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SCANNING TIME-OF-FLIGHT LASER SENSOR FOR RENDEZVOUS MANOEUVRES

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1. INTRODUCTION

Rendezvous and docking/berthing are key manoeuvers for various missions [1]. In those rendezvous phases where the accuracy of absolute navigation (e.g. by satellite navigation services like GPS or GLONASS) is no longer sufficient, sensors have to provide information about the relative position of active vehicle (chaser) and passive vehicle (target). Satellite navigation (differential GPS), radio frequency sensors and more often optical rendezvous sensors are used to perform the required measurements. Two types can be distinguished in the latter category: camera sensors (sometimes called videometers) and scanning laser range sensors (telegoniometers). Subsequently we present an already available, fully qualified sensor based on laser ranging developed for ATV (Automated Transfer Vehicle) and HTV (H-II Transfer Vehicle) and we will describe possible improvements with respect to key features of the systems such as maximum target range by modifying some components of the already existing laser. Furthermore, we will address the usability of the existing and a future improved sensor for imaging applications

Fig. 1. Electronics unit.

Fig. 2. Optical head.

2. SENSOR STATUS

2.1. Measurement Principle and Sensor Setup

The Rendezvous Sensor (RVS) consists of an electronics unit (Fig. 1) and an optical head (Fig. 2). Primary measurement results are the range and the line-of-sight angles (azimuth and elevation) between sensor and target. The range information is derived by a time-of-flight measurement whereas the line-of-sight angles are measured by evaluating the position of two scanning mirrors (Fig. 3). The two mirror axes are installed perpendicular to each other and permit a sinusoidal scanning of the field of view.
Moreover, using range and line-of-sight angles of at least 3 target components (e.g. retro-reflectors) the relative attitude between sensor and target can be calculated. In this case, the orientation of the plane defined by the retro-reflectors is measured w.r.t. the RVS coordinate system.
Within the ATV Rendezvous Pre-development (ARP) project a prototype has been developed and manufactured. This prototype successfully demonstrated its measurement capabilities and performances during two docking manoeuvers of Space Shuttle Atlantis (STS-84 and STS-86) to the MIR space station.

The design of the actual flight hardware for the projects ATV and HTV was driven by requirements stemming from the purpose of the two vehicles which are both dedicated to supply the ISS with different types of payloads, crew items and propellant. Examples for these requirements are e.g.

– the availability of retro-reflectors mounted on ISS (in different configurations for ATV and HTV)
– eye safe operation of the laser
– measurement range from 1 m up to 730 m
– $40° \times 40°$ field of view.

The laser range finder (LRF) is based on a pulsed semiconductor diode laser with a pulse repetition rate of 10 kHz. The time of flight of short infrared pulses is digitally measured using a Time to Digital Converter (TDC), a radiation hard ASIC, which has been specifically designed for this application. Using 10 parallel conversion channels, this ASIC achieves a time resolution of 13 ps for a single range measurement.

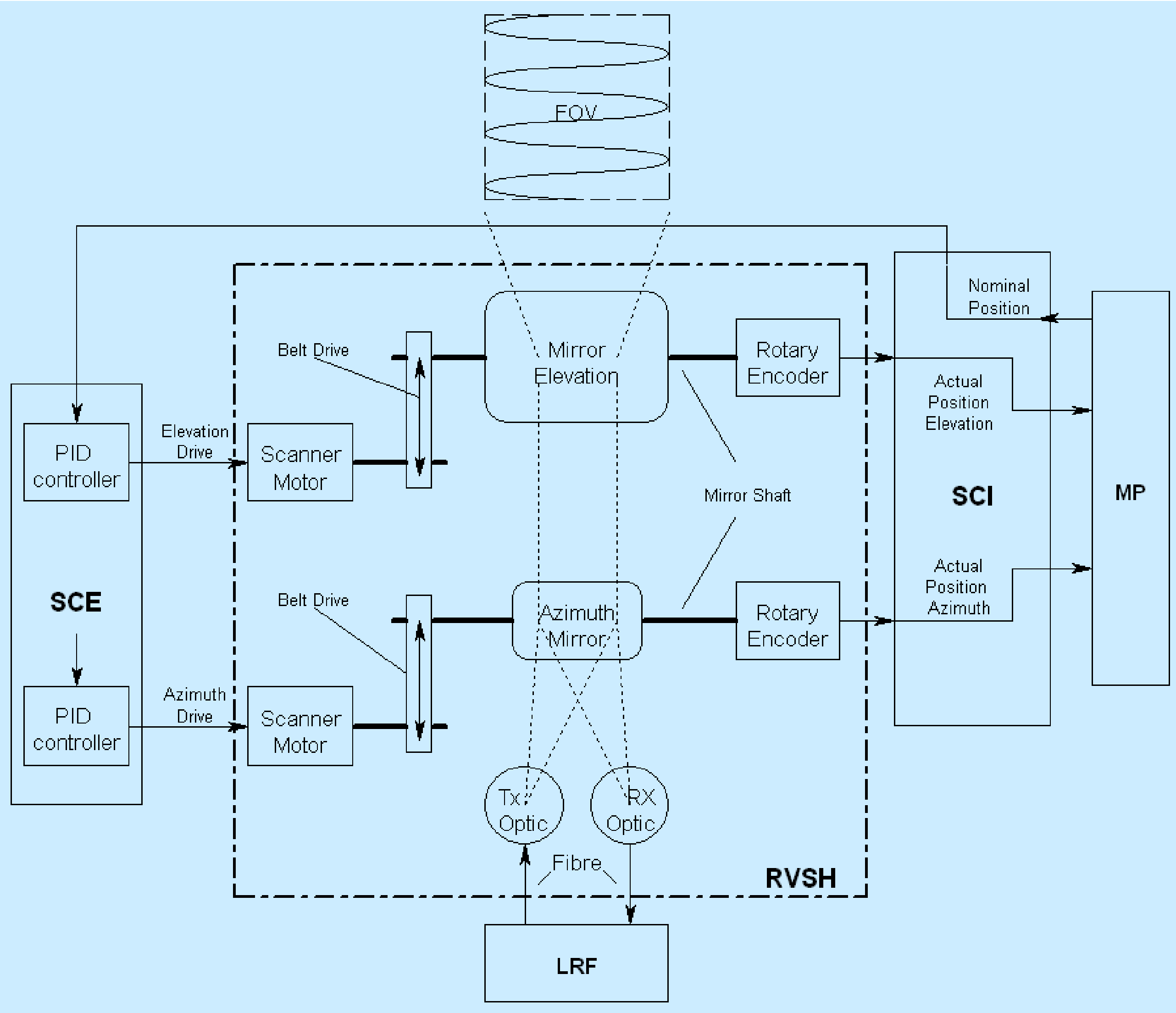

Fig. 3. Block diagram of RVS.

2.2. Sensor Control

The RVS is controlled by a microprocessor containing the flight software (FSW). This software performs various tasks: communication with the Guidance, Navigation and Control (GNC) system, monitoring of the sensor status and processing of the measurement data. Main task of the software is, however, the sensor control within the operational modes of the RVS.

Basically two operational modes can be distinguished: the initial acquisition of the target and its subsequent tracking. Initial acquisition will be commanded after a successful self test of the device. Acquisition of the target(s) and selection of a target to be tracked (in case of more than one retro-reflector in the field-of-view) is a prerequisite for a transition into the track modes.

The control of the mirror motion depends on

– the actual mode,
– some customer specific values (approach corridor of the chaser, relative velocities of chaser and target, target layout, requested data rate etc.),
– sensor parameters such as achievable scan frequency and cross section of the transmitter beam, and on
– the current position of the target after a successful initial acquisition.

The mirror control permits to vary both position and size of the scan window within the total field-of-view by corresponding FSW commands.

A detailed description of the sensor control is given by Ref. [2].

In the configuration described in this chapter, the sensor has been qualified for the projects ATV and HTV. In the qualification campaign, the RVS demonstrated both an excellent measurement accuracy (nearly range independent) and extreme robustness w.r.t. sun and stray light. Table 1 provides the details about the measurement accuracy and main characteristics of the RVS.

Field of View		up to 40° × 40°
Accuracy (1 m –1000 m)	LOS 3σ noise / LOS bias Range 3σ noise Range bias	< 0.1° / < 0.1° (range independent) < 10 mm at near range, < 0.3 m at long range < 10 mm at near range, < 0.5 m at long range
Power consumption		about 35 W nominal, < 61 W maximum
Temperature range	Operational Non-operational	-35°C …+65°C -55°C …+70°C
Dimensions	optical head electronics box	270 mm × 287 mm × 196 mm 315 mm × 224 mm × 176 mm
Mass	optical head / electronics box	6.1 kg / 8.2 kg
Data Rate	ATV / HTV	3 Hz / 2 Hz in the near range, 1 Hz at long distances

Tab. 1. Key parameters of the RVS.

3. POTENTIAL FIELDS OF APPLICATIONS

Up to now, RVS has demonstrated its flexibility mainly by the cooperation with different target types and geometries. In these cases, the RVS has been adapted by a corresponding modification of the software. More interestingly, the RVS can be modified in order to cover a multitude of other applications. To give some examples, this section describes the approaches chosen for using the rendezvous sensor for On-Orbit Servicing (OOS) missions and planetary landing.

Interplanetary missions with the objective to return samples from Mercury or Mars, need range sensors both to ensure safe landing and to perform the rendezvous of a small canister (launched from planet to orbit) with a vehicle for sample return [3].

Especially in case of the landing application the requirements are very different to those from ATV and HTV. A diffusely reflecting surface of the planet would reduce the maximum range of the current RVS to around 300 m. However, while continuing to use the qualified setup and only replacing the diode laser by a fiber laser, it is possible to dramatically improve the RVS performance in these application fields. Section 4 provides more details about this approach and the expected performances.

The diffraction-limited beam quality and the excellent pointing stability of fiber lasers is also advantageous for the application of the RVS as a 3D laser imaging system which acquires 3D information on an object's surface. This capability is illustrated by Fig. 4. The colour-coded range image has been taken with an RVS as qualified for ATV and HTV (i.e. still with a diode laser) with only the software being modified to perform an imaging scan, i.e., scanning the FOV with dense measurements in a regular pattern. For comparison a picture of the same scene taken with a standard digital camera is provided.

The range imaging capability permits an inspection of the target prior to docking in order to safeguard this complex manoeuver. Furthermore, even a detailed survey of any target object is possible.

Typical objectives of On-Orbit Servicing missions are repair or lifetime extension of satellites e.g. by re-fuelling. Those missions impose high requirements on the Rendezvous Sensor, since they request target-less operation on diffusely reflecting surfaces.

These circumstances can be compensated by using more powerful laser sources and extraction and tracking of suitable image features.

A solution for this task is described in Ref. [4]. A terrestrial LIDAR[1] sensor has been used to simulate a navigation and control system for On-orbit Servicing.

[1] Light Detection and Ranging

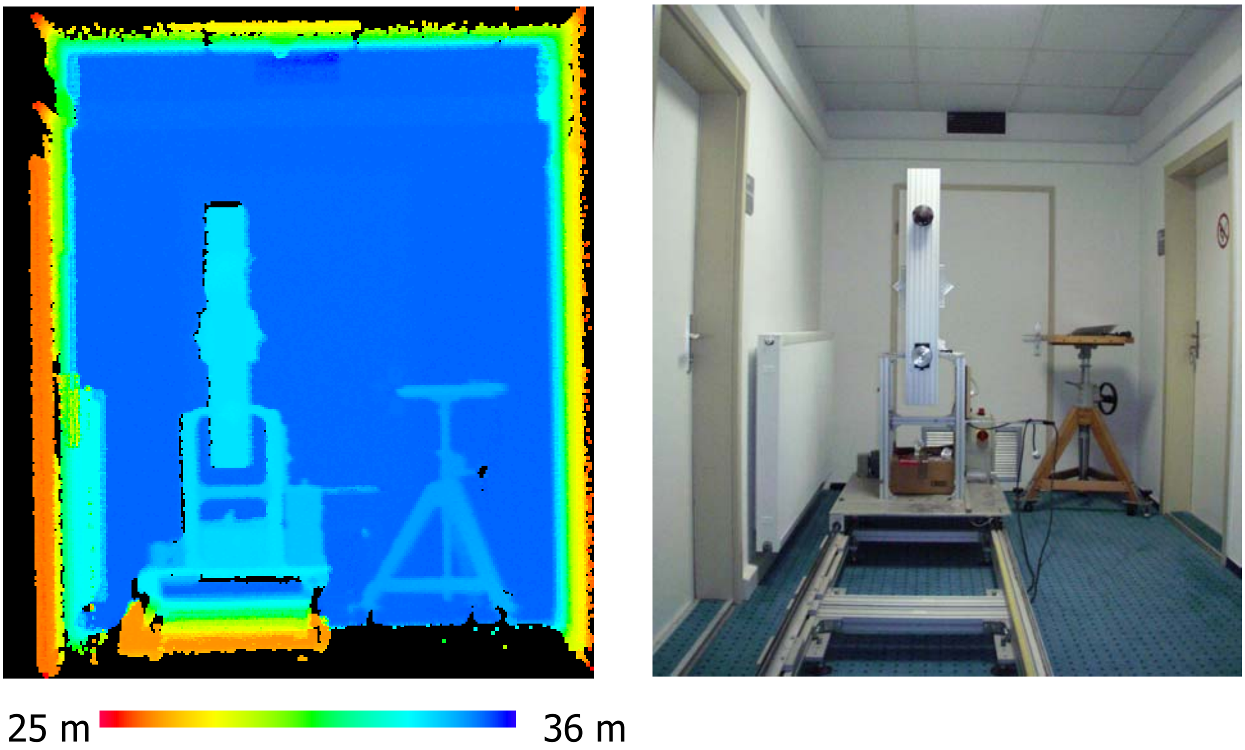

Fig. 4. Usage of the RVS as a range imaging system: comparison of a range image taken by the RVS with color-coded ranges (left) and a photograph of the same scene taken with a digital camera (right).

4. POTENTIAL MODIFICATIONS TO LRF AND ACHIEVABLE PERFORMANCE IMPROVEMENTS

The LRF of RVS is based on a fiber-coupled diode laser with a moderate optical pulse peak power. Although this type of laser source has its inherent advantages such as small size, high power efficiency, low-complexity driver electronics and although this laser type provides excellent performance of the sensor system in combination with the retro-reflective targets, it, however, limits the performance of RVS in the advanced applications as discussed in the previous section. The system parameters directly related to the laser source characteristics include maximum range (determined by laser parameters peak power, beam quality, spectral purity), spatial resolution (beam quality of the laser emission), data acquisition speed (maximum pulse repetition rate of laser), and eye safety (wavelength of laser emission and peak power).

For laser imaging applications, spatial resolution, equivalent to beam divergence of the laser beam, and maximum range to non-cooperative or naturally reflecting targets are of crucial importance [5]. By changing just the laser source of the LRF and by modifying some additional components to cope with the different laser wavelength, the performance can be improved with reasonable effort while using the remaining already qualified components to drastically shorten the overall development time.

Subsequently we summarize the performance estimation carried out to analyze and assess the improvements of an advanced RVS with respect to maximum range and spatial resolution.

Basis for the analysis of the maximum achievable range of the laser rangefinder is the radar equation (compare equ. 1)

$$P_R = P_S \frac{D_R^{\ 2}}{4\pi\beta^2 R^4}\eta_{sys}\sigma \qquad \text{equ. 1}$$

where P_S and P_R denote the peak power of the pulsed transmitter laser and the peak power of the received echo signal, D_R is the diameter of the receiver aperture, β is the beam divergence measured as the full flat angle of the diverging laser beam in the far field, R is the target range, η_{sys} accounts for the losses in the transmitter and receiver optical paths (e.g., transmission of interference filter), and σ is the laser radar cross section of the target.

Time-of-flight laser ranging relies on threshold detection in the receiver. Thus, a second basis for determining the maximum range is the threshold value set in the receiver. This threshold has to be set reasonably with respect to the noise level present in the receiver, as the setting of the threshold directly effects the false alarm rate, i.e., detecting fictitious targets.

Different noise sources have to be considered, e.g. back ground noise due to illumination of the target by the sun or e.g. the amplifier noise of the receiver front end. The dominating noise source for the application in mind is the amplifier noise, as it is intended to use a narrow band filter to suppress out-of-band spectral components and to control the gain of the APD in a way to have back ground noise not exceeding the amplifier noise.

The concept of laser radar cross section is widely used to determine the signal strength of the echo signal in a laser radar. In the literature, the cross sections can be found for various geometrical primitives. For the applications outlined in the section above the following target types have to be considered: extended diffusely reflecting flat target, small diffusely reflecting flat target, small diffusely reflecting spheres, retro-reflecting corner cubes, and retro-reflecting foils.

The term extended means that the target is larger than the laser foot print, which is the typical case for measuring to planetary surfaces from small to moderate distances. In contrast, small means that the target is smaller than the laser foot print and only a fraction of the transmitter energy interacts with the target and is scattered back towards the receiver of the laser radar.

In general, diffusely reflecting targets scatter the impinging optical energy into the a very wide solid angle and thus only a very small fraction of the transmitted signal can be collected by the receiver aperture of the laser radar, especially at longer target distances. In contrast to diffuse scatters, retro-reflecting targets reflect the impinging signal mainly in the direction of the incident beam, thus power density at the receiver will be much larger compared to diffuse scatters resulting in much higher laser radar cross sections. The solid angle occupied by the reflected signal of a retro-reflective target is determined by diffraction and thus size of the reflector and the optical quality of the reflectors. Retro-reflecting foils consist generally of a large number of miniature retro-reflectors. As diffraction is growing larger with the inverse of the diameter of reflector, the solid angle of the reflected signal a reflecting foil is much larger than that of a single retro-reflector of the same size.

In the following numerical examples we use a simple but yet accurate model for the receiver noise taking into account the noise current density of the receiver's front-end amplifier, the bandwidth of the receiver, the current noise of the APD and it's dependence on the internal gain of the APD. For the examples we set the threshold 21 dB above the rms value of the output noise of the receiver giving a negligible false alarm rate and enough margin for actively controlling the APD gain with respect to APD noise and background noise.

For numerical examples we assume:

- fiber laser at 1064 nm wavelength, 10 ns pulse width
- beam collimation, as provided by the transmitter lens in the optical head, is varied in the examples to show the impact of beam divergence on maximum range
- highly-sensitive receiver, narrow-band interference filter
- silicon APD as receiving element
- loss due to beam collimation, two scan mirrors, fiber coupling of APD, filtering, coupling losses.

laser type	fiber laser
beam divergence	0.5 mrad, 1 mrad, 2 mrad
diameter of collimating lens	~ 10 mm
peak power	5 kW
pulse width	10 ns
receiver element	silicon APD
amplifier type	transimpedance amplifier
detection	threshold detection, 21 dB above noise
input noise	5 $pA/Hz^{0.5}$
receiver bandwidth	30 MHz
transmission efficiency from transmitter to receiver	40%
detection threshold of receiver	4 nW at night, 6 nW worst case at day
aperture of receiver lens	40 mm in diameter
bandwidth of interference filter	4 nm
field-of-view of receiver	2 mrad
solar spectral irradiance for day operation	660 W/m²µm

Tab. 2. Assumptions for numerical calculations.

For the calculation of the maximum range we consider the following targets:

T1	flat surface, reflectivity (Albedo) 0.2
T2	flat surface, reflectivity (Albedo) 0.8
T3	sphere, diameter 0.2 m, diffuse reflectivity 0.9
T4	sphere, diameter 0.2 m, retro-reflective foil, 25 cm^2 visible to laser rangefinder
T5	sphere, diameter 0.2 m, reflectors (5 mm),at least 1 visible to laser rangefinder

Tab. 3. Targets considered for simulation.

The subsequent table summarizes the results on the maximum achievable range. Maximum range is also limited by the time-of-flight measurement unit to about 6 km and the pulse repetition rate. In order to have a maximum range of 5 km, the pulse repetition rate has to be less than 31 kHz.

Re-sult	tar-get	day/ night	beam divergence 0.5 mrad	1 mrad	2 mrad
R1	T1	night	6500 m	6500 m	6500 m
R2	T1	day	5300 m	5300 m	5300 m
R3	T2	night	> 6500 m	> 6500 m	6500 m
R4	T2	day	> 6500 m	> 6500 m	6500 m
R5	T3	both	2350 m	1670 m	1150 m
R6	T4	both	15 km	10 km	7.7 km
R7	T5	both	20 km	14 km	10 km

Tab. 4. Summary of simulation results.

The simulation results R1 to R4 show that in order to achieve a maximum measurement range on extended targets, i.e., the planetary surface for a reflectivity of 20% in excess of 5000 m, the pulse peak power of the laser has to be about 5 kW. In the recent past it has been proposed that the laser might be used to illuminate a number of pixels, e.g., 16 pixels, simultaneously with a single laser pulse. To achieve in this case the same ranging performance, the peak power has to be 16 x 5 kW, i.e., 80 kW, which is almost out of scope of a fiber laser, even when multimode operation of the laser is accepted.

Even with 5 kW peak power, the small canister without retro-reflective targets attached can only be measured up to 2350 m in case of a very narrow laser beam. This narrow laser beam contradicts efficient finding of the target while scanning. On the other hand, even modest improvement of the canister's reflectivity relaxes the requirements on the laser rangefinder significantly. Already the reflective foil of only 5 x 5 cm in size would allow to lower the peak power at a beam divergence of 2 mrad. Real corner cube reflectors as assumed in R7 would allow to reduce the laser peak power to about 500 W in a 2 mrad beam and still achieving the 5 km detection goal.

5. CONCLUSION

Due to its high flexibility and accuracy, the presented Rendezvous Sensor comprising a diode laser based Laser Range Finder and a scanner mechanism is well suited for a multitude of applications.

If necessary, an adaptation to customer specific requirements is possible while maintaining the designs, algorithms and key components qualified for the projects ATV and HTV.

It has been proposed to replace the diode laser by a fiber laser. This modification will increase the maximum range in target-less applications of the sensor such as navigation for orbital servicing missions and planetary landing. Whereas the maximum range of camera-based sensors is typically limited to a few hundred meters, this fiber laser RVS can serve up to several kilometers even assuming only a poor target reflectivity.

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