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Evaluating the measurement accuracy of laser distance meters for the purpose of the PNDS system construction

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Abstract

Preliminary outcome of the tests of laser distance measurement modules being a part of the PNDS system (Pilot Navigation & Docking System) developed within the OPIE project (Operational Programme Innovative Economy) in Maritime University in Szczecin are presented in the article. The tests were carried out in laboratory conditions and the actual conditions which may occur during the system's operation. The modules of the digital laser distance meters available on civilian market were compared. Statistical analysis comparing the accuracy of the laser distance meters was presented and based on it, their general effectiveness was evaluated making part of the preliminary prototype of the PNDS system.

Introduction

In the PNDS system the process of approaching a quay by a ship is supported by providing a real time distance of the ship's side from the quay. These measurements are carried out by a set of distance meters placed stationary on a quay [1]. As a fundamental source of information on ship's distance from the quay, the heads have to provide adequate measurement accuracy, as well as reliability in various measurement conditions [2]. As the research has shown, laser distance meters may significantly differ among each other, not only among models of various manufacturers, but also between two models of the same make and series. In the light of the obtained results, it is necessary to conduct an in-depth analysis of available distance meters prior to using them as a commercial product.

As an element of the research on the existing preliminary prototype, five heads were tested:

1. Heads 01, 02 – laser distance meters LD-301, manufacturer: Jenoptic;
2. Head 03 – laser distance meter ILM-500, manufacturer: MDL;
3. Heads 04, 05 – laser distance meters LD90-3300, manufacturer: Riegl.

Research methodology

The experiment consisted of comparing the tested distance meters and evaluating their accuracy in laboratory conditions with external factors minimized and in conditions simulating the actual external conditions which could disturb system's operation.

The first stage included 27 measurement series in a closed room with sunlight intensity below 2000 lx. The conditions were divided based on:

1. Distance (calculated from the head's front to the measurement surface), measurement accuracy ±2 mm:
   a) 5 metres;
   b) 20 metres;
   c) 100 metres.
2. Surface inclination angle, measurement accuracy ±0.1°:
   a) 0°;
   b) 10°;
   c) 30°.
3. Surface type:
   a) aluminium sheet;
   b) white surface, mat;
   c) black surface, lustre.

In the second stage, measurement accuracy in the actual conditions with sunlight intensity over 20,000 lx was performed. It covered the distance measurement for:

1. Simulated precipitation on the distance of 20 metres, for three different reflection surfaces and with the inclination angle of 0°. During the trials, the impact of 2nd grade heavy rain and 10th grade rainstorm was tested. Precipitation grades were based on K. Chomicz's precipitation intensity scale [3].
2. Dynamic change of inclination angle of the measurement surface above water surface.
3. Direct reflection of sunlight in the direction of laser lens (reflexivity test).

From each of the ten minute measurement series equipotent trials were taken and used for conducting statistical analysis. The series in which the laser did not record the correct distance due to a weak return signal or due to a double reflection from measured surface were omitted. Measurements were carried out in conditions isolated from any sources of mechanical (vibrations, shocks) and electromagnetic disturbances.

Applying the variance analysis procedure (ANOVA) for comparing the distance meters efficiency was planned during the tests. For the purpose of using it, it was necessary to meet the prerequisites linked to the measured variable distribution similar to normal and on the variance uniformity within the tested groups [4].

For identifying the distribution the Kołmogorow-Smirnow's and Shapiro-Wilk's tests were used. Based on the obtained statistical values, distributions were evaluated as normal. The uniformity of variance was verified based on the Levene's and Brown-Forsythe's tests. They were conducted by creating groups for the same measurement conditions, comparing the distance meters between each other, as for the same heads, comparing variance value in various measurement conditions. Regardless of grouping, the test statistical values made it necessary to reject the hypothesis on the variance uniformity. The tests were performed on the confidence level of 0.05.

In the course of a comparative analysis it was decided to use the differences of values of distribution parameters and standard deviations, as well as normalized dispersion values of measured variable as a basis. Distributions, in the form of a Gaussian curve, show the deviation value from the mean value in the function of frequency of their occurrence (Fig. 1).

Uncertainty of measurement was calculated according to the Recommendation 1 of the International Committee for Weights and Measures as a standard experimental deviation of arithmetic mean equal to a positive square root of the value of the experimental variance of arithmetic mean [5], according to the formula:

$$u(x) = \sqrt{\frac{1}{n(n-1)}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2} \qquad (1)$$

where: n – number of measurements in a series, x – measurement value, $\bar{x}$ – arithmetic mean.

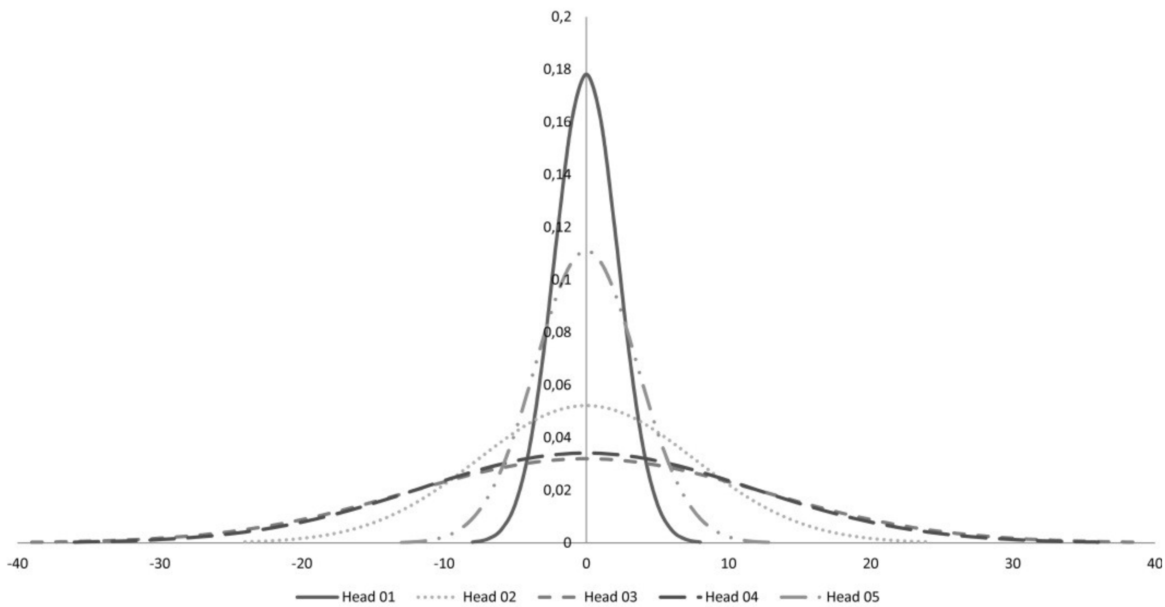

Fig. 1. Comparison of deviation value from the mean value for measurements of heads 01, 02, 03, 04, 05 in the conditions: distance – 5m, inclination angle of measured surface – 10°; surface type – aluminium sheet

For the purpose of the accuracy evaluation, deviation values from mean and values of the maximum dispersions between measurements of one series were used.

Analysis outcome

In the first stage, the analysis was conducted separately for each of the five modules of the distance measurement being an element of the PNDS system, having taken into account the accuracy and the correctness of their indications in the tested conditions. In the second stage of the analysis, individual parameters of all heads were compared in order to determine which distance measurement model would be best in the actual conditions. Figure 1 shows a tendency which occurred most frequently during all the measurement series and correctly illustrates general conclusions drawn from the statistical analysis of the laboratory measurements.

The measurements in laboratory conditions have shown that Jenoptic 301-LD distance meter constituting an element of distance measurement module of head 01 is characterized by a very small dispersion values whose mean from all the measurements does not exceed 20 millimetres (14.9 mm, 12.7 mm and 17.6 mm for measurements on 5 m, 20 m and 100 m, respectively). The maximum observed dispersion value from the correct measurement series amounted to 70 millimetres which is a neglectable value at the expected accuracy of a system measuring distance of the ship's side from the quay. During all the measurements similar values of standard deviations were obtained which in 95% of cases were within 1.00–3.00 millimetres.

Thanks to carrying out a considerable number of trials ($n = 570$), the uncertainty of measurement was low – it did not exceed 1 millimetre.

The largest disadvantage of a distance meter is its ineffectiveness in measurements of distance of black surface and in measurements with sharper inclination angles which made it necessary to reject 25% of all measurements series.

Contrary to the expectations, distance measurement module of head 02 equipped with the same model of laser distance meter as head 01 shown much lower accuracy of measurements. Mean dispersion values from all the measurements does not exceed 70 millimetres (45.7 mm, 92.0 mm and 34.7 mm for measurements for 5 m, 20 m and 100 m, respectively). The maximum observed dispersion value from among the correct measurement series amounted to 544 millimetres. In the course of all the measurements similar values of standard deviations in 95% cases within 3.00–11.00 millimetres were obtained. The common feature of heads 01 and 02 is a low value of uncertainty of measurement and a complete ineffectiveness in the same measurement series.

Distant measurement module of head 03 displayed the lowest measurement accuracy which was decreasing with the increase of the distance of the measurement target. In the distance of 100 metres uncertainty of the measurement amounted to 3.5 millimetre on average with dispersions of over 500 millimetres.

Distant measurement module of head 04 is characterized by the largest discrepancy of measurement accuracy. In as many as six cases zero values of deviations were obtained, therefore, displaying the highest measurement accuracy. Furthermore, in nine series it appeared to be the head with the lowest accuracy with the highest dispersion values amounting to 700 millimetres.

Distant measurement module of head 05 obtained a high stability of dispersion values and deviation distribution. Laboratory tests did not demonstrate falling tendencies of measurement accuracy in any conditions. Taking into account the rejection of only two from among 27 laboratory measurement series, head 05 can be regarded as the most reliable one among the tested heads. When analyzing lower measurement accuracy, in particular in connection with head 01, dispersion values whose mean value from all measurements amounted to 30 millimetres, while the maximum value to 60 millimetres, must be taken into account. In both cases, it is an acceptable value for determining a ship's side location in relation to the quay. Uncertainty of measurement did not exceed 1 millimetre.

The analysis of quantitative data revealed differences in mean values of measurements on various types of surface. It was not explicitly determined whether these differences directly result from the characteristics of signal reflection or from the local irregularities of white and black surface. The degree of these differences changes depended on the head type, as well as the distance and the measurement angle, however, the values always exceeded values of mean deviation of arithmetic mean and root mean square deviation (Fig. 2).

None of the heads did successfully accomplish tests in the conditions of rainstorm. For the measurements carried out in the conditions of rainstorm, heads 01 and 02 displayed on average 20 times worse dispersion and standard deviation values in comparison to the laboratory tests of the same distances. As to the the other heads, no large decrease of the measurement accuracy was observed.

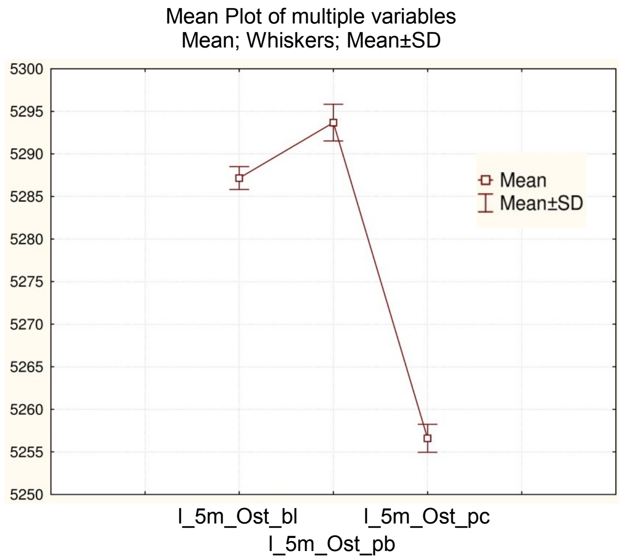

Fig. 2. Comparison of mean values for head 01 in the conditions: distance – 5 metres; inclination angle of measured surface – 0°; surface type – aluminium sheet (bl), white surface (pb), black surface (pc)

The reflexivity test was completed best by heads 04 and 05, which recorded correct values of distance from white surface and from black surface. Heads 01 and 03 performed well only in the conditions of reflection from a white surface, whereas head 02 did not complete successfully any of the trials.

The measurements with dynamic change of inclination angle of measured surface above water surface shown that each of the heads records correct distance up to the angle of about 40°. Above this value a considerable increase of distance value is observed (Fig. 3). It suggests the occurrence of a double reflection of the laser beam: from the measured surface and from water surface.

Regardless of the distance meter type, none of the heads obtained correct measurement for the conditions: distance – 100 metres, surface inclination angle – 30°, surface type – black surface. Heads 01, 02, 03 did not obtain correct

Table 1. A list of dispersions and standard deviations for heads 01–05. Results in millimetres

			01 – Jenoptic		02 – Jenoptic		03 – ILM		04 – Riegl		05 – Riegl	
			disp.	st. dev.	disp.	st. dev.	disp.	st. dev.	disp.	st. dev.	disp.	st. dev.
5 m	0°	as	8	1.33	25	3.96	100	15.93	0	0.00	20	6.80
		ws	12	2.16	38	6.69	70	11.58	100	12.01	20	0.83
		bs	11	1.65	53	7.34	80	10.81	200	45.08	40	1.43
	10°	as	17	2.88	60	10.86	120	16.59	0	0.00	20	3.46
		ws	14	2.24	47	7.63	100	12.47	50	11.69	20	3.55
		bs	–	–	–	–	–	–	500	76.63	20	7.16
	30°	as	–	–	–	–	–	–	50	10.82	20	5.98
		ws	14	2.51	51	8.92	90	14.79	0	0.00	40	2.74
		bs	–	–	–	–	–	–	600	173.3	40	10.05
20 m	0°	as	7	1.07	20	3.32	140	25.45	250	40.26	20	9.97
		ws	12	1.99	32	4.18	140	20.37	50	2.09	40	2.48
		bs	10	1.87	24	3.73	120	18.73	0	0.00	40	8.83
	10°	as	8	1.38	25	3.84	140	21.42	200	38.08	20	6.50
		ws	9	1.50	25	4.10	140	24.51	0	0.00	20	2.68
		bs	70	11.58	544	86.56	120	21.39	100	4.19	40	5.43
	30°	as	17	2.40	40	6.48	140	24.46	700	259.6	40	3.90
		ws	8	1.41	26	4.22	130	22.23	0	0.00	20	7.68
		bs	–	–	–	–	–	–	100	17.09	40	8.92
100 m	0°	as	8	1.35	22	3.66	570	78.26	200	38.20	20	4.44
		ws	12	1.93	33	5.61	410	70.24	50	21.11	20	8.48
		bs	17	2.85	26	4.25	400	57.35	50	2.96	40	6.01
	10°	as	18	2.40	55	8.44	530	90.58	650	213.4	40	6.02
		ws	12	2.12	33	5.72	510	85.76	50	10.44	40	4.89
		bs	–	–	–	–	–	–	200	38.55	–	–
	30°	as	–	–	–	–	–	–	50	25.01	60	10.22
		ws	14	2.15	39	6.66	480	86.61	50	17.29	20	9.62
		bs	–	–	–	–	–	–	–	–	–	–
20 m rain	0°	as	67	6.82	191	8.78	140	26.07	250	40.02	20	9.91
		ws	265	18.01	31	5.45	140	23.78	150	12.96	20	8.26
		bs	117	10.87	258	15.35	170	21.56	50	21.22	40	5.95

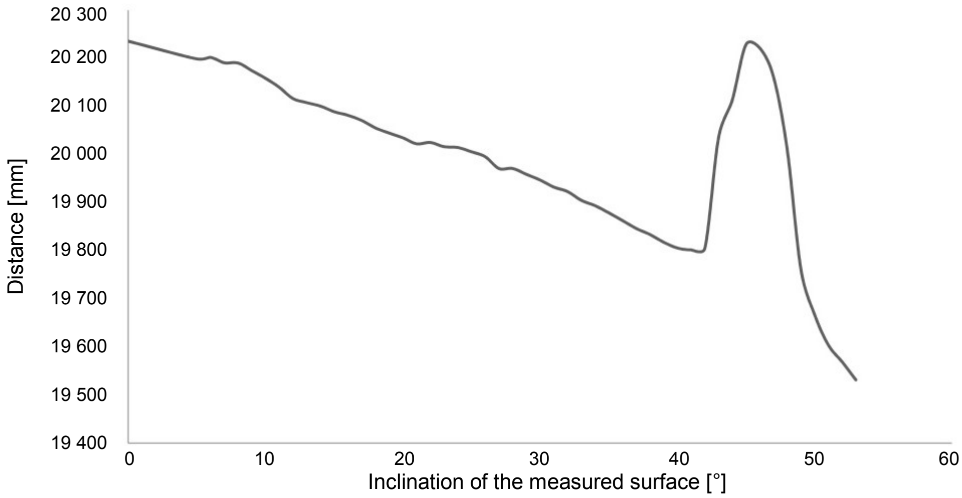

Fig. 3. Relation between distance and angle during dynamic change of inclination angle trial. Measurement for head 01

measurement values in seven identical conditions. In case of the measurement of aluminium surface, with angle of 30° and distance of 5 metres, they shown a distance value significantly larger than expected (more than 9 metres for heads 01, 02 and more than 7 metres for head 03) suggesting a double reflection and recording of additional distance between the measured surface and ceiling surface (Fig 4).

In the course of the tests several technical problems were encountered which had impact on obtained results and later functionality of the whole system. The most serious were:

Understated indications of the distance of head 04 resulting in the measurement encumbered with an additional error up to 500 millimetres. The problem did not occur for any other distance measurement module. It usually occurred at the beginning of measurement series and disappeared by itself during the measurement (Fig. 5).

Lack of indications of the distance measurement deviation resulting from too weak strength of the

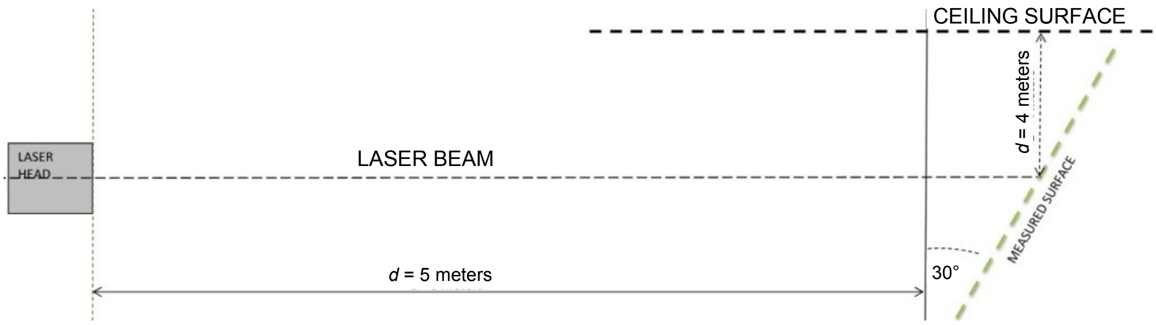

Fig. 4. Deviation of distance measurement due to double reflection of laser beam

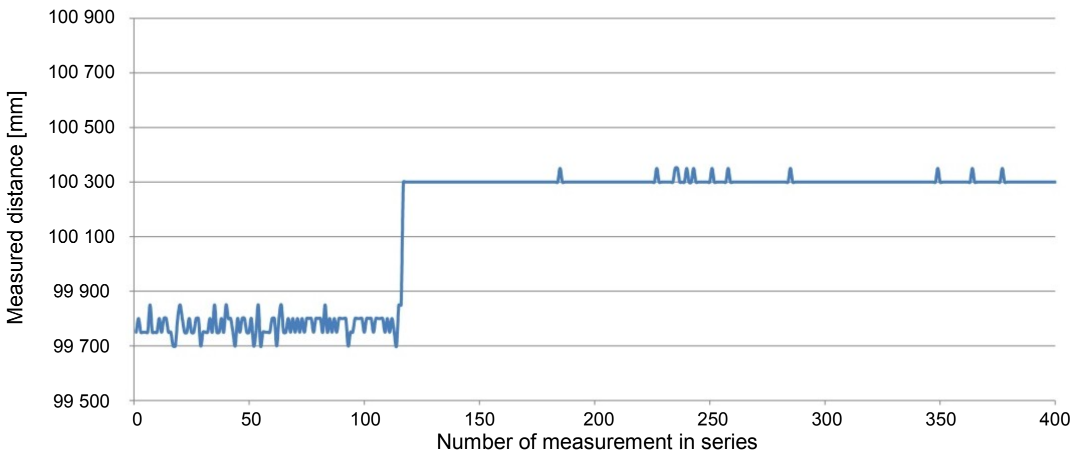

Fig. 5. Graph presenting understated indications of distance for head 04 on the beginning of measurement series

return signal. This problem does not concern head 03 which as the only one signalized error by showing the distance value of 99999990 millimetres (Fig. 6). Other heads transmitted the last saved correct measurement result which made it necessary to actively control the correctness of received distance values.

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$SENS,03,99999990,+0000*06 08/10/11 17:42:00 18618
$SENS,03,99999990,+0000*06 08/10/11 17:42:01 19659
$SENS,03,99999990,+0000*06 08/10/11 17:42:02 20660
$SENS,03,99999990,+0000*06 08/10/11 17:42:03 21682
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Fig. 6. A fragment of head 03 frame with an indication of error of too weak strength of return signal

Fadeout of communication between heads 01 and 04 operating in the slave-master configuration. It occurred occasionally, yet when unnoticed caused empty measurement series until head 01 was restarted. It made it necessary to actively control indicated values during the conducted tests.

Differences in accuracy of the indications between lasers of the same type (heads 01, 02, and 04, 05). During calibration measurements differences in size and brightness of laser spots were observed which can constitute an indirect cause of this problem [6].

Fig. 7. Photos of laser spots of heads 01–05. Uniform scale of photos was maintained. Negative picture. Photos were taken in non-reflection chamber on the distance of 20 metres with flow of external light below 0.001 lx. Exposure time: 15 s

Conclusions

The conducted tests shown that the measurements carried out with head 01 are the most accurate. However, taking into account the reliability of operation in diverse conditions and practical meaning of the size of measurement deviation when a ship is approaching a quay, head 05 is the most suitable to use in the future commercial version of the PNDS system. Before the final choice of the laser distance meters designed for distance measurement modules is made, it is necessary to carry out further laboratory and actual tests, with the emphasis on the measurements in simulated hydrometeorological conditions. It is particularly important to examine the impact of a wide range of temperatures and levels of insolation, as well as of various types of precipitation and atmospheric residues. It is also necessary to carry out measurement trials on the surface with characteristics similar to a ship's side.

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