THE EFFECTS OF INTERSPACECRAFT COMMUNICATION DATA LATENCY AND TIME TAG ERROR ON FORMATION ESTIMATION

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MOTIVATION AND OVERVIEW

Formation estimation of a distributed spacecraft system requires data exchange between spacecraft via inter-spacecraft communication devices. When spacecraft sensor measurements are sampled and digitized, the corresponding measurement epochs are tagged. These streams of time-tagged data from formation members are collected and used in the formation estimator to reconstruct formation state variables [1]. For example, the translational state propagation involves differencing and integrating inertial measurements obtained through inter-spacecraft communications. Since each spacecraft operates and processes data with independent internal clock, asynchronous clock error (i.e. epoch difference) between spacecraft causes the estimation error. Even if the transmitted data are broadcasted in regular time intervals and the data epoch is predicted based on the data reception time, complete elimination of clock errors is difficult. If the time errors are not properly compensated, the formation system will suffer performance degradation, and possibly instability.

Simple solutions to this problem are to synchronize every spacecraft's clock within the formation or to employ an extremely stable clock (i.e. atomic clock). However, such solutions are either operationally challenging or too costly for a large class of future missions. Hardware clock synchronization poses several undesirable features. For example, each spacecraft has to vote for a clock to synchronize to, unless a time reference spacecraft is selected and defined. If a spacecraft clock is used as the time reference, a clock failure can impact entire formation. In addition, the requested dynamic clock adjustment can conflict with the microprocessor operations. Such dynamic adjustments are undesirable when software tasks depend on a fixed time mark. This paper presents an approach to the characterization and evaluation of the impact of time delay on the formation estimation problem. Following the theoretical formulations, several simulation examples are presented to demonstrate the concept.

CLOCK MODELING AND COVARIACNE ANALYSIS

The main objective of this research is: i) modeling of the asynchronous clock processes and ii) assessment of its contributions to formation estimation error. The spacecraft CPU clock is modeled using Alan variance curves [2-3] associated with a typical internal quartz oscillator. The clock error model is further simplified to a linear system driven by a white noise with the intensities approximated from bounds of the Alan variance plot. The resulting model represents the long-term (in order of hours or more) drift of the clock. For an analysis with emphasis on shorter temporal frame, the clock error process is modeled as a constant time delay within an inter-spacecraft communication link. Given these clock models, two types of clock uncertainties are considered: absolute clock error associated with broadcast time tagging method and relative clock error associated with reception time-tagging method. The reception time-tagging method has a distinct advantage of bounded clock error over long-term operation; therefore, only the short-term behavior of the clock error characterization is required.

Considering these clock error models, a generic formation system is formulated. It is assumed that every spacecraft within the formation is similarly configured and equipped with its own processor, inertial sensors and restricted/limited field of view (FOV) relative position sensor assembly (RPSA). The inertial sensors may include gyros and accelerometers, and the restricted FOV sensors may include GPS-like sensors such as Autonomous Formation Flying (AFF) sensors [4] or optic based sensors.

A *Pade* approximation is used to obtain a covariance equation. Similar to a reduced order system analysis, the covariance equation consists of higher order, delay augmented plant model and a simplified estimator model. The resulting covariance equation is a function of input signal and the time delay magnitude. The results characterize the estimation error bound given the delay and input conditions.

In the analysis, three different propagation/update conditions are considered. During a typical deployment phase or during blind formation reconfiguration maneuver (out of RPSA FOV), the inertial navigation sensors, such as 3 axis accelerometers, will be used in a filter propagation mode without filter updates. Two other cases involve both propagation and update in the estimation cycle. If measurements from a spacecraft's own RPSA are available (i.e. direct measurement update), the measurement update can be performed without time delays. On the other hand, if the RPSA measurements are obtained by inter-spacecraft communication, both the propagation and update will be impacted by the delays.

SIMULATION ANALYSIS

Due to the complexity in time tag error processes, the impact on estimation can be best observed through a simulation analysis. Given an example spacecraft configuration of 308kg mass and inertia of 79.5, 57.2, and 44.7 kg-m^2 (x, y and z respectively), a three spacecraft simulator is constructed in the MATLAB environment. Each spacecraft is assumed to carry a standard 6 DOF formation flying sensor suite. Idealized (perfect state feedback) control is designed and implemented on the spacecraft. A formation estimator with a self-centered architecture is designed to run in the open loop condition. Optimal filter gains are calculated without time delay compensations. Similarly to the previous analysis, the RPSAs and the inter-spacecraft communication configurations are manipulated to consider three different estimation scenarios: propagation only, propagation and direct or propagation and indirect measurement updates. For all three cases, a triangular formation is initially maintained with 10 meters separations, and then a formation expansion to 20-meter separations is commanded. During the expansion maneuver, the estimation error is observed. This type of simulation exercise is repeated for various time delays and expansion command magnitudes.

SIMULATION RESULTS

CASE #1: Propagation Only: This is a simulation of a formation initialization or reconfiguration maneuver. In addition to the delay variations, the relative accelerometer biases are adjusted. Prior to the maneuvers, the estimation error is well maintained and slowly grows over time in accordance with an unknown drift. However, the estimation error grows rapidly as the maneuver started. It is shown that the error magnitude depends on the linear acceleration changes during the maneuver.

CASE #2: Propagation/Update with Direct Measurements: This case involves time delay corrupted propagation and delay free measurement updates since measurements are provided directly from the internal RPSAs. For this case, the state propagation contributes more to the estimation error when the time delay increases, while the update corrects the time-tag induced errors. Again, the error contribution during the propagation is the same as the case 1, but the error reduces as reduced sensor noise and more frequent sensor updates are available. It is shown that the delay free suboptimal filter gain (with propagation noise intensity increase) performed better as it can account for time induced error contributions.

CASE #3: Propagation/Update with Communicated Measurements: This case updates with only the communicated measurements. Since the measurements are corrupted with time-tag errors, the measurement update can no longer correct time-tag induced propagation error contributions. Indeed the accelerometer bias estimates are affected and failed to converge.

CONCLUSION

The analysis demonstrates that the time tag errors impact performance of the formation estimator unless time tag errors are properly treated and compensated for. The clock synchronization approach is one approach for solving this problem, but at the cost of complicated clock synchronization hardware and the procedures.

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