ACTIVE SURFACE IMAGING SYSTEM (ASIS)

Reinhold Flatscher

Dornier Satellite Systems GmbH, Programs Science and Earth Observation Department
D-88039 Friedrichshafen, Germany
phone: +49 7545 8 4979, fax: +49 7545 8 4105, e-mail: *reinhold.flatscher@dss.dornier.dasa.de*

Andreas Ullrich

Riegl Laser Measurement Systems
A-3580 Horn, Austria
phone: +43 2982 4211, fax: +43 2982 4210, e-mail: *aullrich@riegl.co.at*

Gerhard Paar

Joanneum Research, Institute of Digital Image Processing
A-8010 Graz, Austria
phone: +43 316876 1716, fax: +43 316876 1720, e-mail: *gerhard.paar@joanneum.ac.at*

Gerd-Joachim Ulbrich

ESTEC, Mechanical Systems Division – Optics Section (TOS-MMO)
NL-2200 AG Noordwijk ZH, The Netherlands
phone: +31 71565 5515, fax: +31 71565 5430, e-mail: *gulbrich@estec.esa.nl*

ABSTRACT

A high-resolution imaging and ranging laser sensor for space applications was designed, realized and tested. The work comprised the scanning laser radar hardware, software for quick visualization of range images, software to calculate and display the related digital elevation model, and a test bed equipped with several calibrated mobile targets. Measuring on diffuse reflecting targets the typical ranging distance is up to 300 m. The maximum scan range is 60 x 90 degrees. A bi-directional scan of 60 degrees is performed within 15 seconds acquiring 300 x 300 range pixels.

For demonstration of the measurement capabilities of the sensor device a test bed was established. "Natural" stationary targets as well as mobile reference targets fixed on a flexible rack were used to characterize the sensor. In the future any active or passive range imaging sensor can be compared to the ASIS "reference" employing that test bed.

1. INTRODUCTION AND HISTORY

Space research in Earth orbit, lunar and interplanetary environment has yielded an urgent demand for autonomous technologies in recent years. One major technique in this context is based on active and passive imaging sensors. Measurements for application in robotics, navigation, surface reconstruction and post-launch quality control make all use of computer vision.

Laser sensor instrumentation and in particular the pulsed direct-detection technique is the ideal choice for reliable distance measurements in space, thanks to their low to moderate system complexity, the excellent performance and their high instrument layout flexibility. The achievable accuracy is in the order of millimeters.

Pulsed systems are very attractive for a wide range of space applications. This clearly has been confirmed by the work performed under Work Order No. 01 of ESA contract 9230/90 "Laser Sensors for Planetary Research". The core of this work covered the design and breadboarding of a modular laser sensor for planetary research missions, typically to be used for mid-range topographic mapping and during the descent and landing phase.

Some applications which have gained major interest recently, such as laser sensors for rover vehicles, rendezvous and docking, robotics, etc., impose much more stringent limitations on instrument size, mass and power consumption. The next activity in the laser radar line was an advanced miniaturized pulsed laser-sensor demonstrator for near-range space applications (DEAL). Particular emphasis was given to the compactness of the sensor, to the interfacing of modules by glass fibers and to sophisticated techniques of fast signal processing.

Apart from these laser-sensor scientific developments, ESA carried out work on the establishment of high-resolution 3D terrain models of planetary bodies within the frame of ESA contract 9195/90. That work was based on optical imaging with a view to identify and demonstrate the required methods and algorithms for end-to-end data processing.

Now, both lines of development were brought together comprising the laser opto-electronic front-end and the signal processing back-end. The realized ASIS setup allows the performance capability of an integrated sensor device to be validated in front of representative planetary terrain models serving as test scenes.

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2. CONTENT OF WORK

ASIS comprises the realization of an imaging laser sensor and the establishment of a test bed equipped with a stationary "natural" target and several mobile targets. The modular approach of the sensor hardware presents only one electronics unit and one scanner unit both connected via fiber links. Range is measured by using the well-established time-of-flight technique that determines the roundtrip time of a short emitted laser pulse. The start event is defined by the firing of the laser, whereas receiver and subsequent signal processing generate the stop pulse.

A standard personal computer (PC) acts as data display and data collection device. It is also possible to test or reprogram the imaging sensor by the PC via an optional serial interface. Range and intensity images are displayed without geometrical correction in real time on the PC's monitor to get a first impression of the acquired scenery. The final data product is a Digital Elevation Model (DEM) which includes the measured angle information, too. It is also displayed in real time on the PC's display.

The laser transmitter is based on a triple-stack pulsed diode laser running at high repetition rate. High basic range resolution is achieved by short laser pulses of 9 ns generated with the aid of paralleled avalanche transistors. The start event for the time duration measurement is directly taken from the electrical signal firing the laser. No thermoelectric cooling is foreseen to keep the power consumption low.

The receiver relies on the direct detection technique yielding lowest complexity. An optical interference filter suppresses background radiation. The backscattered light is detected by an avalanche photodiode (APD) with stabilized bias. The detector is electronically protected against optical and, thus, electrical overload in case of strong reflections in the near range, e.g. from targets marked by retro-reflectors. The signal of the APD is amplified by a transimpedance amplifier realized in "discrete" technology to give a wide dynamic range and fast recovery at strong light levels in the near range.

In parallel, the amplitude of the received signal is sampled and AD-converted on a shot-to-shot basis. As all involved stages introduce signal dependent internal delays the raw range result must be corrected afterwards. Furthermore, this path provides the intensity of the received signal as an add-on data product beside the range information itself. The intensity signal is logarithmically processed to cover the enormous dynamic range of 130 dB the system works with. A zero-crossing network forming a resonant trigger circuit with the highest dynamic range reported ever gains the stop event for the time-of-flight measurement. The received pulse excites the resonant circuit and the first zero crossing is taken as a stop event. A time to digital converter evaluates the time interval related to the distance of the target. It is based on a circular counter chain with gate delays. The basic resolution of the converter is 2.5 cm. Any electronic component inside the signal processing chain and related internal delay induces range errors depending on signal amplitude and temperature. Thus, both terms are measured and serve as range correction inputs to cover the system's huge operational dynamic range on a shot to shot basis.

The optical architecture relies on a biaxial design strictly separating transmit and receive paths. So, an excellent near range behavior can be achieved because the strong light level brought back by near targets is attenuated by the poor beam overlap nearby the sensor. In the far field where weak signals are experienced the overlap is perfectly one.

The fast line scan is based on a polygon scanner with a four-facet wheel. So, the scan range in this direction is fixed to ±30°. Transmitter and receiver beam hit side-by-side the polygon facet. The focal length of both, transmitter and receiver optics, is 82 mm. The rotation speed of the wheel is nominal 5 rps or 20 line scans/s but can be adjusted by software between 2.5 rps and 20 rps. Rotating the entire „mobile" part of the scanner head with the aid of a stepper motor performs the slower frame scan. So, a very compact scanner unit with extended scan range could be realized. The range of the slow scan is nominal ±30° but can be adjusted by software from ±10° up to ±45° maximum.

A standard personal computer is connected to the ASIS hardware. The PC was also used for testing the demonstrator on system and subsystem level. Range and intensity images are displayed in real-time on the monitor without geometrical correction to get a first impression of the scene. Further statistical evaluations are performed by software modules. The final data product is a Digital Elevation Model including also the measured angle information in two axes. It is displayed on-line and in real time as well. All sensor software packages have been realized with Borland's Delphi and are running in the modern operating system environment NT 4.0 or Windows 95.

The active imaging system serves as a reference sensor in a test-bed. A flexible rack has been built equipped with up to nine surface panels (40 cm x 40 cm size) of different shape, texture and roughness. Dedicated pyramidal, spherical or cylindrical targets allow to test the sensor's spatial resolution, linearity, accuracy and dynamic range. The performance of ASIS is superior and a single shot range resolution of 16 mm (1-σ value) has been measured for high SNR (10^6).

Fig. 1 and Fig. 2 show both main units of ASIS and indicate the portability of the realized system. Table 1 summarizes all features and performance characteristics of ASIS. Fig. 5 shows more details of the Scanner Unit.

3. MEASUREMENT RESULTS

Fig. 3 represents typical range data acquired with ASIS. The data set has been collected by a standard notebook providing color encoded range images for quick visualization. A view of a natural stationary target is shown for comparison. The scan range was 60 degree in both, horizontal and vertical direction. The image contains 333 x 333 range pixels with an angular separation of 0.2 grad. Areas in which no laser range measurements can be performed due to low reflectivity or beam deflections are shown in black in the false color encoded range image. The distance range to be displayed can be arbitrarily set between 0 and 300 m. In the shown figure the limits were set to 26 m and 75 m. Distances outside of this preselected range are measured as well but indicated in gray, e.g. the trees in the background.

Fig. 4 shows the Digital Elevation Model processed online from a typical planetary target, a sand dune. The image shows a top view of the dune with color-coded height above ground in world coordinates. The displayed detail measures 10 m times 8 m. In addition isolines are overlaid to that picture indicating smooth slopes. Each line indicates a step in height of 15 cm. The photo on top shows the entire scenery with the detail used for further processing.

4. CONCLUSION

An active surface imaging system with extended scan range was realized. Excellent range resolution and accuracy were achieved. A wide dynamic range characterizes the laser sensor and is available on a shot to shot basis. In addition, the receiver is protected against optical overload. Combining a fast rotating polygon scanner with a stepped mobile part yielded a very compact sensor unit with potential to further extend the scan range. The imaging system is portable, easy to setup and easy to use. The system can serve all short range imaging applications in the robotics, rover and rendezvous and docking business.

5. ACKNOWLEDGEMENT

The ASIS project was sponsored by ESA under ESTEC Contract No. 9230/90/NL/PB(SC), CCN09 and funded by the Technical Research Program (TRP). ASIS is the latest activity of active laser imaging technology embedded in a frame contract initiated in early 1991. Beside Dornier Satellite Systems GmbH (D) leading the consortium, also Riegl Laser Measurement Systems (A) and Joanneum Research Institute (A) were involved. Riegl manufactured the laser sensor and provided the required software whereas Joanneum was responsible for the Digital Elevation Model and delivered the mobile targets.

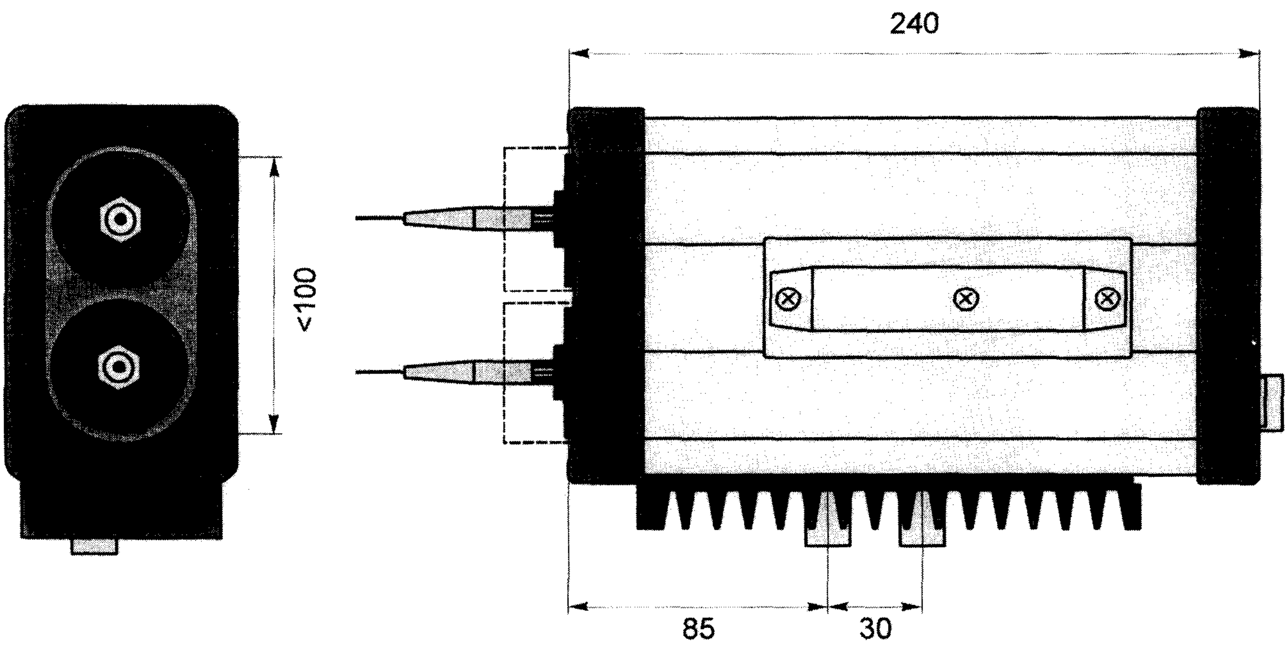

Fig. 1: Electronics Unit (dimensions in mm). Connected to Scanner Unit via glass fibers.

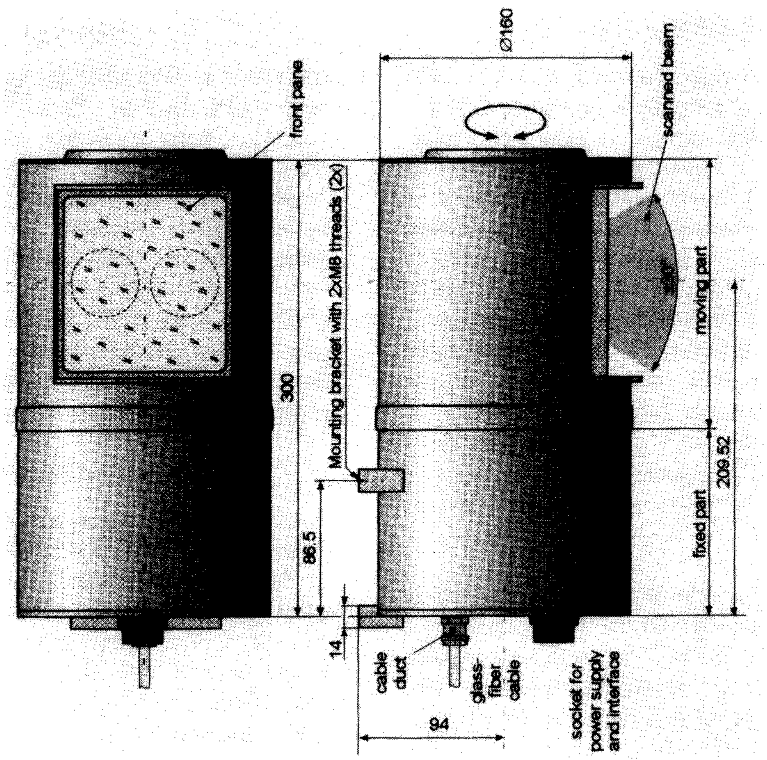

Fig. 2: Scanner Unit (dimensions in mm)

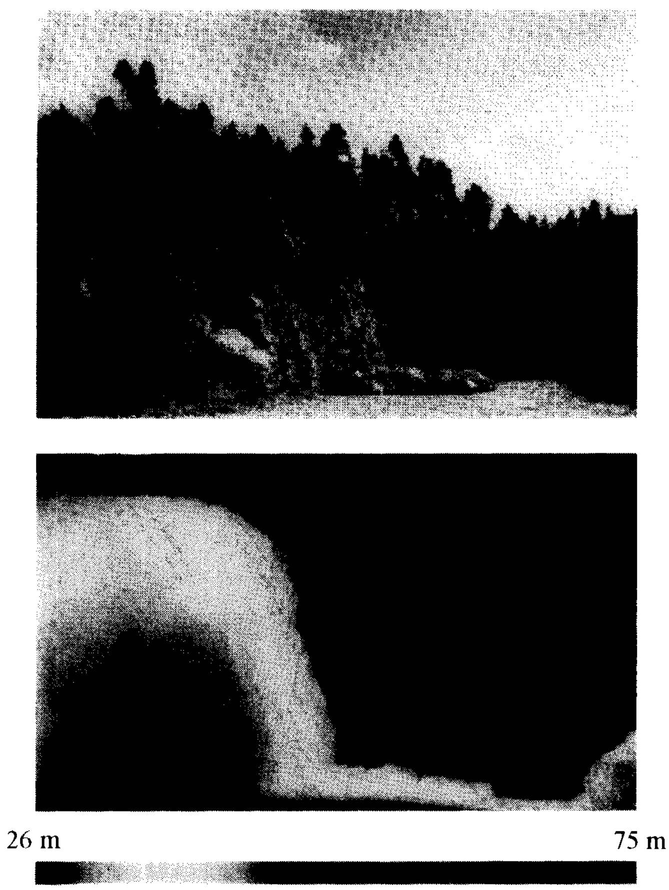

Fig. 3: Measured range image of a quarry. Photo on top for comparison.

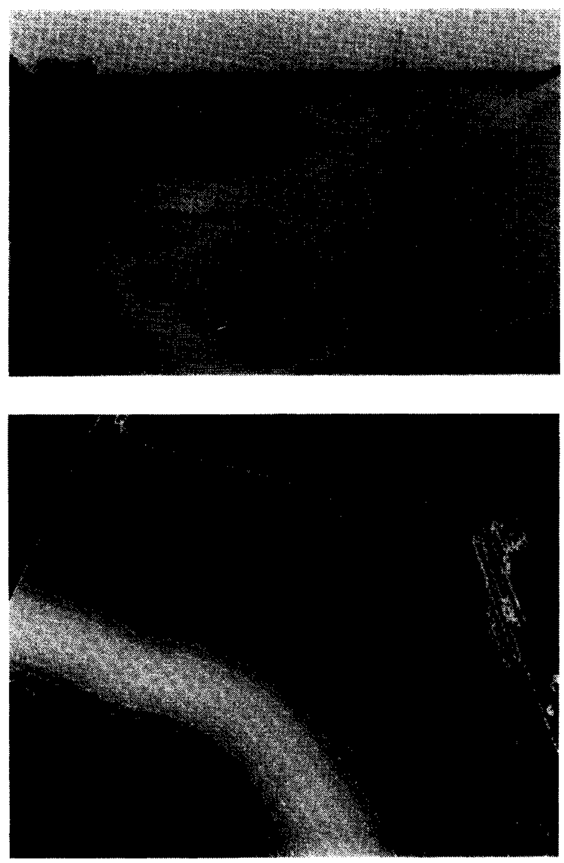

Fig. 4: Digital Elevation Model of a sand dune overlaid with isolines (height steps of 15 cm).

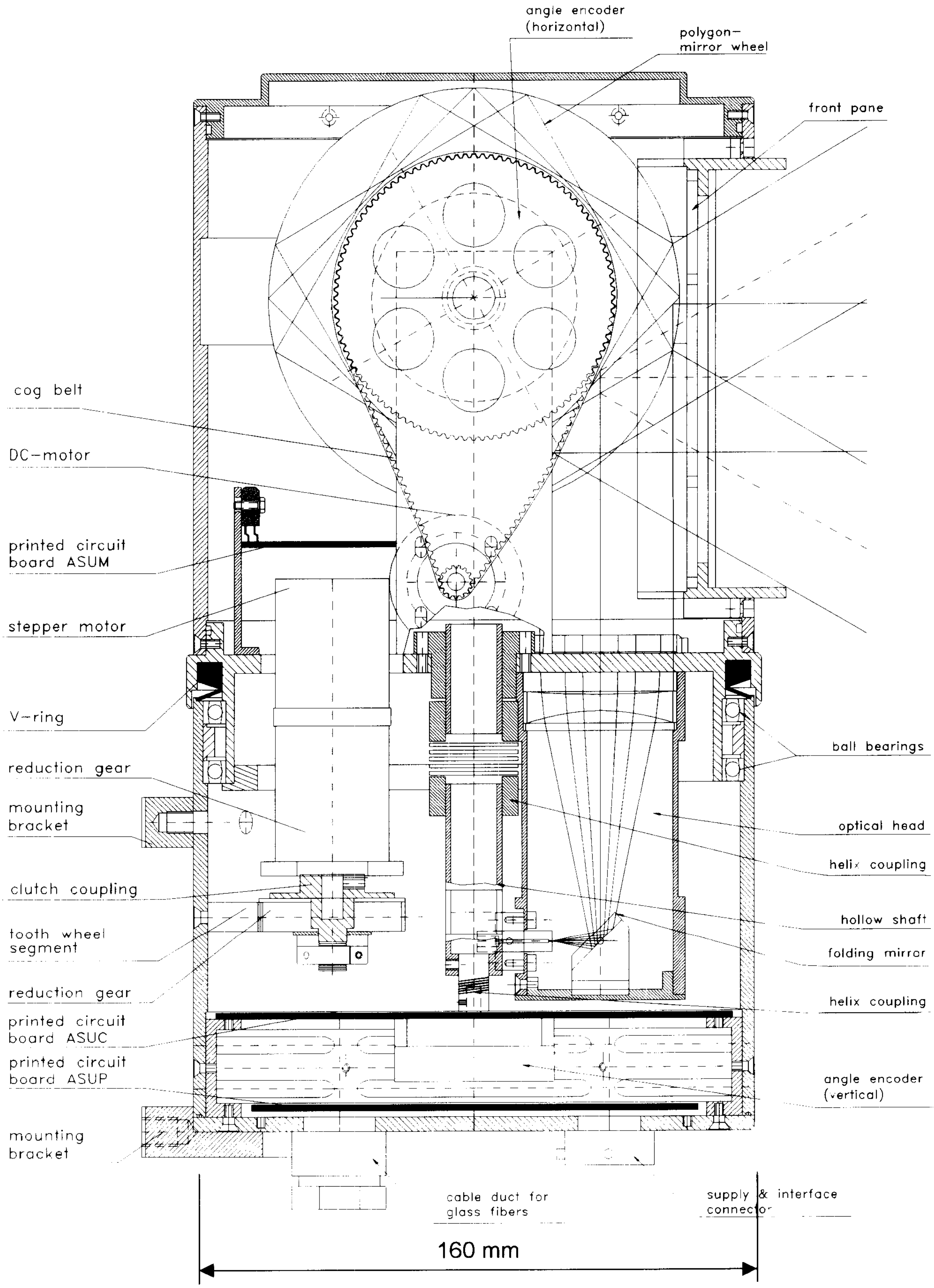

Fig. 5: Cross-sectional view of scanner subsystem.

RANGE MEASUREMENT	
Time-of-flight measurement technique	time-to-digital converter (ring counter with gate delay)
Microcontroller used for range processing	Intel MCS 296, 16 bit, 50 MHz with basic DSP functions
Measurement range	0-300 m
Internal resolution of range measurement	8 mm (all corrections included)
Range measurement standard deviation	1.6 cm at high SNR
Range image acquisition time	15 sec. for 60 x 60 degrees (5 sec. for 20 x 60 deg)
OPTICAL CHARACTERISTICS	
Transmitter / receiver optics (TX / RX)	Ø 42 mm at focal length of 86 mm
Fiber interface to Scanner Unit	300 μm (TX) and 600 μm (RX) multimode
Beam divergence	3.5 mrad (TX) and 7 mrad (RX)
LASER HEAD	
Laser diode	EG&G, PGAU3S09, 3-stack device
Pulse width	9.2 ns
Laser repetition rate	18 kHz maximum during normal operation
	24 kHz with no drop in energy, up to 36 kHz tested
Pulse energy in transmitter fiber	266 nJ at 905 nm
RECEIVER	
Type	direct detection receiver, protected against optical overload
Detector	EG&G, C30902E, 500 μm diameter
Dynamic range of system	130 dB electrical on a shot-to-shot basis
Minimum optical receiver power	1.8 nW at SNR of 9.5 dB optical
Amplitude detection	logarithmic amplifier and 12 bit A/D-converter
SCANNER	
Frame scanner range (programmable)	±10° up to ±45° (±30° nominal)
Scan step	0.2 grad (gon) in both directions
Frame scan speed	4 grad/s nominal up to 16 grad/s
Polygon speed (programmable)	5 rps for 20 line scans/s, range 2.5 rps up to 20 rps
Scanner angle resolution	0.02 grad frame scanner and 0.04 grad line scanner
INTERFACES	
Data delivery to personal computer	one data pack every scan line with 8 bytes/pixel
CODING: Range	2 bytes in units of 8 mm
CODING: Inclination	2 bytes in units of 0.01 grad
CODING: Bearing	2 bytes in units of 0.01 grad
CODING: Intensity	12 bits
CODING: Housekeeping	4 bits
Interfaces to PC	1 parallel (ECP) during normal operation
	1 serial (RS232) in service or test mode only
Internal interface between both units	4 wire synchronous serial port (bi-directional)
Scanner dimensions	300 mm x 160 mm Ø (cylinder)
Scanner mass and power	5 kg and 12 W at 12 V
Electronics dimensions	240 mm x 142 mm x 76 mm
Electronics mass and power	2.5 kg and 7 W

Table 1: Features and characteristics of realized imaging laser sensor.