta Astronautica 122 (2016) 114–136

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Suboptimal LQR-based spacecraft full motion control: Theory and experimentation

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ARTICLE INFO

Article history:
Received 19 January 2015
Received in revised form
18 November 2015
Accepted 18 January 2016
Available online 2 February 2016

Keywords:
Spacecraft
Optimal control
Linear quadratic regulator
Six-degree-of-freedom
Real-time
Experimental test

ABSTRACT

This work introduces a real time suboptimal control algorithm for six-degree-of-freedom spacecraft maneuvering based on a State-Dependent-Algebraic-Riccati-Equation (SDARE) approach and real-time linearization of the equations of motion. The control strategy is sub-optimal since the gains of the linear quadratic regulator (LQR) are re-computed at each sample time. The cost function of the proposed controller has been compared with the one obtained via a general purpose optimal control software, showing, on average, an increase in control effort of approximately 15%, compensated by real-time implementability. Lastly, the paper presents experimental tests on a hardware-in-the-loop six-degree-of-freedom spacecraft simulator, designed for testing new guidance, navigation, and control algorithms for nano-satellites in a one-g laboratory environment. The tests show the real-time feasibility of the proposed approach.

1. Introduction

As spacecraft technology has evolved, robust and efficient automated control has become an essential mission capability. Over the last fifty years, in fact, worldwide aerospace research environments have addressed their work to the optimization of guidance, navigation and control performances, also paying attention to the propellant consumption and time-to-launch costs.

It is clear, then, how high efficiency controls, ensuring both position accuracy and propellant optimization, have become a critical issue in the control systems scope and specifically in the aerospace sector.

The spacecraft six degrees of freedom optimal control problem has been widely analyzed in the literature, lately focusing on spacecraft relative motion, usually requiring numerical methods [1]. Spacecraft formation and the optimization of relative maneuvers are becoming increasingly important topics of investigation. This is due to the benefits

Abbreviation: ADAMUS, Advanced Autonomous Multiple Spacecraft; APF, artificial potential function; AS, attitude stage; BP, balancing platform; CPU, central processing unit; DARPA, Defense Advanced Research Projects Agency; DCM, direction cosine matrix; EKF, extended Kalman filter; GDC, guidance dynamics corporation; IBPS, intelligent battery and power system; IPOPT, interior point optimizer; KKT, Karush–Kuhn–Tucker; LGR, Legendre Gauss Radau; LKF, linear Kalman filter; LQE, linear quadratic estimator; LQR, linear quadratic regulator; LVLH, local vertical local horizontal; MIMO, multi-input multi-output; MP, moving platform; NLP, nonlinear programming; ONR, Office of Naval Research; PWM, pulse width modulator; RTAI, Real-Time Application Interface; S/C, spacecraft; SNOPT, Sparse Nonlinear OPTimizer; TS, translational stage

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http://dx.doi.org/10.1016/j.actaastro.2016.01.016
0094-5765/

Nomenclature

$\mathbf{0}_{m\times n}$	zero matrix with dimensions m, n
$\boldsymbol{A}$	state matrix (Jacobian)
$\boldsymbol{A}_{rot}$	state matrix rotational contribute
$\boldsymbol{A}_{transl}$	state matrix translational contribute
$\boldsymbol{B}$	input matrix (Jacobian)
$\boldsymbol{B}_{transl}$	input matrix translational contribute
$\boldsymbol{B}_{rot}$	input matrix rotational contribute
$\boldsymbol{C}$	output matrix
$\boldsymbol{D}$	feedforward matrix
d	thrusters moment arm with respect to the center of rotation of the AS [d=0.32 m]
${}^{E}\boldsymbol{DCM}_{B}$	direction cosine matrix from the body (B) to the inertial reference frame (E) [23]
F	propellant cost (–)
$\mathcal{F}$	generalized force vector ($\boldsymbol{F},\boldsymbol{M}$)
F_t	nominal thrust (F_t=0.3 N)
$\boldsymbol{F}_{thrust}$	force generated by the onboard thrusters (N)
$\mathcal{F}_{LQR}$	optimal generalized force, output of the LQR Simulink block
G	universal gravitational constant ($\mathrm{m^3\,kg^{-1}\,s^{-2}}$)
$\boldsymbol{H}$	thruster distribution matrix or mapping matrix
$\boldsymbol{H}_f$	force term of the thruster distribution matrix $\boldsymbol{H}$
$\boldsymbol{H}_m$	torque term of the thruster distribution matrix $\boldsymbol{H}$ (m)
$\boldsymbol{I}_{m\times n}$	identity matrix with dimensions m, n
$\boldsymbol{J}$	inertia matrix ($\mathrm{kg\,m^2}$)
J	global maneuver cost (–)
$\boldsymbol{K}$	Kalman gain
K_{pos}, K_{rot}	additional dimensionless gains characterizing the adaptive tuning, applied to the state weighting matrix position and angular terms only
$\boldsymbol{M}$	angular momentum vector (N m)
$M_{\oplus}$	Earth mass (kg)
$\mu_{\oplus}$	Earth gravitational parameter $\mu = GM_{\oplus}$ ($\mathrm{m^3\,s^{-2}}$)
m	spacecraft simulator mass (kg)
$n=\sqrt{\mu_{\oplus}/\boldsymbol{R}_0^3}$	generic orbital rate (rad/s)
$\boldsymbol{\omega}$	angular velocity vector (rad/s)
$\omega_x, \omega_y, \omega_z$	angular velocity vector components (rad/s)
$\boldsymbol{P}$	solution of the Riccati differential equation
P	position cost (–)
p	thrusters inclination with respect to the imaginary square circumscribed to the attitude stage basis ($p=\cos(45^{\circ})=\sin(45^{\circ})$)
$\boldsymbol{Q}$	state weighting matrix (mixed dimensions to generate dimensionless cost)
$\boldsymbol{Q}_{transl}$	state weighting matrix translational contribute
$\boldsymbol{Q}_{rot}$	state weighting matrix rotational contribute
$\boldsymbol{R}$	input weighting matrix (mixed dimensions to generate dimensionless cost)
$\boldsymbol{R}_0$	generic orbit radius (m)
${}^{\omega}\boldsymbol{kin}_{\dot{\theta}}$	kinematics matrix relating the time derivative of the Euler angles with the angular velocity [23]
ρ	additional gain influencing the input weighting matrix (–)
$\boldsymbol{\theta}$	Euler angles vector (rad)
$\theta_x, \theta_y, \theta_z$	Euler angles (rad)
$\boldsymbol{U}^{*}$	generic LQR optimal solution
$\boldsymbol{U}_{cont}$	normalized continuous thrust vector (N)
U_{cost}	net propellant expenditure (–)
$\boldsymbol{u}_{10}$	normalized binary thrust vector (–)
u_a	dimensionless parameter with magnitude correspondent to the nominal thrust
v_x, v_y, v_z	linear velocity vector components (m/s)
$\boldsymbol{X}$	generalized state vector ($\boldsymbol{x},\dot{\boldsymbol{x}},\boldsymbol{\theta},\boldsymbol{\omega}$)
$\boldsymbol{X}_{des}$	desired generalized state
$\boldsymbol{X}_{err}$	actual error vector
$\boldsymbol{x}$	position vector (m)
$\dot{\boldsymbol{x}}$	linear velocity vector (m/s)
x, y, z	position vector components (m)
$\boldsymbol{Y}$	output vector

in cost, responsiveness, and flexibility of a multi-spacecraft system versus the classical monolithic satellite.

Particularly new is the use of continuous on–off engines, appearing on small spacecraft. This control constraint adds new complexity to finding the optimal solution. In fact, most of the literature on spacecraft optimal control assumes that the thrust can be finely modulated, partially to mitigate the aforementioned problem. Unfortunately, this is not the case with real engines, which are usually limited to some sustained value for thrust. As a partial response to this problem, a new methodology has been presented in [2] with the aim to control spacecraft rendezvous maneuvers assuming multi-level continuous thrusters and impulsive thrusters on the same vehicle. Furthermore, very recently, the interests of the Department of Defense have been focusing on time/propellant optimal rendezvous and capture maneuvers of a non-cooperative target satellite [3–5]. This research has been pushing the envelope with regards to fast computation of practical optimal/sub-optimal trajectories.

The recent numerical approaches to the optimal control problem could be in short classified in two main categories:

1. the indirect methods which employ the calculus of variations to obtain the first-order optimality conditions [6], where the resulting boundary-value problem is sometimes impossible or time-consuming to solve;
2. direct methods which approximate the trajectory via parameterization, and transform the cost functional into a cost function [7–9].

These second methods appear to be a viable tool for real-time spacecraft optimal control. However, the major issues with direct methods relate to the difficulties of defining parameters to represent feasible trajectories. The