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Procedia Computer Science 232 (2024) 1289–1298

Procedia Computer Science

www.elsevier.com/locate/procedia

5th International Conference on Industry 4.0 and Smart Manufacturing

Laser Scanning Application for the Enhancement of Quality Assessment in Shipbuilding Industry

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Abstract

The need for a shipyard to improve the quality of its final products is crucial to be competitive in the shipbuilding market. In particular, in the latest years the attention has moved to reducing the presence and occurrence of dimensional non-conformities throughout the entire construction process, in order to facilitate and speed up subsequent phases and ship blocks assembly. This necessity has led shipyards management to evaluate the introduction of dimensional detection systems for the manufactured articles. As an innovative solution, laser scanning technologies have been already tested in extensive ways at industrial level and have recently found application in the shipbuilding sector. Specifically, among the various available technologies, laser scanner systems and laser trackers proved to be the most suitable ones for the targeted purposes. Within the paper, the authors firstly describe the evolution of shipbuilding process and highlight its peculiarities. Then, they focuse on the quality assessment process with a specific reference to both dimensional controls and laser scanning technologies that may support such operation. The application of the latest-generation tools is validated through the presentation and discussion of a real case study related to a ship block. Finally, the authors present the potential future developments and integration of laser scanning technologies within Industry 4.0 framework.

Keywords: Shipbuilding; Industry 4.0; Smart Manufacturing; Quality Assessment; Laser Scanning.

1. Introduction

The shipbuilding industry is still strongly linked to tradition, both in terms of design and production approaches. However, the innovation of processes is of paramount importance in a highly competitive field such as shipbuilding,

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10.1016/j.procs.2024.01.127

where reduced delivery times and high-quality levels are crucial market drivers. With a particular focus on construction operations, establishing an optimal management of these phases and a consequent quality control plan is a fundamental aspect of modern shipyards. To this aim, it is crucial considering that achieving a high overall efficiency of the process is quite complex, as its development involves not only features referred to the construction site, but also aspects related to external suppliers in terms of both personnel and materials. In this context, tools developed within Industry 4.0 for other sectors may result in valuable aids, if properly exploited by taking into account the peculiarities of ships [1–3]. Indeed, recent studies have focused on the development of methodologies aimed at modernizing the entire design and production chain through the integration of the latest-generation technologies already tested and used at an industrial level [4–6].

In particular, Shipbuilding 4.0 sets the goal of establishing *smart* shipyards that are characterized by adaptability, resource efficiency and ergonomics, but also by the close integration between shipowner and shipbuilder, with strict cooperation among the shipyard and suppliers. All these targets may be achieved through a deep transformation of traditional shipyards, and the paradigm of Shipbuilding 4.0 is based on this revolution. As a consequence, new production approaches such as production engineering and lean manufacturing have acquired great importance [7–9]. These methodologies aim at establishing a continuous seeking of efficiency and organizational improvement by empowering all the figures involved in the process and creating connections among them [10]. The exploitation of such novel approaches cannot be implemented without resorting to the use of digitization as a tool able to ensure the successful availability, exchange and processing of relevant data and information in the shipbuilding process [11, 12]. Specifically, the digitization of ship design and construction requires significant developments in the fields of process optimization; standardization; digital interconnection; optimization of information flow; and interfacing of material management and information management within the entire supply chain. All these aspects are crucial to define the performance key indicators of a shipyard, and consequently its competitivity. Among these, the final quality of products is of absolute importance, as it determines the shipowner satisfaction and potential new orders. Quality assessment has therefore taken on an even more important meaning in economic terms, and being able to rely on a well-structured process is essential [13].

As a result, shipyards are now forced to analyse in detail aspects that were usually neglected or not deeply considered until a few years ago. One of these is the dimensional conformity of the various blocks that are assembled to build the ship, which must be compliant with the design documents. When non-conformities are recorded, these must be further processed, requiring the involvement of unexpected personnel and, more importantly, an additional expenditure of time and costs that can lead to delivery delays and budget exceeding. Thus, implementing a modern and efficient process for quality control may enhance even more the shipyard's capabilities and speed up production operations and controls. The need to introduce tools that can facilitate and optimize quality control and management in the best way possible has led the authors to focus on laser scanning technologies, which have been thoroughly and successfully tested for other maritime applications [14–17].

In the present paper, the authors start with the definition of the research context by providing a brief description of the common process adopted for ship production and the benefits coming from approaches such as production engineering and lean manufacturing. Quality assessment and dimensional controls are defined as essential aspects for the successful performance of a shipyard. As a way to enhance these processes, the technology of laser scanning is thoroughly described in terms of working principles, pros and cons, available tools, and potential applications in shipbuilding. Then, the authors present the results of their study on laser scanner technology currently available for shipbuilding applications, by highlighting the fundamental criteria that must be considered for the selection of the most proper equipment, as emerged from literature academic review, technical courses and knowledge providers, and interviews to experts and users. Hence, to show the great potentialities of laser scanning technologies, the paper provides a real case study relating to a ship block, whose dimensions were assessed and compared by the authors with the ones reported within a 3D CAD model elaborated during the design stage. The most important parameters of the entire process in terms of equipment details, settings, and environmental conditions are given. Finally, a brief excursus on the future evolution of laser scanning integration within Industry 4.0 and comments regarding its combination with other technologies such as Augmented Reality (AR) and Digital Twin (DT) are presented, along with conclusive remarks regarding the application of laser scanning technologies in shipbuilding dimensional controls.

2. The evolution of the ship production process

Ships are very complex products whose construction is characterised by the performance of a series of interconnected phases and activities that very often overlap in a tight schedule [18, 19]. To be competitive, shipyards must be able to face and execute all these steps ensuring the highest cost- and time-efficiency possible.

In order to better perform and supervise the various activities, the whole process is split into the so-called Work Breakdown Structure (WBS). The application of such approach is based on the organization of manufacturing activities according to the shipyard's work processes, available technologies and facilities, as well as on the planning and monitoring of progresses and manufacturing costs. Through a WBS, all the ship production phases are divided into hierarchically organized levels, starting from the highest level up to increasingly detailed levels. The common layout of a WBS is a layered tree structure, in which the first level represents the entire ship and the subsequent levels are defined as Work Packages (WPs). Each of these WPs is then subdivided into several sublevels related to simple subsystems as well. The integration of all these systems will give origin to the ship as a whole. The ship is then built by following the criterion of assembling zones, each one made up of an assembly of smaller pieces (Fig. 1), in accordance with the Group Technology production method.

As a way to enhance even more the shipyard capacities, basic concepts traditionally invented and developed in other industrial sectors such as production engineering and lean manufacturing may be employed.

Production engineering is developed through the understanding and application of engineering procedures in manufacturing processes and production methods [7]. Such methodology aims at combining different disciplines that include manufacturing technology, engineering sciences, management science, and optimization of complex processes, systems, or organizations in an interdisciplinary approach. In shipbuilding, production engineering creates connections among the various departmental structures involved in the ship design and production process, by associating several competencies and knowledge: the ultimate scope is to maintain production costs at the minimum level in each phase of the process. The activities already begin in the phase of the proposal to the shipowner to guarantee the identification of any improvements that can be made during the development of the project itself. These interventions make it possible to reduce development costs and the time required for the whole process.

Concerning the lean manufacturing, it was introduced in the automotive sector to increase productivity and make the construction process more efficient [8]. Firstly applied in Toyota production sites, such approach is based on the application of process standardization concept, continuous material flow, and waste elimination [20]. It is well known that ships are definitely not comparable to cars, and also their building process is quite different. The automotive industry expects the production of a complete unit every few minutes with a high standardization level. The shipbuilding industry, on the other hand, has much longer processing and delivery times and deals with highly customized units based on the owner's requests. As a consequence, exploiting lean manufacturing at its best capacities requires understanding the basic philosophy and customising it for the specific necessities of each construction site. The starting point for the implementation of a lean manufacturing transformation in a specific shipyard must be focused on the identification and detailed description of the present production facilities for the typical vessels belonging to the production program. In this framework, shipyards organised through a WBS offer more adaptation receptiveness towards lean manufacturing [21]. Construction should be based on relatively standardised modular design to create a constant flow of defined basic and intermediate products, with the various blocks built in most cases on mobile lines. The Just-In-Time concept is applied to materials management, so the material is available for the correct processing station at the most suitable moment. As for the reduction of waste, in shipbuilding this can be identified as the unexploited times between two processing phases. The ultimate goal is to maintain a continuous flow able to add value as much as possible and reduce the total delivery time of the product. Such concept is made explicit through the Takt Time, that is the required product assembly duration that is needed to match the demand and it measures the average time interval between the start of production of one unit and the start of production of the next unit when items are produced sequentially. As a crucial task, material and component supply and processes must be synchronised and organised to avoid potential bottlenecks.

One of the major benefits of the lean manufacturing is the necessary frequent feedback regarding production times and advancements. As a result, constant monitoring of the product and the possibility of early and less-expensive interventions contribute to considerably improve quality assessment, as detailed in the following.

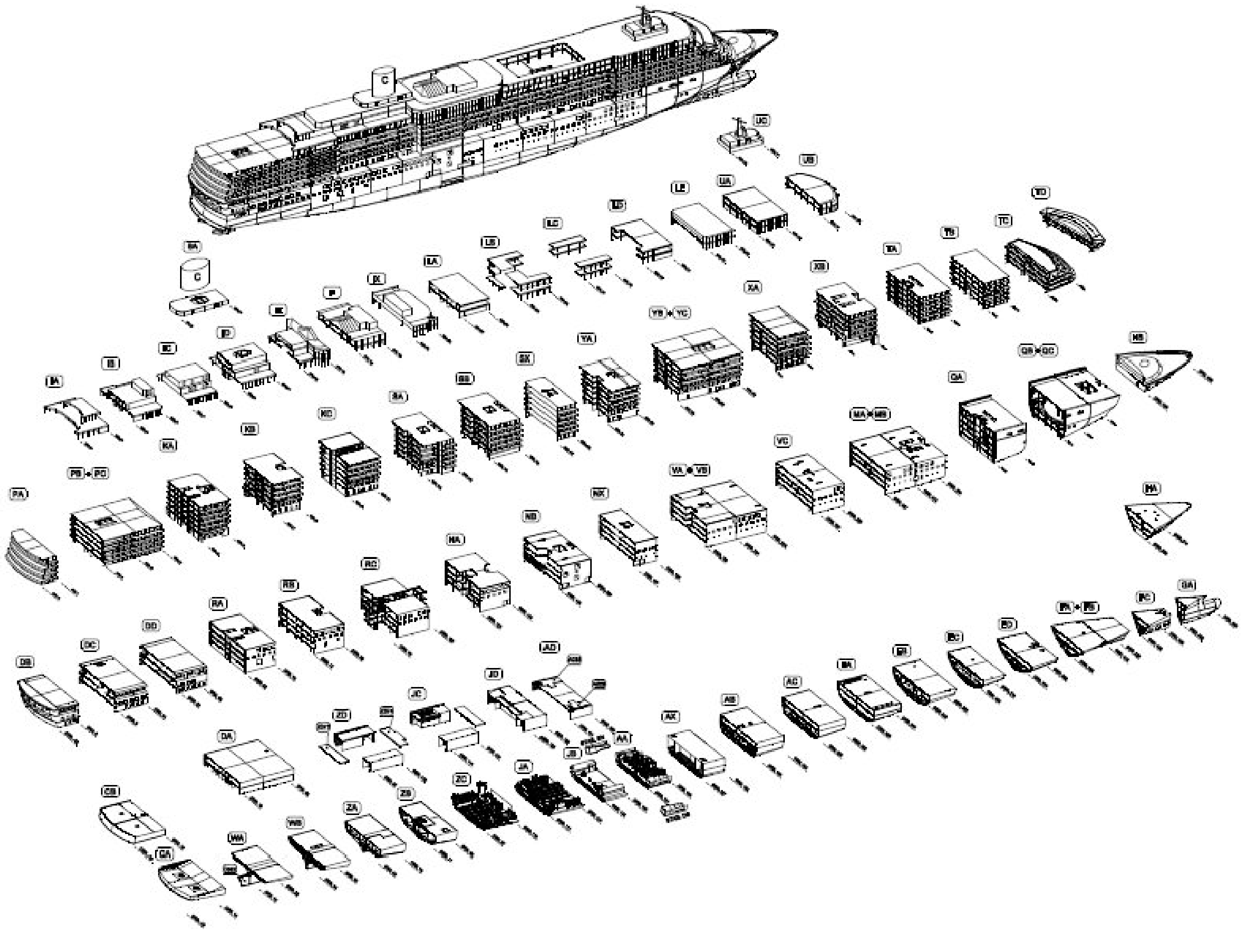

Fig. 1 - Ship module subdivision.

3. Quality assessment in shipbuilding: dimensional controls

With specific reference to the maritime sector, and given the complexity of the shipbuilding process, quality plays a leading role within organisation and management tasks. In fact, quality is the undisputed factor enabling the company to retain competitiveness in an increasingly global market with ever-increasing demands. In this framework, quality assessment represents the most important activity, as it guarantees the compliance of the product with the standard and shipowner's requirements.

Usually, the degree of satisfaction is measured by customer satisfaction; within the shipbuilding process, the "customer" is represented by the consecutive manufacturing stage. Indeed, any non-conformity detected during a certain production phase affects the subsequent phases, as it requires further work for the restoration of the non-conformity and a consequent increase in processing time and costs. The later a non-conformity is observed, the more it affects such parameters. For this reason, quality should not be seen only as a monitoring tool, but as an organised mechanism based on both financial and non-financial metrics for the entire construction process to predict and prevent the occurrence of problems and, if they arise, solve them [22, 23]. Considering that the manufacturing process in shipbuilding is a continuous process, it is necessary to pay particular attention to the phases related to the highest non-compliance costs. Quality management systems differ according to the technological complexity of the product, the phase analysed, and of the level of advancement of mechanical processing in terms of employed facilities and machinery. All these factors sum up to determine the quality costs, which are related to the costs linked to the performance of prevention, assessment, and restoration actions for non-compliances, as well as from both internal and external audits [24].

In terms of quality assessment, in shipbuilding, the dimensional control of production items is a crucial aspect that affects the entire production system. The main objectives of dimensional control are the maintenance of the highest possible precision in each phase of the production of each piece, part, sub-assembly or unit produced; the reduction of work to a minimum in the assembly phases; and the continuous improvement of the production process to obtain maximum precision for all products [25].

The dimensional control process [26] begins in the early stages of design, several months before the start of the construction process. Indeed, the decision-making process for the dimensional control planning involves the designers for the determination of the ship decomposition into units and sub-units and of the manufacturing and assembly sequence. These details are necessary to develop fundamental documents such as the ones related to reference dimensions and standards for tolerance. The planned dimensional controls are then carried out by specialized personnel on product parts and assemblies and the compliance with the control sheet requirements for the given product is checked. The process also involves a data-collection phase: potential remarks are analysed to determine the causes of errors or discrepancies and the information obtained is sent to the relevant bodies to prevent the recurrence of any non-conformities in future projects, with the aim of improving processes, work and management methods, and production techniques.

Due to the very large products involved in shipbuilding, measuring and checking dimensions may turn out to be a difficult and demanding operation. Indeed, during the construction of modern ships, an average of about 800 blocks, 80 sections, thousands of panels are measured and about 10,000 reports are manually filled in for tests recording. These operations are normally carried out with common instruments such as theodolites or manual stations, and errors can be understood and eliminated not in a short period of time, but even after weeks. Moreover, the human errors that may occur during both the detection and recording of measures must be considered, since these are manual and not automatic processes.

Fortunately, with the advance of technologies brought by Industry 4.0 [5] and the development of modern 3D measurement techniques [27–29], the quality control personnel can rely on novel instruments such as 3D laser trackers and scanners that may support the process. Such tools may allow transforming the manual processes currently in use in digital processes, ensuring the reduction of the overall survey time, data processing and structured archiving. Furthermore, they can support the production of test reports, while providing a high ease of operation, a reduction in execution times and a more detailed and precise data collection.

4. Laser scanning technologies in shipbuilding

4.1. Technologies and applications

Laser scanning technologies are based on the controlled deflection of light, visible or invisible, which allows the capture of spatial coordinates of objects in the shape of a point cloud. A scanning system can be an input or output system or a combination of both, as explained as follows [30]. Input systems acquire images in either two or three dimensions, by reacquiring the original light source through either the specular or diffuse reflection or by fluorescing the image with a consequent acquirement of the fluoresced light. For shipbuilding dimensional control, two possible tools may find application: 3D laser scanners and laser trackers.

3D laser scanners are instruments aimed at the detection of the surrounding environment through the emission of a series of laser beams, which are reflected by the object and reacquired back by the scanner. Through the difference evaluated between the original beams and the reflected ones, the instrument is able to determine the distance of the reflection point as well as the angle at which it is located, calculating the Cartesian coordinates of the object in the environment. 3D laser scanners are designed to acquire large volumes of data in a very short time, creating virtual copies that faithfully reproduce the real artefact with high precision and allow the dimensional measurements when contact instruments are not suitable. Several scans are necessary in order to accurately reconstruct one object. The time required for a single scan may vary on the basis of both the dimensions and geometric complexity of the object and on the necessary scan resolution. Anyhow, sufficient-quality images may be obtained in a few minutes. Latest-generation laser scanners offer the ability to scan long range, reproduce high-resolution colour images and very precise measurement within a single instrument. Furthermore, they may be controlled remotely through wireless devices, thus simplifying scanning operations. A limitation of such tools regards the difficulty in measuring a precise point position, since this is evaluated as the average position among the various points detected in all the collected scanned point clouds. Other limitations of 3D laser scanners may be related to potential measurement errors and the intrinsic machine error that characterises instruments accuracy. When performing multiple scans, also the global error recorded during the scanning of the object must be taken under control. In some cases, such error can reach values up to 10-12 mm, thus being greater than the tolerance expected within the project usually equal to maximum 5 mm. However, tools including calibrated targets as dimensional references, total measurement stations, and a combined use of a laser system with a tracker may improve the overall accuracy. Finally, 3D laser scanner systems are affected by the working environmental conditions and the potential presence of suspended particles such as dust, which may act as small prisms able to reflect the light beams. Moreover, temperature and its variation as regards working environment and objects can also significantly compromise the scanning operation. The local variation of the air temperature causes areas characterised by air with different densities, where laser beams may be refracted. These interferences can lead to the presence of shadow areas on the object and to the consequent impossibility to perform a correct scan.

Laser trackers are portable Coordinate Measuring Devices (CMDs) that allow operators to measure the physical and geometric characteristics of an object with ease and accuracy. The measurement is done by sending a laser beam to a retroreflective target probe, which must be kept in contact with the object to be measured at the interested point. The beam is thus reflected from the target back into the tracker: the horizontal and vertical angles and the distance between the tracker and the target is used to determine the point coordinates, using a process known as the Absolute Distance Meter (ADM) [31]. Additionally, this type of measurement is able to track the target probe as it moves in real time: this feature allows the user to digitize data on complex surfaces or measure the position of moving objects. The use of laser trackers involves trained operators that are in charge of positioning and moving the target along the object to detect the different points of interest. This process is facilitated by the ability of the instrument to follow the target along its movements and to also foresee the trajectory in some cases. The use of a tracker system for detecting an object may involve the use of personalised targets. The common feature of the various targets is the presence of a reflective surface which allows the reflection of the laser beam towards the instrument. An advantage of laser tracker is the possibility of measuring specific points also during manufacturing processes, given that measurements are taken on specific reduced areas. This aspect makes the technology suitable for use in a production line where the flow must not be interrupted, with the fundamental assumption of taking measurements far away from vibration sources. As a negative aspect, also laser trackers suffer from the presence of suspended particles, as these will interfere with the light beam by deflecting it. However, due to the greater precision of the instrument in comparison with the scanner, the final error will affect the detection with a smaller percentage and will lead to a better measurement of the point.

For each various application, the selection of the appropriate laser scanner or tracker devices among those available on the market depends on several factors. In order to discover the most desirable features in such equipment, the authors performed a thorough investigation based on literature academic review, technical courses and knowledge providers, and interviews to experts and users. From this study, the following aspects have been identified as the most important ones: availability of maintenance service, presence and accuracy of an inclinometer, absolute maximum measurement error, maximum resolution at 10 meters, single scan speed, and noise at 10 m with 10% reflectivity.

Given their peculiar features and numerous positive aspects, laser scanning technology is generally employed for measurements and visualization in several construction survey applications, and shipbuilding makes no exception [17]. Indeed, these measuring devices provide a quick and accurate way to inspect hull parts and components during construction, allowing a consequent integration among them [14]. Furthermore, laser trackers and scanners may be employed to perform other useful operations such as the digitization of the ship and the acquirement of the as-built documentation, which may be necessary for future maintenance and restoring interventions [15, 16]. In this regard, the digital model can be re-elaborated through the use of advanced modelling software that can assign specific properties to various parts and may allow the performance of calculation and assessment by third parties (e.g., external design offices, ship classification societies, etc.). Ultimately, modern laser scanning technologies for dimensional control allow shipbuilders to minimize human error and obtain repeatable measurements reaching lower tolerances in much shorter times than in the past. Modern solutions also have the great advantage of being portable, thus increasing versatility. Thanks to this aspect, the operator can distribute the measuring stations in the most appropriate way for the purpose, providing on-site measurements even in usually inaccessible and restricted environments.

4.2. Case study

The case study presented in this paper is based on the performance of dimensional controls by means of laser scanners and trackers of an actual ship block. The tests were carried out in an Italian shipyard and their final aim was the quality assessment of the measured objects, achieved through the comparison between the obtained scan and the 3D CAD model elaborated during the design phases. The device used is able of measuring 3D scan data at up to 26,600 points per second with high precision up to 600 meters away, and its operating temperature ranges from -20 °C to +50 °C.

The obtained scanned image of the block is shown in Fig. 2, in which the following welded structural members can be recognised: transversal and longitudinal girders, longitudinal stiffeners, and vertical elements such as bulkheads and pillars. During the scanning operation, the environment temperature was equal to 24 °C and the atmosphere was clear of suspended particles. Table 1 reports the parameters defining the scanning operation: it is worth noting that the mean global error is of the same order of magnitude as the thickness of the measured block baseplate. The detected point cloud was then imported into a specific software for post-processing operations. The superimposition of the scanned image re-elaborated as a digital model and the 3D model allowed the observation of the deformations' trend within the section, highlighting the deviations in certain points. In particular, the authors focused on two specific structural elements: plates, to assess their planarity and verticality, and welded structural members, to assess their correct positioning and intersections and the absence of significant deformations. Aiming at identifying critical points, the authors re-elaborated the scan as shown in Fig.3 to clearly display the difference among the measured values and design data for each significant point. In this Figure, the different intensity of colours represents the deviation of measured data from the theoretical dimensions of the CAD model. These quantities are reported in accordance with a three-coordinate system, whose origin is located at the mid plan of the block baseplate and whose axes are directed as follows: x-axis in accordance with the direction of longitudinal stiffeners, y-axis in accordance with the direction of transversal structural members, and z-axis in the vertical direction.

Table 2 shows the numerical outcome of such assessment: thus, it is possible to identify which points are characterised by higher deviations that exceed the tolerance set for design and production (i.e., ±5 mm for the case study), have a general overview of the dimensional conformity of the block and alert the personnel in charge of the following construction phases that may take into account and recover such deviations. Particularly, for the scanned block, it can be noted that the values exceeding tolerance (reported in bold in Table 2) are located in correspondence with block edges and vertices. These deformations will be definitively solved in further processing phases, as additional pillars and vertical bulkheads are expected to be welded on the block to complete the ship.

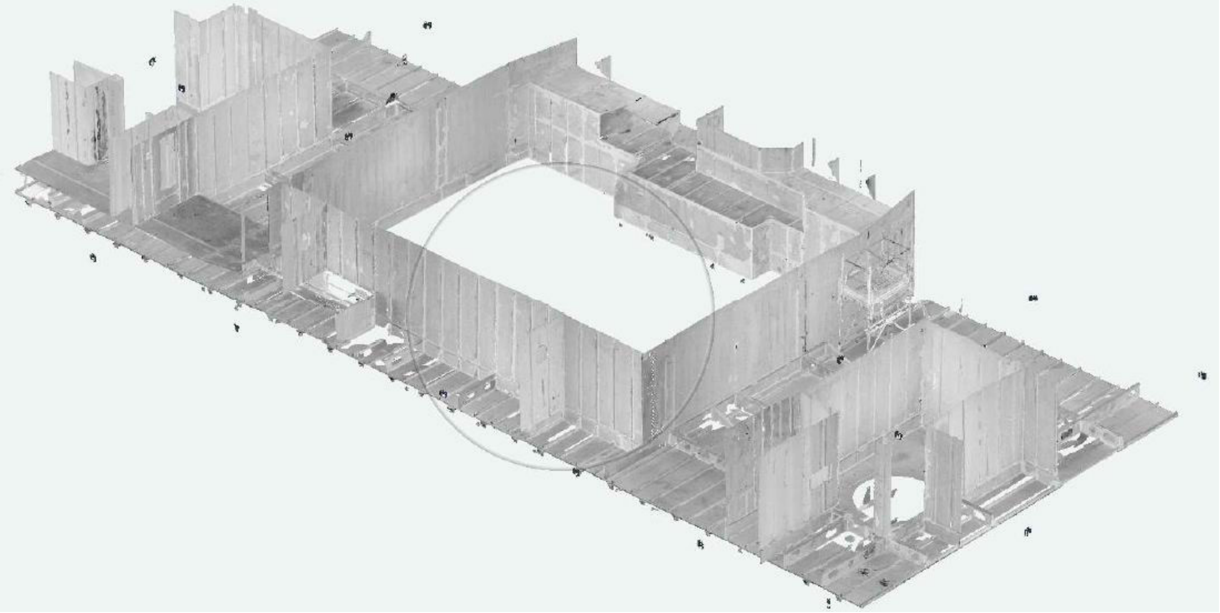

Fig. 2 - Scan of the case-study ship block.

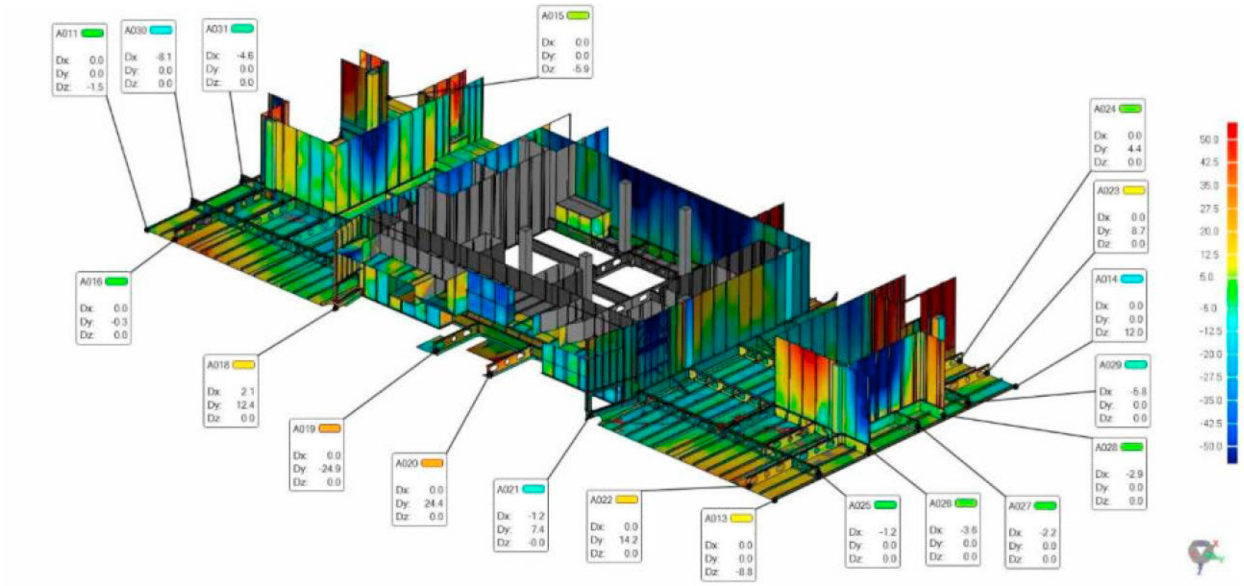

Fig. 3 - Dimensional assessment of the scanned block.

Table 1. Parameters characterising the scanning operation of the ship block in Fig. 2.

Parameter	Value	Unity of Measure
Number of scans	23	-
Resolution	1/4	-
Time required for performing a scan	04:11	mins
Time required for the total scan	96:13	mins
Number of points in the scanned cloud	448,000,000	-
Mean global error (as described in Section 4.1)	3.7	mm

Table 2. Dimensional assessment of the case-study block: calculation of deviations between the scan and the CAD model.

Point ID	Tolerance [mm]	Design dimension [mm]			Measured dimension [mm]			Deviation [mm]		
		X	Y	Z	X	Y	Z	X	Y	Z
A011	±5	66,755.3	-16,412.0	17,600.0	66,755.3	-16,412.0	17,598.5	0.0	0.0	-1.5
A013	±5	66,767.5	16,430.0	17,600.0	66,767.5	16,430.0	17,591.2	0.0	0.0	**-8.8**
A014	±5	80,130.4	16,423.5	17,600.0	80,130.4	16,423.5	17,612.0	0.0	0.0	**12.0**
A015	±5	80,089.8	-16,374.1	16,800.0	80,089.8	-16,374.1	16,794.1	0.0	0.0	**-5.9**
A016	±5	66,786.4	-15,000.0	17,532.7	66,786.4	-15,000.3	17,532.7	0.0	-0.3	0.0
A018	±5	66,836.4	-6617.7	17,515.1	66,838.5	-6605.2	17,515.1	2.1	**12.4**	0.0
A019	±5	66,898.5	-1400.0	17,520.2	66,898.5	-1424.9	17,520.0	0.0	**24.9**	0.0
A020	±5	66,918.3	1400.0	17,530.5	66,918.3	1424.4	17,530.5	0.0	**24.4**	0.0
A021	±5	66,924.6	6632.3	17,487.8	66,923.4	6639.7	17,487.8	-1.2	**7.4**	0.0
A022	±5	66,878.9	15,000.0	17,533.9	66,878.9	15,014.2	17,533.9	0.0	**14.2**	0.0
A023	±5	80,043.3	15,000.0	17,490.2	80,043.3	15,008.7	17,490.2	0.0	**8.7**	0.0
A024	±5	80,015.0	13,600.0	17,456.0	80,015.0	13,604.4	17,456.0	0.0	4.4	0.0
A025	±5	69,240.0	16,417.2	17,354.4	69,238.8	16,417.2	17,354.4	-1.2	0.0	0.0
A026	±5	72,000.0	16,415.7	17,315.3	71,966.4	16,415.7	17,315.3	-3.6	0.0	0.0
A027	±5	74,760.0	16,406.4	17,329.5	74,757.8	16,406.4	17,329.5	-2.2	0.0	0.0
A028	±5	76,140.0	16,414.7	17,363.0	76,137.7	16,414.7	17,363.0	-2.9	0.0	0.0
A029	±5	77,520.0	16,419.9	17,340.0	77,514.2	16,419.9	17,340.0	**-5.8**	0.0	0.0
A030	±5	69,420.0	-16,327.7	17,343.9	69,231.9	-16,327.7	17,343.9	**-8.1**	0.0	0.0
A031	±5	72,000.0	-16,350.5	17,354.5	71,995.4	-16,360.5	17,354.5	-4.6	0.0	0.0

4.3. Future integration of laser scanning within Industry 4.0

Future applications of laser scanning may allow the complete digitization of the processes related to dimensional and conformity assessment, by implementing features that enable the elaboration of semi-automatic control reports.

In addition, this technology may be integrated with other Industry 4.0 technologies in order to enhance the digitalisation of shipyards. Particularly, tools such as Augmented Reality wereable devices may be employed to overlap scanned models with CAD models elaborated during design phases, in order to further increase the accuracy of both dimensional controls and quality assessment operations. Furthermore, this digitization may be extended towards the development of Digital Twins, i.e. digital copies of real ships, able to support the exchange of information among the parties involved during construction in order to solve problems that may arise during assembly processes, increase the level of control execution activities, and enable predictive maintenance. Finally, scanned models may also allow the manufacturing of specific replacement parts, belonging to aged equipment and no longer available.

5. Conclusions

The potential occurrence of non-conformities and dimensional flaws in blocks during the construction phases of ships can have detrimental and substantial impacts on the production process in terms of costs and delivery time. Indeed, due to the complexity of ships and the numerous steps required during production, even a minimum suspension of activities that initially seems negligible can lead to a longer delay. In order to propose solutions to this issue, the authors analysed the possible technologies that may be applied during quality assessment and controls in shipyards without interfering with the working phases. In this context, the capabilities of laser scanning technologies are very promising, as demonstrated by the outcomes related to the case-study ship block presented in the research. Indeed, the combined use of laser scanners and laser trackers enabled the full exploitation of their best capabilities: laser scanners allowed obtaining a point cloud reproducing the block, while laser trackers were used to precisely detect the interested points. As a result, the block model obtained by the re-elaboration of the scan allowed a fast and effective comparison with the 3D CAD model, and a rapid evaluation of crucial deviations from theoretical values. In the case study analysed these deformations were not troubling, since in further steps additional structures were meant to be welded, adding strong constraints to the block and bringing back values within the accepted tolerance. In other cases, deformations could affect more structures and could present greater values; each situation must be carefully addressed to find proper solutions and allow the correct progress of working activities.

As the authors aim at legitimising the adoption of laser scanner technologies for dimensional controls in shipbuilding, also some considerations regarding instruments purchasing expenditure and novelty implementation costs are necessary. Specifically, shipyards must be aware that latest-generation scanning tools require important financial investments; however, the economic return in terms of quality improvement and acceleration of the production process is able to pay off the expenses. In terms of the time required to perform a dimensional control through laser scanners and trackers, the case study block underlined how a single scan with sufficient resolution can be obtained in less than five minutes. Certainly, the geometry complex and the dimensions of the target object are crucial parameters able to affect the time required by both single scanning and whole operations, including post-processing activities involving the re-elaboration of the 3D model.

Finally, laser scanning technology is a promising solution able to improve the performance of the production and design system through a significant reduction in the overall survey and data processing time and can find a fruitful application also in the novel Industry 5.0 paradigm, by enhancing man-machine cooperation in shipbuilding.

Acknowledgements

This research work was supported by "ALSO 4.0 – Automated Laser Scanner Operations" research program, founded by the POR-FESR 2014-2020, Regione Autonoma Friuli-Venezia-Giulia.

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