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Spacecraft relative guidance via spatio-temporal resolution in atmospheric density forecasting

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ABSTRACT

Spacecraft equipped with the capability to vary their ballistic coefficient can use differential drag as the control force to perform propellant-less relative maneuvers. Because atmospheric drag is proportional to atmospheric density, uncertainty in atmospheric density makes the generation and tracking of drag-based guidances difficult. Spatio-temporal resolution, or the mapping of density information to altitude and time, is shown in this work to improve atmospheric density estimation from forecasted density for spacecraft in LEO. This is achieved by propagating simulated orbits for two spacecraft using forecasted density. Additionally, a receding-horizon control algorithm is introduced, with the goal of improving the tracking of guidances. Using a simulated perfect forecast of the atmospheric density for propagation of the orbits, relative guidance trajectories are generated and tracked, establishing the benefit of adding spatio-temporal resolution. Next, imperfect density forecasting is added, indicating that the benefit of spatio-temporal resolution is retained in the presence of imperfect forecasting. Finally, a receding-horizon control algorithm is used with imperfect forecasting, demonstrating that receding-horizon control improves the tracking of guidances compared to single-horizon control.

1. Introduction

Formations of small satellites hold the potential for replacing large complex spacecraft, as explained in Refs. [1–4]. On-orbit inspection and maintenance missions and other complex space tasks can be performed by spacecraft flying in formation, providing redundancy in the case of a loss of a satellite. Additionally, smaller satellites are lighter and can be launched as a secondary payload for existing missions, which reduces the cost of orbit injection [5–7]. Consequently, there is a growing interest in the aerospace community in the development of methods for small spacecraft autonomous formation flying. Formations of spacecraft can cover more ground tracks than any single spacecraft, which may comprise identical or different orbits. Since the atmospheric density varies with both location and time, this implies that spacecraft in a formation will experience different atmospheric density.

Any formation of spacecraft requires the ability for the spacecraft involved to control their relative motion, typically performed using thrusters, requiring propellant to be carried aboard. Hence, alternative means to maneuver spacecraft are of great interest. Leonard et al. [8] proposed varying the cross-wind area of spacecraft to alter the drag force acting on them, as a method for controlling their relative motion at LEO. Differential drag can allow for propellant-less planar relative maneuvering, which can reduce fuel usage and costs for formation flying missions. Sensors mounted onboard spacecraft can also benefit from a cleaner environment due to the lack of thruster plumes. However, using differential drag to maneuver imposes the constraint of operating where the atmosphere is sufficiently dense to generate significant drag forces, and limits the maneuvers to the orbital plane. Moreover, using the drag for maneuvering increases the orbital decay rate of the spacecraft. Despite the downsides of differential drag, future impacts of the ideas here proposed can be foreseen for higher orbits. For example, the concept of exploiting differentials in environmental forces can be also imagined for geosynchronous satellites using solar radiation pressure [9].

In the last few years there have been quite a few papers inspired by Leonard et al [8]. Bevilacqua et al. [10,11] used the linear Schweighart and Sedwick model [12] to create a differential drag based rendezvous guidance assuming constant density. Ben-Yaacov and Gurfil [13] studied the use of differential drag for cluster-keeping purposes. Pérez and Bevilacqua [14] developed a Lyapunov-based controller for relative maneuvering of spacecraft using differential drag. Dell'Elce and Kerschen proposed the use of model predictive control [15] and a three-step optimal control

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Nomenclature

a	orbit semi-major axis (km)
$\vec{a}_{D_{rel}}$	relative acceleration $\left(\frac{km}{s^2}\right)$
A	area (km^2)
B	ballistic coefficient $\left(\frac{km^2}{kg}\right)$
$\underline{B}$	gain matrix
C_D	drag coefficient
e	orbit eccentricity
$\vec{e}$	error vector $\left(km, \frac{km}{s}\right)$
ECI	Earth-Centered Inertial frame
g	gravitational acceleration $\frac{km}{s^2}$
h	altitude (km)
$\vec{h}$	specific angular momentum $\left(\frac{km^2}{s}\right)$
i	orbit inclination (rad)
J_2	second order harmonic of Earth gravitational potential field (Earth flattening)
k_B	Boltzmann constant $\left(\frac{J}{K}\right)$
LEO	low Earth orbit, altitude below 2000 km
LVLH	Local Vertical Local Horizontal frame
m	spacecraft mass (kg)
M	average molecular mass of gas $\left(\frac{kg}{mol}\right)$
μ	Earth gravitational parameter $\left(\frac{km^3}{s^2}\right)$
ω	argument of perigee (rad)
Ω	right ascension of the ascending node (RAAN) (rad)
P	atmospheric pressure (absolute) $\frac{N}{m^2}$
P_o	pressure at sea level (absolute) $\frac{N}{m^2}$
$\underline{P}$	Riccati equation matrix
R	specific gas constant $\left(\frac{J}{kg\ K}\right)$
Re	Earth mean radius (km)
r_{ECI}	norm of position vector, ECI frame (km)
$\vec{r}_{ECI}$	position vector, ECI frame (km)
ρ	atmospheric density $\left(\frac{kg}{km^3}\right)$
5t	time (s)
T	absolute temperature (K)
θ	true anomaly (rad)
UTC	coordinated universal time
$\hat{u}$	control input
V	control volume (km^3)
v_{ECI}	orbital speed, ECI frame $\left(\frac{km}{s}\right)$
$\vec{v}_{ECI}$	orbital velocity, ECI frame $\left(\frac{km}{s}\right)$
$\vec{v}$	velocity relative to a medium $\left(\frac{km}{s}\right)$
$\vec{x}$	relative position and velocity in the LVLH frame $\left(km, \frac{km}{s}\right)$
$\vec{x}_d$	desired guidance $\left(km, \frac{km}{s}\right)$
$\hat{x}, \hat{y}, \hat{z}$	direction vectors in LVLH frame
$\hat{X}, \hat{Y}, \hat{Z}$	direction vectors in ECI frame
Z_{ECI}	Z position in ECI frame (km)

approach [16] for drag based rendezvous maneuvers. There have also been a few efforts for exploiting the differential drag concept in real missions. The ORBCOMM [17] constellation used differential drag for constellation keeping. Also, the JC2Sat [18–21] project developed by the Canadian Space Agency (CSA) and the Japan Aerospace Exploration Agency (JAXA) proposed the use of differential drag for relative maneuvering of spacecraft within close proximity of each other, extending the methodology presented by Leonard and studying implementation issues such as navigation errors. Finally, work by Mazal et al. has focused on using differential drag for long-range maneuvers in the presence of uncertainties in the control forces used [22].

Difficulty in estimating the drag force results in lack of realism in any drag-based guidance trajectory, making tracking more difficult. In the literature on drag-based maneuvering, it is usually assumed that the density is constant for guidance and control purposes (see Refs. [11,17,23–25]). Any guidance trajectory created under the assumption of constant density will be inaccurate due to unrealistic control forces.

In Ref. [26], density from an existing atmospheric model was used for creating a guidance trajectory for a drag based rendezvous. Forecasting was not used; the density was assumed to be known. Pérez at al. subsequently developed an Artificial Neural Network (ANN) forecasting method for atmospheric density along the orbit of a non-maneuvering spacecraft (i.e., with a constant ballistic coefficient and no thrusters) [27]. This forecasting method was later combined with the control methods by Pérez and Bevilacqua in [28].

Because the drag-based trajectory followed by a spacecraft is dependent on the atmospheric density it encounters, over or under-forecasting atmospheric density will result in uncertainty in forecasting the trajectory. When a spacecraft leaves the forecasted trajectory due to inaccurate forecasting, even a perfect forecast becomes inaccurate, since it corresponds to a different location. Adding spatio-temporal resolution to atmospheric density forecasting compensates for spacecraft leaving the forecasted trajectory.

In prior work, a single forecasted trajectory was used to create a rendezvous, where the density was forecasted and assumed to be along this trajectory [28]. Since any deviation from the forecasted trajectory results in an inaccurate density forecast, and vice versa, using a single trajectory does not have sufficient information to provide a complete density and trajectory forecast. Adding multiple trajectories bounds the motion of the spacecraft.

At any given timestep, there exists a set x containing the altitudes of each forecasted trajectory. The deviations between the members of x and the actual trajectory are contained in the set y. For the case of a single forecasted trajectory, both x and y have only a single member, which is by definition the minimum. Increasing the number of forecasted trajectories increases the number of members in both sets, and since the minimum of a set cannot be increased by adding more members, increasing the number of forecasted trajectories can only decrease the minimum deviation between a forecasted trajectory and the actual trajectory.

Previous work has considered atmospheric density as only time-dependent, and independent of location. Since real atmospheric density depends on both time and position, knowledge of a spacecraft's deviation from the expected trajectory can be used to improve the density forecast. This is denoted as spatio-temporal resolution, which reflects both the dependency of the density on both spatial and temporal differences. Using spatio-temporal resolution with an existing differential drag-based relative maneuvering algorithm [29], a rendezvous maneuver is created by modifying the aerodynamic drag on two spacecraft.

Using traditional control methods, or fixed-horizon control, a control algorithm will develop a set of control inputs, which are most effective when the system dynamics nearly match those of the real world. However, in this work, the state at a given timestep is dependent on all previous timesteps, and so small uncertainties in the system dynamics can rapidly result in large uncertainties in the state of the system, which can only be partially compensated with spatio-temporal resolution. Receding-horizon control allows the control algorithm to periodically reset the error state by restarting the control algorithm, which results in control inputs that are more applicable to the real world dynamics.

Receding-horizon control methods have been used previously