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PROCESSES

Dimensional measurements in the shipbuilding industry: on-site comparison of a state-of-the-art laser tracker, total station and laser scanner

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Abstract

Thanks to recent technological innovations, some *large-volume-metrology* measuring instruments—that would have been considered out of context one/two decades ago—are now effective for the shipbuilding industry, where dimensional errors of a few millimetres are generally tolerated. This paper considers three state-of-the-art instruments: a *laser tracker*, a *total station*, and a *laser scanner*, all with the latest generation of technology. While the first instrument type has long been widespread for applications in *industrial metrology*, the last two have traditionally been used in other fields, such as *as-built surveying*, *civil engineering*, *architecture* and *topography*. Instruments are compared using experimental tests concerning the dimensional verification of cruise-ship modules in the relatively under-explored context of the construction of the *hull*, which represents the ship's framework. The comparison is structured based on several qualitative and quantitative criteria, including but not limited to (*i*) *simplicity of use* for operator(s), (*ii*) *time* of acquisition/analysis of measurement data, (*iii*) *metrological performance*, and (*iv*) *cost*. The main contribution of this article is the on-site testing of instruments of interest, in the typical (unfavourable) working conditions of shipyards.

Keywords Large-volume metrology · Shipbuilding industry · Dimensional measurement · Laser tracker · Total station · Laser scanner · On-site comparison

1 Introduction and literature review

Large-volume metrology (LVM) is a scientific field that concerns dimensional measurements of objects with dimensions of several tens of metres [1]. Instruments available in this field are quite varied and can be divided into two families [2]:

- *Distributed* instruments, which consist of a plurality of sensors positioned around the measured object (e.g., *rotary-laser automatic theodolites* (R-LATs), photogrammetric optical sensors (e.g., infrared cameras), or systems based on *wireless sensor networks* (WSNs)) [3];
- *Centralized* instruments, which are composed of a single unit/station (e.g., laser tracker, total station, laser scanner, etc.).

For a more comprehensive classification, see [4].

Most state-of-the-art instruments are based on laser/optical technology and were conceived over three decades ago, with significant evolution over the years [5]. This evolution has resulted in important practical improvements, from multiple viewpoints, like portability, ease of use, metrological performance, etc. [6].

This paper considers the industrial context of shipbuilding yards for manufacturing *cruise ships*, which are real "floating cities". Attention is focused on the construction of the *hull*, which represents the framework of the ship and—(over) simplifying—is made of metal sheets, suitably cut, shaped, bent and stiffened with rigid metal elements (e.g., stringers, beams and eels), joined by welding-carpentry work [7]. The

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construction of the hull is a structured modular process that can be synthesized into four phases [8]:

1. Marking, cutting and shaping metal sheets—also known as "*panels*"—and welding rigid structural elements onto them;
2. Fabrication of the "*units*", having a height of approximately one ship's deck (i.e., 3-to-5 m) and rectangular plan dimensions of approximately 20-to-40 m side;
3. Assembling a number of units, in a vertical direction, so as to create the "*modules*", with a square/rectangular base similar to that of the single units (i.e., 20-to-40 × 20-to-40 m) but composed by stacking 3–4 units, resulting in a total height of approximately 10-to-15 m.
4. Assembly of the modules which—like Lego® bricks—are gradually joined together by means of huge cranes, forming the hull. This operation is generally carried out in a slipway or in a dry dock [9].

The impressive dimensions of units/modules and the important deformations they may undergo—e.g., due to thermal effects or under their own weight—entail that the dimensional tolerances related to reference positions (x, y, z) and distances are generally a few millimetres around the respective nominal values [7]. In order to limit the so-called "error propagation", tolerances generally tend to be tighter in the early hull-construction phases and more relaxed in the later ones [10].

The flow of materials in the early phases is considerably faster than in the later phases, requiring much quicker dimensional verifications. On the other hand, the size and complexity of the manufactured elements tend to gradually increase, as well as the complexity of the respective dimensional verifications [7].

Although non-compliance with tolerances may not affect the final functionality of the assembled parts, it can significantly extend hull-construction time/cost, requiring additional repair interventions. This additional effort generally grows more than proportionally with respect to the project's progress. It would therefore be desirable to detect any non-conformity and take prompt action to resolve them as soon as possible and in the right hull-construction phase. Hence the need for monitoring the hull-construction phases through appropriate intermediate dimensional verification of the production output (e.g., panels, units and modules). Constant and effective monitoring of the hull-construction process is also a prerequisite for its improvement (e.g., in terms of reduction of the variability and, consequently, the non-conformity rate of the production output) [11].

The fact that typical dimensional tolerances are of a few millimetres makes it appropriate to use instruments with a measurement uncertainty of a few tenths of a millimetre. This is in line with the metrological *rule of thumb* that the instrument's measurement uncertainty should reasonably be at least one order of magnitude smaller than the *measurand's* intrinsic variability [12].

Returning to the shipbuilding operational context, the elements to be measured are huge one-offs, as ships are extremely complex products that are typically built to the owner's specifications. The areas around the elements should be free of obstacles, to allow picking them by giant cranes and gantries. The time available for dimensional verifications is inevitably limited, due to the extensive welding and carpentry operations on the elements and their frequent displacements.

Although the shipbuilding industry is traditionally known more for the use of plumb bobs, steel tapes and transits, in the last two-to-three decades it has gradually opened its doors for the use of more current 3D-type instruments, as also witnessed by some contributions in the scientific literature. For instance, [13] documents the integration of a photogrammetric technique in the 3D plate burning process, [14] refines some measurement techniques based on the use of theodolites and tachymeters, [15] proposes an experimental method based on the use of a constellation of R-LATs, while [16] illustrates a new method to solve the limited measurement range problem of laser trackers. Most of the contributions, however, propose prototype solutions and/or ad hoc applications to specific operational contexts. Since technologies are now more mature and commercially-available instruments are more established, it can be of interest to compare state-of-the-art measuring instruments in the relatively unexplored shipbuilding context.

The presence of obstacles and the short measurement times, peculiar to shipyards, make the use of *distributed* measuring instruments inappropriate, as they would require the positioning of a plurality of sensors/units around the measured element and their calibration prior to measurements [17]. The very large measurement volumes of shipyards also make it inconvenient to place measuring sensors/units with limited measurement range around the area where the elements are supposed to be, as it may happen in other contexts [18]. On the other hand, the measuring instruments that seem most appropriate for this context are the *centralized* ones, as they consist of a single portable unit that can be moved and positioned relatively easily in the vicinity of the measured elements [3].

The objective of this paper is to carry out a structured comparison of three state-of-the-art centralized measuring instruments, which seem appropriate for the shipbuilding operational context:

- A *laser tracker* with a (contact) probe for measurement of undercuts and hidden points and the possibility of non-contact measurement [19];

- A *total station* with an integrated scanner and mini-vector probe (for measurement of undercuts and hidden points, based on the classical "two-prism method" [20]);
- A compact *laser scanner* with automated *registration* of scans in the case of *multi-station measurements*, i.e., measurements that combine data acquired through repositioning multiple times the instrument around the measured element, in order to exploit different perspective views and reach all points of interest, even those partly "obscured" by obstacles [21].

While the laser tracker is certainly very popular in the LVM field for two decades now [5], the other two instruments are more characteristic for other contexts such as *as-built surveying*, *civil engineering*, *architecture*, and *topography* [22] or *reverse engineering* [23]. The relatively limited use of total stations and laser scanners in LVM is probably due to their not very high accuracy—until several years ago hardly lower than a few millimetres [24]—as well as relatively laborious data acquisition and processing (e.g., they generally require multi-station measurements). Thanks to the technological innovations of the last decade, most of these limitations have been overcome, allowing their "metrological" use in contexts that were once out-of-reach, such as shipbuilding.

The comparison of measuring instruments will be structured according to multiple criteria, some qualitative and others quantitative, ranging from *simplicity/time of use*, (e.g., in preparation, measurement and data analysis), *measurement performance* (e.g., information content, accessibility of undercuts and hidden points, etc.) and *cost*.

The "test bench" of the three measuring instruments is represented by experimental tests of dimensional conformity verifications on cruise-ship parts (panels, units, modules, etc.). The tests took place in the FINCANTIERI shipyard in Castellammare di Stabia (Italy), which is one of the more historic in the world, founded in 1783 [25]. These tests make it possible to evaluate the performance of the measuring instruments in typical environmental conditions, characterised by a multiplicity of uncontrollable factors (e.g., variable air temperature/humidity, vibrations, elastic deformations on the measured elements, variable light conditions, etc.). Additionally, the proposed analysis will provide useful insights to answer the research questions: "*Are the three instruments really suitable for the operational context of interest?*" and "*Which of the three instruments is most appropriate?*". It is worth noting again that the issue of dimensional measurements and related measuring instruments in shipbuilding has been relatively little explored in the scientific literature to date [26].

The remainder of this paper is organised into three sections. Section 2 describes the analysis methodology, including specific instrument models, comparison criteria and experimental tests. Section 3 presents and discusses the results of the on-site comparison. Section 4 summarizes the main contributions of this work, its limitations, and possible hints for future research.

2 Comparison methodology

This section illustrates the methodology adopted for instrument comparison and is organised into three subsections. The first one briefly describes the specific measuring instruments, the second introduces the comparison (sub-)criteria, and the third describes the experimental measurement tests.

2.1 Measuring instruments

Although being based on very different technologies [4], the instruments of interest have three common features, which make them attractive to shipyards:

- A *centralised* (non-distributed) hardware architecture, to speed up the instrument set-up and preparation, fully exploiting the relatively short time available for measurements;
- A relatively *large measuring range* (i.e., several tens of metres) to cover large portions of the surface of the measured elements, reducing the need for multi-station measurements;
- A *portable* and *wireless* structure, with relatively low mass/size and powered by a battery (power sockets for non-industrial use are not taken for granted in a shipyard).

Among the types of instruments considered, a number of top-of-the-range models incorporating the latest technological innovations were selected. An individual description of them follows.

2.1.1 Laser tracker: "Leica Absolute Tracker AT960" model

This laser tracker has a mass of about 20 kg including a tripod, with a measurement range of over 100 m. By measuring two angles (*azimuth* and *elevation*) and a distance with respect to the instrument, it is possible to determine the spatial coordinates of a target point of interest, e.g., $P \equiv (x_P, y_P, z_P)$ [4]. There are two possible types of measurement:

- *Contact* measurements, where the target is represented by a classical *spherically mounted retroreflector* (SMR) or *six-degrees-of-freedom* (6DoF) probe, placed by the operator in contact with the surface of the measured element (hence the term "contact"). The distance between the instrument head and the target point can be deter-

Fig. 1 Measuring instruments and accessories in use: **a** Leica Absolute Tracker AT960 with **b** T-Probe and **c** SMRs of various types (12.7 mm and 38.1 mm diameter), **d** Trimble SX10 scanning total station with **e** mini-vector accessory, and **f** Leica RTC360 scanner

mined with *interferometric* technology (more accurate) or *absolute distance meter* (ADM) technology (less accurate). The downside of using a probe, such as the *T-Probe* (see Fig. 1a, b and c), is that the measuring range is limited to only 20–25 m around the instrument [27].

- *Non-contact* measurements, in which a laser spot is projected onto the surface of the measured element and its spatial coordinates are determined with *electronic distance measurement* (EDM) technology [27], which is far less accurate than the ADM and, *a fortiori*, the interferometric one.

2.1.2 Total station: "Trimble SX10" model

This instrument embodies recent innovations that make total stations more and more similar to laser trackers, albeit less accurate but also expensive [see Fig. 1d] [28]. This total station can perform contact measurements using (at least) three different targets: traditional prism, SMR, or a *mini-vector* probe accessory. Unlike the laser tracker's 6DoF T-probe, the mini-vector requires to be in a fixed position for a few seconds during the measurement, thanks to a magnetic fixture (see Fig. 1e); this makes measurement more time-consuming and difficult. This instrument also integrates a time-of-flight scanner to perform (non-contact) acquisitions of point clouds around the points of interest, and a distance meter based on EDM technology.

2.1.3 Laser scanner: "Leica RTC360" model

Light and compact (total mass of about 8 kg, including tripod and battery pack), this instrument implements phase-shift technology and is equipped with GPS tracking system, inertial measurement unit and cameras that automate the *registration* of scans in the case of *multi-station measurements* (see Fig. 1f) [21]. It does not require to be connected to any PC/tablet during acquisition and allows very fast collections of dense geo-referenced point clouds (i.e., including tens of millions of points). This instrument is relatively robust to possible disturbances (e.g., reflections on shiny surfaces, flashes from welding in progress, etc.) and does not require the application of sticky markers on the surface of the measured element.

2.2 Comparison criteria

A team of experts—from academic and industrial backgrounds—identified a set of (sub-)criteria that would make the comparison structured and comprehensive, both from the operator's and shipbuilder's point of view. These (sub-) criteria are as follows:

1. *Simplicity/time of use*;

   1.1 *Preparation*;

      1.1.1 *Portability* (related to the instrument's mass and overall dimensions);
      1.1.2 *Set-up time* (time for positioning, warming up, initialising the instrument and coupling any accessories);

   1.2 *Measurement*;

      1.2.1 *Operator dexterity* (ability to handle the instrument and its accessories, reach the points of interest and master the software application);
      1.2.2 *Amount of measurements to be taken* (typical amount of single/multi-station measurements);
      1.2.3 *Acquisition time* (typical time required for single/multi-station measurements);

   1.3 *Data analysis*;

      1.3.1 *Degree of complexity* (operator's required expertise for cleaning/analysing measurement data and identifying the reference features—e.g., positions or distances—of interest);
      1.3.2 *Time for data analysis* (time required for the same activities in the previous point);

2. *Measurement performance*;

   2.1. *Information content* (features of the measured object that can be determined through measurement data; e.g., single points, distances, complex surfaces, etc.);
   2.2. *Accessibility of undercuts and hidden points* (also related to the accessories in use);
   2.3. *Range and precision*;

      2.3.1 *Operating range* (effective measuring range around the instrument);
      2.3.2 *Repeatability, reproducibility, systematic error* (quantitative experimental evaluation in the shipbuilding context);

3. *Cost*;

   3.1 *Acquisition of instrument and accessories* (i.e., market price);
   3.2 *Operators' training/competence* (i.e., raising the level of technical-scientific skills of operators implies a certain cost).

2.3 Experimental tests

Experimental tests were carried out in the FINCANTIERI shipyard in Castellammare di Stabia (Italy) and spread for eleven days (from 18 to 28 January 2022), covering all three daily shifts (from about 8 a.m. to 9 p.m.). Tests took place under typical shipyards working conditions, which are characterized by several uncontrollable "disturbing" factors, such as:

- Variable air *temperature* and *humidity* conditions (e.g., presence of spatial thermal gradients, draughts, etc.).
- Variable *light* conditions (e.g., artificial/natural light, flashes caused by welding in progress, etc.).
- Presence of *vibrations* (e.g., induced by carpentry work, handling parts through cranes and gantries, etc.).
- Elastic *deformations* on the measured elements (e.g., by the passage of operators on them, etc.).

Tests can be divided into two types:

1. *Unstructured tests* concerning the quick conformity verification of crucial features (i.e., reference positions/distances), which is necessary during ordinary shipyard work, but cannot be planned very precisely in time. These tests involve all phases of the hull-construction process; for example, Figs. 1 and 2 show dimensional verifications on marked and cut panels, Figs. 3 and 4, represent the dimensional verification of a unit corresponding to the lower deck, while Fig. 5 represents the dimensional verification of another unit (upside down) to which planking is applied. It is interesting to note the presence of workers on the measured parts, even during measurements.

   Most of the measurements could not be repeated using all three instruments because of the relatively short time available. Moreover, it was decided to use the instru-

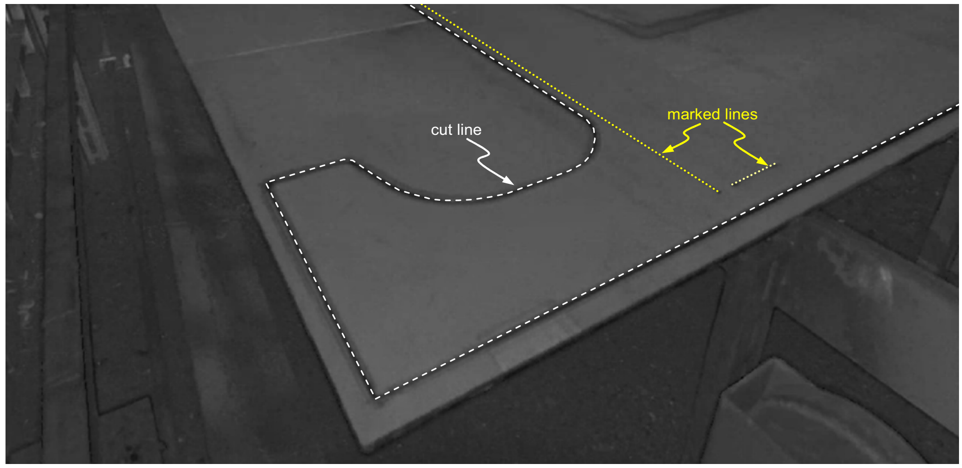

Fig. 2 Example of sheet-metal panel marked out and cut, in the initial phase of the hull-construction process. Dimensional verifications generally concern a set of reference positions and distances along the dotted lines (for marking) and dashed lines (for cutting)

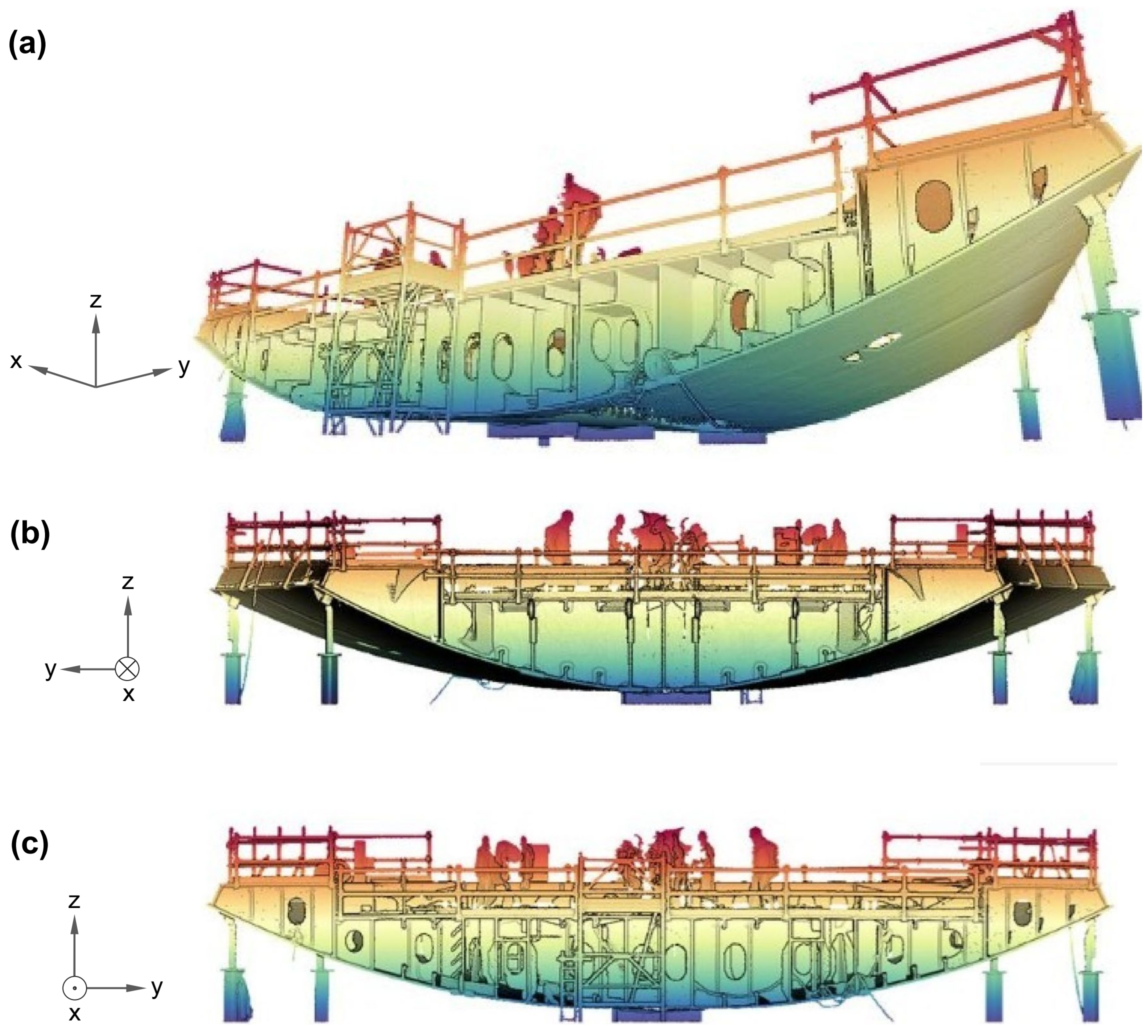

Fig. 3 3D point cloud obtained by scanning a "unit" corresponding to the lower deck of a cruise ship, during an *unstructured* test. **a** Perspective view, **b** aft front view, and **c** fore front view. Referring to the Cartesian coordinate system in use, the horizontal *x*-axis is longitudinal and directed towards the ship's prow, the horizontal *y*-axis is orthogonal and directed laterally, and the vertical *z*-axis is directed upwards

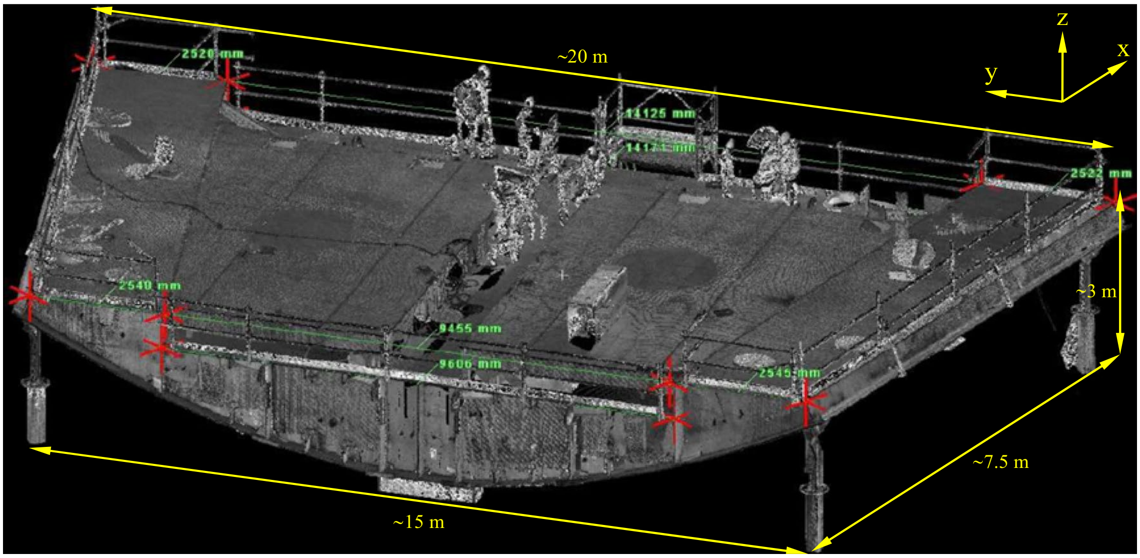

Fig. 4 Example of reference positions and distances to be checked in the dimensional verification of the same "unit" in Fig. 6. The Cartesian coordinate system is analogous to Fig. 3

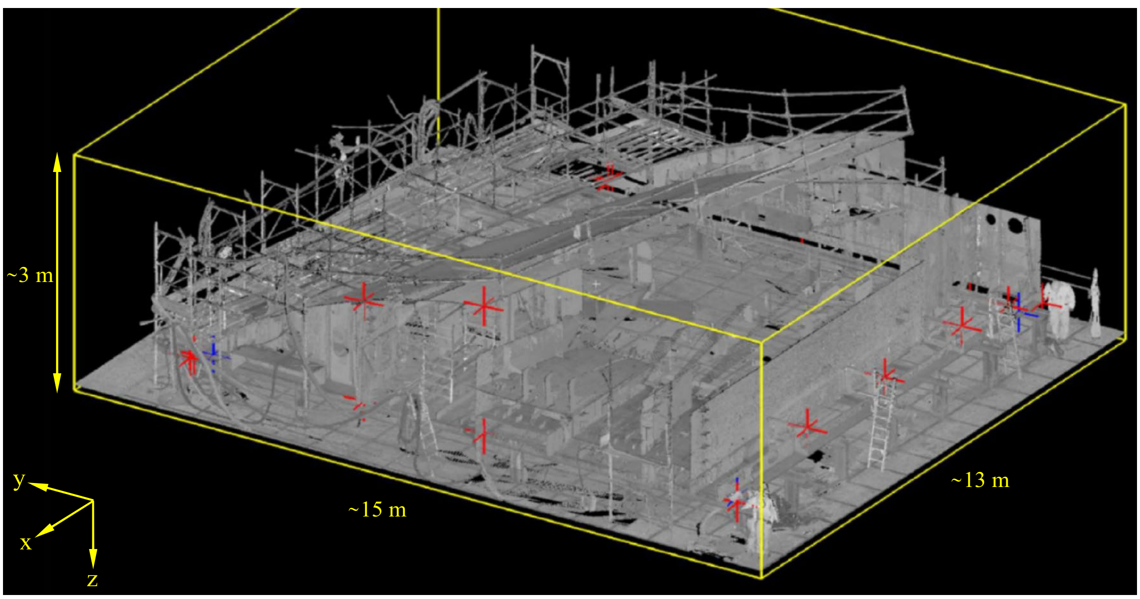

Fig. 5 Example of reference positions to be checked during the dimensional verification of a "unit" corresponding to the lower part (upside down) of the hull of a cruise ship. The presence of scaffolding and support structures around the hull planking may complicate measurements. The Cartesian coordinate system is analogous to those ones in Figs. 3 and 4

ments concurrently on different elements, rather than sequentially on the same one, in order to maximize the number of measurements. The hundreds of measurements collected on panels, units and modules made it possible to evaluate the instruments, from the perspective of all the (sub-)criteria in Sect. 2.2, except for "2.3.2 Repeatability, reproducibility, systematic error", which instead required the following *ad hoc* tests.

2. *Structured tests*, which were planned and carried out using each of the three instruments in turn. These tests allowed us to evaluate the instruments' metrological performance of *repeatability*, *reproducibility* and *systematic error*, under typical shipyard operating conditions. A calibrated artefact was used: a Renishaw scale bar with a Zerodur® structure (i.e., a material with a very low thermal-expansion coefficient [29]) and four three-ball kinematic supports for positioning reference spheres—

Fig. 6 Calibrated artefact (scale bar) used for the *structured* tests, to assess the instruments' metrological performance in the shipbuilding context

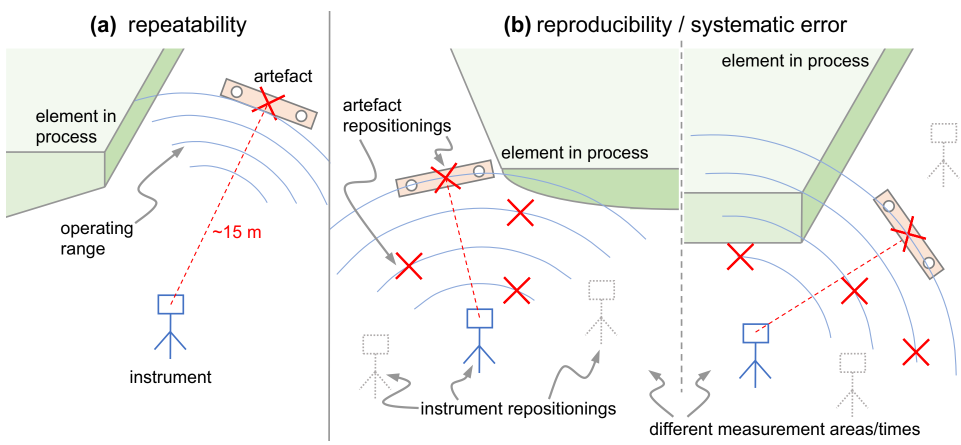

Fig. 7 Conceptual scheme of the measurements performed in *structured* tests. **a** *Repeatability* measurements were performed in a very short time (i.e., a few minutes), with the instrument and artefact in a fixed position, at about 15 m. **b** *Reproducibility* and *systematic-error* measurements were replicated over several days in different areas of the shipyard, changing the position of the instrument and artefact, so that their distance uniformly varied from about 6–20 m. All measurements were performed in the vicinity of elements being processed within the shipyard, under normal operating conditions

such as SMRs, contact-probe (T-probe or mini-vector) spherical tips or other spherical targets (see Fig. 6). The "true values" of the distances between the centres of calibrated spheres, of identical diameter to those used during the tests, were determined in advance through a dedicated calibration process, using a *coordinate measuring machine* (CMM) DEA Global Image with a *maximum permissible error* (MPE) of about 2 µm and a valid calibration certificate [17].

The following sub-sections illustrate the structured tests of repeatability, reproducibility and systematic error respectively (see also the conceptual scheme in Fig. 7).

2.3.1 Repeatability

Referring to the *international vocabulary of metrology* (VIM), *repeatability* can be defined as "closeness of the agreement between the results of successive measurements of the same *measurand* carried out under the same conditions of measurement" and "may be expressed quantitatively in terms of the dispersion characteristics of the results" [30]. At the risk of oversimplifying, repeatability describes how much variability in the measuring system is caused by the measuring instrument. It is usually expressed in the form of measurement variability, assessed through the standard deviation (σ) of the results obtained from a number of consecutive measurements, repeated over a short period of time (i.e., with same measurand and same environmental/operating conditions) [31]. Repeatability tests were carried out with the artefact in a fixed position with respect to the measuring instrument, placing a spherical target alternately on the two kinematic mounts. Then the Cartesian coordinates of the two points, $A \equiv (x_A, y_A, z_A)$ and $B \equiv (x_B, y_B, z_B)$, were measured by the instrument and the Euclidean distance (i.e., measurand) was calculated as:

$$d_M = \sqrt{\left(x_A - x_B\right)^2 + \left(y_A - y_B\right)^2 + \left(z_A - z_B\right)^2}. \qquad (1)$$

The targets used were respectively: (i) SMR (38.1 mm diameter), (ii) T-probe and mini-vector, both with spherical tip (12.7 mm diameter), for laser tracker and total station, and (iii) calibrated sphere (40 mm diameter) for laser

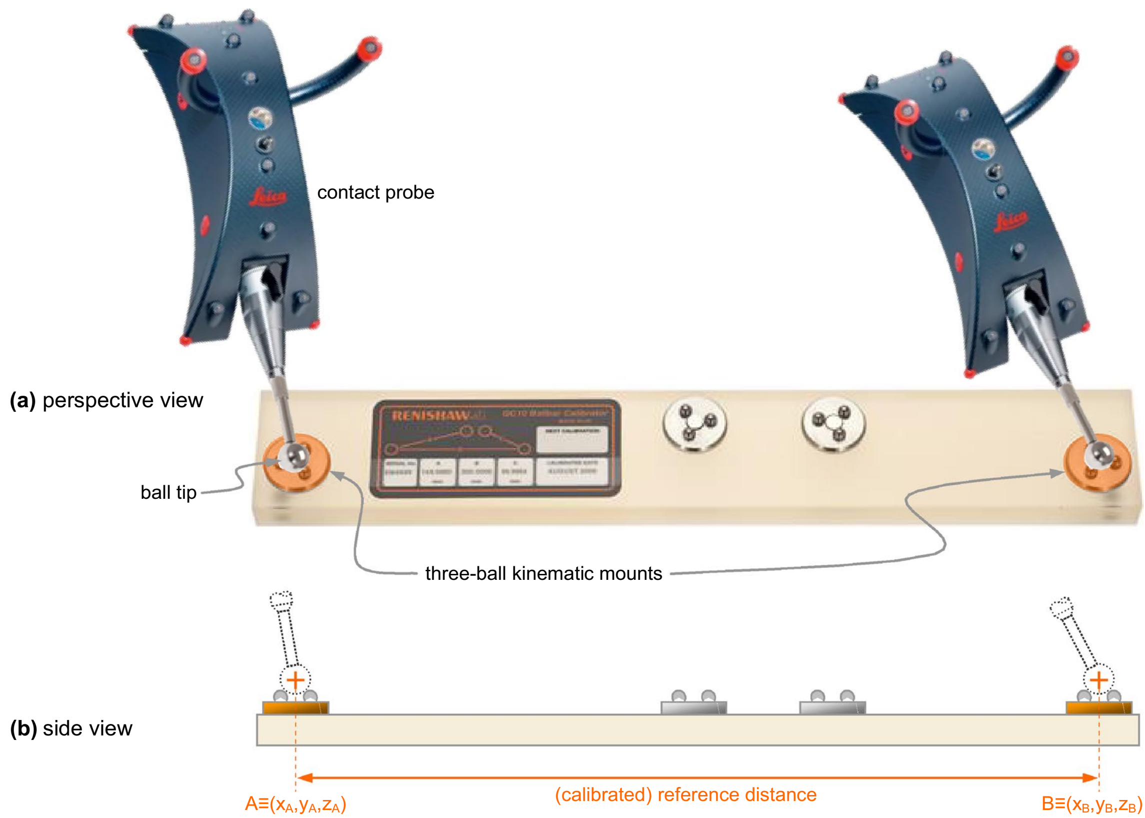

Fig. 8 Schematic example of performing structured tests using a contact probe (like T-probe or mini-vector) and the scale bar in Fig. 6. **a** Perspective view and **b** side view

scanner. Figure 8 exemplifies the test using a probe with spherical tip. While laser tracker and total station automatically provide the coordinates of the (target) sphere centres (A and B), for laser scanner, the least-square sphere centre can be obtained with a best-fitting of the points scanned on each sphere, in line with the ISO 10360 (part 13) standard [32] (see Fig. 9).

Thirty consecutive measurements of d_M (see Eq. 1) were carried out by placing each instrument at a fixed distance, of about 15 m, from the artefact. Then, the relevant σ was calculated.

2.3.2 Reproducibility

Recalling the VIM, *reproducibility* can be defined as "closeness of the agreement between the results of measurements of the same *measurand* carried out under changed conditions (e.g., different principle/method of measurement, observer, measuring instrument, reference standard, location, conditions of use, time)" and "may be expressed quantitatively in terms of the dispersion characteristics of the results" [30]. It is worth noting that reproducibility expresses a broader concept of variability than repeatability, as it embraces other effects, such as possible variations in the conditions of the measurement environment, in the position of the measured element and/or instrument, differences between operators, etc. In other words, it expresses the typical variability of

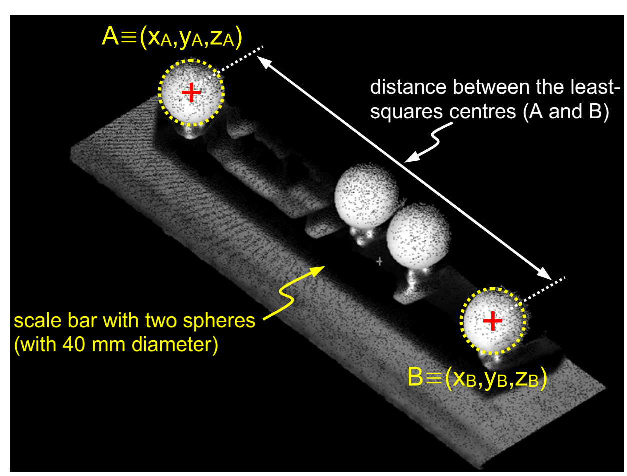

Fig. 9 Determination of the distance between the centres of the spheres (A and B) on the scale bar, constructed through a least-squares fitting of the point clouds scanned on each sphere, during the *structured* tests (i.e., *repeatability*, *reproducibility* and *systematic error*)

Table 1 Connotation (positive "+" or negative "−") of each (sub-)criterion and corresponding performance levels for the three measurement instruments

(Sub-)criteria	Connotation	Performance levels		
		Laser tracker	Total station	Laser scanner
1. Simplicity/time of use				
1.1 Preparation				
1.1.1 Portability	+	L	M	H
1.1.2 Set-up time	−	L/M	M	H
1.2 Measurement				
1.2.1 Operator dexterity	−	L	L	H
1.2.2 Amount of measurements to be taken	−	L/M	L/M	L/M
1.2.3 Acquisition time	−	M	L/M	H
1.3 Data analysis				
1.3.1 Degree of complexity	−	M/H	M/H	L
1.3.2 Time for data analysis	−	M/H	M/H	L
2. Measurement performance				
2.1 Information content	+	L	L	H
2.2 Accessibility of undercuts and hidden points	+	M	M	M/H
2.3 Range and precision				
2.3.1 Operating range	+	M/H	H	M/H
2.3.2 Repeatability, reproducibility, systematic error	+	H	L	L
3. Cost				
3.1 Acquisition of instrument and accessories	−	L	H	M
3.2 Operators' training/competence	−	M	M	L

L Low, *L/M* Low/Medium, *M* Medium, *M/H* Medium/High, *H* High performance

the entire *measurement complex* (i.e., instrument, operator, environmental conditions and *measurand*). As with the repeatability tests, thirty distance measurements (d_{M}) of the artefact points A and B were taken, estimating the respective variability via the relevant σ. Substantial peculiarities of reproducibility tests compared to repeatability tests are:

1. Measurements are spread over time, not infrequently over several days;
2. The relative position between the instrument and the artefact was varied at regular intervals within a range of about 6 to 20 m, reproducing common measurement conditions.
3. Measurements took place in different areas and workshops of the shipyard, so they were subject to typical variability factors.

As with repeatability, reproducibility was quantitatively assessed by means of the σ of the thirty calculated d_{M} values. Reproducibility values are, of course, expected to be significantly higher than repeatability ones.

2.3.3 Systematic error

According to VIM, the *accuracy* of a measuring instrument is a qualitative concept that expresses "the closeness of agreement between the result of a measurement and a (so-called) 'true value' of the measurand" [30]. As a proxy for accuracy, which by definition cannot be quantified, we considered the *systematic error*, defined as "the mean value that would result from a large number of measurements made under reproducible conditions minus the 'true values' of the relevant measurands".

To quantitatively assess the systematic error of the three instruments, the same thirty measurements of the reproducibility test were used, as they represent the typical conditions and variability factors characterising measurements in the shipyard.

Each i-th distance measurement (d_{M_i}) was compared with the respective "true value" (d_{T}), previously obtained in the calibration phase (cf. Sect. 2.3), calculating the corresponding error (ε_i):

$$\varepsilon_i = d_{\mathrm{M}_i} - d_{\mathrm{T}}. \quad (2)$$

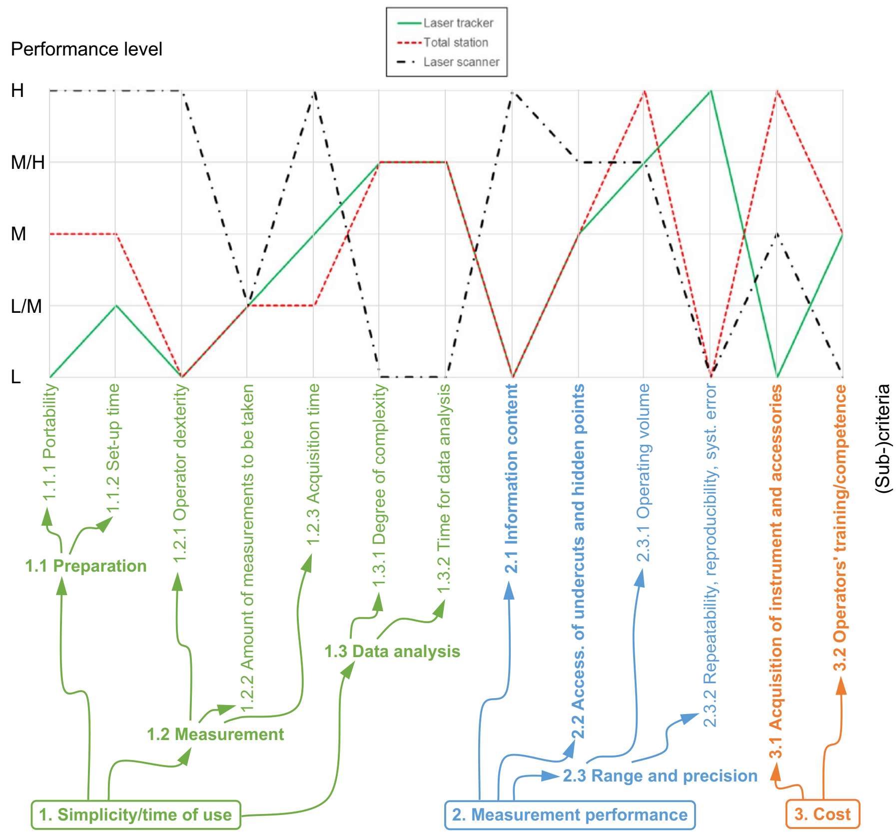

Fig. 10 Chart summarizing the results of the comparison in Fig. 13, for the three instruments. The performance level related to each (sub-)criterion is expressed using a five-level ordinal scale: *L* low, *L/M* low/medium, *M* medium, *M/H* medium/high, *H* high performance

The systematic error can then be quantitatively estimated by means of the mean value of the absolute errors[1]:

$$\overline{|\varepsilon|} = \frac{1}{m} \cdot \sum_{i=1}^{m} |\varepsilon_i|. \tag{3}$$

Being based on repeated measurements of the same measurand on a calibrated reference artefact, this method of estimating accuracy is in line with ISO 10360 (parts 10 and 13) [33, 34]. Additionally, the maximum absolute error can be determined as:

$$\varepsilon_{\mathrm{MAX}} = max\left(\left|\varepsilon_i\right|\right). \tag{4}$$

Being systematically greater than the $\overline{|\varepsilon|}$ value (in Eq. 3), $\varepsilon_{\mathrm{MAX}}$ can be interpreted as a sort of MPE of the specific method adopted.

[1] It should be noted that the quantity $\overline{|\varepsilon|}$ is systematically higher than the absolute value of the mean error $|\overline{\varepsilon}| = \left|\frac{1}{m} \cdot \sum_{i=1}^{m} \varepsilon_i\right|$, as it is not subject to compensation between the possible positive and negative error values, which (at least partially) cancel each other out when added together. The first indicator can therefore be considered more conservative than the second one.

3 Results

Figure 13 (in the Appendix section) summarizes the results of the tests according to the (sub-)criteria in Sect. 2.2, for each of the three instruments. To make the comparison between measuring instruments easier, the judgements for each criterion were translated into *performance levels* defined on a five-level ordinal scale: *low* (L) performance, *low/medium* (L/M) performance, *medium* (M) performance, *medium/high* (M/H) performance, and *high* (H) performance [11].

While some (sub-)criteria have a positive connotation, i.e., improvement in performance coincides with an increase in their value/quantity (e.g., "2.1 Information content"), other (sub-)criteria have a negative connotation, i.e., improvement in performance coincides with a reduction in their value/quantity (e.g., "1.1.2 Set-up time"). Table 1 specifies the connotation of each (sub-)criterion and the corresponding performance levels assigned to the three individual measurement instruments.

These results do not indicate a clear superiority of one instrument over the others, as also evidenced by the profile chart in Fig. 10, which shows multiple intersections between the profiles related to the three instruments [35].

Table 2 Summary of the results of the structured tests

Instrument	Accessory/target	Test type				MPE from data sheet*/mm
		Repeatability σ/mm	Reproducibility σ/mm	Systematic error		
				$\overline{\|\varepsilon\|}$/ mm	ε_{MAX}/ mm	
Leica absolute tracker AT960 (laser tracker)	SMR of 38.1 mm diameter	0.06	0.10	0.07	0.14	±(0.025 + 0.006·L) e.g., for L = 15 m → MPE = ± 0.115 mm
	T-Probe with 12.7 mm diameter tip	0.21	0.37	0.12	0.29	±(0.025 + 0.007·L) e.g., for L = 15 m → MPE = ± 0.13 mm
Trimble SX10 (total station)	SMR of 38.1 mm diameter	0.09	0.25	0.24	1.11	±(1 + 0.0015·L) e.g., for L = 15 m → MPE = ± 1.0225 mm
	Mini-vector with 12.7 mm diameter tip	0.14	0.65	0.55	1.60	Not available
Leica RTC360 (laser scanner)	Spherical target of 40 mm diameter	0.13	0.60	0.45	1.25	±(1 + 0.01·L) e.g., for L = 15 m → MPE = ± 1.15 mm

*L is the distance between the target and the instrument and is expressed in meters; for more information, see the relevant datasheets [27, 36] and [37]. The MPEs from the data sheets—although derived from specific tests other than those carried out here—are to a first approximation reasonably comparable with the ε_{MAX} values from the systematic-error test (cf. Sect. 2.3.3)

The *laser tracker* dominates for metrological performance, with repeatability/reproducibility/systematic-error levels one order of magnitude lower than the other instruments, which—however—still seem to guarantee acceptable performance for the shipbuilding context. On the other hand, its considerable weight/size seems to limit portability. The use of the laser tracker also requires a certain degree of dexterity by the operator(s) handling the target (SMR or T-Probe) and involves quite considerable set-up times (e.g., when starting-up and repositioning the instrument). In general, this instrument is indicated in operating contexts in which the measured element has a relatively simple shape that does not obscure the field of view of the instrument, thus not requiring multi-station measurements.

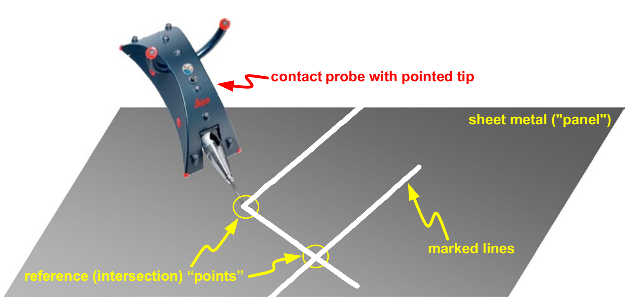

Fig. 11 Example of possible difficulties in unambiguously identifying two reference points, corresponding to the intersection of lines marked on a panel

The *total station* is an instrument that is in some ways similar to the laser tracker, albeit relatively lighter and more compact, less fast and with a significantly lower metrological performance, although still acceptable for the shipbuilding context. A strength of this instrument is its price (~ 35 k€), which is considerably lower than for laser scanner (~ 60 k€) and, even more so, for laser tracker (> 200 k€ with T-Probe accessory).

The possibility of the laser tracker and the total station to perform non-contact measurements, using the respective integrated distance meters (EDM technology), does not seem to be suitable for the operational context of interest, due to the difficulty in univocally identifying/tracing the measurand (i.e., specific points and distances of interest). In addition, the scanning system integrated in the total station appears unsuitable due to the relatively long acquisition time and limited resolution.

The *laser scanner* in use is a state-of-the-art instrument with an extremely light and compact design. Individual acquisitions are relatively simple and fast, with low set-up and instrument-repositioning times. The most critical aspect of the instrument is the need to transfer and analyse (offline) the acquired data, without providing the measurement results in real time. The laser scanner is particularly suitable when measuring complex features and/or when their full 3D reconstruction is needed.

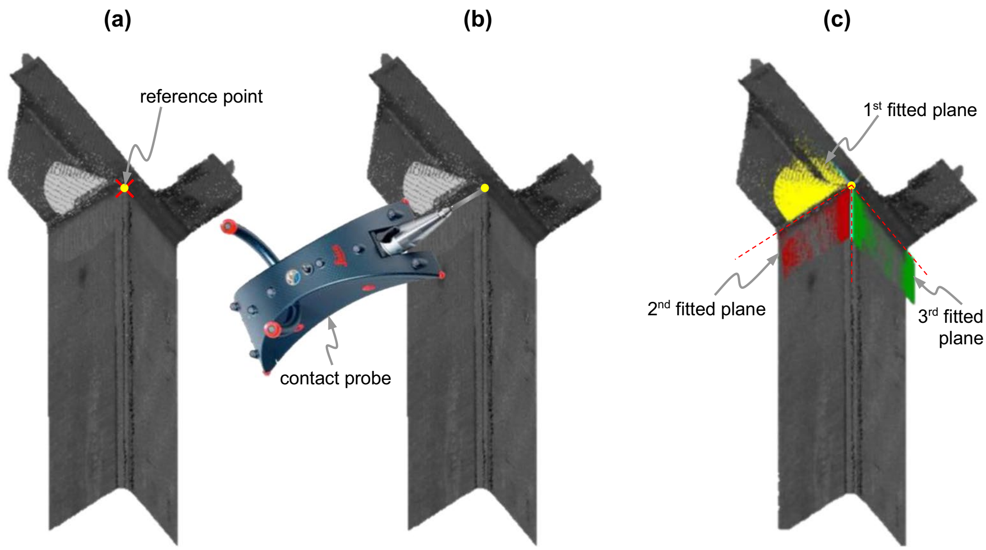

Fig. 12 The **a** Example of possible difficulties in unambiguously identifying a reference point at a vertex. **b** Attempt to reach the point of interest with a contact probe, like the *laser tracker*'s T-probe or the total station's *mini-vector*, and **c** geometric construction of the point of interest through the intersection of three planes appropriately fitted to a point cloud scanned with a *laser scanner*

Special attention should be paid to the results of the structured tests, which are contained in Table 2 and briefly summarised below.

- In the case of SMR measurements, the laser tracker is undoubtedly the instrument with the best metrological performance.
- The performance of laser tracker and total station deteriorates considerably when using their probing accessories (i.e., T-probe and mini-vector respectively), due to unavoidable error propagation [38].
- From the point of view of repeatability, reproducibility and systematic error, the results related to the laser scanner are very close to those related to the total station, when using the mini-vector accessory.
- Non-contact measurements using laser tracker and total station are not included in the structured tests as they are unsuitable for the operational context of interest, due to the difficulties in identifying and targeting reference points. In general, contact measurements with SMR are also impractical, especially if the points to be reached are relatively hidden. The only truly feasible contact measurements seem those made with the laser-tracker and total-station probing accessories. On the other hand, the only reasonably practicable non-contact measurements seem those using laser scanners.
- The standard deviation resulting from reproducibility tests is systematically higher than that for repeatability tests (sometimes about twice or even three times as high). This result reflects the considerably greater incidence of variability factors.
- The last two columns of Table 2 show that the measurement performances observed in the shipbuilding context appear to be systematically worse than those stated in the datasheets of the instruments. This is probably due to the fact that the latter ones were obtained under more controlled conditions and in the absence of external disturbing factors (cf. data sheets of the three instruments in [27, 36] and [37] respectively).

4 Concluding remarks

The following three sub-sections respectively summarise the contributions of this article, its limitations and possible suggestions for future research.

4.1 Original contributions

The main contribution of this research is on-site testing of three innovative measuring instruments in the relatively under-explored context of shipbuilding, particularly in hull construction. A comparison based on a plurality of qualitative and quantitative (sub-)criteria showed the strengths and weaknesses of these instruments.

Returning to the research questions raised in Sect. 1 (i.e., "*Are the three instruments really suitable for the operational context of interest?*" and "*Which of the three instruments is most appropriate?*"), it can be said that all three can probably be very useful. However, the choice of the most appropriate one may depend on many aspects, including but not limited to characteristics of the measured element (e.g., dimensions, height, presence of obstacles, etc.), measurement type (e.g., single point, distance, geometric reconstruction of surfaces, virtual matching, etc.), measurement area (free space, visibility of critical points, etc.), interference with the production process (available measurement time, possibility of instrument repositioning the for multi-station measurements, etc.), skills required by the operator(s), and time to deliver the measurement result.

Now the exercise is done of identifying the most appropriate instrument(s) for the characteristic phases of the hull-construction process (cf. Sect. 1), as described below.

- *Panel processing*. Measurements in this phase are relatively simple and with a fairly obstacle-free "field of view" of instruments, without the need for any multi-station measurement (cf. results for sub-criterion "1.2.2 Amount of measurements to be taken"). The dimensional tolerances are generally smaller than in the other phases (cf. results for sub-criterion "2.3.2 Repeatability, reproducibility, systematic error") and, given the relatively rapid transit of the elements to be measured (i.e., panels), measurement results should be made available immediately (cf. results for sub-criterion "1.3.2 Time for data analysis"). The instruments best suited to this phase are therefore laser tracker and total station. The former is certainly faster and more accurate but also more expensive (cf. results for the criterion "3. Cost"); the latter is certainly easier to handle (cf. results for sub-criterion "1.1.1 Portability") and less expensive, although with lower metrological performance but still acceptable with respect to the expected tolerances (i.e., a few millimetres around the nominal values of the reference features).
- *Production of the "units"*. This operational context could involve the use of all three instruments, in a relatively interchangeable manner. In the presence of units of relatively simple shape and in the absence of obstacles, the laser tracker and the total station would be more competitive than the laser scanner. On the other hand, the laser scanner would be more appropriate for geometric reconstructions of the measured elements (cf. results for sub-criterion "2.1 Information content") and measurement of undercuts and points that are difficult to reach with contact targets (cf. results for sub-criterion "2.2 Accessibility of undercuts and hidden points").
- *Production of the "modules"*. The considerable height of the modules (~ 10 m) and the presence of supporting structures (e.g., scaffoldings) or obstacles make *contact* measurements with laser tracker and total station very impractical (cf. results for sub-criterion "2.2 Accessibility of undercuts and hidden points"). On the other hand, *non-contact* measurements with the laser scanner—as well as being more practical due to the greater portability of the instrument (cf. results for sub-criterion "1.1.1 Portability") and less dexterity required by the operator in acquisitions (cf. results for sub-criterion "1.2.1 Operator dexterity")—allow the reconstruction of the external geometry of the measured module and the possible assessment of its compatibility with adjacent modules (virtual matchings) (cf. results for sub-criterion "2.1 Information content"). The time for data transfer and analysis times—of the order of magnitude of a few hours—appears to be compatible with the stationing time of the modules in the dedicated areas (cf. results for sub-criterion "1.3.2 Time for data analysis"). The metrological performance also appears to be acceptable with respect to the expected tolerances, generally of a few millimetres around the nominal values of the reference positions/distances (cf. results for sub-criterion "2.3.2 Repeatability, reproducibility, systematic error").

4.2 Limitations

This analysis has several limitations, as described below.

- Firstly, the comparison (sub-)criteria are, by definition, inevitably arbitrary. Furthermore, the analysis did not include the assignment of weights and the possible synthesis/aggregation of performance through multi-criteria methods or related techniques.
- With reference to the structured tests, the authors are aware that the metrological properties of all three instruments tend to deteriorate as the distance between the measured point and the instrument increases (i.e., angular error amplification) [24]. The reproducibility and systematic error of the instruments were assessed in general terms, based on thirty measurements at varying distances, in order to reproduce realistic measurement conditions. For repeatability, a relatively conservative assessment was made, placing the instrument at a fairly large

distance of approximately 15 m from the artefact. A more thorough analysis of the distance factor would have required more tests.

- The structured tests were carried out using a calibrated scale-bar that ensures perfect positioning of the (spherical) targets at the points of interest (see Fig. 6). In real-world measurements, however, there can be problems in the unambiguous identification of the measurand for technical/practical reasons. The following two examples clarify this aspect.

  1. When marking the panels, a number of lines are drawn, with paint lines approximately 3–4 mm thick. These lines serve as references for the subsequent welding of rigid elements. The marking verification requires the control of specific positions, such as the intersections of marked lines. Considering the finite thickness of these lines and the intrinsic difficulty in positioning the target exactly at the intersection of the “midlines”, inevitable errors/ambiguities arise in the determination of the points of interest (see Fig. 11).
  2. When verifying units/modules, it is often impossible to identify the reference points without ambiguity. For example, Fig. 12a shows a theoretical position at the apex of a (vertical) bar welded to an (overlying) beam. The theoretical point will simply not be identifiable, due to a multitude of unavoidable imperfections, including but not limited to:

     – Surface flatness defects;
     – Presence of imperfections related to the weld seam;
     – Lack of sharp edges, due to bending of the sheet metal.

  Additionally, for contact measurements, the probe tip—no matter how sharp—can never be truly point-like [see Fig. 12(b)]. The problem of unambiguously identifying the point of interest also exists in the case of non-contact measurements; for example, Fig. 12(c) shows the offline identification of the (presumed) point of interest by means of the intersection of three fitted planes.

4.3 Future research

The proposed analysis can be deepened by future research arising from the above limitations. Specifically, the influence of the distance between one instrument and the measured point will be thoroughly analysed to obtain a more precise estimate of the metrological performance in shipbuilding. Furthermore, the possible error sources related to the identification of the measurand will be analysed, modelling them with an appropriate balance of the measurement uncertainty, according to the GUM [12].

Appendix

See Fig. 13.

Comparison criteria	Laser Tracker (Leica Absolute Tracker AT960)	Hybrid total station (Trimble SX10)	Laser scanner (Leica RTC360)
1. Simplicity/time of use			
1.1 Preparation			
1.1.1 Portability	Low performance: - mass > 20 kg with tripod; - relatively large overall dimensions.	Medium performance: - mass ~12 kg with tripod; - acceptable overall dimensions.	High performance: - mass ~8 kg with tripod; - acceptable overall dimensions.
1.1.2 Set-up time	Low/Medium performance: - 15-20 min on start-up; - ~10 additional min for each instrument repositioning.	Medium performance: - ~10 min on start-up; - ~15 additional min for each instrument repositioning.	High performance: - ~5 min on start-up; - ~2 additional min for each instrument repositioning.
1.2 Measurement			
1.2.1 Operator dexterity	Low performance: - the operator must direct the laser beam; - potential difficulties in reaching points of interest with SMR; - Interferometric contact measurements (for which the laser beam should never be interrupted) and non-contact measurements with only EDM are unpractical in the operational context of interest.	Low performance: - the operator must direct the laser beam; - potential difficulties in reaching points of interest with SMR; - non-contact measurements with only EDM are unpractical in the operational context of interest.	High performance: - positioning of markers/targets is not required; - the operator only checks the success of individual scans.
1.2.2 Amount of measurements to be taken	Medium performance for simple shapes, given the rather limited amount of single-point measurements required; Low performance for complex shapes, due to the increasing amount of multi-station measurements required.	Medium performance for simple shapes, given the rather limited amount of single-point measurements required; Low performance for complex shapes, due to the increasing amount of multi-station measurements required.	Medium performance for simple shapes, given the rather limited amount of scans required; Low performance for complex shapes (multi-station measurements needed), due to the increasing amount of multi-station scans required.
1.2.3 Acquisition time	Medium performance: - with T-Probe ~½ min per acquired point; - with SMR ~1 min per acquired point; - significant impact of instrument repositionings (~10 additional min for each one).	Low/Medium performance: - with vector-bar ~4 min per acquired point; - with SMR ~2 min per acquired point; - with (non-contact) scanning several tens of minutes per scan ("slow" time-of-flight technology); - significant impact of instrument repositionings (~15 additional min for each one).	High performance: - < 2 min per scan ("fast" phase-difference technology); - instrument repositionings do not require additional measurements.
1.3 Data analysis			
1.3.1 Degree of complexity	Medium/High performance: Each instrument repositioning requires alignment and registration of local reference systems.	Medium/High performance: each instrument repositioning requires alignment and registration of local reference systems.	Low performance: the cleaning/registration of point clouds acquired in scans and the construction/identification of points of interest require considerable experience from the operator.
1.3.2 Time for data analysis	Medium/High performance: depending on the amount of instrument repositionings. Fair familiarity with 3D modelling software required from the operator.	Medium/High performance: depending on the amount of instrument repositionings. Fair familiarity with 3D modelling software required from the operator.	Low performance: - 3-4 h for data transfer and analysis; - operator mastery of 3D modelling software required.
2. Measurement performance			
2.1 Information content	Low performance: - limited to the acquired single points; - in case of measurement errors/accidents the measurements should be repeated.	Low performance: - limited to the acquired single points; - in case of measurement errors/accidents the measurements should be repeated; - potentially intermediate with integrated scanner (possible reconstruction of complex shapes), but with unacceptable resolution and acquisition time.	High performance: - complete reconstruction of the measured element geometry; - possibility of ex-post revisions/corrections, without repeating measurements; - possibility of virtually matching elements measured separately.
2.2 Accessibility of undercuts and hidden points	Low/Medium performance with SMR; Medium performance with T-Probe.	Low/Medium performance with SMR; Medium performance with vector bar, which must be fixed to the measured element.	Medium/High performance: geometry reconstruction of the measured element makes it possible to determine points and geometric features that are difficult to reach.
2.3 Range and precision			
2.3.1 Operating range	High performance with SMR: > 100 m; Medium performance with T-Probe: < 20-25 m.	High performance: > 50 m.	Medium/High performance: ~50 m.
2.3.2 Repeatability, reproducibility, systematic error	High performance: - repeatability: with SMR σ ≈ 0.06 mm, with T-Probe σ ≈ 0.21 mm; - reproducibility: with SMR σ ≈ 0.10 mm, with T-Probe σ ≈ 0.37 mm; - syst. error: with SMR |ε-bar|≈ 0.07 mm, with T-Probe |ε-bar|≈ 0.12 mm.	Low performance: - repeatability: with SMR σ ≈ 0.09 mm, with mini-vector σ ≈ 0.14 mm; - reproducibility: with SMR σ ≈ 0.25 mm, with vector-bar σ ≈ 0.65 mm; - syst. error: with SMR |ε-bar|≈ 0.24 mm, with vector-bar |ε-bar|≈ 0.55 mm.	Low performance: - repeatability: σ ≈ 0.13 mm; - reproducibility: σ ≈ 0.60 mm; - syst. error: |ε-bar|≈ 0.45 mm.
3. Cost			
3.1 Acquisition of instrument and accessories	Low performance: - instrument ~120 k€; - T-Probe accessory ~120k€.	High performance: ~35-40 k€ (instrument + accessories).	Medium performance: ~60 k€.
3.2 Operators' training/competence	Medium performance: - good dexterity required for measurements; - fair familiarity with 3D modelling software for data analysis required.	Medium performance: - good dexterity required for measurements; - fair familiarity with 3D modelling software for data analysis required.	Low performance: although scans/acquisitions are relatively simple and fast, strong mastery of 3D modelling software for data analysis is a must.

Fig. 13 Results of the instrument comparison, based on the criteria defined in Sect. 2.2. Judgements are synthesized into performance levels defined on a five-level ordinal scale: *Low*, *Low/Medium*, *Medium*, *Medium/High*, and *High* performance

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