MULTI-MODE SYNCHRONIZED CONTROL FOR FORMATION FLYING INTERFEROMETER

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Abstract. This paper describes the design of an RCS based formation flying control for the Starlight space interferometer mission, consisting of two spacecrafts. Both slew and tracking control are seamlessly integrated within the same control architecture, allowing for position and velocity mode of operation, while ensuring smooth transition between slewing and tracking. To minimize the duration of thruster induced disturbances during interferometric observations, thruster activities on each spacecraft are synchronized and limited to the first second of each 30 second time window.

1. Formation Flying Control for Starlight Space Interferometer

Two spacecrafts, collector and combiner, form the Starlight space interferometer (Fig. 1) [1,2]. Control for combining the light in proper phase (optical path/diffraction control) is multilevel: control of the two spacecraft relative position (3 DOFs), inertial attitude of each spacecraft (6 DOFs), and vernier control of the optical elements placed on each spacecraft, namely, motor, voice coil and piezo-element for the optical delay line actuation [3], and siderostats.

Fig. 1 Interferometer spacecraft formation

In this paper we describe the control design based on cold gas thruster system for the spacecraft formation flying. The control is centralized (on the combiner), and the thrusters placed on both spacecrafts are used. The number of the thrusters provide full decoupled control authority on all axes. Each thruster has a thrust level of 7.5 mN. Thrusters are placed in pairs at a level-arm of approximately one meter from the spacecraft center-of-mass (cm). Minimum pulse duration of a thruster is 10 msec.

The available feedback of the attitude/position control is limited by the thruster minimum impulse and by the sampling rate. The plant transmission functions for different control axes are similar, double integrators, and only differ by the inertia ratios. All structural mode frequencies of the spacecraft are higher than 50 Hz and do not affect the thruster control law.

The spacecraft and the thruster parameters are well known, and the spacecraft inertia matrix is diagonal dominant. The transfer function matrix of the actuator and plant is decoupled by the thruster decoupling matrix. Due to this decoupling, a single axis control design is undertaken and optimized for maximum feedback bandwidth, and extended to all control axes with minor adaptations. Although positive feedback will in this case occur in all channels over the same frequencies, this will increase the positive feedback by less than 2dB over that of a single, stand alone channel, due to the small off-diagonal terms, i.e. small loop cross-coupling. This is deemed acceptable.

Disturbances are caused by the thruster firings, the delay line motor friction, and mechanical valves movements of different actuators (particularly, the gas tank pressure control).

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2. Tracking and slewing control requirements

To minimize duration of thruster induced disturbances during interferometer observation, it is desirable to limit all thruster activities (on both spacecrafts) to a time window with a specified period. Starlight mission requires such thruster activity to be limited within the first second of every thirty seconds time window. The accuracy of this tracking control is determined by the thruster minimum pulse duration limit and the 30 sec sampling period (and not by prescribing the dead band, as in the traditional dead-band based control design).

During a retargeting slewing, the above mentioned 1 out of 30 sec thruster activity window restriction is not required, and sampling interval of 1 sec is chosen for the slew control. For both slew and track control mode, it is desirable to have small rise-time and settling time, to limit the velocity, and to economize the propellant usage, without excessive cycling of the thrusters.

Thrusters are sized to provide constant force amplitude of 7.5mN with a minimum command on-time of 10 ms.

3. Tracking and slewing control - position DOF

Control block diagram for the single-dof tracking and slewing control system is shown in Fig. 2. The same controller structure is used for other DOFs (e.g., inertial attitude of each spacecraft) with simple changes in the gain scaling.

Tracking and slewing compensators are configured in a “hot” configuration, i.e. with the feedback error permanently applied to their inputs, and the compensators outputs combined in a nonlinear way automatically, based on specified thresholds.

The slewing controller, in turn, has two automatically switched sub-modes: position control and constant velocity mode.

Due to automatic switching of the control modes, the guidance function can potentially be simplified, requiring only the terminal position (or attitude) to be commanded instead of the entire maneuver profile.

4. Track control

The tracking control law is designed with 0.05 Hz crossover frequency $f_c$. The compensator’s output is the duration of the thrusters on-time at the beginning of the 30 sec cycles. This regime is defined by the required thruster firing duration of no greater than 1 sec at the beginning of the 30 sec period.

The sampling period for thruster firing in tracking mode is limited to a minimum of 30 seconds.

For small signal amplitudes, the employed sample-data controller is linear time-variable. Stability margins in such a system can be estimated by using equivalent worst-case linear time invariant Bode diagram. Such diagram for the tracking channel is shown in Fig. 3. It is plotted with the digital sampling phase delay approximated by \((-s+0.13)/(s+0.13)\), and the 1 Hz sampling delay together with the delay by one 1 sec control interval, by \((-s+1.2)/(s+1.2)\).

The guard point phase margin is $31^\circ$.

The achieved ratio $f_{samping}/f_c = 0.033/0.0048 = 7$ is close to the minimum possible for the response resulting in transient response with small overshoot and short settling time.
The closed loop response is shown in Fig. 4. The 3 dB bandwidth is 0.07 rad/sec, or 0.011 Hz. The rise time is therefore [5] approximately \( \frac{0.35}{0.011} \approx 32 \text{ sec.} \)

Spacecraft is modeled as a double integrator with the loop phase lag at the lower frequencies of \( 2\pi \). To guarantee global stability of the system, the integral and the proportional branches of the compensator include saturation links, so that at lower frequencies the outputs of these branches will be limited for large signals and the relative weight of the derivative channel increases. The saturation level also affects the overshoot for large level signals, however, this is less important for the tracking channel.

The describing function analysis and absolute stability method analysis of the system with nonlinear dynamic compensators can be performed with the methods and software presented in [4,5,6].

4. Slew control

The regime of slewing, retargeting, and target acquisition is implemented using 1 sec sampling period, and correspondingly, with the 0.05 Hz crossover frequency (0.3 rad/sec), resulting in the rise time of about 4 sec. This rise time is much shorter than the rise time in the tracking mode (these numbers are calculated for the linear state of operation, i.e. for small signals). The slew control law includes nonlinear dynamic compensation [4,5] for good performance in the nonlinear mode of operation.

The transient response of the slewing channel is shown in Fig. 7. Its overshoot is very small. A saturation link placed in the proportional path eliminates the wind-up. The steady-state accuracy is defined by the dead-zone link in front of the compensator, as shown in Fig. 2.
As seen in Fig. 7, the controller can perform in two submodes: (1) position tracking and (2) velocity profiling, i.e. motion with the velocity not exceeding certain limits and profiled such as to reduce the settling time.

The details of the slewing controller are shown in Fig. 8. It is a PD compensator with band-limiting linear derivative term and nonlinear proportional term.

To reduce the propellant usage and to provide transient responses with small settling time and small overshoot in nonlinear mode of operation, the velocity limit is set such that the duty cycle for large slewing motion \((\text{acceleration} + \text{deceleration duration})/(\text{acceleration} + \text{coast} + \text{deceleration duration})\) will not exceed 0.5.

In addition, operating range of the star tracker provides the angular rate saturation limits.

The choice of the velocity limit can be explained as follows. When the saturation threshold in the proportional path is achieved, the path output \(U\) can be considered as a constant amplitude input to the closed loop system at the input of the actuator, and with feedback path limited to the derivative \((Ds)\) path of the compensator. If the feedback is large, the transfer function of the system is, approximately, \(1/Ds\), and the output position therefore equals \(U/Ds\), i.e. the output velocity is \(U/D\). Thus, for example, if \(U = 140\) and \(D = 50\), the velocity limit is 2.8.

By properly setting this limit, the desired duty cycle can be specified. With two parallel proportional branches with appropriate saturation in each (with several such branches in parallel, any nonlinear curve can be, generally, well approximated [5]), but in this particular case using two parallel branches suffices), duty-cycle was tuned as required for rather large dynamic range of the feedback errors.

The parallel branches preceded by saturation links also provide good stability margins in the nonlinear state of operation, along with small overshoot and settling time for large commands. This can be explained as follows: the loop describing function for large level signals being limited by the maximum thrust level approaches the critical point at some frequency (at which the describing function absolute value is about 1). This frequency depends on the signal level. The larger the command and, therefore, the error, the lower is this frequency. Therefore, to provide appropriate phase stability margins for the loop describing function, the phase of the compensator describing function must be increased (i.e. phase lag, decreased) at this frequency and, at the same time, the absolute value of the describing function should not drop too much, for the control to be sufficiently fast. This is accomplished by the nonlinear elements in the compensator in Fig. 8 for a wide range of the command amplitudes.

The relation between the frequency responses and the time-response for linear systems, to a certain extent, is valid also for iso-amplitude describing functions [5]. Due to this, the step-responses of the
designed system become quite good, with small overshoot and small settling time, for the wide range of the command amplitudes.

5. Slew-track transition

The saturation link at the slew compensator input limits the input signals to provide a smooth transition from slewing to tracking control mode. Other conditions and means for enacting the appropriate compensator are described below.

The tracking compensator is turned off when it is not needed (during large maneuvers) in order to reduce the number of thrusters on and off cycles. It is turned off when the relative velocity between the two s/c (or, a s/c inertial angular velocity in the case of attitude control) exceeds a specified constant, as shown in the block diagram in Fig. 2.

The slewing compensator becomes inactive when the relative position (or inertial attitude) error decreases below the dead zone of the link at the input of the compensator.

The condition for the second (higher velocity) channel to operate is that the error signal expressed in the required thrust duration exceeds 2 sec per the 30 sec interval.

Roughly speaking, the areas on the phase plane of the output signal (position or angle) for the slew and track controllers to operate are as shown in Fig. 9. Using this method of making the transition between the two major modes of operation alleviates problem of guaranteeing the minimum phase lag of the channel composed of two parallel compensators [4,5].

The transient responses to step commands of different amplitudes are shown in Figs. 10, 11, 12. The plots show that the transition is quite smooth for various levels of the step command.

![Fig. 10 Output position(mm), velocity(mm/s) and commanded force (mN) of the multimode control system to 10 mm step command, without taking into account the differential solar radiation between the two spacecrafts](image_url)

![Fig. 11 Zoomed position (mm), velocity(mm/s) and commanded force (mN) of the multimode control system to 10 mm step command, with maximum possible difference of solar radiation between the s/c](image_url)

Fig. 9 Zones on the phase plane where the track and slew controllers are operational
300 350 400 450 500 550 600

Fig. 12 Position (mm), velocity (mm/s) and commanded force (mN) of the multimode control system (without accounting for solar radiation) to 400 mm step command, and position zoomed

9. Multivariable controller

Nine degrees of freedom controllers for the two spacecraft formation was implemented and tested, first, with ideal rigid body plant, nearly symmetrical, with 0.2 and 0.15 coupling coefficients between the variables (in practice, the coupling is much smaller than this), and then, with a realistic plant model.

As evident from Fig. 13, the system overall slewing and tracking performance is quite reasonable.

In this design, each of the 9 DOFs (3 relative positions DOF, and 3 inertial attitude DOF for each of the two spacecrafts) is controlled using thrusters, while accounting for dynamics and thruster coupling of less than 10%.

As mentioned, the plant can be considered a rigid body, i.e., a double integrator for each of the single axis (DOF) controllers. Control bandwidth is primarily limited by the sampling frequency, and therefore the loop transfer functions in all control loops can be nearly identical.

Fig. 13 The output position variables

Differences in the plant inertia for different loops are compensated by the corresponding changes in the loop gain/scaling coefficient. The robustness of the system to the loop coupling is quite good. The tolerance to the crossover frequencies variations (in the bandwidth where all loops have positive feedback) is also reasonably good due to rather shallow slope of Bode diagrams. A small improvement to this controller can be achieved by dispersing crossover frequencies of the elementary controllers within an octave.

Control loops for different variables (relative positions in mm or pointing angles in rad) of the multivariable control system (for the two s/c formation, with a total of 9 DOFs) are nearly decoupled. The control loop gain for each of the DOFs is a function of the s/c mass or inertia, and size, location and orientation of the thrusters. This difference between the various DOFs is accounted by introducing an appropriate linear gain (scaling) block multiplying the feedback error such that in the linear
state of operation the Bode diagram remains the same as in the nominal case.

The output of the compensator gives the duration of the thruster firing that produces the torque or force for the corresponding DOF (axis) control. The durations for all DOFs go into the thruster decoupling matrix to generate the durations for individual thrusters. These durations must be limited to a minimum of 10 msec.

For multivariable simulations without the thruster decoupling matrix, the minimum limit can be imposed on the thruster firing duration for each DOF (axis).

7. Conclusions

Formation controller design as presented in this paper integrates both the slewing and tracking control in a seamless fashion, exhibiting excellent performance while satisfying a deterministic thruster activity duty cycle for interferometric observations. Random nature of traditional dead-band based RCS control is avoided by using a synchronizing pulse between the two spacecrafts, ensuring all thruster induced activity (disturbances) to be limited within the first second of each 30 seconds period (during interferometer observations). This ensures acceptable level of self-induced disturbances while maintaining formation relative position (interferometric baseline) and inertial attitude (target star direction) during interferometer observations.

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References


