A Solar Sail Integrated Simulation Toolkit

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Condensed Abstract

This paper describes an integrated set of high fidelity software tools that are being developed for the design of solar sail missions and analysis of the guidance, navigation and control (GNC) of these missions. This integrated set of simulation tools will be able to predict, re-calibrate and optimize the trajectory, maneuvers and propulsive performance of a sail during a representative flight mission. This tool has capabilities for mission design and for simulation of the sail attitude determination and control, navigation based on ground based and on board tracking, feedback control performance evaluation, parameter estimation and covariance analysis and analysis of attitude control systems. It is capable of evaluating the sail performance accounting for structural dynamic effects, billowing, bending and material degradation effects. The paper will also describe the use of a prototype delivery of the toolkit to analyze the GEOSTORM mission-which is designed to place and maintain an observing spacecraft at a Sun-Earth libration point (sub-L1) at a distance of 3.0 million kilometers from the Earth.

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Solar sails have been studied for a variety of NASA missions to achieve orbits that cannot be reached with conventional propulsion techniques. Unique applications include missions to a sun-earth sub L1 libration point, pole sitter missions that hover above the earth's pole and solar missions. This paper describes an integrated set of high fidelity software tools that are being developed for the design of solar sail missions and analysis of the guidance, navigation and control (GNC) of these missions. This integrated set of simulation tools will be able to predict, re-calibrate and optimize the trajectory, maneuvers and propulsive performance of a sail during a representative flight mission. This tool has capabilities for mission design and for simulation of the sail attitude determination and control, navigation based on ground based and on board tracking, feedback control performance evaluation, parameter estimation and covariance analysis and analysis of attitude control systems. It is capable of evaluating the sail performance accounting for structural dynamic effects, billowing, bending and material degradation effects. The plan is to demonstrate the simulation tools by supporting a NRA prototype solar sail design that is currently in progress.

The toolkit consists of the five functional modules shown in Figure 1 which illustrates the Modular architecture of the toolkit and the interfaces and data flow between the modules. Capabilities include the following:

OPT – the Trajectory Optimization Module - determines an optimal trajectory and sail control strategy which optimizes a given performance criteria (i.e. minimum time, control effort or sail dimension) subject to control and/or state constraints. A second order-gradient optimization algorithm is used to converge to the optimal trajectory. This module outputs the optimal control and control gain matrices which are used by the simulation and control modules

TCN - the Trajectory Control Module - updates the thrust control profile based on the current estimate of the spacecraft state provided by the DET module. This module includes capabilities to use the gain matrix from OPT in combination with previously designed control laws to update the control and predict the updated target conditions. The updated controls (thrusts) are input to the OPT module.

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ADC- the Attitude Dynamics and Control Module - simulates the attitude determination and attitude control. It transforms the thrust commands provided by the TCN module into desired sail-craft attitude; converts desired torques into actuator deflection commands accounting for limits on the attitude rates, control characteristics and constraints. It has capabilities to model attitude control strategies based on use of vanes or center-of-mass center-of-pressure offset (cm-cp); and to model rigid body and structural dynamic effects. It may be used as a stand-alone module to study the performance of the attitude control system and the interaction of structural dynamic and control effects.

DET - the Orbit Determination Module - is designed to be used for Monte Carlo simulation and navigation performance studies. It integrates equations of motion, simulates the observations and process the observables with a Kalman type filter to estimate the current state and statistics. For analysis of mismodeling effects and nonlinearities , trajectories can be generated based on two dynamic models-truth model and a planned model. DSN range and doppler observations and on board optical images-computing observables can be generated for true and planned trajectory. Current state (position and velocity) estimates and statistics of solar sail trajectory are determined based on processing simulated observations.

SRP- Solar Radiation Pressure Module - is the central source of the solar radiation pressure thrusts and torques for the OPT, ADC and DET modules. Using sail and spacecraft characteristics and knowledge of the spacecraft state and orientation, this module computes the thrust and the total torque due to solar radiation pressure. It includes capabilities for modeling structural dynamic effects, simple billowing, beam bending and degradation; modeling vanes or cp-cm offset.

While the modules can be used in an integrated sense as shown in Figure 1, capability exists to use the modules as a stand-alone basis for mission design studies; navigation and covariance analysis; attitude control and sail technology studies. This paper describes the detailed algorithms for each module and the interaction and interface between modules. The paper will also describe the use of a prototype delivery of the toolkit to analyze the GEOSTORM mission-which is designed to place and maintain an observing spacecraft at a Sun-Earth libration point (sub-L1) at a distance of 3.0 million kilometers from the Earth.

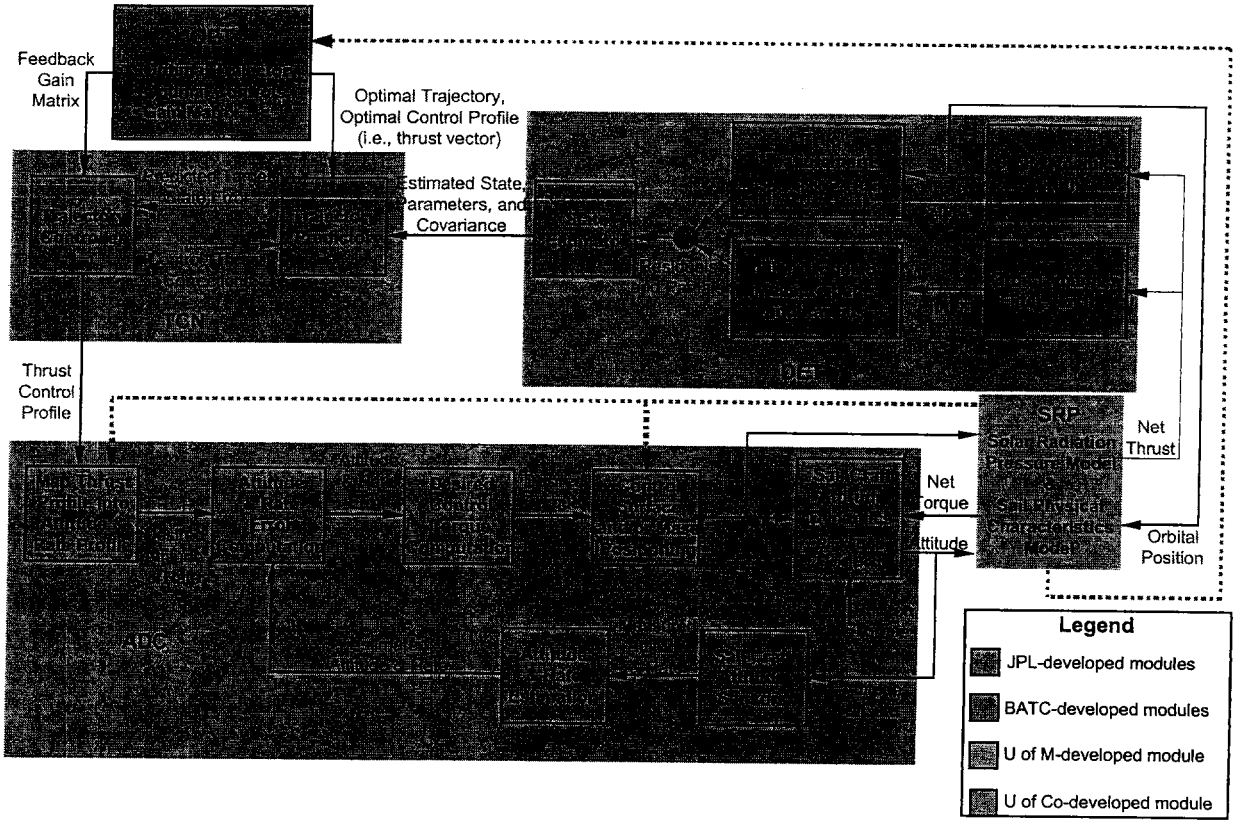

Figure 1 Solar Sail Integrated Simulation Tool Modular Architecture