Experimental Study of the Hybrid Laser Radar

Nikolai A. Gryaznov, Sergey I. Artamonov*, Victor I. Kuprenjuk and Evgeny N. Sosnov

Department of Medical Equipment, Central Research Institute of Robotics and Technical Cybernetics, Saint-Petersburg, Russia Federation; gna@rtc.ru, s.artamonov@rtc.ru, kuprenjuk@rtc.ru, sosnov@rtc.ru

Abstract

Objectives: The aim of this work was to perform experimental studies of hybrid laser radar as an intermediate option between the classical scanning pulsed laser radar and a system built in accordance with a 3D-Flash LADAR technology. **Methods:** The studies were performed on the ground optical track using modern equipment for the registration of measurement results. Modern methods of mathematical modeling were applied for data processing. **Findings:** Hybrid laser radar provided location frame frequency significantly greater than the frequency of the classical pulse radar, without the use of a matrix photodetector required for 3D-Flash LADAR. Frame frequency of 28 frames per second was obtained in the experimental settings with the view field of 20×20°. A signal/noise ratio was also determined imitating maximal operating range of 2 km on the ground track or of 5 km in space. **Improvements:** Hybrid laser radar can be used in robotic systems as a 3D technical vision system.

Keywords: 3D-Flash LADAR Systems, 3D Images, Hybrid LIDAR, Scanning Systems, Time of Flight

1. Introduction

Large number of practical issues including air and space cartography, ecological environment controls, selfpropelled robotic systems, means of radar detection, tracking and self-homing space, air, ground, surface and underwater equipment requires the use of the use of threedimensional information on the spatial location of objects relative to the observation system, and in some cases, relative to the outside (in relation to the supervisory system) coordinate system. One of the main ways of receiving 3D images of objects in the field of view observation system is laser location of the area with the measurement of the time of flight of the laser radiation to the observed objects and back. Laser radar system consists of the transmission channel, forming a pulsed laser beam illumination of the visual field, and the reception channel, in which the measurement of the angular coordinates of the object and the time of flight of the laser pulse is performed. The result of the measurement is a 3D cloud of dots creating an image of the observed area.

Currently the most used systems are classic point wise scanning systems¹⁻⁴. They are characterized by large

*Author for correspondence

maximal measurement range, high signal to noise ratio and weak influence of speckle noise of the laser radiation. The main disadvantage of these systems is a long time to receive information.

Systems made in accordance with 3D-Flash LADAR technology allow to capture 3D image in a single laser pulse^{5.6}. However matrix photodetector sized N×M has to provide measurement of the flight time of laser pulse at each pixel, and the pulse energy has to be N×M times higher compared to classic scanning system.

Element of resolution in such a system is determined by the pixel size (or the size of the scattering circle for the lens being used, if it exceeds the size of a pixel), the field of view is determined by the laser beam divergence. Main disadvantages of this system are a small range for large fields of view (lighting area) and limited bins, while the main advantage is high performance. Recently, hybrid schemes of laser locators have been developed that use a combination of a multi-element photodetector and scanning system^{7–9}. In particular cases hybrid systems allow finding a compromise between contradictory system requirements, cost and technological limitations. In this article we provide the results of experimental studies of the layout of hybrid laser radar proposed in other source¹⁰.

2. Materials and Methods

A block diagram of a laser radar system layout on the basis of the one-dimensional scanning and linear Time of Flight camera (TOF camera) is presented in Figure 1.



Figure 1. Structural scheme of the hybrid laser radar. 1 – Solid repetitively pulsed laser, 2 – optic system, forming laser emitting, 3 –intermediate mirror of the laser channel, 4 – drive of the scanning mirror, 5 – sensor of mirror angle position, 6 – scanning mirror, 7 – lens of the receiving channel, 8 – fiber optic harness, 9 – an array of individual photodetectors, 10 – timeslot measurement system, 11 – the laser control unit, 12 – start-pulse sensor, 13 – central processor, 14 – scanning mirror control board.

The main differences between the circuit of the hybrid laser radar system based on one-dimensional scanning and linear TOF camera¹⁰ and the classical pointwise scanning laser radar system is a method of implementation and the parameters of the following components.

The forming optical laser system forms not a rotationally symmetrical probe laser beam with low (and the same in orthogonal transverse axis) angular divergence, but an astigmatic probe beam with divergence which differs significantly for two main coordinates. The divergence along one coordinate, hereinafter called the slow, is low and close to the value corresponding to the predetermined angular size of resolution element of the location system. The divergence along the other coordinate (fast coordinate) exceeds slow divergence in N times, where N – number of resolution elements for the fast coordinate (perpendicular to direction of the one-dimensional scanning). The scanning mirror is one-coordinate and it provides the deployment of astigmatic probe laser beam in a direction perpendicular to the fast coordinate at an angle corresponding to the desired field of view in this direction.



Figure 2. A block diagram of multichannel timeslot measurement system 1.1...1.N – triggers fixing the start of the measurement; 2.1...2.N – triggers fixing the end of the measurement; 3.1...3.N, 5.1...5.N – multivibrators; 4.1...4.N – phase detectors; 6.1...6.N, 7.1...7.N – counters; 8 – reference frequency measurement unit; 9 – frequency measurement unit; 10 – switch unit; 11 – seconds pulse generator; 12 – reference frequency generator, 13 – controller.

One-element photodetector used in a classic radar circuit which has angular size 3-5 times higher compared to resolution element and is placed in the image plane of the lens is replaced with linear photodetector with the larger line size being oriented along the fast coordinate of the probe laser beam, and the angular size of line for a given lens focal length are equal to the angular divergence of the probe beam for the fast and slow coordinates, respectively. The system sensor is built based on the set of discrete commercially available photodetectors, and the distribution of the incoming light flux is performed by means of a fiber optic bundle with one end being formed into the line of fibers and located in the image plane of the lens, and the second end is divided into separate fibers which are bred by receiving areas of photodiodes. It should be mentioned that potentially reachable range and resolution parameters in this case could be higher compared to use of a single linear receiver, because the size of the receiving element (the input end of the fiber optic line) can be made greater than the size of a pixel line.

Multichannel timeslot measurement system is based on the principle of Vernier time meter. A block diagram of this system is shown in Figure 2.

Multivibrators in the measuring channel has special architecture in which first multivibrator 3 generates signal with a period T1 and second multivibrator 5 generates signal with a period T2. T1 > T2 and the difference DT = T1 - T2 is a few tens of picoseconds. By lowering DT we can lower the measurement error but it would increase time on a single measurement.

Timeslots measurement starts when a rising front on the trigger input 1 "Start pulse" appears. At that point trigger 1 captures appearance of the pulse and is set to logic "1". Because the output of this trigger is connected to the control input of the multivibrator 3, the multivibrator 3 starts to generate pulses with a period T1. Pulses are applied to the input of the counter 6 and to the first input of the phase detector 4. After the appearance of the rising front of the echo pulse at the input "Stop impulse" trigger 2 captures it and goes to logic "1". This signal induces pulse generation by multivibrator 5 with a period T2. These pulses are applied to the input of the counter 7 and to the second input of the phase detector 4. At the moment of overlap of the signal phases of two multivibrators detector 4 produces a pulse resetting triggers 1 and 2, thus stopping the generation of multivibrators 3 and 5. The same impulse is applied to the controller 13 signaling the end of the measurement. Controller 13 performs reading from counters 6 and 7.

The measured timeslot is calculated using formula:

$$T = (C1-1) \times \left(\frac{M1 \times \frac{1}{F}}{D}\right) - (C2-1) \times \left(\frac{M2 \times \frac{1}{F}}{D}\right)$$

where T – measured timeslot, C1 – value from counter 6, C2 – value from counter 7, D – multivibrator frequency division ratio in the frequency measurement unit, M1 – a value obtained by measuring the frequency of the multivibrator 3 with measurement unit of multivibrator 9 frequency (indicates the number of reference frequency periods fit into a time interval equal to the period of the multivibrator signal multiplied by the factor D), M2 – value obtained by measurement of multivibrator 5 frequency with measurement unit of multivibrator 9, F– reference signal frequency obtained from measurement unit of reference frequency 8.

Other blocks and elements of the structural scheme are traditional but their parameters should be coordinated with parameters of previously described non-traditional elements of the system.

3. Experimental Results

3.1 Study of the Scanning System

The scanning system was built based on the brushless torque motor with parameters described in Table 1. Sizes of the scanning mirror were 70×50 mm³.

No.	Parameter	Value
1	The outer diameter of the stator, mm	40
2	The axial length of the stator, mm	26
3	The inner diameter of the rotor, mm	18
4	The axial length of the rotor, mm	15.5
5	Stator weight, kg	0.067
6	Rotor weight, kg	0.039
7	Engine weight, kg	0.106
8	Moment of inertia (calculated), kg·m ²	5.8×10 ⁻⁶
9	Supply voltage, V	27
10	Rated load, H∙m	0.04
11	Resistance phase, Ω	5.31
12	Rotation frequency of ideal idling, rotations per min	5000
13	Starting torque, H⋅m	0.17
14	C_e of an engine led to phase, V·s/rad	0.038
15	$C_{_{M}}$ of an engine led to phase, N·m /A	0.038
16	Electromechanical time constant, ms	13.9
17	Static quality factor, N-m/(kg·W ^{1/2})	0.18
18	Engine constant N-m/W ^{1/2}	0.0198

Table 1. Engine parameters of the scanning system

Graph of scanning speed changings in the deployment cycle (there and back) is formed in computer memory by the drive scanner control processor via the established control program on the host computer. The value of the scanning speed in the areas of acceleration, uniform motion and braking of the scanning mirror can be obtained from this graph. Processor control program also provides a reference mirror movement law within the parameters allowed for the scanning unit. In case of an exit from the acceptable range of loads to the drive motor processor disables drive operation and outputs the appropriate message. The maximum permissible value was determined in the course of experimental studies for the frequency scanning mirror of 0.5 Hz and up. It should be noted that scanning frequency was equal to double mirror scanning frequency because the images were formed at both direct and reverse mirror courses. Waveform control signal (top) and graphs of the angular positions of the mirror changes are presented in Figures 3 and 4.



Figure 3. Signal of control and change in angular mirror position at a scanning speed of 1.2 Hz.



Figure 4. Signal of control and change in angular mirror position at a scanning speed of 4.0 Hz.

As seen in Figure 3 and 4 good linear speed of the angular beam deployment in space was seen for scanning frequencies from 1.0 to 3.0 Hz. At 4.0 Hz there is a slight shift of the mirror out of angular motion range values during deceleration and switches to reverse.

As the scanning frequency increases a deployment linearity distortion in time occurs. Example of such distortions is presented in Figures 5 and 6.



Figure 5. Signal of control and change in angular mirror position at a scanning speed of 9.0 Hz.



Figure 6. Signal of control and change in angular mirror position at a scanning speed of 14.0 Hz.

As you can see from Figure 5 and 6 at high frequencies the mirror moves in a sinusoidal manner, which is difficult to linearize, but it may be taken into account when processing the information received by laser radar system.

It should be noted that no deformations of the mirror surface were noted at frequencies up to 14 Hz (frame rate 28 Hz). Also no heating of the scanning system was registered at frequencies lower than 10 Hz, while at 14 Hz the temperature of the engine increased by 20°C in 30 minutes. Therefore the last regimen was considered as critical for the scanning system with such mirror and engine.

3.2 Parameter Study of the Timeslot Measuring System

Multichannel timeslot measuring system was implemented on the basis of a Programmable Logic Device (PLD) Spartan-6 by XILINX (USA). One measuring channel in this system occupies 9 logic cells. All 64 channels were placed in the left part of the crystal to prevent conflicts in the trace of the project. All generators in the channels had different generation periods which were measured in the process. All generators produce a frequency close to 310 MHz. Differences in generators frequency were within 85 ps in 64 channels which provided discreteness in measured distance of 13 mm. Timeslots measurements were performed at temperatures in a range from 15 to 50°C, and no temperature influence on the accuracy of the measurements was found.

The stability of time delay in the amplification, digitization and transfer of measurement data of flight time was evaluated during statistical analysis of measurement data by subtracting laser pulse emission moments measurement error, incoming of echo pulse measurement error, passport values of clock frequency instability and current time counting discreteness from the total time of flight measurement error.

The bar chart for the real timeslots measurements errors is presented in Figure 7.



Figure 7. The histogram of experimental errors in the determination of timeslots.

The standard deviation of the measured timeslot did not exceed 45 ps, which ensures measurement accuracy of 135 ps with a probability of 99.73%. These values correspond to the measurement accuracy of the distance of 21 mm. Maximum deviations registered did not exceed ± 190 ps.

3.3 Study of the Main Characteristics of the Hybrid Laser Radar

Because of the limited length of the airway of experimental stand (50 m), evaluation of the maximum working distance to the object was performed by reducing the emitting power in the estimated number of times corresponding to the difference of atmospheric absorption in the short and long tracks, as well as to the weakening of the emitting intensity due to inverse square dependence of emitting intensity from a distance.

To calculate energy received by the photodetector to laser energy ratio for the object at distance z with sizes exceeding the size of a laser beam probe in the object plane a well-known location equation can be used:^{11,12}

$$\frac{P(z)}{P_0} = \frac{1}{N} T_0 \rho_0 \frac{r^2 \alpha_1^2}{z^2 \alpha_2^2} \exp\{-2\varepsilon z\}$$

where N – number of fibers in photodetector line; T_0 – transmission of the optical path of the laser locator; ρ_0 - object reflectance coefficient; z – track length; ε - averaged in distance indicator of attenuation, scattering and indicatrix scattering parameter for the propagation medium; r - the radius of the receiving lens of the photodetector; $2\alpha_p$, $2\alpha_2$ – the angular laser beam divergence in scanning coordinate and the angular size of the detector element.

Therefore to simulate maximum distance z_m with the transition to the stand distance z_0 energy of the probe laser has to be lowered in *K* times from its maximum value, where

 $K = (z_{\rm m}/z_{\rm 0})^2 \exp(2\varepsilon(z_{\rm m}/z_{\rm 0})).$

In real experiments there is a nonlinear dependence of laser pulse power and energy from the pump energy level. To provide a linear dependence a set of filters (attenuators) decreasing signal at an input (output) of receiving lens, thus changing T_{opt} , can be used. To simulate 2 km atmospheric track using 50 m laboratory stand it was necessary to decrease power of the laser emitter approximately in 2 560 000 times. Our calculations showed that in these settings (50 m of a track) an operation of the laser radar can be simulated in terms of the testing of the maximum operating distance determined by signal level. Maximum operating distance in space for radar like that is 5 km. This distance corresponds with maximum operating distance of 2 km in terms of an atmospheric track with medium turbulence. Calculated dependences of signal / noise (S/N) ratio are presented in Tables 2-4.

 Table 2. Calculated dependency of S/N ratio for

 diffused reflecting object in a ground track

	Distance, m					
	500	1000	1500	2000	2500	3000
S/N	231.54	52.24	19.68	8.34	3.60	1.61

Real timeslots between start-pulse and echo-pulse were simulated as follows. For distances 45 m and 4.5 km

the difference between time-lags was 2 orders. To simulate time-lag a start-pulse sensor was off. Start-pulse and laser trigger pulse were formed with a time-lag of 30 msc (which corresponds to a 4.5 km distance) by means of a universal signal generator. Experiments showed that timeslots measurement system works properly even with such time-lags between the signals and the measured distance corresponds to the true value with an error of less than 3 cm Table 5.

 Table 3. Calculated dependency of S/N ratio for

 diffused reflecting object in a space track

	Distance, m						
	1000	2000	3000	5000	8000	10000	
S/N	212.46	53.11	23.61	8.50	3.32	2.12	

 Table 4. Calculated dependency of S/N ratio for

 diffused reflecting object in experimental stand

	Distance, m					
	10	20	30	40	50	60
S/N	294.71	72.92	31.42	16.1	8.91	5.12

Real distance,	Distance measured by the	Error, cm	
cm	model of laser radar, cm		
151.4	153	1.6	
463.1	462	-1.1	
984.4	986	1.6	
1147.5	1146	-1.5	
1541.2	1543	1.8	
1960.3	1959	-1.3	
2485.8	2484	-1.8	
2899.4	2991	1.6	
3658.1	3660	1.9	
4540.3	4542	1.7	

In preliminary measurements of S/N ratio it was found that calculated values were significantly higher than experimentally determined S/N ratios especially at the edge of the view field. Decrease in the measured value compared to the calculated value in the center of the view field was 10.5-13.0% from the calculated value, when at the edge of the view this decrease was 34.0-45.0% (distance – 45 m).

The first calculations did not take into account the following factors:

- Transmission of the transmitting channel is not 100%. The measurements showed that transmission of the transmitting channel with two mirrors and forming negative cylindrical lens is 0.925.
- Original uneven spatial distribution of the emitting in the fundamental Gaussian mode does not allow for uniform illumination of the entire band of the formed anisotropic spatial distribution of emitting using a simple cylindrical optics.
- To provide lower gradient from the center of the band to the edge additional defocusing was introduced, reducing the gradient, but which has made an additional loss of 10% from the emitting power.

These factors were taken into account by introducing a numerical coefficient simulation into the program. These coefficients were determined experimentally and they adjusted the power level of the probe emitting at the edge and in the center of the view field. Total coefficient for energy correction was 0.8325 in the center of the view field (or 1.04 mJ instead of 1.25 mJ in laser pulse) and 0.4995 at the edge of the view field (or 0.624 mJ).

Results of S/N calculations using the corrected scheme and experimental results are presented in Table 6.

Table 6. Results of experimental studies and corrected calculations of S/N dependency from the distance to an object in experimental stand from the view field center and at the edge of the view field

Distance, m	Measured S/N (calculated S/N)				
	Center of the view field	Edge of the view field			
9.84	272.2 (277.6)				
10.00		195.3 (208.1)			
11.48	199.8 (203.8)				
11.66		143.5 (152.9)			
15.41	110.5 (112.7)				
15.65		79.2 (84.4)			
19.60	67.8 (69.2)				
19.90		48.3 (51.6)			
24.86	41.4 (42.3)				
25.24		29.1 (31.2)			

28.99	29.8 (30.4)	
29.44		20.6 (22.1)
36.58	17.5 (17.9)	
37.14		11.5 (12.5)
45.40	10.0 (10.3)	
46.10		6.2 (6.8)

This data shows good accordance between the calculated and measured S/N values both in the center of the view field, and at the edges. The difference between measured and calculated values was less than 3% for the center of the view field and less than 9% at the edge of the view field.

We performed calculations of S/N ratios for ground and space tracks taking into account correcting coefficients received during analysis of experimental data. Calculations showed that for the 2 km ground track with medium turbulence the S/N ratio is 7.3 in the center of the view field and 4.9 at the edge of the view field. For the 5 km space track these values were 7.8 and 6.0 respectively.

Control experiment in the natural conditions allowed receiving signal from the real object (pipe) remote at a distance of more than 1.5 km.

Before starting experiments studying resolution in angular coordinates the angular distribution of the probe emitting at the output of the laser radar was checked. To do that an optic system was made including highquality lens with focus F, placed at a distance F from the output aperture of the laser radar. Matrix photodetector ("MrBeam", Laser laboratory, Göttingen) for analysis of laser beams was placed behind the lens at a distance F. Angular power distribution which is fixed by matrix photodetector is formed in the lens focus. Therefore in order to determine the values of divergence for a given intensity or energy level processing of the resulting focal distribution is needed, which the software built-in beams analyzer implements. The measurements showed that emitting divergence in smaller angular coordinate which has to determine angular sizes of the resolution element is 5.3 mrad or 0.3°.

Consistency and quality of the laser radar stand adjustment were checked experimentally using laboratory stand with 6-lane Foucault pattern placed at a distance z0 from the laser radar stand. The distance between strokes of Foucault pattern changes stepwise from $0.5 \times 2\alpha_1 \times z0$ to $3 \times 2\alpha_1 \times z0$ through $0.5 \times 2\alpha_1 \times z0$. Foucault pattern has high (more than 0.5) contrast of reflection coefficient at the working wavelength. For z0=5M the size of Foucault pattern was 2 m×2 m, minimal and maximal distances between strokes were 2.65 and 15.9 cm correspondingly.

We performed series of measurements and in each measurement the location of the strokes in Foucault pattern was changing in 90°C. Resolution in angular coordinates was calculated as value of the distance between strokes in Foucault pattern divided by distance z0 where the contrast of Foucault pattern decreased in two times compared to the contrast of Foucault pattern with the maximum distance between strokes. Measurement results for the contrast are presented in Table 7.

Table 7. Results of the contrast measurement

Distance	15.90	13.25	10.60	7.95	5.30	2.65
between						
strokes of						
Foucault						
pattern, cm						
Median	0.93	0.89	0.83	0.72	0.61	0.46
value of the						
contrast						

Resolution in angular coordinates determined that way was fully consistent with the value obtained using the laser beam analyzer «MrBeam».

4. Conclusion

Complex of experimental studies showed that hybrid laser location system constructed on the basis of the onedimension scanning in the space of a laser beam with a line form and emitting registration system with a set of individual photodetectors allows achieving combination of characteristics making it competitive compared to other systems building 3D-images. In terms of the maximum operating distance in space the studied radar matches Rendezvous Lidar Sensor (RLS) (MDA Optech, Canada) and in terms of operating speed it even has advantages over the last. Time to achieve full frame 20×20° in RLS system is 1 s while in our system scanning speed of the same area of 28 frames per second is achieved. It should be noted that such regimen with nonlinear beam deployment is tense. However with scanning speed of 15 frames per second a good linearity and non-loaded operation of the engine of scanning system is observed.

Compared to the FlashLADAR Vision Navigation Sensor (VNS) developed by NASA research center, the

developed and studied laser location system has significantly higher maximum operation distance. VNS is currently the best system designed using FlashLADAR technology, and it allows building 3D-image of the object with a resolution of 256×256 frames at a frequency of updating information up to 30 frames per second. Maximal operation distance of VNS does not exceed 250 m when viewing area is $20\times20^\circ$. In our system in case of viewing area is $20\times20^\circ$ resolution is 400×400 elements at a frequency of updating information up to 15 frames per second (ultimate frequency is 28 frames per second).

Therefore the studied hybrid laser radar system is close to existing radar systems in terms of information operating speed and is better in terms of maximal operation distance.

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