Automatic 3D design tool for fitted spools in shipbuilding industry

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Synopsis

The objective of this paper is to show the initial research results obtained with an automatic 3D design software tool we have developed for spool fitting in the pipe workshop of the Navantia Ferrol shipyard. This software tool requires, as input, a CAD file containing the scene with the two pipes to connect, and provides, as output, a CAD file with the fitted spool design. The software detects the features of the spool, and a heuristic pipe routing algorithm generates the output by computing several routes and providing one solution that is near to the optimal one. This output design considers the characteristics and capacities of the manufacturing process, as well as the library of materials used in the shipyard, so it is possible to use it for direct manufacturing. The preliminary results presented here were obtained using real data captured with different commercial 3D scanners over a test setup.

Keywords: Automatic design; Pipe routing; 3D scanning; Spool fitting; Marine systems

1. Introduction

Pipe assembly is a process that is carried out in different stages throughout the construction of a ship. This task is part of the outfitting of products such as the module, sub-block or block. The connections between pipes belonging to different constructive and/or functional elements such as the block, module and equipment, are made through fitted spools.

A main function of the spool is to absorb deviations between the connecting pipes. Therefore, it is necessary to have margin distance between both ends of the pipes to be joined, which depends on the diameter of such pipes, as shown in Figure 1. On the other hand, there are cases in which the use of spools is not due to deviations derived from the assembly, but the original arrangement of the pipes implies their use. This is the case, for example, of the pipe joint with perpendicular axes, as illustrated in Figure 2.

Spool design and fitting must be carried out on board, when all the structural and complementary elements are installed, taking measurements directly from the pipes already placed in their final disposal. This measurement process is not a simple task and, in many cases, it does not even allow to obtain enough data to guarantee a complete design of the spool. Moreover, the measurement must be carried out by experienced operators, because it must be determined which is the best solution from a constructive point of view, limited by the specific regulation applicable in each case.

As a consequence of the complexity in the measurement process, it is usually required to perform later on-site checks in any of the stages of the spool manufacture. Therefore, after the initial measurement stage, the pipe is manufactured in the workshop, and then it is tested in the ship to carry out the necessary on-site verifications in order to finally finish its manufacture in the workshop again. This pipe transfer workshop-ship-workshop is not a minor problem due to the dimensions of some of the pipes, implying a high time consumption.

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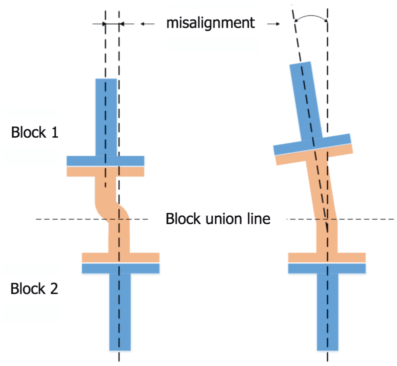


Figure 1. Examples of misalignments: a misalignment due to a non-concentricity of the axes of the pipes to be joined (left pipe), and a misalignment with an angular deviation (right pipe).

Figure 2. Two pipes with non-confronted disposition.

As can be seen, spool fitting is a time-consuming process, which implies a substantial delay and cost in the ship construction. In the Navantia Ferrol shipyard (Navantia, 2018), the amount of fitted spools is around 11% of the total number of pipes in a typical ship construction. Consequently, from the Mixed Research Unit UDC-Navantia (UMI, 2018), we decided to research and test a new solution to improve the spool fitting process in a more agile and efficient way. The presentation of this solution and the preliminary results obtained with it is the main objective of the current paper.

The proposed solution is focused in the development of a 3D design software tool that automates the spool fitting process, and which operation is summarized in Figure 3. This tool requires, as input, a CAD file containing the scene with the two extreme pipes to connect, and provides, as output, a CAD file with the spool design. The input CAD file is obtained through a 3D scanning process that captures the real dimensions of the pipes to join once they are mounted in the ship. Such remote scanning is a key aspect in the overall improvement of the process, because it significantly reduces the time required for the on-board measurements. Once the polygonal mesh of the pipe scene is created, the software detects the features of the spool, and a pipe routing heuristic algorithm generates the output by computing several routes, and providing a solution that is reasonably near to the optimal one. This output design considers the characteristics and capacities of the manufacturing process.

The remaining of the paper is structured as follows. First of all, the basic nomenclature used in this work is described. Next, the 3D scanner analysis stage that has been developed in parallel with the software tool development is described, and preliminary conclusions in this issue are presented. Then, a summary of the previous approaches to pipe routing is presented. Next, the core section of the paper is focused on the details of the 3D

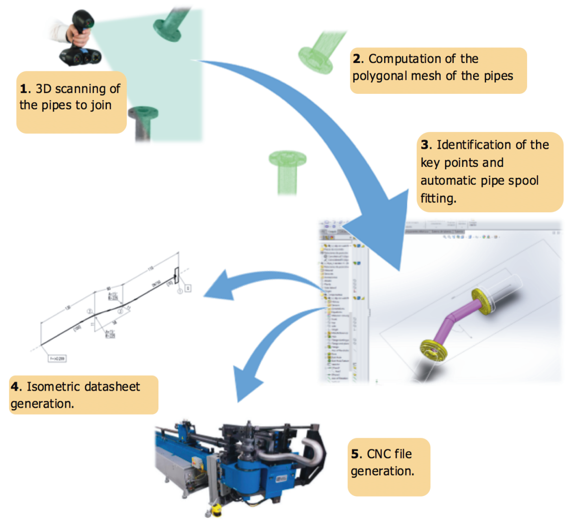


Figure 3. Schematic representation of the five steps involved in the spool fitting tool.

Figure 4. Mock-up installation where the empirical comparison of the 3D scanners was performed.

design software tool, and the initial results that have been obtained using it. Finally, some conclusions and future work are commented.

2. Nomenclature

Fitted spool: it is a pipe that is designed to absorb possible assembly deviations between two fixed elements, specifically:

- Joint between blocks.
- Joint between pipe and equipment.
- Joint between flexible connections to equipment and pipes.
- Joint between block pipe and module pipe.

The main features of the fitted spool are the following:

- *Length*: it must be of long enough to absorb the deviations caused by the assembly.
- *Weight*: it should be transported, handled and installed easily by a human operator.
- *Joint connections*: they must be compatible with the system to which the pipe belongs. It can be welded, flanged or joined with mechanical connectors.
- *Free space for the block assembly*: the space reserved for the installation of the spool must be sufficient so that the blocks can be joined together and welded.
- *Material*: in the spool design, the materials that make up the theoretical project must be respected.
- *Bend*: in some cases, the inclusion of bend accessories (elbows) is required to change the joint direction.

3. Scanner selection process

As it can be supposed, the automation of the fitted spools is highly dependent on the accuracy of the input data. It is a key aspect for the routing algorithm in order to achieve an optimal solution and, furthermore, for the creation of the output CAD that will contain the design of the pipe to be manufactured. Consequently, in parallel with the development of the 3D design tool, we have performed a detailed analysis of several scanning technologies and commercial systems that fit into this project in terms of usability and quality.

As first approach, a tracer scanner was used to develop a set of preliminary tests. Tracer scanners are not affected by illumination, which is a drawback for existing portable remote solutions. However, it is not a totally portable system and is not practical to transport and use on board. In addition, its considerable dimensions and the operating way (articulated arm) means that there may be places where the sensor does not reach the points to be measured.

Thus, to select the most appropriate scanner for this application, an empirical study and comparison of commercial solutions, based on different capturing techniques, was performed. Thus far, five commercial systems based on the following technologies have been compared:

- Structured light.
- 3D laser triangulation.

- LIDAR.
- Photogrammetry.

The comparison was based on a decision matrix that allows gathering all the information that is considered of interest. Some of the selected fields have been covered by consulting the data sheets or websites of the manufacturers. Others have been empirically obtained through the comparison of the point cloud files obtained with the scanners, and a reference CAD obtained with the tracer scanner. This comparison was carried out by scanning a mock-up installation, that is displayed in Figure 4.

The decision matrix was based on the following features:

1. Noise level.
2. Primitive adjustment (compared with tracer).
3. Edge resolution.
4. Distance based resolution.
5. Point size.
6. Resolution.
7. Point accuracy.
8. Working conditions within operating ranges.
9. Working in poorly illuminated environments.
10. USB connection.
11. Artificial marker requirement.
12. Laser technology.
13. Capture processing time.
14. Capture time.
15. Scanning area.
16. Handling complexity.
17. Weight.
18. Dimensions.
19. Endurance.
20. Autonomy (battery).
21. Dependence on external units (e.g. PC).
22. Associated applications for post-processing.
23. Price.

With the aim of quantifying the deviations suffered by the point clouds or meshes obtained against the reference model, that is, to verify the accuracy of the capture, there are some additional critical points to analyse:

- Co-planarity of the faces of the flanges.
- Co-axiality of the flange centres.
- Degree of rotation of the holes in the flange.

The methodology used for the comparison was the following:

1. The mock-up displayed in Figure 4 was scanned with each of the five scanners and technologies.
2. The obtained point cloud file of each of them was imported in three different post-processing software tools: PolyWorks, 3D Reshaper and GOM Inspect.
3. The reference CAD obtained with the tracer was imported too into these tools.
4. Permissible tolerances were ± 2 mm for distances and ±1° for angles.
5. Alignment by Best-Fit from object to reference was performed.
6. Generation of the ColorMap and first approach to visual inspection was carried out.
7. Isometric presentation from two points of view of the mock-up was created, in which general deviations can be observed. The tolerance range for the visualization was ±4 mm.
8. Flange surface geometry control: several control points were defined on the reference CAD. The objective was to have a first approximation to the flange co-planarity.
9. Creation of geometrical entities: flange plane, flange cylinder, central point of flange (intersection between the two previous entities), drill cylinders (four holes are chosen, one every 90º), centre points of holes (intersection between plane flange and hole cylinder) and vector / connecting line between flange centre and hole centre.
10. Creation of transverse and longitudinal cutting planes to the chosen flanges.
11. Bridle cylinder geometry and centre point flange controls. The objective was to know the flange centre deflection.

12. Normal flange face vector geometry control. The objective was to know the deviation in the co-planarity between data file and reference file.
13. Deviations (general and hole centres) in superficial cross-section flange. The objective was to know the deviation.

It is out of the scope of this work to show the detailed results of this comparison and, in addition, the analysis is still under development because new solutions are being studied. Nevertheless, we can conclude, in a preliminary way, that, using the most recent scanning systems, the critical aspects are more related with the usability in the work environment than with technical aspects, such as resolution or accuracy. The most relevant here is that this methodology has shown to be successful to compare the hardware, so now the selection process is much simpler.

4. Previous approaches to pipe routing

We can define pipe routing as the design of a route between one or several pairs of pipes to be connected, avoiding obstacles. The problem of finding the route between two pipes, can be formulated as the search for the shortest path between their ends. However, finding the shortest route is not sufficient in most cases, since the route must comply with restrictions and constructive requirements that must be taken into account. Several existing approaches to this problem have been analysed, both those carried out by the scientific community and the existing commercial software.

4.1. Scientific approaches

A first classification can be performed from the point of view of the problem complexity. Thus, there are studies focused on the simple optimization of the pipe route, others on the optimization of more complex pipe routes with branches and, finally, some focused on the optimization of routes in a set of interfering pipes.

Starting from the simplest case, there is a basic restriction that must be fulfilled in the route design, even in the simplest scenario, which is to avoid collisions with the obstacles in the path, including other pipes. In addition to this basic restriction, some more are typically considered (Shin-Hyung et al., 2013): physical, economic, security, constructive, maintenance, etc. In the case of pipes with branches, the problem of obtaining the route between two points is extended to several points. The number of references that has dealt with this specific case is reduced, but some of them must be highlighted, like (Haiteng and Wentie, 2016). Finally, the most general case is the optimization of multiple pipes, considering the interferences between different routes in the optimal design. Obviously, this is the most complex case, which is still under development, although some promising solutions have been presented (Ando and Kimura, 2013).

From a computational perspective, a classification can be made in two large groups of solutions: deterministic algorithms and heuristic algorithms. In the case of deterministic algorithms, the existing approaches are mainly based on graph theory, in which one of the fundamental tasks consists of visiting the vertices and edges of the graph until finding the shortest path (Ando and Kimura, 2011). The same authors, in (Ando and Kimura, 2013), apply again the graph theory to propose an optimization system for a set of pipes. Another example of graph theory approach is found in (Dong-Myung et al. 2013), where authors propose a system for optimizing the pipes of a machine room. In (Shin-Hyung et al., 2013), they apply a slightly different approach to expand the route through a graph plotted from the 3D mesh that represents the search space.

Regarding the heuristic approaches, some successful approximations based on genetic algorithms must be remarked such as (Changtao et al., 2015) for simple routing, or (Haiteng and Wentie, 2016) for routes with branches. Other type of heuristic algorithms is the one based on ant colony optimization (ACO). In this sense, (Wen-Ying Jiang et al., 2015) uses an improved ACO algorithm for the optimization of pipe routing with branches. The problem is divided into several simple pipeline optimization problems that are represented by different populations. In (Xiaoning et al., 2006), an ACO algorithm outperforms a genetic approach in a set of test cases with restrictions. Regarding routing problems with ramifications, in (Yanfeng et al., 2016) a graph is constructed to define the 3D model, and from it an ACO approach is applied to find the optimal routes. An application case for a more complex problem is that of (Wen-Ying Jiang et al., 2015), where an automatic routing system is proposed that takes into account ramifications.

Finally, an approach based on particle swarm optimization (PSO) must be commented (Changtao et al. 2016). The authors focus their attention in the geometric model of the pipeline. The proposed algorithm offers successful results, both in simple and complex scenarios with multiple obstacles.

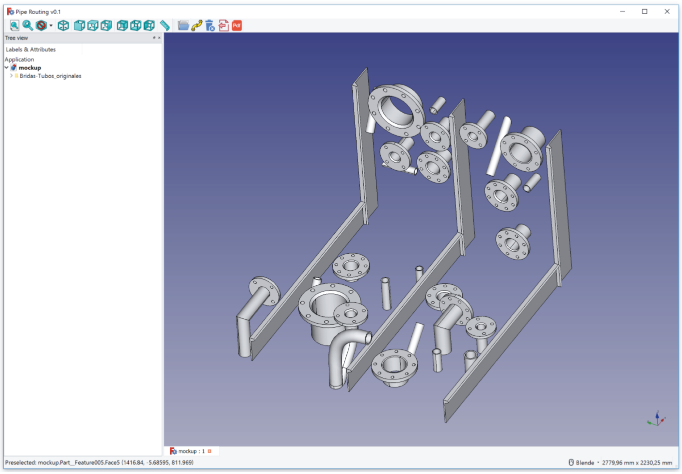


Figure 5. Screen capture of the developed software tool, showing a 3D model of the experimental set up used in this work.

4.2. Commercial solutions

Most CAD design solutions include some type of module or complement dedicated to the assistance in the pipe routing. We must point out FORAN (Foran, 2018), CATIA and its Piping & Tubing module (Catia, 2018), Solid Works and its supplements Solid Plant and Smap3D Plant Design (Solid, 2018), the CADPIPE environment based on Autocad (Cadpipe, 2018) or the Pipe Routing of Microstation (Microstation, 2018).

All of them provide assistance systems for pipe design based on similar premises. Specifically, starting from a previous manual design and allowing the user to generate semi-automatically new pipes between two points, these tools are able to take into account certain restrictions or rules defined by the user a priori (for example, minimum or maximum radius of curvature or maximum length of a single tube). However, in a real case, it is necessary to evaluate a large number of parameters in real time, including the fact that the need to modify other closure pipes could be generated as a consequence of the design of a new one. This means that the solutions provided by these CAD systems are only partial.

Moreover, one important aspect for a shipyard it to be able to include their specific pipe database and manufacturing standards in the design tool. As a consequence, the development of a new tool was clearly justified.

5. 3D design tool

The main interest of the shipyard for this design tool was that the provided solution was directly transferable to the workshop, so the pipe could be manufactured and tested in real scenarios. Consequently, we decided to design the application in a layered configuration, so an incremental development methodology could be used. Thus, in a first approach, we have not considered interferences with other elements or multiple pipes. Thus, the software could be tested in simple situations, but quite common in the ship construction, focusing the attention in the manufacturability. Once the reliability of the tool has been tested in such real cases, in later phases the design of multiple closing tubes and the detection of interferences between them will be added.

The developed algorithm explores the possible variations of pipe routes between the two ends, complying with the restrictions imposed by the shipyard. It generates routes in a graph between a source and destination node and, based on a set of restrictions, it selects one of the best routes, which represents a pipe that provides a solution close to the optimal. Also, the implemented algorithm seeks a compromise between searching for an optimal solution and the resolution of the problem in a reasonable computation time (few seconds).

In more detail, the current algorithm is based on the following design criteria:

- The 3D layout space is discretized into grid of cells, currently using steps of 5 mm. (the value is configurable). We found that this is a reasonable value, that provides a good balance between the accuracy of the design and the computation time.
- The problem of finding a valid route for the tube is reduced to scenarios with a maximum of three curves. This is a reasonable assumption in the spool pipe fitting problem.

- In order to speed up the pipe path searching, the algorithm only needs to explore a reduced amount of cells. Specifically, on every step, the algorithm gives priority to straight paths that contribute to reduce the number of necessary bends to reach the end of the pipe. Also, the algorithm tries to follow, first, the normal vector of the both ends (a maximum of 3 degrees of deviation tolerance is allowed due to the possibility of absorb this deviation with the end joints).
- The pipe routing algorithm should minimize the fabrication costs among the set of feasible solutions restricted by physical and operational constraints. Thus, we use a heuristic function that includes pipe length, number of bends, number of elbows, increaser/reducer connectors and physical restrictions due to the pipe bending machines.

Furthermore, the current version of the design tool incorporates some material restrictions, using a subset of the complete set of pipe materials typically used.

Within this set, compatible materials are selected for the different elements that make up the designed tube. Within the design restrictions, the bending constraints provided by the Pipe Workshop Head have been incorporated into the algorithm, considering the minimum lengths of the straight sections before and after the curves, and the minimum length between two curves, for the different diameters of pipe and curvature radius.

Moreover, a set of proposed priorities has been applied, prioritizing machine bending over commercial elbows and commercial elbows over cut commercial elbows. This last approach is used only in cases where any other solution is not applicable. The pipe length has also been considered as the result of the best route proposal among the candidate routes found by the algorithm.

The main technologies used for the development of the prototype have been the Python programming language and the FreeCAD 3D modeling software. Moreover, the Networkx Python package, for the creation and manipulation of complex networks, and the SVG format, for the creation of the isometric files of the spools, have been used too.

In order to validate this approach, we use a set of dozens of real scenarios, for which we have a design solution provided by pipe engineers. This set allowed us to compare the solutions provided by the tool with solutions from human designers. In these cases, the proposed algorithm always obtained a similar or better solution in terms of cost optimization and ease of construction. However, there are still some rare cases for which the tool is not able to provide a solution.

To illustrate the tool environment and basic operation, the experimental mock-up created in the Pipe Workshop, (see Figure 4), will be used. The CAD model of this mock-up was obtained with a tracer scanner and imported in the tool, as shown in Figure 5. It displays the initial screen of the tool, where it is shown the viewer that allows to move around the 3D mock-up in different ways. In the top part of the window, the software includes a button bar that allow to perform different actions over the model.

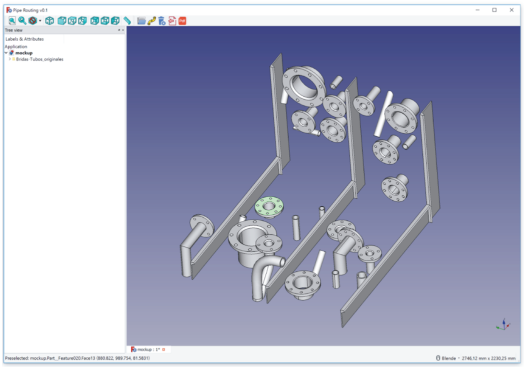
The fitted spools are carried out automatically between two ending pipes selected by the user. The objects that can be selected as ending pipes are the faces of the objects, specifically, in this mock-up should be the faces of the flanges and the ends of the pipes located in the mock-up that do not end in a flange. The process for designing the spool is described in Figure 6 and it works as follows:

1. Selection of the first pipe end by clicking it (Figure 6 (a)).
2. Selection of the second pipe end (Figure 6 (b)).
3. The software executes the routing algorithm, which provides a pipe design according to the restriction set defined (Figure 6 (c)).

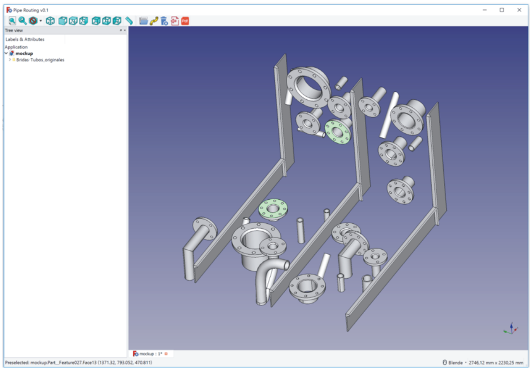
The spool displayed in Figure 6 has been generated between two ends that are flanges with the same diameter, and the resulting design (Figure 6 (c)) uses only machine bends. But the spools can be generated with other characteristics depending on the conditions of the ends:

- In cases where the necessary requirements are not met to include machine curves in the design, because the distance between the ends does not allow it, a pipe with commercial elbows would be generated. As a final option the solution could include commercial elbows cut off, if it is not possible to design the tube in another way (Figure 7 (a)).
- It is possible that the flanges of the pipe ends have different diameter, so it is necessary to add a reduction. In this approach, the reductions are always added in the pipe ends (Figure 7 (b)).
- It is also possible to design a spool without flanges at the ends, which is joined to other spools of equal (Figure 7 (c)) or different diameter (Figure 7 (d)). In the latter case, a reduction is added at the larger end.

Furthermore, the tool automatically generates an isometric view of the spool (Figure 8). Additionally, the software allows to export a modelled pipe in STP format, the most standard format in pipe design. Finally, this software automatically generates the CNC file of the spool according to the format used in two different examples of bending machines.



(a)



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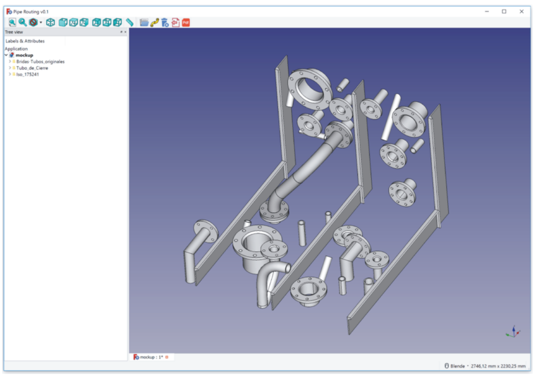
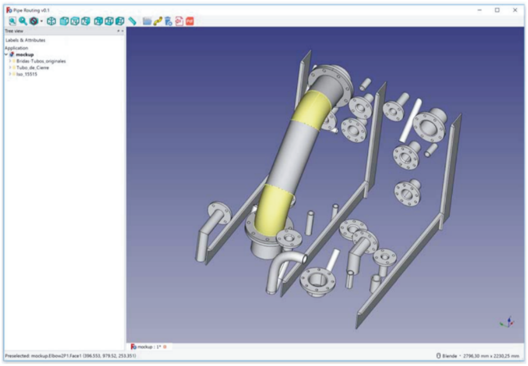
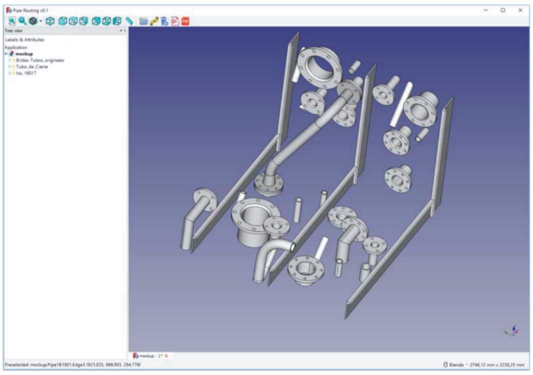


(c)

Figure 6. Step by step of the pipe design process.



(a)



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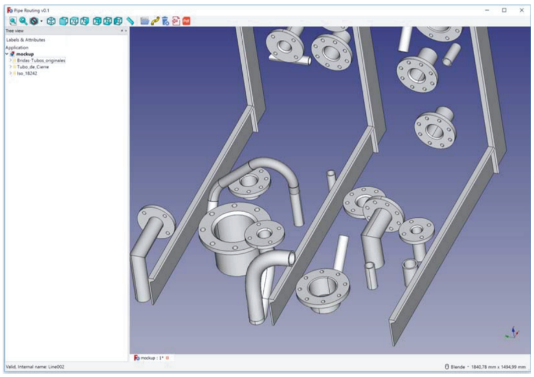
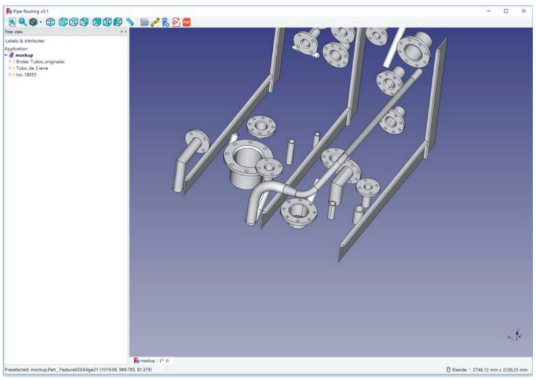


(c)



(d)

Figure 7. Different automatically generated solutions according to different conditions of the pipe ends.

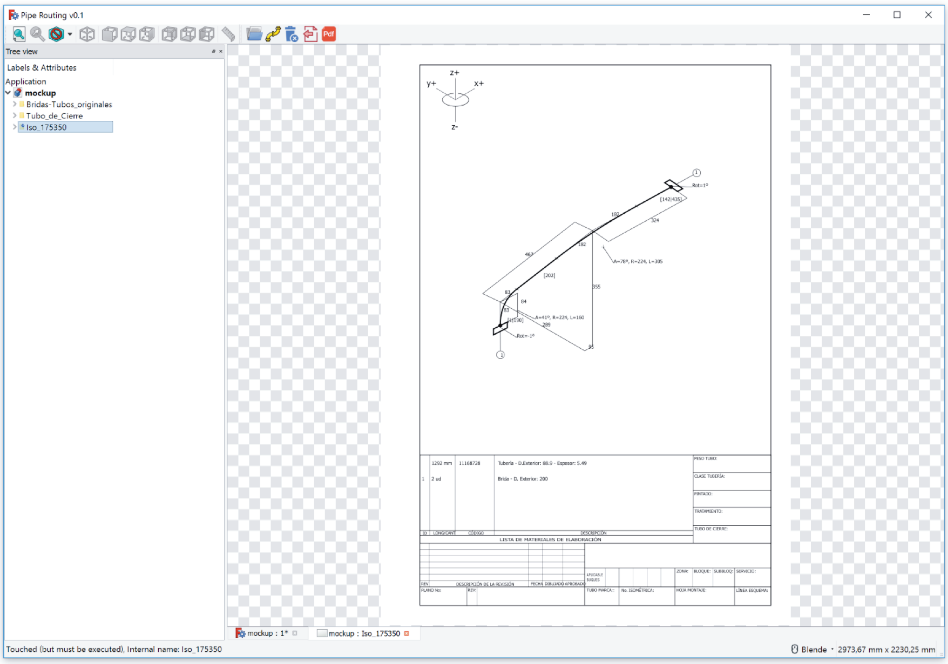


Figure 8. Example of isometric view generated by the software tool.

6. Conclusions and future work

The 3D design software tool that has been described above is a prototype version that illustrates the possibilities of automating the spool fitting process accordingly with a real shipyard requirements and restrictions. It has been tested in the mock-up shown in Figure 4 and all the possible combinations of ending pipes have been successfully solved, and what is more relevant, providing a CNC file that can be directly applied in commercial bending machines used in pipe workshops. That is, the pipes designed by the tool are completely usable and manufacturable, which was the main objective of this first stage of development.

However, at this stage, the software prototype presents a series of limitations that must be taken into account, and that may be overcome in future developments:

- The set of test scenarios must be increased to consider a larger and more exhaustive sample of different test cases.
- The algorithm performs an exploratory search for design solutions only in one direction of pipe advance. We plan to optimize it by performing the search starting from both ends.
- The current algorithm does not take into account interference with other pipes or other elements in the design of the fitted spools.
- The tool does not incorporate a complete database of materials that can be used in the design of closure tubes.

As commented above, the tool depends highly of the accuracy of the input CAD files, so the project must continue with more research effort for the selection of the optimal 3D scanner that provides enough resolution together with the necessary ease of use.

Apart from that, we plan to continue working to achieve the next level of functionality by applying genetic algorithms to pipe routing, introducing an evaluation function that combines the current set of constraints with a new one orientated to avoid physical obstacles and support routing for multipipes.

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