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Analysis of a distributed estimation and control scheme for formation flying spacecraft

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ABSTRACT

The stability characteristics of a distributed consensus-based Kalman filter estimation and control scheme are studied through analytic and numerical means. This estimation scheme seeks to minimally reduce the necessary bandwidth for communication while maintaining overall stability. A weaker form of the separation principle is proven to hold whereby control could be designed independently but not estimation. However, actuation limitations still provide the possibility for a semi-independent design of estimators. Numerical simulations confirm that the stability depends very heavily on consensus on estimation and ultimately the amount of information available to the system as it evolves.

1. Introduction

Formation flying satellites are becoming a major new development in space operations. The commercial, scientific, and military sectors all wish to expand the mission capabilities of their satellite fleets such as increased communication volume for information transfers, increased field of surveillance, and improved navigational accuracy for military and civilian aircraft [1]. While current distributed missions, such as GPS, are conducted in satellite constellations, these constellations do not have a coupled control law that takes into account the states of other satellites. Therefore, formation flying would be able to perform missions with more stringent requirements on formation positions. With limited funds, implementing formation flying into existing satellite technology is a cost-effective way to extract more utility. Formation flying capabilities increases not only the scope of satellite missions but also the reliability. In addition to performing synchronous measurements, formations have redundancies in operation, which means failure of one spacecraft would not endanger the integrity of the mission [2].

A notable but novel use of formation flying can be seen in the distributed aperture telescope system [3]. In light of current restrictions on the cost and logistics of sending large telescopes for scientific observations, formation flying spacecraft could be used to circumvent this problem. Each of the satellites within the formation would act as a section of a larger reflecting telescope, and the formation, as a whole, would become a “virtual telescope” with an aperture several times larger than their conventional reflecting counterparts [4]. This would give astronomers access to better clarity and resolution compared to individual telescopes. Lastly, the robustness of architecture would avert a incident similar to the Hubble telescope, which had a manufacturing defect in its lens and had to be repaired in space. Smaller mirrors would be more cost-efficient to manufacture, and satellites with defective instruments can be replaced and substituted fairly easily. This application is notable for its tight requirement on the shape of the formation in order to achieve satisfactory resolution. Thus, accurate estimation of the global formation structure is paramount to the success of such a mission.

Distributed space systems are seen to be the successor to current monolithic systems that are too cumbersome to organize. Through the comprehensive survey on guidance and control techniques for formation flying spacecraft by Scharf et al., one can see that a central-control framework lacks robustness to changes within the formations [5,6]. Distributed systems also allow for additional autonomy in conducting missions as they can reduce the reliance on receiving instructions from a ground station [2]. However, the fundamental challenge to the implementation of distributed systems is achieving a desired global outcome from isolated, local interactions. Tillerson et al. [7] investigates the effectiveness of an LP controller with regards to different methods of localizing a formation of satellites; however in order to implement distributed control, the control input to each spacecraft would have to be published through a fully-connected network. From an estimation perspective, Olfati-Saber proposed using a distributed

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Nomenclature

Note that units for all variables depends on designer's choice of state and control variables

n	number of agents
x_i	state of agent i
u_i	control input to agent i
$\tilde{A}$	dynamics matrix of environment
B_i	control matrix of agent i
v_i	process noise of agent i
X	global state vector
U	global control input
V	global process noise
z_i	measurement vector of agent i
H_i	measurement matrix of agent i
W_i	measurement noise of agent i
A	global dynamics matrix
B	global input matrix
H	global measurement matrix
K	state feedback gain
$\hat{x}_i$	global state estimate from agent i
K_i	Kalman gain of agent i
P_i	covariance of state error perceived by agent i
R_i	covariance of measurement noise perceived by agent i
Q	covariance of process noise
γ	consensus coefficient
$\mathcal{N}_i$	neighborhood set of agent i
Π_i	control selection matrix of agent i
$\hat{U}_i$	global control input perceived by agent i
η_i	global estimate error of agent i
η	concatenation of all estimate error

Kalman filter scheme that incorporates a consensus algorithm so that a group of observers can, collectively, estimate and agree on the states of a process [8]. Olfati-Saber and Jalalkamali furthered these results with moving observers who estimate a moving target [9]. Ranzer provided insight into using multiple controllers, accessing different measurements to control a distributed system and proved a separation principle for these cases [10]. Smith and Hadaegh sketched a formation controller that uses parallel estimators, however the full formation states have to be observable by every estimator [11]. Building on all of this, Rahmani et al. presented a distributed estimation and control architecture in which each spacecraft would generate its own estimates of both the states and controls of the entire formation. These estimates are derived from both its sensors and the information transmitted by neighboring spacecraft [12]. Thus through local interactions, each spacecraft can build its own image of what the entire formation is doing and respond as required.

From a design perspective, one of the most powerful theorems from linear control has been the separation principle, which states that it is possible to combine independently designed controller and estimators together to form a stable system. For distributed systems, with each spacecraft performing local communication, the fundamental issue is: *Is there a generalization for the separation principle for distributed systems? If so, what form will it take?* Unfortunately it will be shown that the separation principle strictly does not apply to these distributed systems. However, by relying on engineering constraints and a weaker formulation of the separation principle, designers would still be able to design local estimators while ensuring stability.

2. Formulation

The problem considered is to determine how would the separation principle hold in the context of distributed systems. First, a framework is needed to consider the states of such a system. For this analysis, a spacecraft flying formation is considered, but the framework would be valid for any linear system. The dynamics of a distributed system can be formed by first considering the dynamics of a single spacecraft and aggregating their respective states to form the state of the entire formation. Again, we will only consider linear dynamics for each spacecraft. While at first glance this might look restrictive, in practice dynamics of most planned formation flying missions can be represented by linearization around an operation point of interest, like the Clohessy–Wiltshire–Hills equations for relative orbital dynamics [13]. Since spacecraft formation operate in relatively close proximity, the use of linearized dynamics is justified.

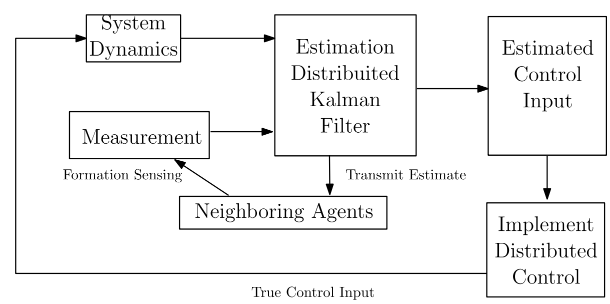

Fig. 1. Sketch of distributed estimation and control.

A sketch of the control scheme, along with its inter-dependencies, is summarized in Fig. 1. The major concept is that each spacecraft is not only estimating its own states, but also the states, controls, and formation assignment of the other spacecraft. Using its estimate of the formation control and orientation, it would then implement its own control and select its own goal, respectively. Communication of information enables estimation of states even if no spacecraft can observe the entire formation. With this framework in mind, the following sections will implement the structure with respect to the linear dynamics on the spacecraft formation.

2.1. Dynamics

Consider first, n spacecraft, each under linear dynamics influenced by an exogenous, zero mean white Gaussian noise, v_i.

$$\dot{x}_i = A_i x_i + B_i u_i + v_i \tag{1}$$

The states of each spacecraft, x_i, can be concatenated to form an aggregated state vector, $X = [x_1^T \cdots x_n^T]^T$. Similarly, the control input and noise disturbances can also be aggregated as $U = [u_1^T \cdots u_n^T]^T$ and $V = [v_1^T \cdots v_n^T]^T$ respectively. Under this formulation, the state and control matrix can be written in a block diagonal form: $A = diag(A_1, \cdots, A_n)$ and $B = diag(B_1, \cdots, B_n)$ respectively. These aggregated dynamics can now be written in a form analogous to equation (1). Note that while the use of different individual state matrices A_i keeps this analysis general for diverse, heterogeneous systems, for homogeneous systems within the same environment, the state matrix would be identical.

$$\dot{X} = AX + BU + V \tag{2}$$

We assume, each spacecraft i can measure a subset of these aggregated states z_i, usually their own and a few select states of their