ON SEPARATION PRINCIPLE FOR THE DISTRIBUTED ESTIMATION AND CONTROL OF FORMATION FLYING SPACECRAFT

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ABSTRACT

Distributed space systems are expected to enable us to carry out space missions perceived impossible under the current monolithic design. The distributed nature of these spacecraft allows us to launch missions that rely on coordination among smaller spacecraft, improving the overall system reliability. However, a number of technical challenges should be resolved before such systems can successfully function, to their maximum potential, and as a coherent unit. One fundamental question is how the control system for such a space system should be designed? One approach is to use a centralized estimation and control scheme. While possible, this approach does not allow for easy transition for changes in information exchange network or number of spacecraft in formation. In the distributed estimation and control architecture, each spacecraft individually estimate the formation state based on the information received from its neighbors. This estimated estate is used to locally create the control signal used for each spacecraft.

Figure 1. (a) Information exchange network in distributed spacecraft constitutes a graph, each spacecraft can measure a set of its own states along with measurements of the neighboring spacecraft (b) Proposed distributed estimation and control architecture.
This work presents a distributed estimation and control architecture for formation flying spacecraft. We show how spacecraft can individually create a local estimate of the formation and create their own control action using that estimate. Proofs are provided to show that such a scheme is asymptotically stable and spacecraft will reach consensus on the formation states.

We assume linear dynamics for each spacecraft, where $x_i$ is the state of spacecraft $i$ and $x$ represent the collection of all spacecraft states. Each spacecraft can measure some of its own states and that of its neighboring spacecraft with measurement noise $w_i$.

Figure 1(a) depicts how the information exchange network is presented as a graph with spacecraft as nodes and communication links as edges.

Each spacecraft run its own estimator for the full formation. In this distributed estimation scheme, individual spacecraft use its local measurements $y_i$ in the correction process of the Kalman filter, however they improve their prediction using the estimates of the formation shared by their neighbors. Each spacecraft use the sum of the differences between its own estimate and that of its neighbors weighted by its error covariance matrix (a measure of confidence in its own estimates) as an additional term in driving the state estimate. Under this setup, as long as the collection of the $C_i$ and $A$ (diagonal matrix of all $A_i$) is observable and the underlying information exchange network is connected, one can show that estimation process is asymptotically stable and the spacecraft will reach consensus on state estimates.

We use state feedback to generate the control signal, $u$, necessary for the formation control. Each spacecraft will then only use its own part of this control signal, $u_i$, ignoring that of the rest of the formation.

$$u = K \hat{x}_i$$

Gain $K$ can be obtained using pole-placement or other control synthesis tool. The second term in the above equation represent formation state estimate as perceived by spacecraft $i$.

When all spacecraft use the same control signal implemented in control and used in estimation, separation principle holds and the formation will be asymptotically stable. However, in our setup each spacecraft generate its own control signal based on its own estimate of the formation states. Also spacecraft do not have perfect knowledge of everyone else’s control action. Providing a Lyapunov analysis, we show the formation is stable and the separation principle still holds under our proposed distributed estimation and control scheme.