Abstract

The RendezVous Sensor (RVS) shall guide berthing of the Japanese H-II Transfer Vehicle (HTV) and docking of the European Automatic Transfer Vehicle (ATV) on ISS during the last few hundred meters between Chaser and Station, based on a tele-goniometer measurement principle vs. retro reflector targets.

The operational modes of the sensor have to consider different operating conditions, as target geometry and position on ISS, relative dynamics during approach and retreat, sensor inherent properties, specific constraints for an automated or commanded target selection.

An optimisation of acquisition and tracking performance under completely different requirements hence on similar hardware conditions shall be demonstrated.

1. Introduction

The RendezVous Sensor (RVS) — a Scanning Tele-Goniometer (TGM) — shall guide berthing and retreat of the Japanese H-II Transfer Vehicle (HTV) as well as docking of the European Automatic Transfer Vehicle (ATV). In a precursor project called ARP-RVS, a TGM sensor concept was successfully demonstrated during two in-flight tests on Space Shuttle - MIR docking manoeuvres.

2. Sensor Measurement Principle

A pulsed laser beam is transmitted via a collimating transmitter lens and two scan mirrors, covering Azimuth and Elevation directions. After reflection on a target consisting of corner cubes, the laser beam is received via the scan mirrors and a receiver lens on the laser range finder receiver part.

The scan mirror axes are arranged perpendicularly one to the other, a mechanical scan domain of +/-10 deg each covers an optical Field of View (FOV) of approximately 40deg * 40deg.

Fig. 1: RVS TGM range measurement principle

This figure – called Total FOV – is the upper limit of the RVS TGM scan capability. The actual scan window size is significantly smaller (depending on the actual sensor mode) due to the sensor capability to adjust the scan window position and thus to track a target which has been acquired once.

Fig. 2: Line of Sight measurement principle

Range measurement, see Fig. 1, means time of flight measurement of the laser beam on the sensor – target – sensor path. In this way, short range attitude measurements of the actual Roll, Pitch and Yaw angles can also be performed by the RVS TGM, depending on customer request and target geometry.
Figure 2 demonstrates the RVS TGM measurement principle for the Line of Sight (LOS) determination.

Figure 3 is a view into the sensor head (TGMH), containing the main optical-mechanical components of the RVS TGM. The TGMH protection cover is removed for visibility of the functional units.

3. Sensor Operation

3.1 General
The RVS software has to fulfil several tasks: measurement data evaluation, sensor health supervision, sensor communication with Guidance and Navigation Control (GNC) on the chaser and - in particular - target acquisition and track. These tasks are performed during the so called operational modes. In the next paragraphs, content of the operational modes – Acquisition Mode and Track Mode - shall be derived from the specified operation conditions of the sensor.

3.2 Sensor Operation Conditions
The operational moding concept of the RVS TGM is tailored to a lot of conditions. The most significant ones are listed below, conclusions for the RVS TGM operation are shortly described.

3.2.1 Approach and retreat characteristics of the chasers
Approach / retreat corridors and maximum allowable dynamical conditions have been specified by the Japanese and European customers. These figures are considered for a definition of scan window size and position, to achieve an efficient target acquisition and a subsequent continuous track. As a general rule, the scan window size during acquisition and track should be large enough to avoid target loss due to dynamical motions of chaser and target, but as small as possible to limit the scan duration and to achieve a multiple coverage of the scan window by the laser beam during the Track Mode.

3.2.2 Physical properties and constraints of the sensor
On one hand, the required sensor FOV determines a least dimension of the scan mirrors, on the other hand, mirror scan frequency and acceleration capability are limited by the inertia of the mirrors. For a sinus scan in Azimuth direction and a saw tooth motion in Elevation direction, and considering the range depending laser beam properties, scan window size and scan duration have to be matched accordingly to guaranty target acquisition and track.

3.2.3 Target design and properties
The sensor performance is strongly connected to the properties of cooperative targets, mounted on the Space Station.

High performance Laser Retro Reflectors (LRR) are arranged in specific target patterns. But the ATV and HTV target patterns are not the only LRR arrangements on ISS. Thus, efficient methods for a differentiation between those retro reflectors which are dedicated to the sensor and "alien" retro reflectors on ISS have to be implemented.

Position and distance of the LRRs on the Space Station impact the sensor capability to detect, distinguish and track the sensor dedicated targets. Considering the relative position figures of the LRRs, the RVS TGM beam properties, and the allowable chaser dynamics, range figures for an unambiguous differentiation between targets and LRRs can be derived.

Furthermore, optical-mechanical properties of the LRR, as reflectivity, free aperture and manufacturing accuracy, will influence the RVS TGM operational conditions, e.g. range and hot redundancy capability.

3.2.4 Special customer requirements
These customer requirements are mainly related to the unlike geometrical - optical presumptions for the chaser approaches to ISS:

While HTV approaches on an R-bar during the last few hundreds of meters, i.e. on a trajectory
perpendicular to Earth surface, ATV will move towards ISS via a v-bar, i.e. via a trajectory along the ISS X axis and ISS velocity vector at the same time.

While ATV is going to dock on a port at the very end of the ISS X axis, i.e. on the Russian Service Module SM, HTV will move towards the very opposite region of ISS and uses a retro reflector target on a “side-piece” of the ISS X axis, on the Japanese Experiment Module JEM, for rendezvous measurement.

Consequently, the sensor related LRR target pattern for the ATV can be considered as the closest one with respect to the tele-goniometer sensor.

In this way, the ATV approach conditions are rather similar to those of the precursor project ARP-RVS. Automatic acquisition and track of the target will be based on the closest-target-property: By comparison of the Range figures measured on the RVS TGM, the ATV target shall be selected automatically, out of all retro reflector target patterns inside the scan window. GNC influence to Operational Moding is specified as an allowable commanding to overwrite default figures as generated automatically by the sensor.

The situation is completely different for HTV-RVS: during HTV approach on an R-bar, other retro reflector targets may be closer to HTV-RVS than the one mounted on JEM. Thus, the customer requests a replacement of a fully automatic target acquisition procedure by a partly commanded one. This means in particular that HTV target selection decisions (out of all visible targets in the scan window) are performed by the HTV Guidance and Navigation Control, but figures as the size of the subsequent scan window and the scan velocity are defined by the RVS software, based on the specified HTV dynamics and the sensor properties.

These different customer requirements concerning the degree of automatism in the operational moding concept have been real challenging during the sensor development.

### 3.3 Target Acquisition

#### 3.3.1 Initial Acquisition

Target acquisition is performed during one of the operational modes of the sensor, the so called Acquisition Mode (AM). This mode usually covers large scan windows, with an extension of some arc degrees up to the total FOV of the RVS scanner.

Depending on the AM scan window size, each scan will last some seconds, and the total upper limit of the scan frequency of the RVS scanner usually will not be reached due to the extension of the scan.

During the acquisition scans, the relative motion between Chaser and Space Station, i.e. between sensor and target, continues. Therefore, a limitation of the scan duration and thus of the scan window size is reasonable to be able to reduce the subsequent scan window size without loosing the once acquired target due to Sensor-Target dynamics, and consequently to achieve a convergent behavior of the acquisition scan window size. An effective method for minimization of the AM scan duration is a single coverage only of the scan window by the transmitted beam.

During the acquisition scans, the RVS will receive target returns not only from the target dedicated to RVS, but also from other retro reflectors accommodated on the Space Station. Therefore, a discrimination method between the “right” target pattern and alien targets becomes necessary. Differentiation is conducted either by the RVS itself (e.g. selection of shortest target return), or by commands from the higher level system. Application of the second method requires waiting times on RVS for processing and command creation on the higher level system, furthermore a reasonable back up solution for an autonomous RVS target selection should be implemented to avoid target loss in case of a missing command.

During the waiting time for target selection commands, the relative motion between target and sensor continues. Thus, very limited relative dynamics are advisable to limit the acquisition time. With other words: a similar acquisition time for a pure automatic acquisition and for an acquisition that is commanded, can be achieved with lower lateral dynamics for the commanded version only.

Depending on the actually specified acquisition conditions, some AM sub-modes may be defined.

#### 3.3.2 Re-acquisition

Apart from the initial acquisition as described above, re-acquisition may be necessary for several reasons, for instance after target loss due to chaser motion out of the specified corridor and dynamics.

In general, re-acquisition shall be feasible after target loss in any operational mode. Furthermore, a command re-acquisition shall be possible in a way, that a command overwrites the automatic moding.

Fast re-acquisition, in particular under short range conditions, is safety relevant considering that a chaser of several tons is going to meet a manned Space Station. Therefore, re-acquisition procedures with the shortest possible duration under the specified dynamics conditions are mandatory.
In general, target loss due to well-known reasons, and target loss due to unknown reasons has to be discriminated in the frame of re-acquisition definition.

In case the reason for target loss is unknown, or a specification of dynamics limitation for re-acquisition is missing, the re-acquisition scans should cover the specified worst case dynamics conditions, leading to a large re-acquisition duration.

In case the reasons for the target loss and the dynamics conditions during target loss and re-acquisition are well specified, re-acquisition can be defined dedicated to these dynamics conditions. A detailed analysis of the very specific dynamics conditions as well as their consideration in the re-acquisition mode definition leads to a minimized re-acquisition time under the given conditions in general.

On the other hand, not all reasons for target loss can be covered by one re-acquisition mode than. A complicated moding diagram covering several re-acquisition cases, and leading to a strongly increased verification effort, is one of the consequences from a tailoring of re-acquisition to very specific conditions.

An other one is a need for a definition of a certain priority of re-acquisition cases: The sensor SW has to contain a default re-acquisition case that may be overwritten by Guidance and Navigation Control commands. In case the command is missing, or if the command is given late, a second re-acquisition case has to be applied. Consequently, the total re-acquisition duration may be larger in worst case than for a direct application of a Re-Acquisition Mode covering all target loss cases at the same time.

3.3.3 Application to ATV-RVS and HTV-RVS Acquisition

Figure 4 demonstrates the situation for ATV-RVS: After a commanded start of initial acquisition, the sensor switches into Acquisition Mode 0. Out of the acquired targets, those with the shortest range shall be selected, and an automatic switch into the next Acquisition sub-mode (AM1 or AM2 – depending on the measured range figure - for scan window reduction) shall be performed. Furthermore, during initial acquisition the sensor may be commanded into AM3 or back to AM0 by GNC. Thus, an operator on Earth has the chance to overwrite automatic sensor actions.

In case there is a need of re-acquisition, the sensor switches automatically in Propulsion Error Mode (PEM). This mode has been established based on a specified scenario for target loss. Thus – on one hand – it is the most probable reason for a target loss from current point of view. On the other hand, it is the quickest chance to re-acquire the target, because scan window size and scan duration are matched to a defined target loss scenario.

In case PEM fails, or if there is any doubt on GNC or operator side concerning the result of the PEM, transition to AM0 or AM3 can be commanded.

![ATV-RVS Moding Diagram - overview](image)

Figure 5 demonstrates the HTV-RVS situation: After a commanded start of initial acquisition, the sensor switches into Acquisition Mode 0. Out of the acquired targets, GCC will select the most probable position of the HTV target and send this position to the sensor as a commanded centre of the subsequent scan window. Due to the expected number and location of retro reflector targets on ISS, and thus due to their angular distance measured by RVS, a stepwise selection of target groups down to an identification of the actual HTV target will be performed over an extended range domain.

In case a commanded selection was performed once, the sensor will automatically re-select the relevant target out of all targets in the next scan windows, based on certain criterions, derived from implemented information and measured figures.

If re-acquisition becomes necessary, the sensor will switch automatically in one of the re-acquisition modes. This default re-acquisition mode can be overwritten by GCC command. Furthermore, both re-acquisition modes (covering different
reasons for target loss and thus different dynamics scenarios between sensor and target) can be commanded directly by GCC.

Re-transition to Track Mode will be performed automatically, based on criterions as mentioned above.

A differentiation of the several retro reflectors of the target pattern depends on the actual angular distance of the target forming reflectors, i.e. from their geometrical distance, the range between sensor and target, and their relative dynamics. The introduction of several Track-Sub-Modes is related to the reflector discrimination status during Track Mode.

As mentioned above, a transition from one Track-Sub-Mode to the next one can be performed either automatically or by command. An automatic mode transition requires an unambiguous discrimination criterion for the “correct” subsequent target. For the ATV-RVS Tele-Goniometer, this discrimination criterion results from the shortest-range-criterion for the ATV target on one hand, and from an exact knowledge of the accommodation positions of the original and the redundant sensor on the other hand. Thus, the RVS TGM selects the correct target respectively the correct single retro reflector during the Track Mode transitions without outer commands in case of ATV-RVS.

In case of HTV-RVS, a commanded mode transition between the several TM sub-modes is required just when the respective transition is performed first time during approach or retreat of the sensor. The reason for this need for a command is described in paragraph 3.2.4 of this publication: due to the HTV target position on ISS, an unambiguous retro differentiation criterion has not been specified, and thus the customer requires a commanded target selection.

The following example shall demonstrate the Track-Sub-Modes for the precursor ARP-RVS program. Here, the retro reflectors were arranged in an circle of about 1.5m diameter. Furthermore, some alien retro reflectors were accommodated on the MIR Space Station, hence several meters behind the ARP-RVS target pattern. A discrimination between the ARP-RVS Target Pattern was performed automatically, according to the shortest range criterion, and the following Track-Sub-Modes had been defined, see Fig 6:

The retro reflector positions are represented by small circles, the scan windows by squares, and the mode transitions by arrows. Each Track-Sub-Mode covers several scans (not visible in the schematic sketch in Fig. 6).
TM1: Under long range conditions, the retro reflectors of the ARP-RVS target can not yet be differentiated due to their small angular distance. They are tracked within one scan window.

TM2: The retro reflectors can be differentiated unambiguously now under worst case dynamical conditions, but are still tracked in one scan window. TM2 is a kind of transition stage before switching into TM3, it is necessary for the scan window position definition for TM3.

TM3: Each retro reflector is tracked in a separate scan window, the scanner "jumps" from one retro reflector to the next subsequently.

TM4: The same as TM3, but besides of range and LOS determination, the relative attitude between RVS and the target is also calculated and delivered to the guidance control system.

The Single Reflector Mode (SRM) is a special case of track mode: one retro reflector is tracked, all other reflectors of the target are ignored. SRM is applied if measurement of range and LOS is required only. For the current example of ARP-RVS, the SRM is performed when the distance between and the relative position of RVS and the target pattern are such that the full target pattern is no more visible in the RVS total field of view.

4. Summary

Different specifications and conditions for the TGM RendezVous Sensors for HTV and ATV, their interactions and consequences as well as the experiences gathered during two flight missions of ARP-RVS on Shuttle Atlantis to the MIR Station, have been considered for a definition of the sensor operational modes - Acquisition and Track Modes - and mode transitions.

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6. References