Spacecraft Simulator for Deep Space Missions

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***Abstract*- Many nations have attempted for the deep space missions to earth's moon, neighboring planets and distant planets. All such mission durations spans across several years and calls for several in-orbit corrections and challenging maneuvers. All such corrections or operations are usually autonomous as there are large communication delays involved with control center and spacecraft (real-time decision making from mission control room is not feasible). At the same time, a small procedural or operational mistake may lead to mission failure. In order to gain confidence and to get hands-on experience it is desirable to perform a rehearsal or simulation on ground.**

1. Introduction

A typical deep space mission essentially houses a liquid engine and highly directional antenna. Liquid engine is mandatory to perform in-orbit corrections and several on course maneuvers. Moreover, it is a critical system which decides the fate of whole of the mission. Along with it, Housekeeping (HK) data transmission antenna which beams spacecraft health to ground station and receives commands fromground station also needs to be fault tolerant and sturdy.

Typically, all systems of spacecraft are connected to HK command reception system which routes the received command to intended system.

Attitude and Orbit Control System (AOCS) controls and maintains attitude of spacecraft and does required maneuvers with the help of sensors and actuators.

For any planned or desired maneuver, ground stations transmit the set of commands which are received by on-board Telecommand Reception System. This systemvalidates and routes the received command to intendedsystem. For majority of the timethese commands are intended for the AOCS and/or payload operations.It is desirable and also a practice followed in all space agencies to have a model (which is combination of simulated sub-system and Emulators) at ground to perform a rehearsal of maneuvers or payload operations to get a knowledge of sequence of events. Moreover, it comes handy in evaluating new procedures in case of any unforeseen event.

Spacecraft houses several systems which are affordable to be simulated. It will result in lesser turnaround time and lesser cost incurred. Entire sub-system behavior can be captured by mathematical model and emulation of external interfaces.

Most of the sub-systems, behavior can be completely modelled using Finite State Machine for:

- System functionalities
- Response to TC and TM
- Response to external disturbances

It includes the functional and thermal behavior of system.

This paper brings out the details fordesign and implementation of a ground spacecraft simulatormodel, which comprises of replica of flight hardware, simulation models, and emulated hardware.

2. Implementation Proposal

The model shall simulateall the tasks which are required in-orbit covering all scenarios such as earth bound maneuvers, trans-orbit corrections. Major sub-systems in a spacecraft are:

- Telecommand Reception System
- AOCS
- Telemetry System
- Star Sensor, Sun Sensors
- Inertial Reference Sensors
- Accelerometers
- Actuators (Liquid Engine and Thrusters)

Fig-1 shows proposed block level schematic of Spacecraft Simulator. It comprises of a combination of simulated and emulated systems and is controlled by an external Simulation Software for user interface.

The building blocks include

- Telecommand Reception and Distribution system (identical to flight model)
- AOCS System with interfaces to sensors and actuators identical to flight model
- Mathematical model of Sensors (Inertial Reference System, Star Sensor, Sun Sensor), the response of which can be simulated as desired.
- Mathematical model of actuators (thrusters, liquid engine, wheels) with measurable output (duty cycle, pulse-width, torque)
- Feedback of actuators output to AOCS through Sensors via External Simulation Software to mimic satellite dynamics.

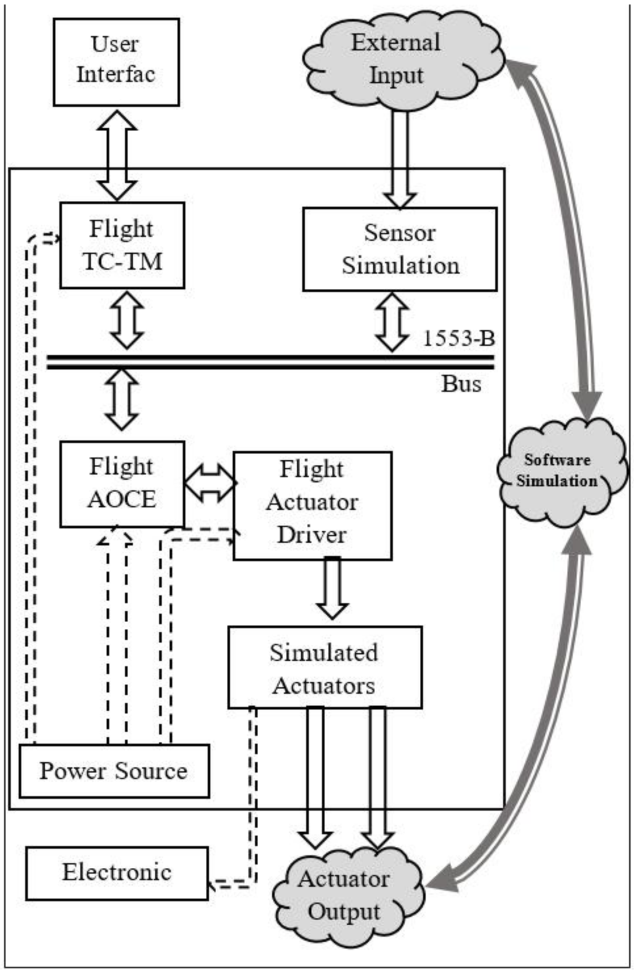

Fig-1: Overall block diagram of model

Inclusion of flight model replica of Telecommand Reception system, Power System, AOCS system and flight-identical interfaces for AOCS with simulated sensors and actuators will give assurance to mission team and enable to carryout in-orbit operations. The individual blocks of spacecraft simulator depicted in Fig-1 are discussed in following sections.

Sensor Simulation

The complete characteristics of sensors can be modeled by Finite State Machine (FSM) along with flight identical external interface (to AOCE, TC and TM). The behavior of sensor in all the possible states can be implemented by means of mathematical equations, which provides definitive outcome to every known input condition. Also, the environmental conditions such as temperature variations andmechanical drift can be incorporated seamlessly. For example, Dynamically Tuned Gyro (DTG) simulation is illustrated in the following sections.

DTG is an inertial sensor, which is used to sense angular rotational rates. Each DTG provides rotational information along two axes. With three DTG's mounted orthogonally, all the three axes information with redundancy can be obtained.Typical electro-mechanical DTG has a rotational wheel with two axis gimbaled, and this needs tobe rotating at a specified speed (Sync speed). On power ON, the wheel starts running up and reaches Sync speed, after reaching sync speed, external command to be issued to control the rotational plane of the wheel in closed loop. The measure of angular rates in two axes is proportional to the control drive issued to maintain the rotational plane.

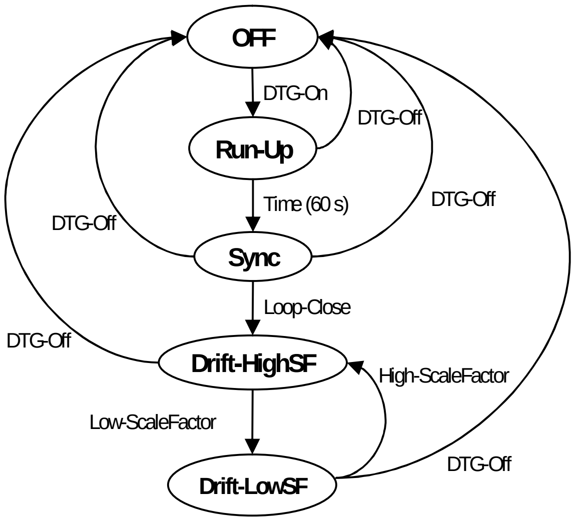

Fig-2. State diagram of DTG

The digitized control drive in each axes is output of DTG. To support wide range with coarse resolution, and narrow range with fine resolution, range selection command is facilitated. To capture these characteristics, various states of DTG operations are shown in Fig-3. Here, the output of DTG follows a defined profile in each state, and state transition is by an external trigger (TC) / time elapse. Also model has to respond to external inputs from Simulator software (like Body rotation, temperature variation etc.,).

Actuator Simulation

The orbit and attitude control actuators are driven by AOCE (based on error generated from sensors). Actuator Simulation is essentially an electronic circuit which has to senses the drive signal from AOCE and provides stimulus to Electronic load to simulate the profiled load on power bus, hence meeting the objective of offering flight identical impedance to AOCE drivers. Here, Electronic load will demand power from power bus as per the actuator characteristics defined. To close the loop of simulation, the Actuator simulation has to convey the thrust developed profile to simulator software.

Simulator Software

This software will act as a link between actuator output and sensor input closing the loop of simulation. The output of the actuator will be measured and appropriately indicated to sensor simulation to update the error. By this closed loop, the behavior of AOCS and its drivers will be captured.

This software facilitates to incorporate measured profile of sensors and actuators, also facilitates to include deviations of response in sensor or actuator in-orbit due to anomaly.

User may program it to simulate and observe the behavior of entire system and certain conditions such as delta-velocity (ΔV), specific maneuver profile, Payload Planning Sequencer etc.

Besides, this software facilitates user requirements such as:

- Satellite dynamics, external disturbances such as planets gravity, solar flux.
- Induce deviation in sensors / actuators response due to anomaly.
- Modulate the behavior of any of the actuator.
- Observe the step response.
- Repeat the behavior.
- Hold the simulation at specified time and analyse the states ofvarious systems.

The level of actuators or sensors simulation can be scaled based on the requirements. If all the environmental variables such as temperature, induced drift and inherent friction because of mechanical movement are implemented in the simulation, it would provide a closer result which would be closer to in-orbit space conditions. Also, simulation accuracy of actuators with respect to response time and damping profile would improve the measurement of its action duration.

Spacecraft Power systems

Power System being a critical system, it is essential to use flight-identical system. However, battery and solar panels may be simulated. Need for flight identical power interface originates from the fact that the system will exhibit its true behavior and response for transients and switching loads.

3. System Implementation Illustration

In order to achieve a holistic spacecraft simulator, it is essential to realise the systems in its entirety. Few systems and interfaces, which forms the core of the spacecraft must be emulated (flight replica). Such systems include:

- Power interfaces
- Serial Communication interface between systems(typically, 1553-B bus)
- On, Off Control from TC system
- Analog and Digital TM Interface (Temperature sensors, health monitoring signals)

In the proposedmodel, sub-systems which are to be simulated can be implemented in a general platform (Hardware and Software) as in fig-3. At the core of it lies the behavior Simulation Software which interacts with TC, TM, serial communication interface, Sink Current Control and simulator software.

The behavior of different sub-systems can be modeled by a Finite State Machine (FSM), where in, the output from this model is pre-defined for a given state.

The state transition will be by a user TC or command from communication interface or by instruction from Simulator software.

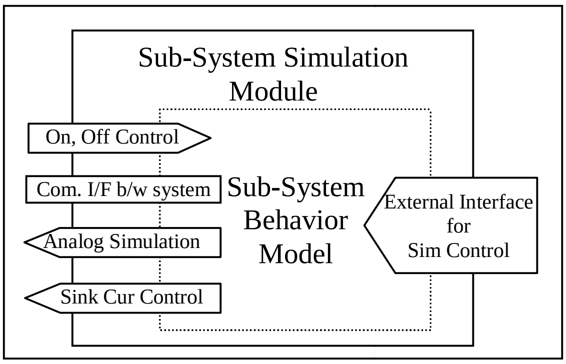

Fig-3: Block diagram of simulated sub-system

To simulate the load current, sink current control signal (profile specific to state) will be generated which drives the common electronic load.

For to simulate any specific in-orbit scenario, desired stimulus will be provided by External Simulator Software to sensor, which in-turn will depict the profile behavior to AOCE and telemetry.

Sub-sequent sections discuss the implementation methods for Communication interface between sub-system, and the On/Off Control command from HK system.

Communication Interface (1553B Bus)

Flight model identical interface of TC and TM with spacecraft systems enables the real environment in which in-orbit systems work. Even though utmost care is being taken during the process of system realisation and to the best of the knowledge checks and steps are implemented in the system software implementation, there always remains some untested routine or path which may result in non-nominal behavior. Such behavior may not occur during routine testing and surface only when system is subjected to a real-time environment with all live, working interfaces. Implementing such flight-identical interface will aid and benefit in encountering such conditions and will provide better knowledge about the system. At the same time it will benefit in foolproof sequencing of in-orbit operations.

On/Off Control Command Interface

It is essential to have command interface identical to flight model so as to assesapriori how it affects command generation system if any malfunction or degradation develops in the target system (for which command is intended to). Since all the systems are not flight identical, it is always possible to simulate the degradation or failure on the target system.

4. RF Interface Simulation

RF link to and from satellite is the only link available to command it to do intended function and to receive TM to get information about system health.

In order to gain confidence and to have a feel of close to in-orbit experience, it is desirable to have a flight equivalent RF link through waveguides or coaxial cables.

To simulate in-orbit condition with comparable link margins in RF path, delay lines with programmable attenuation may be introduced to simulate the in-orbit delay.

With such setup, simulation will be close to in-orbit conditions.

5. Case Study

This section discusses an implementation plan, simulator setup for a typical deep space satellite.

The said spacecraft is designed with a battery regulated bus with S-band TTC link. The details of spacecraft are:

a. Power System with single battery and spacecraft bus voltage is same as battery voltage. (Direct Energy Transfer)
b. Inertial Systems consists of 3 DTGs with each provides two axes information
c. Sensors consist of 2 nos. of Star Sensors, 5 nos. of Sun Sensor mounted in 5 locations to form annular ring around spacecraft.
d. 4 nos. of reaction wheels and 8 nos. of attitude control thruster and one Liquid Engine.
e. S-band TT&C link, with 2 distinct frequencies for Transmitter and Receiver each.
f. AOCE for sensor data acquisition, processing to drive actuators.

The setup comprises of flight equivalent systems for:

i. Power System
ii. Telecommand and Telemetry system
iii. AOCE
iv. TT&C Receivers and transmitters

and simulated systems for:

i. DTGs
ii. Reaction wheels
iii. Sun sensors
iv. Load simulation through electronic load which in turn in controlled by software simulator with inputs from user interface.

All the above listed systems are interfaced with 1553-B bus as applicable.

For the simulation of in-orbit conditions, user keys-in the simulation environment and provides the sensor behavior to study the generated actuator response.

6. Conclusion

This paper discusses an approach to realise a Spacecraft Simulator which is close to actual Spacecraft and at the same time it is cost effective and can be realised in lesser turnaround. Also, deviations or malfunctions observed in any of the sub-systems can be incorporated to evaluate the spacecraft behavior in such scenarios.

The criteria for selection of flight-equivalent hardware, software simulation or emulator in realisation of spacecraft simulator are stressed on.

7. References

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