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Fault detection and recovery of spacecraft formation flying using nonlinear observer and reconfigurable controller

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ABSTRACT

This paper addresses fault tolerant spacecraft leader–follower formation control through the development of a fault observer and a re-configurable control law. Using carrier-phase differential GPS measurements for relative position and velocity, an estimate of the true thrust output on all three axes of the follower spacecraft is accomplished using a pair of super twisting sliding mode observers. Modifications on the 'broken' super twisting observer are applied in order to accommodate additional sensor feedback inputs for relative position and velocity between the leader and the follower spacecraft. A fault observer estimating the true thrust output of the follower spacecraft is developed which functions in parallel with a re-configurable control law capable of formation maintenance in the event thrust in the along-track and radial axes are no longer available. Simulation results show fault reconstruction and recovery with formation stabilization even in the presence of external disturbances which are unknown to both the controller and the observer.

1. Introduction

Autonomous capabilities for spacecraft systems have become a source of great interest in recent years to support the requirements of future space mission needs. One application of spacecraft autonomy would include the mitigation or adaptation to sub-system failures. Consequences of not reacting to failures in time can lead to mission degradation, or at worse, catastrophic loss of the mission entirely. Autonomous decision making in unmanned spacecraft will be required to ensure mission robustness and reliability.

The current trend on the development of smaller, low-cost, low-mass and low-power satellite systems has imposed severe limitations in terms of actuator and hardware redundancy. Such methods have been used in traditional satellite engineering design to ensure full functionality in the event a subsystem in current use fails. For instance, the use of additional thrusters has been commonly practiced but is difficult to implement on smaller spacecraft. In order to develop a fault tolerant attitude and orbit control system (AOCS), analytical redundancy must be examined to accommodate such restrictions. Analytical redundancy approach to developing a fault tolerant system relies on having a real-time software for mitigating or recovering from system errors and faults rather than having on-board redundant hardware.

The orbit control subsystem of a spacecraft is critical for the success of many space missions. Precise positioning accuracy and capability are needed to accommodate the goals and needs of the mission, especially in applications related to spacecraft formation flying (SFF). SFF is a challenging new concept which will provide a multitude of benefits such as greater cost savings and enhanced reliability. Several space missions in the near future will

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Nomenclature

a	semi-major axis of the reference orbit
e	eccentricity of the reference orbit
e_x	relative radial position tracking error
e_y	relative along-track position tracking error
e_z	relative cross-track position tracking error
i	orbit inclination of the leader spacecraft
m_l	mass of the leader spacecraft
m_f	mass of the follower spacecraft
r_e	radius of the Earth
r_f	radial position of the follower spacecraft from the Earth centre
r_l	radial position of the leader spacecraft from the Earth centre
x	radial separation between leader and follower spacecraft
y	along-track separation between leader and follower spacecraft
z	cross-track separation between leader and follower spacecraft
θ	true anomaly
μ_e	gravitational parameter of the Earth

require the use of formation flying maneuvers in order to complete various mission objectives. Such examples may include a cluster of satellites functioning together to act as a telescope or an interferometer. The Magnetospheric Multiscale mission aims to measure Earth's magnetosphere at key locations with four satellites flying in a tetrahedron-shaped configuration. Future missions such as Nearby Earth Astrometric Telescope (NEAT) and Micro-Arcsecond X-ray Imaging Mission (MAXIM) will involve the identification of planets and observation of deep space celestial bodies will require centimeter to micrometer precision. With strong emphasis on precise relative station keeping of SFF, the need for reliable fault tolerant control laws has been investigated in a variety of aspects.

Compounding the desire to develop more autonomy in space systems and the recent trend of developing smaller satellites has generated a great deal of research in the development of fault tolerant attitude and orbit control laws. For an autonomous fault tolerant system, some form of detection would be required for unsupervised fault recovery. Numerous approaches for fault detection may include the use of Kalman filtering, statistical inference, least squares residual generation and diagnostic fault tree analysis, to name a few [1,2]. In many of these examples, fault isolation is considered, which allows the exact knowledge of which sub-system in the actuator module is at fault. In such cases, parameter estimation is often applied to determine the health or status of each of the fail-prone components in various spacecraft actuators. Such parameters may include properties of the actuator that cannot be directly measurable; using a reaction wheel as an example, such estimated parameters may include bus voltage of a reaction wheel, current drawn, bearing friction and back electromotive force (EMF) [2].

Because of the nonlinear nature of spacecraft attitude dynamics, traditional estimation mechanisms such as Linear Quadratic Estimators or linear Kalman Filters are not appropriate. Usage of such methods may lead to estimation inaccuracies due to linearization of the nonlinear system model. While nonlinear estimation techniques do exist and are abundant in the literature, many are computationally intensive. The unscented Kalman Filter for instance requires a transformation to be applied to the system model. One simple approach to estimation includes the sliding mode observer, which offers a simple elegant solution to state estimation without the burden of computational expense and is shown to be resilient to model mismatch and measurement noise. In the literature, there are numerous cases of the utilization of sliding mode observers for estimating attitude actuator faults [3,4] however this ‘broken’ super twisting method has not been applied for the estimation of attitude actuator faults. This method has been applied to estimating thruster faults in a formation flying [5] scenario at the Earth-Sun L2 point.

It is noted that in the literature, most methods which use the broken super-twisting sliding mode observer do not make use of full state sensor feedback. This can be shown in numerous examples such as in [5–8]. In [5,6] only position sensor feedback is used in the fault estimation of spacecraft actuators. In many satellite systems, position and linear velocity feedback are usually available to the controller from the navigation system. The super-twisting broken sliding mode observer in its current form cannot accept velocity information without modifications. The same sliding mode technique was shown to work with wavelet networks [9] in the spacecraft formation flying problem, however the inclusion of wavelet networks increases the computational complexity of the fault analysis. Additionally, the work here does not make use of the additional relative velocity measurements which are readily available for most spacecraft systems. Many other papers explore the use of sliding mode observer (SMO) based fault estimation for the formation flying problem but do not utilize ‘broken’ super-twisting SMO variant. Some range from Luenberger/SMO-type observers [10] while others require transformations prior to using the observer [11]. In most cases, the aforementioned SMO methodologies require additional computations.

An approach similar to the one presented in [5] is adopted in this work with modifications. The sliding mode observer technique used here offers several advantages, such as taking into account nonlinear dynamics and being robust to uncertainties and sensor noise.

The main contributions of the work presented here are as follows:

1. A novel single fault detection and isolation scheme which will identify actuation faults for the follower