ACCURATE AND AUTONOMOUS NAVIGATION FOR THE ATV

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The Automated Transfer Vehicle (ATV) is a European Space Agency (ESA) funded spacecraft developed by EADS SPACE Transportation as prime contractor for the space segment together with major European industrial partners. It is intended to service the International Space Station (ISS), providing logistic supply, station reboost and waste disposal. The ATV is designed to perform automated Phasing, Rendez-vous and Docking to the ISS, then Departure and Deorbitation. The ATV, called Jules Verne for the first flight, will be the first European vehicle to perform an orbital rendez-vous. Its innovative Navigation chain has been developed by EADS ST together with their partners EADS Astrium, EADS Sodern, Laben. Its architecture, designed to answer the spacecraft performance and safety requirements, is presented here and the main Navigation functions are described.

Design drivers

Due to its very specific rendez-vous mission toward a manned orbital facility, the Navigation chain of the ATV shall fulfil drastic reliability and availability requirements, so as to ensure an unequalled level of safety with respect to collision hazards.

The ATV Navigation is active through the ATV flight, from injection on orbit by ARIANE 5 to Docking with ISS, from ISS Departure to Earth Re-entry. The phasing duration may extend from 10 to 18 days (including first flight demonstration manoeuvres), whereas the total mission may last more than 6 months. Accuracy of manoeuvres and minimization of fuel consumption are permanent requirements.

The ATV attitude control handles a large set of manoeuvres in all flight phases, such as free drift in yaw steering mode, transfer and approach boosts, slew manoeuvres and acquisition of commanded attitude profiles, tumbling motion in re-entry. For this, the ATV absolute attitude and angular rate shall be autonomously and continuously available with a very high reliability through the mission duration. The phasing manoeuvres being computed by the ground segment, ATV absolute position and velocity are also estimated on ground, from downloaded GPS raw data.

With respect to proximity operations, the design of the ATV Guidance, Navigation and Control (GNC, [1]) shall allow to perform the following flight sequences on request of the Mission and Vehicle Management (MVM) function, respecting at each step specific Safety requirements driven by ISS proximity (see Fig.1 and Fig.2):

- Pre-Homing Drift (transfer S_0 to S_1),
- Homing (S_1 to S_2 and hold in S_2),
- Closing (S_2 to S_3 and hold in S_3),
- Final Approach 1st part (S_3 to S_4 and hold in S_4) and 2nd part (S_4 to mechanical contact with ISS Russian Docking System),
- Retreat to S_3 and to S_4 (current position on $\overline{V}$ axis to S_3 or S_4),
- Brake and Hold manoeuvre on $\overline{V}$ axis,
- controlled Escape (withdrawal from the current point away from the ISS Approach Ellipsoid (AE)),
- Departure from ISS.

Hence a relative state vector shall be available on-board. When Far Rendez-vous controls the ATV to ISS Centre of Masses relative position and velocity, Final Approach shall cope with the docking ports relative state vector, including relative attitude in the last meters. These two phases are then treated separately. If Relative GPS Navigation is the natural candidate in Far Rendez-vous to fulfil the GNC and Safety requirements - linked to the ISS AE in Homing and Keep-Out-Sphere (KOS) in Closing - a specific and innovative Navigation system is developed to aim to automated Docking and to respect Safety requirements in the Approach Corridor.

The ATV Navigation shall cope nominally with ISS proximity link coverage constraints and RF hazards, GPS signal multi-paths, dazzling of sensors by Sun, Earth or ISS, optical environment at the ISS vicinity (Sun reflections)…

Concerning failure tolerance, after the detection of a first failure or in case of double failure of different pieces of equipment (considered as successive single failures), the ATV GNC algorithms shall keep running and be able to complete current operations. In case of double hardware failures leading to the loss of both the nominal and redundant equipment, or one hardware failure followed by one software failure, or after one software failure, the ATV GNC shall be compatible with a triggering of the vehicle Survival mode, possibly after the execution of an auto-Collision Avoidance Manoeuvre (CAM) performed with a specific control chain, the Monitoring and Safety Unit (MSU), or after an Escape manoeuvre. In any case, Safety requirements shall be respected after any second failure and the KOS shall remain un-violated after 24 hours of ATV free drift.

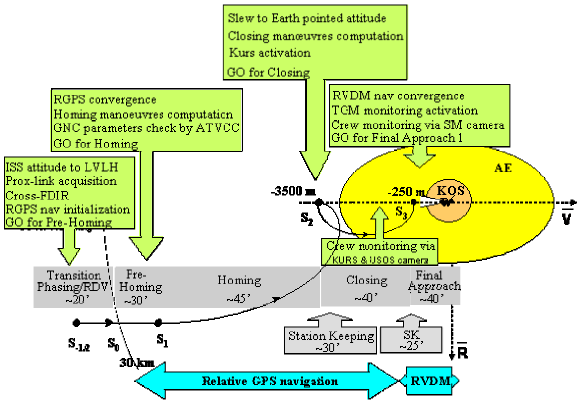

Fig. 1 - Nominal Far Rendez-vous scenario

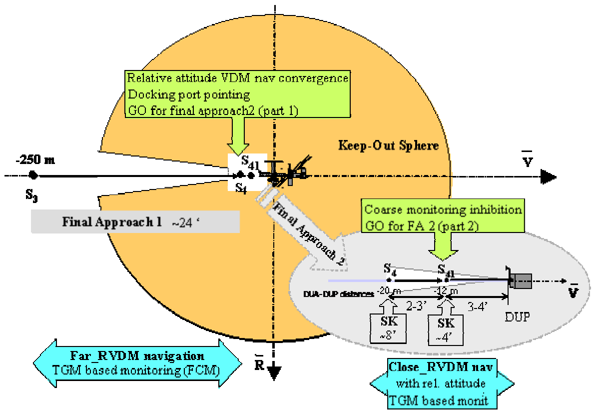

Fig. 2 - Nominal Close Rendez-vous scenario

Navigation architecture

The whole ATV Navigation system has been designed to fulfil these very stringent requirements. Based on fully redundant hardware, the Navigation algorithms present optimal estimators and multi-layers Failure, Detection, Isolation and Recovery (FDIR) capabilities to ensure the continuity of the state vector in case of failure. Several functions provide to Guidance & Control (GC), Flight Control Monitoring (FCM) and to the ATV Control Centre (ATV-CC) the required parameters estimations and health reports, according to the flight phase (see Fig.3 and Fig.4).

The Attitude And Drift Estimation (AADE) function continuously estimates the vehicle absolute attitude and angular rate during the whole flight. Using data from a Gyrometers Assembly (GYRA, of four 2-axis Dry Tuned Gyros DTG) and from two Star Trackers (STR) in cold redundancy, three parallel estimation filters perform an accurate attitude and gyros drifts estimation with an autonomous reconfiguration capability after a first or a second failure. In Survival mode, a dedicated Attitude Estimation in Survival (AES) function provides a robust attitude and angular rate solution with reduced sensors availability.

Absolute position and velocity during orbital phases is performed on ground from the telemetry of two on-board GPS receivers. For the Far Rendez-vous, at 30 kilometres from the ISS, relative position and velocity are provided by the Relative GPS (RGPS) navigation function. Raw data in C/A code from both the ATV and ISS (via radio link) receivers are processed in an in-line 8-states Kalman filter with non-stationary gains.

RGPS cannot provide the accuracy and reliability necessary for the Docking conditions. Dedicated relative navigation functions (Far_RVDM from 250 to 20 meters and Close_RVDM in the last 20 meters) with Videometer (VDM) sensor apply in Close Rendez-vous, in the final approach along $\overline{V}$. VDM data are processed by specific robust navigation filters and FDI algorithms that return a very accurate position, velocity and mean attitude (in the last 20 meters) relative to the docking port.

A monitoring function Navigation Transition Validity Check (NTVC) checks the validity and the consistency of the successive navigation functions in rendez-vous (approach and retreat) before authorising the transition from one to the next.

Last the ISS Parameters Conversion (IPC) function interfaces with ISS GPS data to compute the ISS Local Horizontal Local Vertical (LVLH) current orientation, ISS attitude and an AGPS solution for ATV absolute position and velocity.

These functions interface with the navigation sensors [2] via the GNC Measurements System (GMS) function [3] that processes the raw equipments outputs and delivers the requested functional data associated to various FDI reports. At this stage, FDI concerns sensors health statuses monitoring and validity tests performed on similar sensors measurements, such as the consistency equations using the multiple redundant gyro measurements. Both sensors and individual measurements health statuses, and any detected failure whether isolated or not concerning the gyros, are directly reported to the navigation functions that reject corrupted measurements on a case by case basis before they are used in the estimation process, continuously disregard the measurements from an equipment unit identified as failed, and immediately reconfigure their state vectors. Complementary FDI tests are performed within the estimation filters of the navigation functions. Any failure isolated either by GMS or by a Navigation function is reported via an alarm to MVM for hardware reconfiguration and to the ground segment for analysis.

Although the ATV GNC is autonomous, the ATV dynamics is monitored regarding Safety criteria by an independent FCM chain, using specific algorithms and, as far as possible, its own set of sensors (e.g. the Accelerometers Assembly (ACCA) and the laser-based relative sensors, called Telegoniometers (TGM), for the Final Approach), or dedicated measurements (GPS). This function is able to autonomously trigger a CAM or an Escape as soon as any safety threshold is reached. It provides the failure robustness complement, regarding any failure not detectable within the GNC, such as a Control software failure. This function is not detailed here, since it does not belong to the nominal GNC loop.

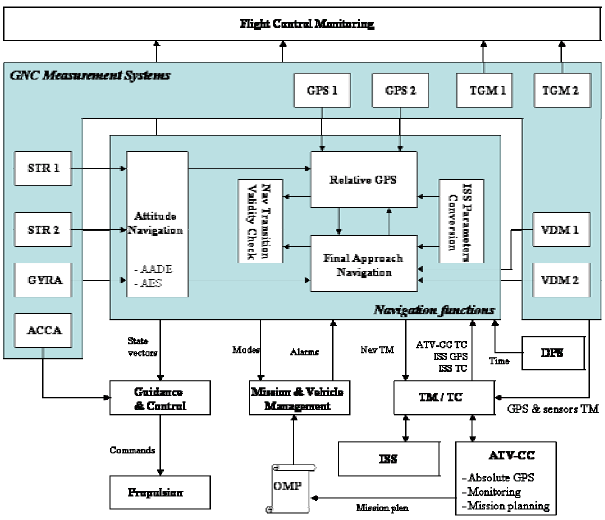

Fig. 3 - ATV Navigation functional synoptic

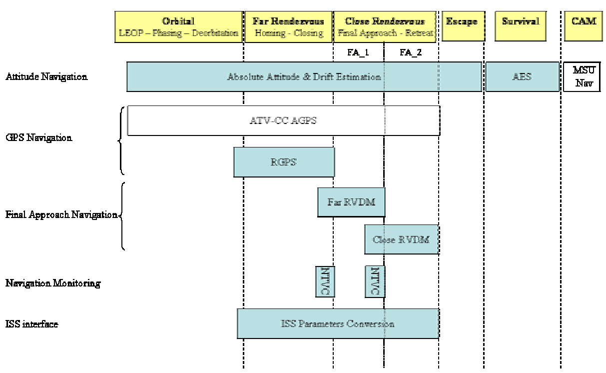

Fig. 4 - Navigation functions activation

Attitude estimation

The absolute attitude and rotation rate estimation function is based on a gyro stellar filter using the measurements from four 2-axis DTG in a GYRA assembly, updated with the measurements from one of two Star Trackers providing 3D inertial attitude with lost-in-space capability.

Accuracy requirements (typically 0,2 deg/s and 1 deg (3σ) in orbital phases) are driven by the slews and boosts performances and shall comply with the pointing requirements of the RDV sensors and with the respect of the ISS Safety approach corridor. These requirements shall be met in case of periods of STR unavailability (reconfiguration, erroneous data, dazzling or masking in final approach), as well as after any first failure in the navigation chain. The function shall also be robust to a gyrometers second failure and remain active and compatible with an Escape manoeuvre in Far and Close Rendez-vous.

The ATV inertial attitude quaternion is propagated at 10 Hz. This ensures the continuity of the solution in case of temporary loss of STR, from a weighted average of all available active gyro axes.

The attitude is updated in a stationary Kalman filter using the propagated attitude and any valid dated quaternion output by the STR.

Drifts of all gyro axes are also estimated independently in three Kalman filters, with objectives to compensate the raw measurements and to isolate a possible drift failure. This contributes to the global FDI, together with the STR innovation monitoring within the filters. Furthermore, after any gyro failure, it allows the continuity of the solution by permutation to one of the valid asymptotic solutions, while reallocating the state vectors according to internal coherency tables. To improve the reactivity, reconfigurations are performed autonomously, without looping to MVM, after each failure, whether detected at GMS or at Navigation level. Reconfigurations are reported to the ground segment that can keep track of the current onboard configuration. Software health is also monitored and numerical anomalies are reported.

All sensors alignment data are calibrated data, updated from measurements performed along the hardware integration process.

Memory management and computing load were a particular design concern, given the high number of configurations to be handled by the algorithm, and very tight software optimisation has been carried out.

AADE performances have been established by Monte Carlo campaigns. In order to demonstrate the FDIR performance, worst cases of failures have been systematically looked for in the various flight phases. This let us show that, even in the absence of STR in the most critical manoeuvres, any case of single DTG failure is compatible with the respect of nominal GNC performances requirements and any case of double failure remains compatible wrt Safety requirements and the triggering of an Escape manoeuvre anywhere in the Rendez-vous phases.

In Survival mode the attitude estimation function shall allow to bring and maintain the spacecraft in Sun pointed orientation, with degraded sensors modes and without any link with the ground. A dedicated robust function has been developed. From a lost-in-space situation, the attitude is autonomously initialised and propagated from any valid pair of gyros and STR data.

RGPS Navigation

Relative GPS Navigation provides the state vector relative to ATV and ISS CoM during Far Rendez-vous, from prox-link activation at 30 km range.

RGPS accuracy requirements are set so as to allow manoeuvres compatible with ISS Safety requirements linked to the AE, KOS and relative semi-major axes. Furthermore they shall be compatible with the acquisition of targets by the Rendez-vous sensors in S3. 3σ performances shall be better than 15 meters on horizontal axes, 20 meters vertical (LVLH reference) and 10 cm/s.

General failure tolerance requirements apply that conduct to use two receivers in hot redundancy with an autonomous FDIR capability. Beyond this, RGPS shall cope with errors specific to the GPS system: measurement errors with C/A code, multi-path errors due to reflections on large ISS surfaces (leading to up to 100m error on pseudo-range measurements in worst cases), visibility issues (the number of GPS SV visible by both ATV and ISS being reduced by ISS solar arrays masking).

The RGPS Navigation filter is a linearized Kalman filter, with on-board gain computation, processing an eight-dimension state vector (relative position and velocity, relative clock bias and drift) propagated with first order Clohessy-Wiltshire equations. Raw data from a maximum of 9 common visible satellites are processed: pseudo-range (from ISS ASN receiver) and code-phase (from ATV receiver) are used for position estimation with compensation of the GPS satellites bias errors. Relative velocity is computed through derivation of Doppler count (ISS) and integrated carrier-phase (ATV) difference.

Robustness is increased with different monitorings along the processing chain: management of GPS ephemeris, comparison tests on ISS raw data to avoid multi-paths errors, compensation for possible data desynchronization, innovation monitoring, convergence monitoring of the covariance matrix. These high level monitorings add to tests performed within GMS on each receiver, on both receivers (cross-validation) and on their raw measurements. Any confirmed failure of the nominal receiver leads to autonomous reconfiguration. In case of second failure, or of an unisolated failed receiver, an Escape manoeuvre is triggered. It is then up to the ground segment to investigate and resume the mission.

More details concerning the filter design and implementation may be found in [4].

Close RDV Navigation

Final Approach starts at 250 meters from the ISS Docking Unit Interface Plane (DUP). It is first performed along the local horizontal, then along the DUP axis until Docking. At 200 m from DUP ATV enters the ISS KOS defined around the ISS. Within this last phase the ISS Safety requirements are extremely severe and raise strong design constraints on the ATV Navigation. From 200 m ATV shall remain within a nominal approach corridor defined by a cone of 8 deg half angle around the DUP axis (4 deg within the last 20 meters). The relative approach velocity is also constraint to a given profile against range. The range control performance itself is constraint in the hold points and the relative attitude in the last part of the approach. All these relative dynamic constraints shall obviously include the ISS motion.

The final conditions to be reached at Docking, including Navigation and Control are the following (3σ):

- relative longitudinal closing velocity in [0.05 - 0.10 m/s],
- relative lateral velocity < 0.02 m/s,
- misalignment angles < 5 deg,
- angular rates < 0.15 deg/s (transverse),
- angular rates < 0.40 deg/s (roll),
- lateral misalignment < 0.10 m.

FDIR requirements remain the same: robustness to any single failure, and preservation of the ISS Safety after a second failure.

The Videometer is based on imaging sensor technology. Two units are used in hot redundancy together with a dedicated Rendezvous target, made of Laser Retro Reflectors, installed on the Service Module near the docking port and illuminated from ATV by a laser light source. The resulting image produced on the CCD is processed to provide range, Line-Of-Sight (LOS) angles and relative attitude data in the last 30 meters.

The target is autonomously acquired and tracked by the sensor with its own prediction - update scheme, variable according to the range and to the number of reflectors in the field of view.

VDM data are processed by two Navigation algorithms, developed jointly with the Far and Close RDV controllers in order to fulfil the accuracy and stability requirements of the closed GNC loop. These functions provide 3-axes positioning and the velocity of the ATV Probe-Head relatively to the ISS DUP in both Approach and Retreat manoeuvres. Though, the level of noise of VDM raw data at long ranges would result in a saturation of the propulsion controller commands. Therefore low-pass filtering is applied to satisfy the controller's requirements. Such filtering is no more applied at low ranges in order to favour the reactivity of the GNC chain.

Attitude data can be provided by the VDM from 30 meters range. Raw data are processed, so as to filter not only the measurement noise but also the ISS high frequency motion and to deliver a relative approach angle around the mean ISS orientation (the ISS rigid motion period is nearly 300 s).

Innovation monitoring is performed against the function own prediction. In case of lack of data, whether invalidated by GMS or rejected by Navigation, the continuity of the estimation is ensured with state propagation, based on the first order Clohessy-Wiltshire equations for the ATV-ISS relative motion dynamics, and using the commanded acceleration. Would this propagation be maintained for a too long duration, an Escape manoeuvre would be immediately triggered for safety.

Due to the high integration of the Navigation and Control algorithms, close loop accuracy and stability performances have been established on a dedicated unitary GNC simulator. It also allowed to test FDIR principles and to demonstrate the capability of the GNC loop to cope with all requirements after any first failure.

NTVC

This monitoring function validates the transitions between navigation modes RGPS / Far_RVDM / Close_RVDM by concurrent processing of their outputs.

The successive monitorings include the correct initialisation of the activated function, its filters convergence, and the consistency of both state vectors over a given duration. The coherence is established, based on the expected covariance of each estimate.

Operation

The ATV Navigation chain proves a very high level of autonomy. Nevertheless all state vectors and major data flows are downlinked to the ATV Control Centre for monitoring. A large set of commands are also made accessible to the operators for nominal (e.g. RGPS initialization), contingency (e.g. attitude re-initialization) or expert tasks (e.g. FDI thresholds update).

Qualification process

The ATV Navigation chain undergoes numerous validation and qualification steps. Functional validation and performances of algorithms are first assessed in open loop. Software unit tests are performed on all elementary functions before integration. After integration tests, a numerical validation campaign validates the real-time behaviour (reactivity, computation precision…) of the Flight Software on the target computer within the Software Validation Facility.

In parallel, heavy Monte Carlo campaigns are applied on the non real-time Functional Engineering Simulator [5] to validate the GNC performance against its high level requirements with the real characteristics of the modelled equipments. Specific tests are also elaborated to evaluate the robustness domain of the GNC, validate the ATV behaviour and performances with hardware failures, and verify the transitions between the flight phases.

The sensors have been qualified by their manufacturers (e.g. [6]). Furthermore the RDV sensors are tested in a realistic dynamic and optical environment for the Final Approach, together with the ATV GNC and a RS Docking Port mock-up, on the unique ESA real-time EPOS-X facility which offers a continuous rendez-vous capability from 300m down to Docking. As concerns RGPS, a specific campaign (named BIVP) is held in Moscow under realistic conditions for the Russian segment.

Finally, the sensors, GNC running on ATV Fault Tolerant Computer and all ATV avionics are integrated in the Functional Simulation Facility for the final qualification campaign.

Conclusion

The ATV innovative Navigation chain is now being fully validated and qualified in unit tests, dynamically within the whole GNC and after integration on the target computer with hardware in the loop. It provides the high level of performance, robustness and autonomy required by modern spacecrafts involved in human programs, today in Earth orbit but also for future space exploration missions.

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