Distributed Control Topologies for Deep Space Formation Flying Spacecraft

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Overview

A formation of satellites flying in deep space can be specified in terms of the relative satellite positions and absolute satellite orientations. This paper addresses the problem of controlling such a formation based on relative position and velocity measurements. The redundancy in the relative position measurements, and the lack of an absolute position measurements means that globally specified tracking design problems require special treatment in order to handle observability and controllability constraints.

The redundancy in the measurements generates a family of equivalent controllers with equivalent stability and reference tracking performance. This can be exploited to show that there exists a control topology which achieves a global tracking objective using only local controllers. This is referred to as a local relative topology and can be implemented without requiring communication between the spacecraft in the formation.

Problem Outline

Our work is motivated by formation control problems for spacecraft in deep space. In such a scenario each spacecraft would have precise attitude and relative position measurements available, but would not have a precise estimate of absolute position. Attitude control can be designed locally for each spacecraft, and implemented locally, using only that spacecraft's inertial measurement unit and sun/star sensors. The control of relative position is somewhat more problematic and this is the focus of this work.

The spacecraft in the formation are free flying and their dynamics are coupled only through the application objectives and relative measurements of the spacecraft positions and velocities. We consider the problem of designing a controller in a centralized manner (i.e. using all available measurments), and implementing this controller in a local, decentralized manner (i.e. where each spacecraft uses only those measurements available from its own sensors).

Figure 1 illustrates the definition of the local and relative variables in a formation. The relative positions satisfy $r_{ij} = -r_{ji}$, and in an N spacecraft formation there are $N(N-1)/2$ relative three dimensional distances that can be defined modulo the opposite direction equivalences. We assume that r_{ij} are measured, but p_i are not. Specification of the r_{ij} (and ϕ_i although we do consider this aspect here) defines the formation.

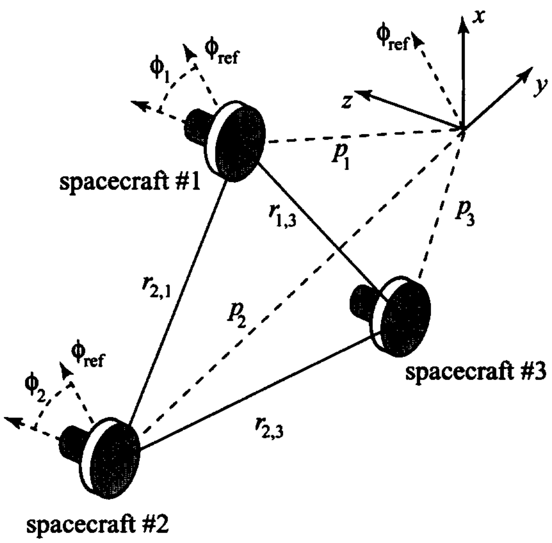

Figure 1. Spacecraft formation definitions. The ith spacecraft attitude is ϕ_i, and its absolute position is p_i. The relative positions are defined by,

$$r_{ij} = p_j - p_i = \begin{bmatrix} x_j \\ y_j \\ z_j \end{bmatrix} - \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix},$$

for $i, j = 1, \ldots, N$, $i \neq j$. The location of the absolute position frame origin is not relevant to the problem considered here.

We consider two problems:

Relative design: Given $N(N-1)/2$ relative measurements, r_{ij}, and force actuators u_i, $i = 1, \ldots, N$, design a global controller to track a prespecified vector of relative position reference trajectories.

Local control implementation: Given a global relative position design from the previous step, decompose it into a series of controllers, each using only the measurements available on the local spacecraft.

Relative Design Problem

We consider a global design specification; the tracking of a prespecified trajectory in terms of the relative position and velocity, r_{ij}, $\dot{r}_{ij}$, $i, j = 1, \ldots, N$. Each spacecraft has force actuators and a measurement (or estimate) of the full set of relative states.

As stated the resulting control problem suffers from two difficulties; it is neither controllable nor observable. The lack of controllability arises from the fact that there are only $N-1$ of the $N(N-1)/2$ relative states are independent. The algebraic constraint between the relative states leads to an apparent lack of controllability. We give a decomposition which reduces this to an observable subproblem.

The center of mass of the formation cannot be deduced from the relative states, making the control problem unobservable. Furthermore, the uncontrollable states are unstable. In deep space applications, precision in the formation center of mass is not required, and the technical difficulties can be handled by a controllable decomposition in a similar manner to the above.

Because the relative state based controller does not attempt to control the center of mass there is a degree of freedom which may be exploited to achieve additional objectives. We present a characterization of this freedom and show how it may be used to minimize fuel consumption, or balance remaining fuel between spacecraft.

We present a methodology for the relative state based control design using linear matrix inequalities. The software required for the solution of such problems is readily available in several common design environments (MATLAB or SCILAB for example).

Local Control Implementation

In previous work[1] we used the redundancy inherent in relative position and velocity measurements to define a set of input transformations for each controller. These are applied to the relative information (whether obtained by measurement or communication) and effectively reconfigure the control measurement set for each individual spacecraft. The stability and tracking performance of the network is not affected by the transformation chosen for the individual spacecraft.

There exists one transformation for each spacecraft which allows that spacecraft to implement the globally designed relative state controller using only local relative state measurements. This allows the control to be implemented without requiring communication between the spacecraft. The transformations may also be switched to replace local measurements with communicated information when measurements are lost due to faults or spacecraft shadowing.

The input transformations are specified as a matrix premultiplying the above global controller. We give the algebraic derivation of the matrix corresponding the local relative controller, as well as those required for the switching required when one spacecraft is masked by another during a maneuver.

Acknowledgements

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[1] *"Control Topologies for Deep Space Formation Flying Spacecraft,"* Smith & Hadaegh, ACC, 2002.