Mission automation and autonomy for the Mars Orbiter Mission

Ritu Karidhal, Nandini Harinath, P. Robert and V. Kesavaraju*

Mission Development Group, Indian Space Research Organisation Satellite Centre, Bengaluru 560 017, India

For interplanetary missions such as the Mars Orbiter Mission (MOM), operating at considerable distances from the Earth, the paradigms of autonomy and automation are especially pertinent. For mission autonomy, the reasons are identified to extend the existing features and adding new mechanisms on-board the spacecraft, which were not available in earlier satellites. For mission automation, space segment and ground segment elements such as mission planning system and automation in the control room are reviewed and necessary elements added.

For interplanetary missions where distances and times for to and fro travel are more, S/C has to micro manage itself. Therefore it would be essential to use on-board to use on-board autonomy to recognize problems on-board the spacecraft and fix them automatically. Thus, autonomous fault detection becomes vital for such long-term, long-distance missions. Various FDIR (Fault Detection, Isolation and Reconfigure) logics were proposed to be added to take care of several autonomy actions. Safe mode recovery and reconfiguration is one of the most critical autonomy features as the ground intervention is not possible till the on-board antenna is automatically oriented towards Earth by the spacecraft.

Similarly, mission automation concepts have been added for various operations with known timelines such as performing Mars Orbiter Insertion operation through an on-board sequencer and various payload operations within an orbit using CCB and Macros features of the on-board TCP processor. One of the most important aspects of mission automation is mission planning, i.e. to work out a proper timeline for all on-board and ground operations using an Executive Scheduler on ground and make the spacecraft ready to take actions based on set timelines.

Keywords: Ground station, Mars Orbiter, mission automation and autonomy, payload operations.

Introduction

FROM the first spacecraft launch to the present, all missions have been micromanaged from the ground, where mission planners and schedulers painstakingly determine the minute-to-minute activities aboard the spacecraft. This has become a finely honed science, but has its limits. As the round-trip light time between Earth and a spacecraft (s/c) increases (Figures 1 and 2), near real-time operations become ever more difficult. Instructions to the s/c on a mission to Mars can take up to approximately 30 min to reach their destination, and the responses naturally take just as long to reach the Earth. Thus, in the interest of efficient use of mission time, the s/c must operate independently from ground controllers for majority of the mission, perhaps communicating with the Earth few times a day, receiving high-level goals for the day. As a result of this limited communication time, autonomy and automation are essential in completing various tasks.

Autonomy

This is defined as the ability of a system to take decisions and perform actions based on pre-defined stimuli. In spacecraft operations it is established in the early mission design phase and is encapsulated within the flight software.

Automation

This is a process or methodology, seeking to perform pre-defined activities in a pre-defined timeline so as to remove or reduce the need for human interaction. The management and implementation of an automation concept is within the remit of a flight control team or science planning team. It is one which may undergo frequent (even substantial) evolution as the mission ages, science priorities change, or as the operations concept evolves based on in-flight experience. Moreover, mission automation can be realized in many ways by design of, and modifications to, the supporting ground segment.

Communications interruption

Apart from large round-trip time, there are many occasions when the spacecraft communication is interrupted.

Mars Orbiter behind Mars planet

Whenever the Mars Orbiter is occulted by the planet Mars (goes behind Mars), communication cannot be

*For correspondence. (e-mail: kesava@isac.gov.in)

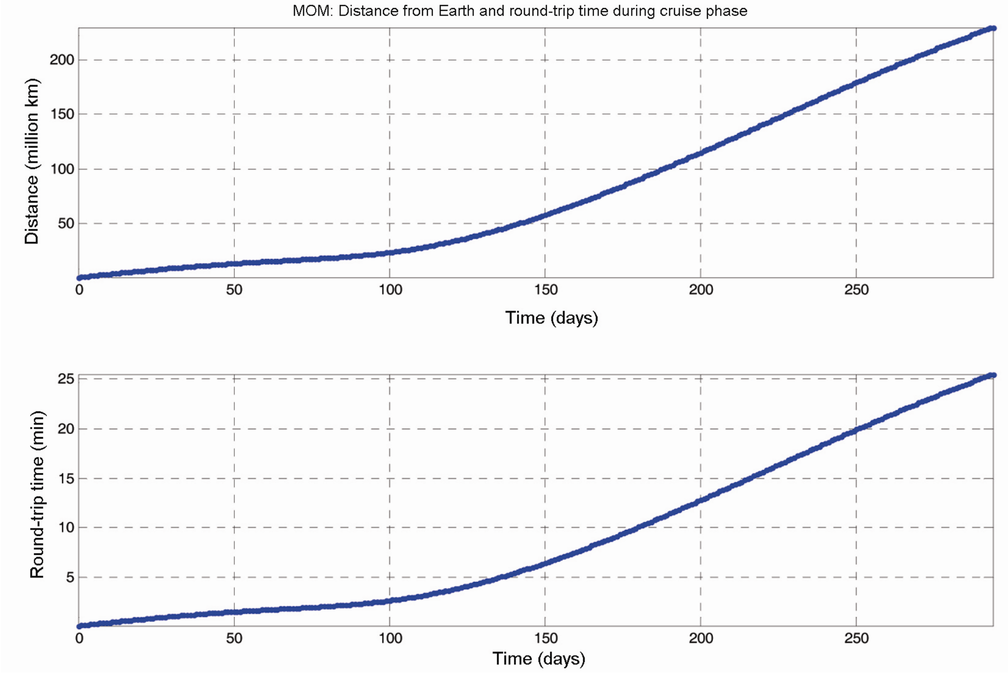

Figure 1. Distance from Earth and round-trip time during MTT phase.

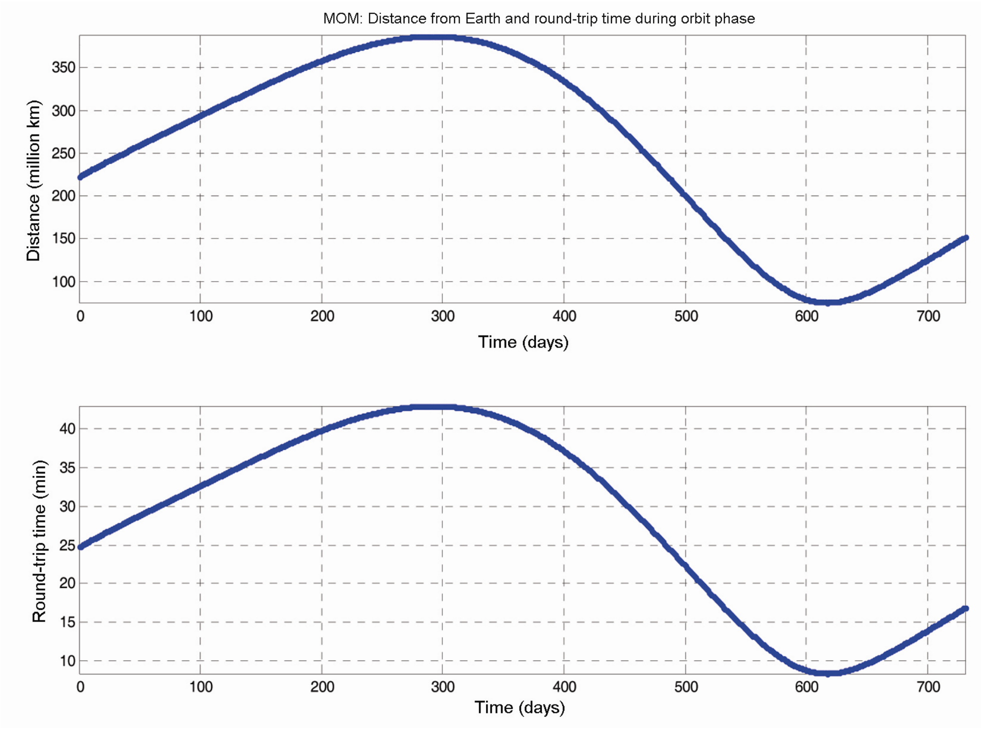

Figure 2. Distance from Earth and round-trip time during in-orbit phase.

established between ground station and the spacecraft. The duration may be of the order of few minutes.

Blackout/whiteout (Earth–Sun–Mars in line)

A communication 'blackout' occurs when the Sun is between Earth and Mars (i.e. the Sun–Earth–Mars angle is within 7°) and no voice or data link can occur for that period of time. The maximum duration of the blackout is around 17 days (6–22 June 2015) (Figure 3).

A 'whiteout' occurs when the Earth is between the Sun and Mars and too much solar radiation may make it impossible to communicate with the Earth. The maximum duration is around 14 days (16–29 May 2016).

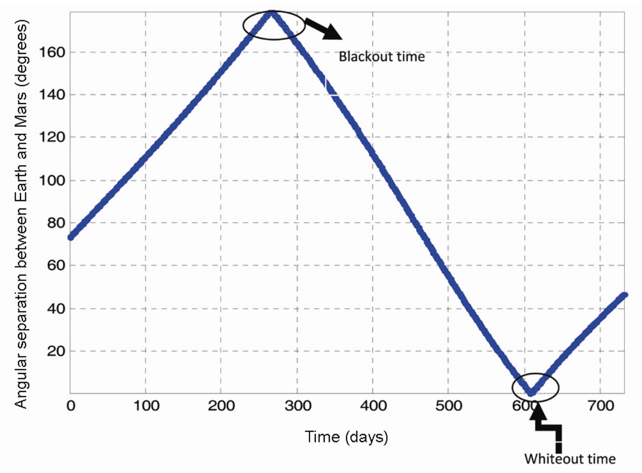

Figure 3. Angular separation between Earth and Mars at Sun centre.

TWTA operating in duty cycle mode

As TWTA requires high power to operate, it becomes necessary to use the duty cycle mode, during certain phases of the mission, providing sufficient time for battery charging. During these times when TWTA is off, the spacecraft telemetry is not available to the ground station.

Special operations and payload operations

As during TCM, when the spacecraft roll axis is aligned about the velocity vector, the HGA antenna boresight moves away from Earth. Even during payload operation times, the spacecraft attitude is Mars-centred which again takes the communication antenna away from Earth-pointing.

Safe mode occurrence/Sun-pointing mode

In case of Safe mode when the spacecraft is made to go to power-safe condition, i.e. roll axis (about which the HGA is mounted) is pointing towards Sun, the communication link is interrupted till the spacecraft comes back to roll Earth-pointing through an autonomous path.

Proposed method of achieving autonomy

As discussed above, in MOM, the basic constraint is on the communication link. The link is totally the function of spacecraft attitude unlike other IRS or INSAT missions, where omni antennas ensure continuous monitoring even during loss of lock. Therefore, the continuous Earth-pointing or returning to proper Earth-pointing after payload operations becomes a necessity. To achieve such a stringent requirement, the proposed method of autonomy is based on Continuous Watch, FDIR without disturbing the Earth-pointing attitude. In case of any sudden failure (before reconfiguration occurs), safe mode may occur which should ensure automatic recovery to Earth-pointing.

Step 1: Continuous watch on major subsystems: (i) Sensors (gyros, star sensor, CASS); (ii) Actuators (thrusters, wheels); (iii) Transmitter/TWTA/telemetry/TCP/power; and (iv) Solar panel (for power generation).

Step 2: Automatic reconfiguration on occurrence of failure detection: (v) Wheels to thruster; (vi) SS1 to SS2 or vice versa; (vii) Selected gyro to non-selected gyro; (viii) Thruster block-1 to block-2 or combination of thrusters; (ix) Transmitter/TWTA/TM/TCP change over from one system to another; (x) Battery charge monitoring; and (xi) Solar panel drive (main to redt).

Step 3. Fault analysis after receiving telemetry data: Once spacecraft health data are downloaded, fault analysis is to be performed to verify the on-board actions and ensure that the faulty chain is isolated completely.

Classification of on-board autonomous actions

The on-board autonomy management functions shall be capable of performing all operations to safeguard the space segment in the presence of a single failure. Table 1 lists the various levels of autonomy. Level-B autonomy plays an important role in MOM as it prevents the spacecraft from entering into safe mode (level-D) and losing the contact with the Earth unexpectedly and also keeps the spacecraft in defined attitude even in the times of known blackouts or communication interruption.

Mission autonomy design

The MOM spacecraft has two computers which perform fault management activities, the TCP subsystem and the AOCE subsystem. The AOCE provides fault management for attitude control functions, while the TCP provides fault management for the remainder of the spacecraft as well as serving as the spacecraft executive. These executive functions include fault checks on the AOCE and AOCE–TCP interfaces.

The spacecraft design should use block redundancy extensively, such that many fault correction algorithms rely on switching redundant elements to alleviate a problem. High priority is placed on maintaining Earth-pointing and a downlink and maintaining command capability. Additional goals of fault management include ensuring spacecraft health by managing power, minimizing expenditure of consumables (fuel), and checking the internal operation of the TCP and AOCE.

As discussed earlier there are four different levels of autonomy. Level A is internal to AOCE or TCP. Level B is based on FDIR logics. Level C is related to actions for

Table 1. Various levels of autonomy

Level of autonomy	Type	Impact	Handling
Level-A	SEU due to ionizing radiation	No impact to mission.	It is handled internally within processors.
Level-B	FDIR	Attitude is maintained to defined orientation and radio link is not interrupted.	It is handled through various types of communication across the processors and sub-systems.
Level-C	Payloads/TWTA OFF due to the occurrence of battery soft emergency level-1 (i.e. battery voltage <35 V) set	Payload is suspended and radio link in interrupted.	It is handled through various types of communication across the processors and sub-systems.
Level-D	Safe mode detection and renormalization Safe mode detection: (1) CASS detecting Sun in non-nominal region. (2) S/c rates more than set value. (3) Occurrence of battery safe level-2. (4) Command loss occurs, i.e. AOCE does not receive command for more than some set duration.	Communication interrupted.	Safe mode detection occurs at AOCE end and recovery happens through TCP and AOCE processor. Radio link resumes after renormalization is completed.

payload abort or battery safe level 1. Level D is related to attitude safe mode occurrence or battery safe level 2 occurrence and the subsequent normalization process.

All AOCE-related FDIR logics are part of the on-board flight software, while non-AOCE FDIR logics are realized using the EBC feature of TCP.

Mission automation design

There are many events during mission operations which are known a priori and can be executed on-board in a chronological order without ground intervention. One such major event is the MOI, which starts with forward manoeuvre then actual burn followed by return manoeuvre. Figure 4 depicts the timeline of operation. This was realized through the execution of events sequentially by on-board TCP and AOCE processor without any ground intervention, which was loaded 10 days in advance on the spacecraft.

There are many on-board events required to be performed in an orbit such as orbit determination-related activities (Delta-DOR/Doppler/ranging), payload operations (imaging and SSR-PB), TWTA in duty cycle mode (if required), and so on. Similarly, there are many ground events such as ground station visibilities and support pattern. Both on-board and ground events are judiciously merged based on pre-defined rules and a timeline of ground and on-orbit operations is worked out. The Executive Scheduler is implemented at ground control centre to take care of automation of mission operations and payload operations based on various rules as provided by payload scientists. The next section focuses on those requirements based on which the on-board sequencer is worked out and gets loaded on the spacecraft well in advance.

Payload operation and automation concepts

MOM carries five payloads, viz. MCC, MSM, TIS, MENCA and LAP. MCC and MSM are imaging payloads while the other three are science payloads. The key parameters considered for imaging are the Sun illumination and imaging altitude or position in the orbit, since the orbit proposed is highly elliptical with the altitude variation of 72,000 km at the apoareion to 370 km at the periareion. The large difference in satellite/ground-track velocity within an orbit calls for special modes of data acquisition to cater to the varying resolutions of the payload. The payload orientation requirements are diverse, calling for on-board algorithms to distinctly reorient the orbiter to the desired payload orientation, from the nominal Earth orientation. On-board algorithms are designed for imaging in any desired orientation with any desired translation rate, payload scanning across the Mars disc with a specified scan rate and also to image the two satellites of Mars, Phobos and Deimos, at the closest possible distance. The algorithms also support imaging in the Earth-bound cruise phase and special operations like tracking of comet Siding Spring during its closest approach in October 2014.

MCC, MSM and TIS

MCC, MSM and TIS are mounted with the bore-sight along the spacecraft body yaw axis. They are operated with the spacecraft yaw pointing towards the centre of Mars. The nominal orientation of the spacecraft is with its roll axis pointing towards the Earth. Payload operation calls for a manoeuvre to reorient the spacecraft from nominal roll Earth-pointing to payload view direction requirement. Further, the imaging strategies for payloads

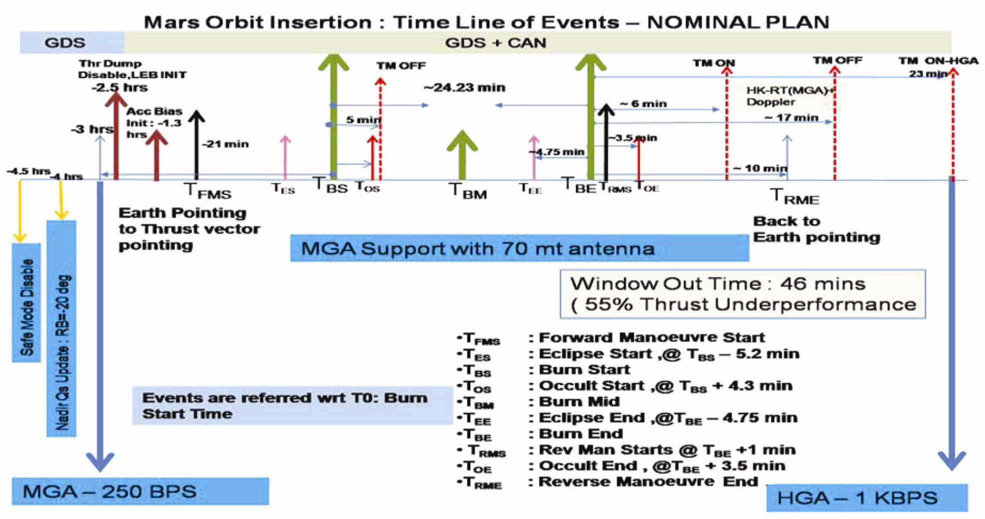

Figure 4. MOM–MOI timeline of events.

are tuned to realize the science goals of a particular sensor within the limitations of the present mission. Since the orbit of MOM is highly elliptical, the altitude of the satellite, ground track velocity, IFOV of sensors, angular extent of Martian scene, etc. vary to a large extent during an orbital period.

Apoareion imaging

Around apoareion region ground-track velocity is small and so push-broom mode of operation is not possible. The payload data have to be acquired in scan mode by slewing the spacecraft in the along-track direction. The Mars subtended angle at the apoareion is of the order of 4°. Hence the entire Martian disc can be covered by scanning a field of about 4° × 4° extent. MCC FOV is 5.7° and hence one frame of MCC can cover the entire Mars disk at the apoaerion. The swath coverage of MSM is only 0.388° and hence multiple lines have to be acquired to cover the entire Mars disk at the apoareion. Radiometric performance of the sensor is also enhanced by scanning at a slow rate. Key advantage of apoareion scanning is the global coverage. When the geometry favours Sun illumination in the apoareion region, in one payload session, all the three payloads are operated by scanning across the Mars disc. While for MSM three scan lines are required for covering the entire Martian disc, TIS covers the entire disc in a single scan line. MCC will acquire multiple frames with multiple exposure levels. The entire operation is again repeated at 12 h intervals. The number of scans and payload operations is constrained by the data that can be downloaded in one orbit.

Periareion imaging

During periareion imaging, all the three instruments are nadir-pointing. TIS, MSM and MCC acquire data only when the scene is illuminated. The data will be acquired in push-broom mode for MSM and TIS. MCC always operates in frame mode in both the apoareion and periareion regions.

MENCA operation

This requires that the roll axis be pointed towards the velocity vector. MENCA attitude is already defined in the algorithm such that full power generation is ensured even in that orientation.

LAP operation

Lap requirement is such that the positive yaw axis needs to look at the bright limb. A transition between illuminated Mars disc and exosphere is desired.

Figure 5 shows altitude, imaging duration and imaging resolution for MCC when the Sun illumination is within 45° for a period of two years.

It can be seen from the figure that immediately after MOI, the apoaerion is illuminated and after 100 days, the illumination moves towards the periaerion and again 400 days after MOI the illumination moves towards apoareion again. The payload operation is carried out with built-in automation through the ground software.

Rules for MCC, MSM and TIS based on geometry

- MCC, MSM and TIS are operated only in the altitudes when Sun illumination <45°.
- First payload session 30 min after eclipse exit and in best illumination condition.
- Second session possible only with session-to-session gap of 2.5 h is present and at that time illumination is better than 45°.

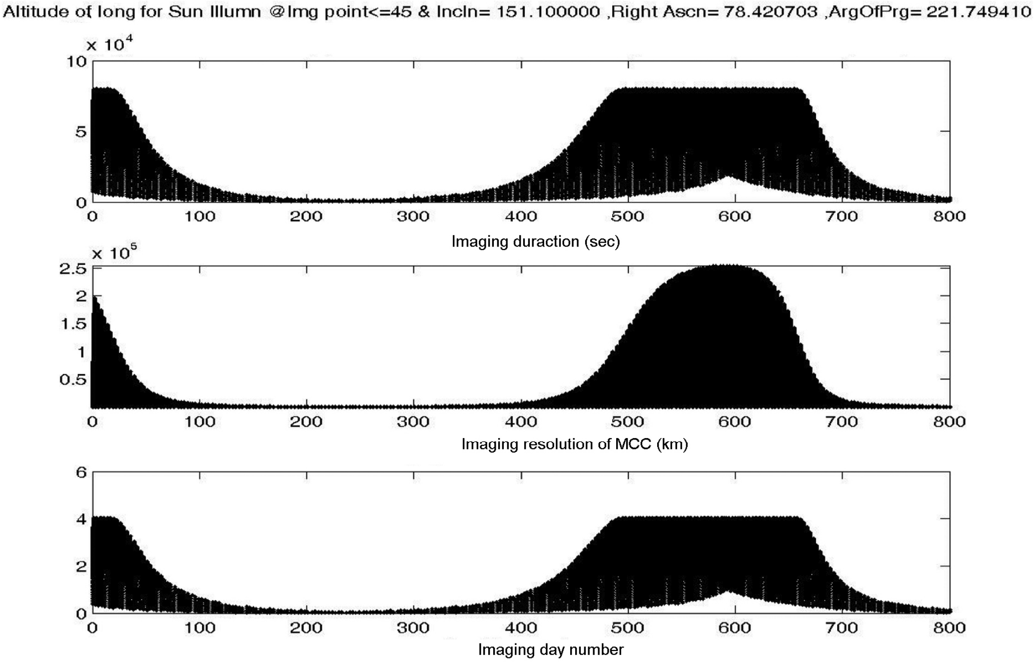

Figure 5. Altitude, imaging duration and imaging resolution for MCC.

- TIS is operated only once in an orbit.
- If subtended angle <13°, apo session planned with three scans.
- If subtended angle >13°, push-broom scanning is planned for 40 min for MSM, TIS is operated for 10 min, 4 snaps of MCC are taken in an orbit.

Rules for MENCA and LAP

- MENCA is being operated four times for 12 h each time in an orbit.
- LAP is operated whenever illumination is favourable, along with MCC, MSM and TIS for 30 min.

Conclusion

In this article, methodology of MOM and payload operations using on-board autonomy and on-board automation have been presented.

Nomenclature

MOM: Mars Orbiter Mission
MOI: Mars Orbiter Insertion
TCM: Trajectory Correction Manoeuvre
TCP: Telecommand Processor
AOCE: Attitude and Orbit Control Electronics
SSR: Solid State Recorder
HGA: High Gain Antenna
FDIR: Faul Detection, Isolation and Reconfigure
CCB: Configurable Command Block
TCP: Tele Command processor
TWTA: Travelling Wave Tube Amplifier
IRS: Indian Remote Sensing Satellites
SS1/SS2: Star Sensor 1/Star Sensor 2
SEU: Single Event Upset
AOCE: Attitude and Orbit Control Electronics
IFOV: Instantaneous Field Of View
FOV: Field of View
MCC: Mars Colour Camera
MSM: Methane Sensor for Mars
TIS: Thermal Infrared Imaging Spectrometer
MENCA: Mars Exospheric Neutral Composition Analyzer
LAP: Lyman Alpha Photometer
DOR: Differential of Ranging
MTT Phase: Mars Transfer Trajectory Phase

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