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Development and experimentation of LQR/APF guidance and control for autonomous proximity maneuvers of multiple spacecraft

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ABSTRACT

This work introduces a novel control algorithm for close proximity multiple spacecraft autonomous maneuvers, based on hybrid linear quadratic regulator/artificial potential function (LQR/APF), for applications including autonomous docking, on-orbit assembly and spacecraft servicing. Both theoretical developments and experimental validation of the proposed approach are presented. Fuel consumption is sub-optimized in real-time through re-computation of the LQR at each sample time, while performing collision avoidance through the APF and a high level decisional logic. The underlying LQR/APF controller is integrated with a customized wall-following technique and a decisional logic, overcoming problems such as local minima. The algorithm is experimentally tested on a four spacecraft simulators test bed at the Spacecraft Robotics Laboratory of the Naval Postgraduate School. The metrics to evaluate the control algorithm are: autonomy of the system in making decisions, successful completion of the maneuver, required time, and propellant consumption.

1. Introduction

The ability of multiple spacecraft systems to autonomously track, rendezvous, inspect, and dock has many potential benefits for spacecraft applications. Among them the possibility to resupply consumables, perform repairs, replace failed components and construct modular structures on orbit. There is a current appeal to build smaller and lighter spacecraft to reduce production time and cost, decrease launch costs, and increase launch availability. Fractionated spacecraft, composed of multiple smaller spacecraft, independently launched and configured in space, may be one way of achieving the benefits of larger satellites with the launch flexibility of small satellites [1]. Control algorithms allowing multiple spacecraft to autonomously avoid each other or rendezvous and dock with each other are a critical component of making autonomous close proximity spacecraft operations.

Previous research and on orbit demonstration of autonomous rendezvous and docking dates back to 1998 [2]. The Air Force Research Laboratory (AFRL) has worked on a series of close-proximity satellite experiments beginning with XSS-10, launched in 2003 to test close-in satellite inspection techniques [3]. Subsequent AFRL programs are under development as described in Refs. [4–7].

NASA tested similar technologies and concepts with the DART mission [8,9].

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Nomenclature

Abbreviations and acronyms

AFRL	Air Force Research Laboratory
APF	artificial potential function
BCS	body-fixed coordinate system
COM	center of mass
DARPA	Defense Advanced Research Projects Agency
DOF	degrees of freedom
ESA	European Space Agency
ICS	inertial coordinate frame
iGPS	indoor global positioning system
LQR	linear quadratic regulator
LVLH	local vertical local horizontal
NASA	National Aeronautics and Astronautics Administration
NRL	Naval Research Laboratory
NPS	Naval Postgraduate School
PD	proportional-derivative
POSF	Proximity Operations Simulator Facility
RTAI	real-time application interface
SPHERES	synchronized position hold engage and reorient experimental satellites
SRL	Spacecraft Robotics Laboratory

Symbols

$\mathbf{A}$, $\mathbf{B}$, $\mathbf{C}$, $\mathbf{D}$	state space matrices
$\underline{a}$	acceleration determined by LQR/APF control
$\underline{a}_{APF}$	acceleration determined by APF control effort
$\underline{a}_{LQR}$	acceleration determined by LQR control effort
a_m	maximum available acceleration magnitude
$\underline{a}_o$	acceleration of chase spacecraft toward the obstacle
$\underline{a}_\perp$	perpendicular acceleration determined by enhanced LQR/APF control
$a_{X,Y,Z}$	acceleration components due to control effort in ICS
$a_{x,y,z}$	acceleration components due to control effort in BCS
D_o	obstacle region of influence
D_{stop}	stopping distance
d_a	decay constant for acceleration toward goal
d_o	factor of safety for obstacle region of influence
$F_{i,req}$	required equivalent force of thruster i
F_t	spacecraft available thrust force
F_θ	force required to affect commanded angular acceleration
J	cost function
$\mathbf{K}_{LQR}$	LQR state feedback gain
k_a	acceleration shaping function
k_s	safety shaping function
k_v	velocity shaping function
L	half the length of the spacecraft simulator measured in the x–y plane
L_{max}	distance between opposite corners of the spacecraft in the x–y plane
L_o	minimum approach distance from chaser COM to obstacle center
L_t	distance from spacecraft simulator COM to each thruster
m_s	mass of spacecraft
$\mathbf{N}$	LQR state-control combination gain matrix
$\mathbf{Q}$	LQR state gain matrix
$\mathbf{R}$	LQR control effort gain matrix
v_m	maximum allowed velocity
$\underline{r}_{ch}$	spacecraft simulator's own position in ICS
$\underline{r}_{dock}$	vector from target COM to the docking port
r_g	chaser's current distance to the goal
r_{init}	chaser's initial distance to the goal
r_m	maximum allowed distance from chaser to goal
r_o	distance between the chaser's COM and the center of the obstacle
$\underline{r}_{obs}$	position of other chase spacecraft simulator in ICS
$\underline{r}_t$	vector from chaser COM to target COM
$\underline{r}_{tg}$	position of the target spacecraft simulator in ICS
$\mathbf{S}$	solution of the algebraic Riccati equation
T_z	torque about the z-axis
u	control effort
$\underline{v}$	relative velocity of chaser spacecraft and obstacle
$\underline{v}_{ch}$	chase simulator's own velocity on the POSF floor in ICS
$\underline{v}_{obs}$	velocity of other chase spacecraft simulator on the POSF floor in ICS
$\underline{v}_{tg}$	velocity of the target spacecraft simulator on the POSF floor in ICS
v_m	maximum allowed relative velocity between spacecraft
$\underline{v}_o$	chaser's velocity toward the center of the obstacle
α_Q	LQR state performance gain
β_R	LQR control effort gain
γ	angle measured counter-clockwise from $\underline{r}_{dock}$ to $\underline{r}_t$
σ	standard deviation for obstacle region of influence
θ_{ch}	chase spacecraft simulator's angular displacement about its z-axis
θ_{tg}	target spacecraft simulator's angular displacement about its z-axis
$\dot{\theta}_{ch}$	chase spacecraft simulator's angular velocity about its z-axis
$\dot{\theta}_{tg}$	target spacecraft simulator's angular velocity about its z-axis
$\ddot{\theta}$	angular acceleration about the z-axis
ω	LVLH angular velocity
x, y, z	LVLH coordinates
$\dot{x}$, $\dot{y}$, $\dot{z}$	LVLH velocities
$\underline{x}=\{x,y,z,\dot{x},\dot{y},\dot{z}\}^T$	state vector

Subscripts and superscripts

$(\cdot)_e$	error