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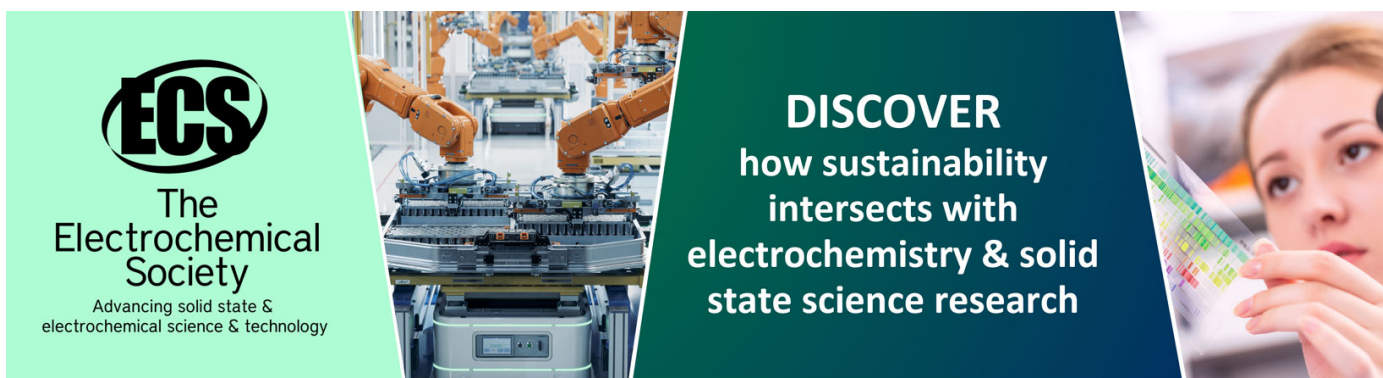
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Human-free offshore lifting solutions

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Abstract. With single elements weighing up to hundreds of tonnes and lifted to heights of 100 meters, offshore wind turbines can pose risks to personnel, assets, and the environment during installation and maintenance interventions. To increase safety during offshore lifts, this study focuses on solutions for human-free lifting operations. Ideas in the categories of logistics, connections, as well as guidance and control, were discussed and ranked by means of a multi-criteria decision analysis. Based upon 38 survey responses weighting 21 predefined decision criteria, the most promising concepts were selected. Logistically, pre-assembled systems would reduce the number of lifts and thus reduce the risk. A MATLAB-based code has been developed to optimise installation time, lifted weight, and number of lifts. Automated bolting and seafastening solutions have high potential to increase safety during the transport of the wind turbine elements and, additionally, speed up the process. Finally, the wind turbine should be lifted on top of the support structure without having personnel being under the load. A multi-directional mechanical guiding element has been designed and tested successfully in combination with visual guidance by cameras in a small-scale experiment.

1. Introduction

Lifting operations in the offshore wind energy industry involve heavy loads in the order of hundreds of tonnes, as well as working heights of around 100 meters, all while the lifting operation is being subjected to the wind and wave conditions at sea. This makes offshore lifting operations and offshore wind turbine installations hazardous. Guidelines and standards for health and safety in lifting operations in general [1–4], as well as specific to the offshore environment [5–7], exist. Despite this, having people directly under the load for guiding and securing is still common practice in offshore wind turbine installations. G+ (formerly G9) [8] provided, in addition to the publicly available annual incident reports [9–11], the full data for health and safety incidents occurring during offshore lifts from 2014 to the third quarter of 2016. From these reports the total number of incidents and dropped objects per hour of work is determined and shown in figure 1.



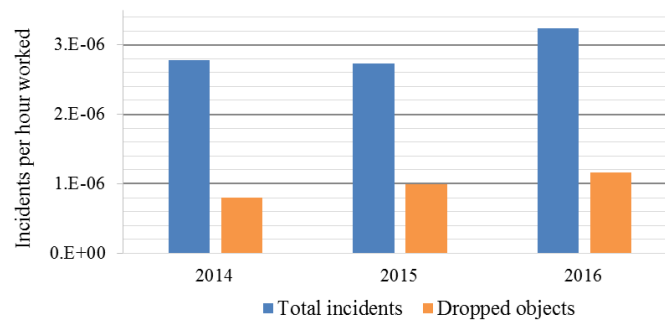


Figure 1. Total incidents and dropped objects per number of hours worked.

Whilst the number of incidents per number of hours worked decreased slightly from 2014 to 2015, it rose again in 2016. Over the same period, normalised incidents due to dropped objects increased year on year. Although small, these increases are important, especially as the installed capacity of offshore wind energy, and thus also the number of lifting operations performed each year are expected to grow significantly, based on the estimations by [12]. A recent study [13], matching safety indicators against the same G+ incident data, draws similar conclusions and the authors advise having safety indicators for dropped objects, particularly during lifting operations, as this is a crucial area for offshore health and safety incidents. The more details in the incident reports [9–11] on the statistics for the reasons, areas, and consequences for incidents substantiate as well the importance of safer and improved handling in offshore lifting operations.

Thus, the motivation for this study was to conduct research into methods and technologies that could reduce the need for personnel near lifting operations, and to assess their feasibility. Different concepts for human-free offshore lifting operations in the categories of assembly and logistics, connections and seafastening, as well as guidance and control, have been collated and investigated, mainly based on broad literature reviews and industry reports on current practices, but also based on patents for new designs and innovative solutions proposed by the authors. The broad range of concepts was assessed with respect to 21 predefined criteria and ranked by means of a multi-criteria decision analysis of 38 survey responses. More details on this analysis can be found in [14]. The concepts most worth developing were investigated in more detail and are presented in this work.

In the following, the most promising solutions are presented for the three categories: assembly and logistics (section 2), connections and seafastening (section 3), and guidance and control (section 4). A short summary of existing concepts precedes each section. At the end of this paper (section 5) the results are concluded.

2. Concepts for logistics and assembly solutions

Installation pre-assembly concepts can be applied as a positive path towards achieving human-free lifting operations offshore, minimizing the number of lifts and reducing the human exposure to lifting hazards. Existing transportation and installation methods are:

- the bunny-ear (BE) method for installation of the rotor in two lifts (figure 2a): first two blades attached to the nacelle are lifted on top of the tower, and then the third blade is connected to the wind turbine in a second lift;
- the rotor star (ROT) method for fully pre-assembled installation of the rotor (figure 2b): the nacelle is mounted in a separate lift on top of the tower and then the entire rotor-hub assembly is lifted as one unit;

- single piece installation (SP) of the rotor-nacelle assembly (RNA) (figure 2c): each blade is lifted individually, as well as the nacelle with pre-assembled hub;
- installation methods for the tower: the tower can be lifted as one piece (1T) or two sections (2T).

Combining the pre-assembly methods for RNA and tower, a wind turbine can be installed with three to six lifts. Installation is also possible in only one or two lifts if the tower section and RNA are fully pre-assembled.

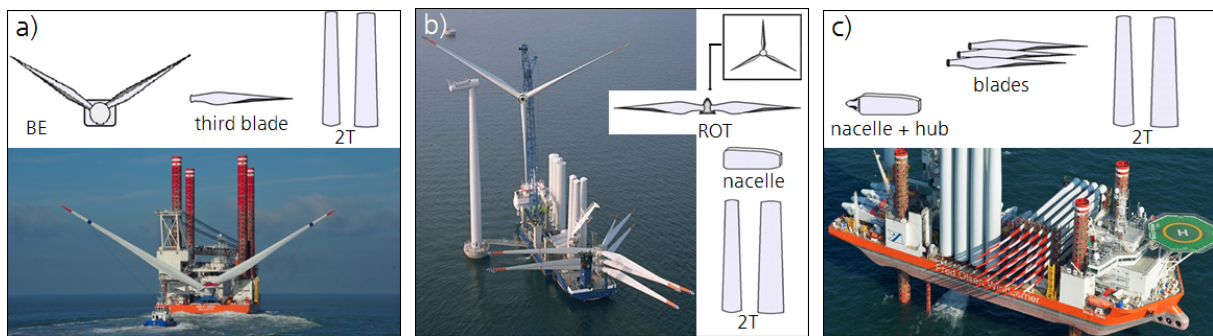


Figure 2. Pre-assembly methods: (a) Bunny-ear [15, 16], (b) Rotor star [15, 17], (c) Single pieces [15, 16].

Even if pre-assemblies of wind turbine components would require fewer lifts and thus reduce the number of hazardous offshore lifting situations, pre-assembled systems are heavier than single pieces and have larger wind exposed areas, which could actually increase the lifting hazards. Furthermore, vessel requirements, lifting capacities, and stability limitations for transportation and installation of pre-assemblies constrain the feasibility and advantages of this pre-assembly method. Thus, a good compromise between number of lifts and lifted weights has to be found.

For this purpose a discrete-event simulation model of lifting operations for the installation of a wind farm is implemented in a MATLAB script file (m-file) and integrated into a graphical user interface, to allow a more user friendly inclusion of the input data. Although the code has been developed for deterministic data input and output, as a future work, the time quantities could be integrated as random variables to model the system stochastically. Due to the coexistence of different criteria the program does not clearly outline the optimal practise, but aims to offer an overview of pros and cons of the different transportation and installation methods.

Figure 3 presents a flow chart of the developed installation optimisation program. Based on data input for the turbine and the vessel, systems-fitting functions derive information on the vessel loading-condition, and the lifting-operation hazard for the previously described BE and ROT configurations, as well as traditional SP transportation. Additionally, special tower and blade transportation methods, such as gathering single blades in a cage and having the tower as one piece or split into two sections, are allowed. Transportation constraints, due to vessel limitations, have been integrated as well. Despite the possibility to include overboard limits, the orientation of the pre-assembly on the vessel (transverse or longitudinal for BE, as well as inside- or outside-pointed transportation for ROT), and other user specified positioning along the deck, simplifying assumptions have been made concerning the vessel's stability. Specifically, asymmetric loading is not allowed and the maximum allowed position of the vessel's centre of gravity cannot be checked. Furthermore, a time counter provides an estimate of the time it

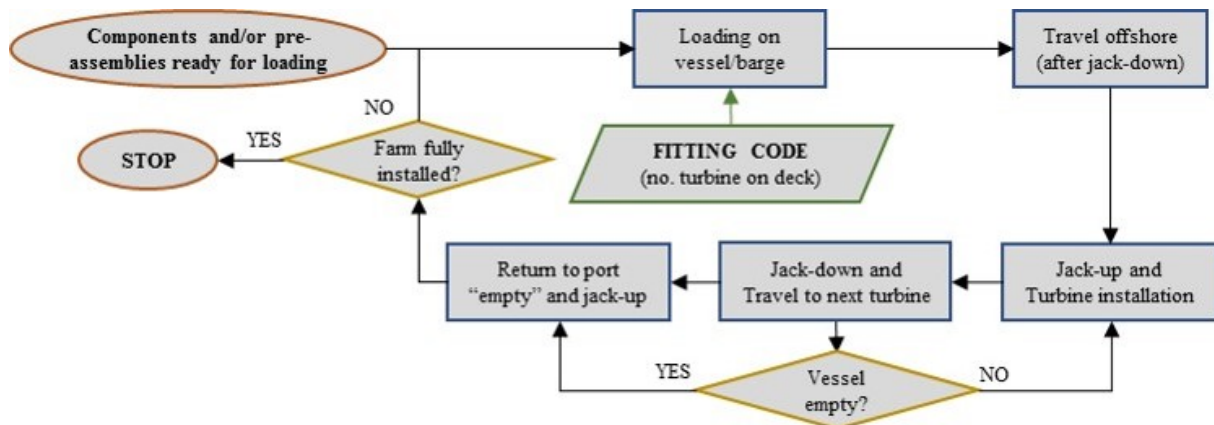


Figure 3. Installation pre-assembly MATLAB code flow chart.

would take to install the turbines based on the specified configurations. This estimation, however, is affected by time variables which have to be assumed, such as the time to load components and pre-assemblies on the vessel. As it was also necessary to account for the effect of weather windows and vessel's availability, a time variable for the average working hours per day is defined.

At this preliminary stage, the program was validated against two real case studies: Thanet and OWEZ (Egmond aan Zee) wind farms. For the latter, three possible configurations, along with characteristic properties, are presented in figure 4. The 36 wind turbines of OWEZ wind farm were transported in a BE-2T configuration, starting from Ijmuiden port, and installed by the A2SEA Sea Power jack-up vessel within around 67 days [15, 18]. The assumed loading and offshore installation times for each component were taken from [19], while a sensitivity analysis has been performed on the working hour, as shown in figure 5. As expected, in general the SP transportation would have led to a considerable increase in installation time. Although, as verified by the simulations, the adopted BE-2T configuration has the highest time saving, a ROT solution could reduce the amount of the maximum weight lifted by the crane, with the same number of lifts and slightly increased time required to install (about 10 days).

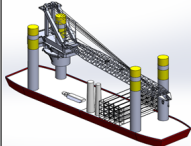
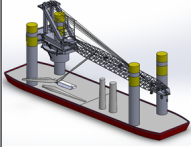
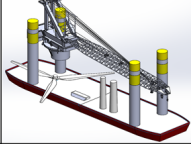
		Occupied area [m ²]	Net load on deck [tons]	No. turbines per voyage	Total no. of lifts	Max. lifted load [tons]	Configuration visualization
SP-2T	4 blades in cage	1007	1339	5	216	88.0 (nacelle with hub)	
BE-2T	Transverse	969.1	535.6	2	144	101 (BE pre-assembly)	
ROT-2T	Inside-pointed	325.8	267.8	1		83.6 (upper tower element)	

Figure 4. Exemplary transportation possibilities for OWEZ wind farm case study.

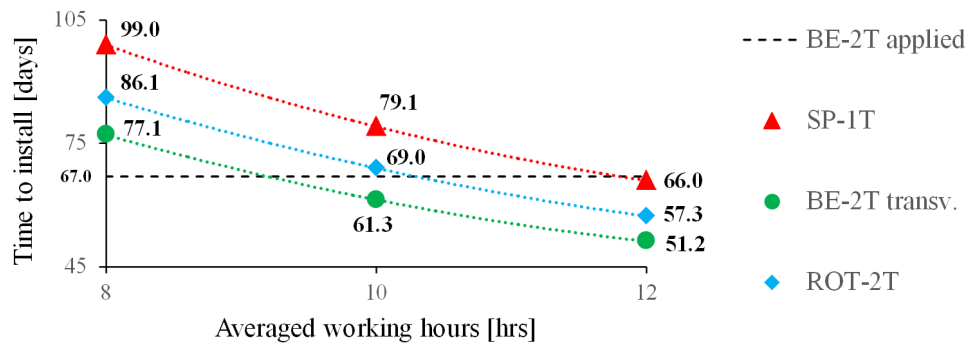


Figure 5. Sensitivity study on the average working hours per day, exemplarily for the OWEZ wind farm case study.

In regard to Thanet wind farm, installed as a SP-1T configuration by the MPI Resolution jack-up vessel [15, 18], it emerged that, although pre-assembly configurations could have reduced the installation time by approximately a month, the highest criticality for lifted weight remains with the tower. As the transportation of the tower in a single piece is generally preferred, the tower is indeed usually the heaviest component, and thus presents the greatest lifting hazard. However, due to vessel limitations, transporting the tower in two sections is increasingly required for larger turbines. This may be more cost effective than designing and building specialised “ad hoc” vessels. Subsequently, the following technologies and concepts for transportation and installation are focussed on the tower assembly.

3. Concepts for connections during installation and seafastening during transport

Connections play an important role in offshore wind turbine installation: for the final connection of single lifted pieces, but also for seafastening the turbine components on the transportation vessel. Ring-flange connections are most common for the major components of an offshore wind turbine. Typically more than 120 high-strength, pre-stressed bolts of large sizes (around M64 or M72 [20]) are used at each flange connection. Mostly, the bolts are already positioned on the wind turbine elements, which saves the labour of manually placing the bolts in the holes. Still, every single bolt needs to be tightened accurately, requiring special equipment such as hydraulic bolt tensioners.

An extensive review has been done on new connection and seafastening methods and designs. Innovative connection solutions include concepts based on friction [21] or the recently developed technology BLUE Wedge [22]. Besides the latter technology, which can also be used for seafastening, hydraulic systems and an internal jack system are proposed as seafastening solutions [23]. Staying with the traditional bolted flange connection, auxiliary systems for accurately tightening the bolts are required to ensure that no failure or hazard occurs due to loose bolts. Automated bolting systems exist [24, 25]; however, in the case of offshore wind turbine installation, the robot has to get on site and up the turbine as well.

The greatest possibility for improvement was found to be in enhanced seafastening methods, particularly regarding tower sections. Hydraulic seafastening would offer both safer and quicker seafastening, and thus increase the weather window compared to the conventional method of manual bolting. In addition, a robot arm employment for automated seafastening bolting is suggested (figure 6), which would retain the reliability of manual bolting while still reducing the risk and increasing the speed. However, the technology and logistical complexity set this study at a preliminary analysis phase.

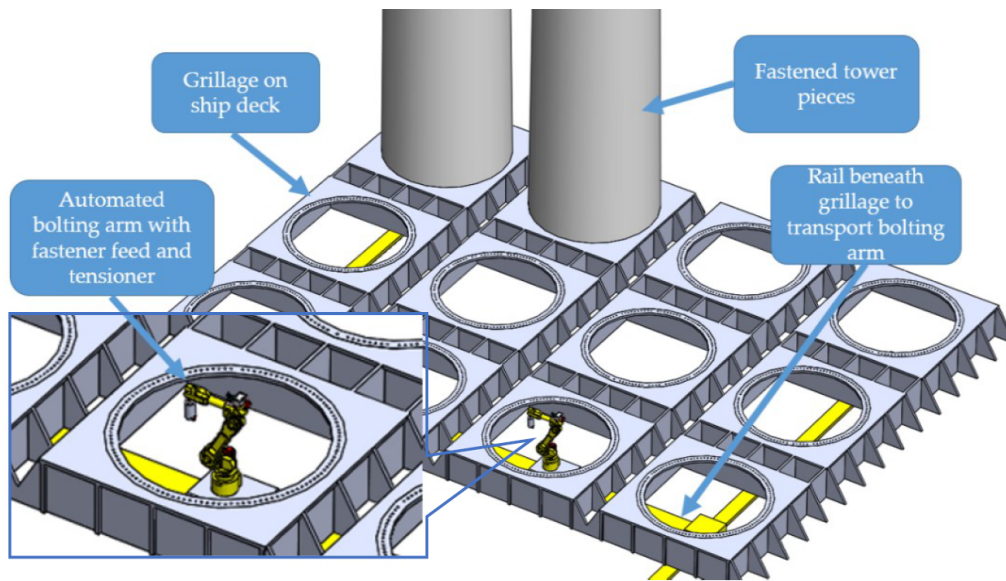


Figure 6. Automated bolted seafastening, concept illustration [14].

4. Concepts for guidance and control auxiliaries for lifting and installation

Guidance and control equipment for global hoisting, the mostly vertical lift from the ground to the aimed level, are already widely employed in lifting operations for wind turbine installations. Large movements during lifting are controlled via taglines. Developed systems, as presented in figure 7, are the Boom Lock [26], the Tagline Master [27], which can be controlled remotely, and the Blade Dragon [28], a remote controlled blade yoke.

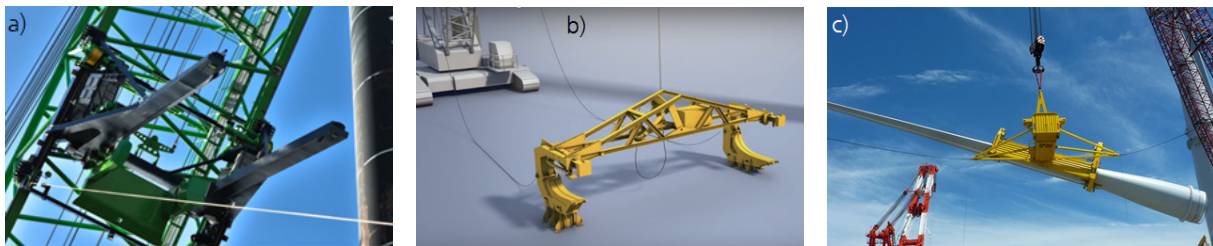


Figure 7. Global hoisting systems: (a) Boom Lock [26], (b) Tagline Master [27], (c) Blade Dragon [28].

When bringing the load close to the counterpart, correct positioning for the final installation has to be ensured. Thus, auxiliaries for centring and rotational alignment are required. Guide pins (figure 8a) or guide rods with corresponding socket sections help to align bolts and bolt holes, whilst cones or funnels (figure 8b) center the lifted section with respect to the counterpart. The latter method has already been used for a human-free met mast installation [29], but it is quite limited in size. Guide pins on the other hand are commonly used for installation of wind turbine elements; however, as it can clearly be seen in figure 8a, people are still directly involved in the lifting procedure.

To remove personnel from beneath the payload, innovative solutions, such as camera systems together with novel mechanical guidance designs for rotational alignment and centralisation, are



Figure 8. Current use of fine hoisting systems: (a) Guide pins [30], (b) Guiding funnel [29].

required. In this study, simplified small-scale tests were performed to quantify changes in accuracy, operability, and time when banksmen were moved from beneath the payload and visual and/or mechanical guiding elements were employed instead. Thus, three results were of interest: time taken for the lift, centrality, and rotational alignment.

The experiments were performed with a cylindrical steel section of 1.314 m outer diameter, 0.022 m wall thickness, and 0.55 m height. This was lifted by means of a standard gantry crane with three axes of movement and a freely rotating boom. Each lift started at the same position, 3.05 m from the target destination - a cylinder cross section drawn on the ground, with markings for bolt locations -, with the same crane operator standing behind a screen and listening for instructions from a banksman. Each test was performed five times and two banksmen alternated instructing the lifts for a more meaningful average result.

Visual guidance was tested for two types of camera - standard cameras (Swann 650TVL CCTV with night vision and 55° field of vision) and a 360-degree camera (Samsung gear-360) - in four different configurations:

- (i) three standard cameras equally distributed on the circumference of the lifted cylinder section;
- (ii) three standard cameras as in (i) and a fourth attached to the top of the lifting chains;
- (iii) one 360-degree camera located in the middle of the target position, as shown in the two videos [31, 32];
- (iv) three standard cameras as in (i) combined with the 360-degree camera as in (iii) (figure 9a).

For mechanical guidance, a holistic design was developed, bringing together the technical ideas of existing guiding systems, such as cones for centralisation or guide pins and socket sections for rotational alignment. This mechanical guiding element is removable and reusable as it consists of two parts: a guide rod attached to the lifted part and paired with a socket section within a conical extension attached to the fixed section, as visualized in figure 9b. Three guiding element pairs, equally distributed on the circular flanges, were considered to be sufficient. Adding threads to three sets of two or three bolt holes, the guiding elements can directly be screwed to the top and bottom turbine sections, respectively. After each lift, the elements can be removed again and reused for another lift. The experiments were performed with a simplified model of the mechanical guiding system design, as shown in figure 9c and video [33].

The first experiments focused only on centralisation of the lifted section on top of the (drawn) bottom cylinder with the help of cameras, while the second test campaign focused on centrali-

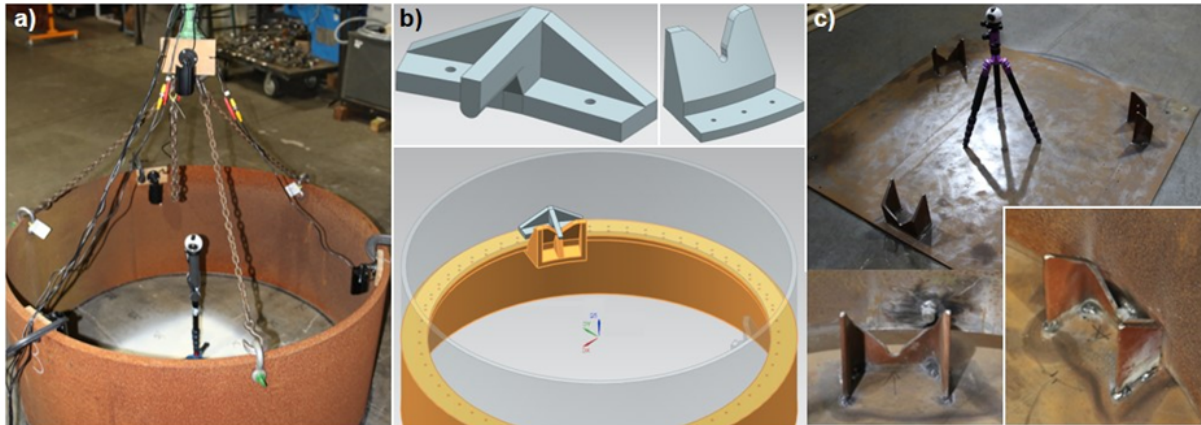


Figure 9. (a) Cameras for visual guidance, (b) Holistic mechanical guiding system, (c) Visual and mechanical guidance experiment setup.

sation as well as correct rotational positioning, firstly using the best camera setup found from the first set of experiments, then utilizing in addition the mechanical guiding system as shown in figure 9c.

The results are shown in table 1, representing the accuracy with respect to centralisation and rotational alignment, as well as the time taken, including a comparison to manual handling (with banksmen under the load). The first test campaign showed that with the combined setup (case iv) of three circumferential standard cameras and one central 360-degree camera the least eccentricity could be achieved. However, considering the additional criterion of rotational positioning happens at the expense of time and accuracy. Bringing together visual and mechanical guiding systems speeds up the lifting process enormously, while at the same time yielding a perfect fit. The best camera setup (case iv) allows rough and fast positioning of the lifted element above the target position, while the mechanical guiding system automatically positions the two pieces perfectly above each other as soon as the guide rod and bottom guiding element come in to contact (figure 9c).

Table 1. Comparison of the average results for all the configurations tested.

Configuration tested	Time taken [s]	Centralisation error [mm]	Rotation error [deg]
<i>Centralisation only</i>			
Banksmen under load	175.6	4.4	
Case (i): 3 cameras	551.2	15.6	
Case (ii): 4 cameras	496.0	5.2	
Case (iii): 360° camera	349.4	9.0	
Case (iv): 3+360° camera	391.0	4.2	
<i>Centralisation and rotational alignment</i>			
Banksmen under load	225.6	7.8	0.48
Case (iv) (3+360° camera)	498.4	4.9	1.36
Case (iv) + mech. guidance	202.0	0.0	0.00

Although, one has to keep in mind the time for connecting and removing the guiding element, the manually guided lift would take much longer than stated in the experiment, as it would have to be performed as slow enough to eliminate any eccentricity and rotational misalignment with the help of guiding hands. Therefore, the use of cameras in combination with the developed mechanical guiding elements could speed up an offshore lifting process by a factor of two, based on not too optimistic estimations, without posing risk to any person.

The wind turbine installation time can be related to the corresponding costs, which make up around 2% of the total offshore wind farm installation cost, based on information from Offshore Design Engineering Limited [34] for an offshore wind farm with around £1.6M/MW installed. Assuming that performing the lifts makes up just 20% of the total time for the wind turbine installation due to the long travelling distances, it can be estimated that lifting operations account for 0.4% of the capital expenditure for an offshore wind farm. Depending on conditions and size of a specific wind farm, it can be expected that the fabrication costs of the reusable mechanical guiding elements, as well as the acquisition costs for the cameras will at least pay for itself and may even enhance economic gains during the installation of one offshore wind farm.

5. Conclusion

The present work provides feasible solutions for human-free offshore lifting operations. Guidance and control systems, automated bolting or hydraulic seafastening, as well as a tool for optimised planning of offshore wind turbine logistics and installation, can help to remove people from beneath loads and thus contribute to increased safety in offshore lifting operations. In particular:

- The developed program for installation logistics outlines advantages and possible sensitivities of different installation procedures.
- A novel, although preliminary, concept for seafastening has been suggested.
- Supplementing existing tools, such as Boom Lock and taglines, by a holistic solution for visual and mechanical guidance, consisting of three circumferential cameras and one 360-degree camera, as well as innovative reusable guiding elements, can lead to faster and highly accurate offshore lifting procedures without putting personnel in dangerous areas. This will not only speed up the lifting operation itself, but is also expected to entail financial benefit in offshore wind farm installation.

Regardless of the additional economic benefit, cameras and mechanical guiding elements are easy to implement and would crucially reduce the number of incidents during installation work by removing people from the high-risk areas. Increased safety and protection of life should be of highest priority.

Acknowledgments

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