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PRODUCT DESIGN METHODOLOGIES FOR DEVELOPMENT OF LOW-COST ROBOTS

Frederico Allevato Ramalho Filho; fcnc05@gmail.com
Alexandre Queiroz Bracarense; bracarense@ufmg.br
Universidade Federal de Minas Gerais. DEMEC-GRSS; Av. Antônio Carlos 6627, Pampulha, Belo Horizonte, Minas Gerais, Brasil.

This paper proposes a different point of view and design methodology that can bring multiple benefits to the design of robots. The use of laminate object modeling (LOM) associated to welding allows the manufacturing of high complexity components with low cost even with small scale production. Design methodologies like design for manufacturing and assembly (DFMA) can be used to simplify the design and make it more adequate for manufacturing in metal plates and assembled with welding. In special applications, such as orbital welding robot, ultrasound scanning and part positioning, this methodology was used and the results are presented. The benefits of such design approach and the results are shown through robots presented in this paper.

***Keywords**: LOM, DFMA, Welding, Design Methodologies, Robotics.*

1. INTRODUCTION

Despite all the uncertainties that surround the design conception process, the characterization of common elements for any type of development can help to rationalize the creative cycle through a methodological plan. This methodology is an approximation, which captures the nature of the conception process and takes away the intuitional side and makes it more objective (Bonsiepe, 1978). This methodology should be extensive enough to adapt to any job, but still be useful for the project at hand.

The importance of having a design methodology was explained by Roozemburg and Eekels (1997): “One of the most important tasks of the design methodology is to indicate how design process should be arranged so that they nevertheless lead to a reliable, effective conclusions and are efficient as well”. Even if the use of a simple method does not bring great gains, but prevented large errors, the method has shown its use validated.

A methodology should give formalization to the procedures in the project and externalize the creative thinking (Cross, 1996). However, it is possible to expect the following advantages and trying to avoid the disadvantages described in Table 1.

Table 1: The advantages and disadvantages of using a methodology.

Advantages	Disadvantages
• Focus • Organization • Repeatability • Objectivity	• Increased workload • Bureaucracy • Internal resistance • Inhibition to creativity (in a few cases only)

The robot industry is in a developing stage, and its products still have a high degree of innovation and novelty. For the innovative products it is normal that the initial situation and the final project be ill defined, or should we say that it is an unstructured problem where the problem and the solution are not well understood.

“The difference between structured and unstructured projects, with the initial and final situations defined or not, in no way establishes the degree of difficulty of the project” (Bonsiepe, 1978). However the classification of the project determines the posture and the behavior of the designer, and it is important to identify the most adequate methodology.

The non structured projects have universal characteristics, and even if a large amount of data is available, to consider it non structured is a conservative attitude, since one should keep in mind the following characteristics compiled by Cross (1996):

- There is no definite solution for the problem. Temporary solution must be developed, but should be discarded every time new information is made available;
- Any solution may incorporate inconsistencies;
- The problem definition is based on the solution. The approach for the solution will influence how the problem is seen;
- Proposing solution is the best way to understand the problem;

- There is no definite solution for the problem. "Different solutions may be equally valid for the initial problem. There is no true or false basis to judge the solution, only good or bad, appropriate or not" (Cross, 1996).

The robotics field, mainly composed by non-structured problems, needs its own design methodology, so the project can be developed at the speed demanded by the market. For that, solutions have to be created rapidly, and should be verified at the same pace. According to Boothroyd and Dewthrust (1996), 80% of the design time is spent with 20% of the problems, so knowing all the problems involved is of the utmost importance. The reduction of lead time and cost without sacrificing quality is the objective.

Prototypes are considered very expensive and the actual trend in the industry is to eliminate them. But, if the prototyping could be made at extremely low cost, it is the fastest way to find out all the problems involved in the design. The robot industry is a flourishing technology field that creates new standards and technologies every day.

In this paper will be analyzed three case studies, and in each one a different result of the design conception optimization. The methodological tools will be presented next, followed by the results in each case study.

2. DESIGN METHODOLOGY

The design methodologies used, are tools to optimize a certain characteristic, on this specific case the assembly, manufacturing and rapid prototyping. Each methodology has to be applied on the presented order, so there will be no conflict. In sequence, the decision of the latter prevails over the first.

The design for manufacturing and assembly (DFMA) is a methodological tool created by Boothroyd and Dewthrust, for systematic analysis of different design solutions based on the assembly and manufacturability. Based on the experience acquired by these researchers, many different rules of good practices were developed, and it can be applied to any project with considerable gains. According to Boothroyd (1996), DFA has to be applied first, making the product structure simpler. After that, the best material and manufacturing process has to be chosen, along with geometry changes to better match these choices, and this is the design for manufacturing.

2.1. "Design for Assembly" (DFA)

The design for assembly is divided in two parts. The first are three simple rules that can be applied to any project. The second is the analysis of the assembling time for each component, and the workmanship needed, to decide which kind of assemble is viable and enhancing the design. This second part depends on high production scale.

The first rule of the design for assembling states that two parts can only exist separately if:

- There is movement between the two parts;
- The parts should be made of different materials (example: one part has to be electrically conductive and the other not);
- It has to be possible to take it apart (example: for maintenance or recycling reasons).

This small set of rules are very easy to learn, and has an enormous capacity to effectively simplify the project. In Figure 1 there is a classical example where the use of this set of rules simplified the design.

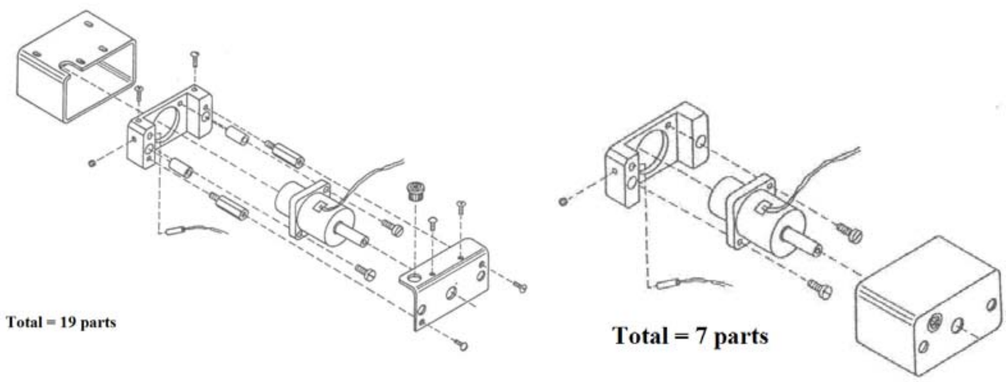

Figure 1: Classical example of DFA use (Boothroyd, 1996 – adapted).

The benefits are clear, but the impacts of these tools in prototypes are not well studied. It is possible to highlight the fewer part count, less fixtures, manufacturing steps, calculations, dimensioning and CAD models.

2.2. "Design For Manufacturing" (DFM)

The design for manufacturing is a methodological tool that will lower the manufacturing costs of a product without compromising quality. For each material chosen, there are only a few methods to manufacture it adequately. For each manufacture process, there is a set of rules that should be followed for optimum results. Beyond this set of rules, that acts only locally, piece by piece, some things have to be optimized globally, among others:

- Reducing the number of processes to manufacture the whole project;
- Minimizing the types of raw material;
- Lowering cost, developing and lead time, without compromise of quality.

For effective results with design for manufacturing applied to prototypes, each component cannot be optimized separately, since the number of parts manufactured is not enough to make the difference. But, when a manufacturing process is chosen and extended to most of the pieces in the assembly, even if it's not the most appropriate for one or other piece, there will be global advantages, due to simpler logistics and larger scale in the manufacturing process. This is the only way to give the benefits of manufacture scale to a prototype.

The shape is given by the design and simplified by the DFA. The final geometry is worked around these restrictions to match with the best way to manufacture with the chosen process. A classical example how the geometry can be changed to adapt manufacturing needs is shown in Figure 2.

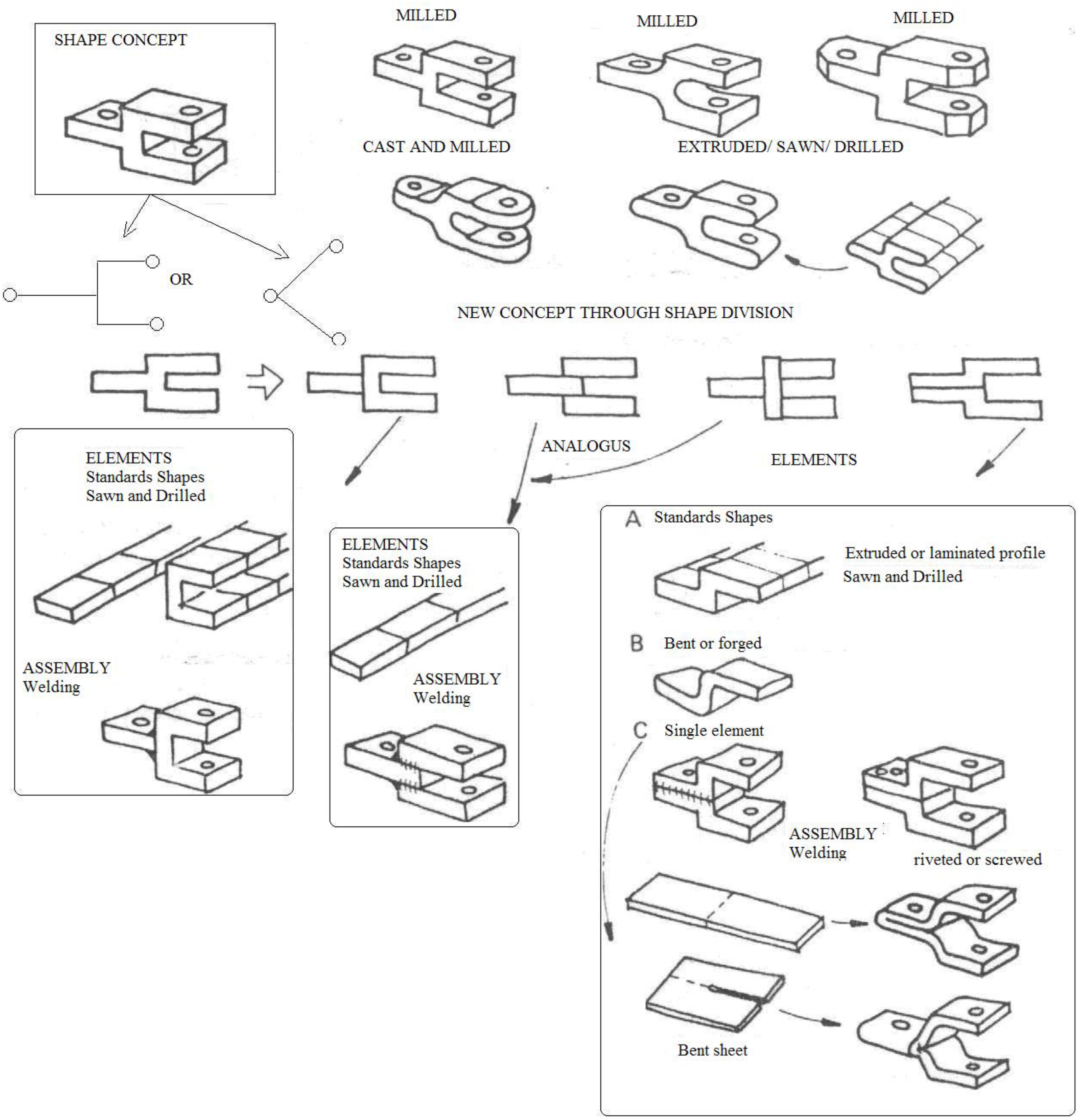

Figure 2: Example of design for manufacturing (Boothroyd, 1996 – adapted).

2.3. "Laminate Object Modeling" (LOM)

The laminate object modeling (LOM) is part of a set of techniques for rapid prototyping and manufacturing (RP/M), where prototypes or final products may be built directly from the data available at integrated CAD/CAM platform (Yoon, 2005). Among many kinds of LOM, most are RP techniques; with the LASER cutting of metal sheets and welding assemble the only one to do RM, delivering functional metallic parts of low cost and high complexity.

The LASER cutting of sheets is also capable of providing rapid tooling, but further processing with milling is necessary, and thus, not providing the final part for consumer use. But the example seen in Figure 3 serves as inspiration for a technique where no milling would be necessary if the needed chances are incorporated in the design methodology.

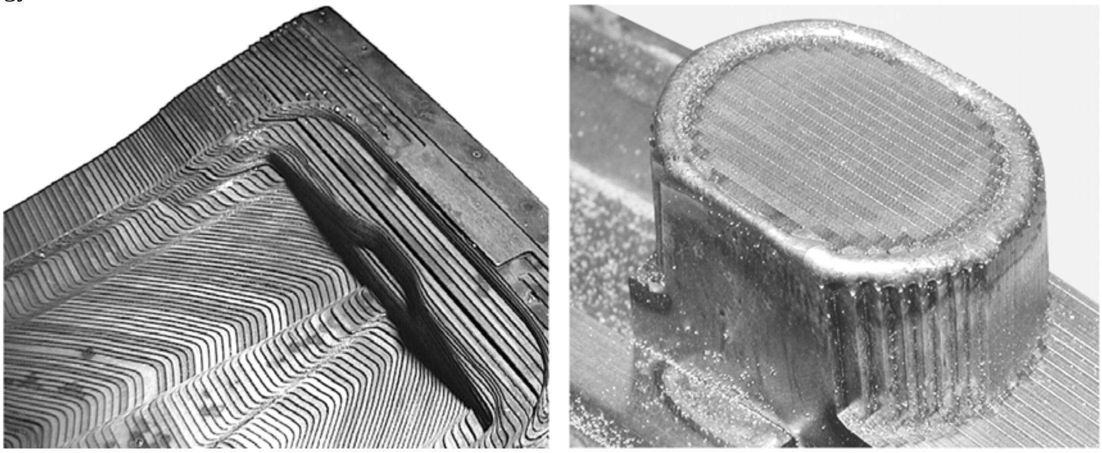

Figure 3: Metal laminated tooling (Himmer, 2004).

2.4. Material and Equipment

The LASER cutting is a technology in development and cost reduction phase, but already capable to manufacture parts at low cost as long they are designed to be cut from a sheet (2,5D). The orientation of the component in the steel plate has to be taken in account due to sheet anisotropy, caused by the lamination process. To be economically viable, cutting and welding have to be the only processes involved in the part manufacture.

To act in accordance with the rules of the DFM, using other manufacture methods, like turning and milling, was used only when there where no other options. The cut parts were welded with the GMAW process in the first and GTAW in the second prototype of case study A, and GTAW only on case studies B and C.

3. CASE STUDY A – ORBITAL WELDING ROBOT

The problem was to research, develop, build and operate a robot capable of autonomous welding of gas and oil pipes in a fast and reliable manner, and that could be use to any pipe size. Since it was a product that has never been developed in Brazil, there was no basis on the shape of the mechanism to accomplish the task. Also, no orbital welding robot already developed has four degrees of freedom, in order to mimic the movement of the welding torch handled by a human.

The costs could reach very high values if the product could not be designed and manufactured easily. Since it was a innovative product, many revisions and prototypes would be necessary until a satisfactory result. At the same time, a prototype with minimal working conditions should be provided for testing of the motion control electronics and welding qualification.

With this in mind, the first prototype was developed in three months. To lower the costs, half of the parts were LASER cut, but since some basic rules weren't observed at the time, the design had an excessive number of parts and most parts needed further cleaning, deburring and milling. The first version, shown in Figure 4, had nine modifications before it was exchanged for a new version better adapted to the task. This new version was totally redesigned based on the methodological tools described above and was divided in three parts: Torch manipulator, tube fixture and power train.

One of the first changes needed that was indicated by the DFA was the modularization, pointing that the torch manipulator, main component of the robot, with its motors scattered in the structure and too hard to reach for maintenance, and without the necessary movement. With a design so inefficient, this was the first part chosen to be redesigned. A new conception where the part is completely independent was necessary, and is shown in Figure 5.

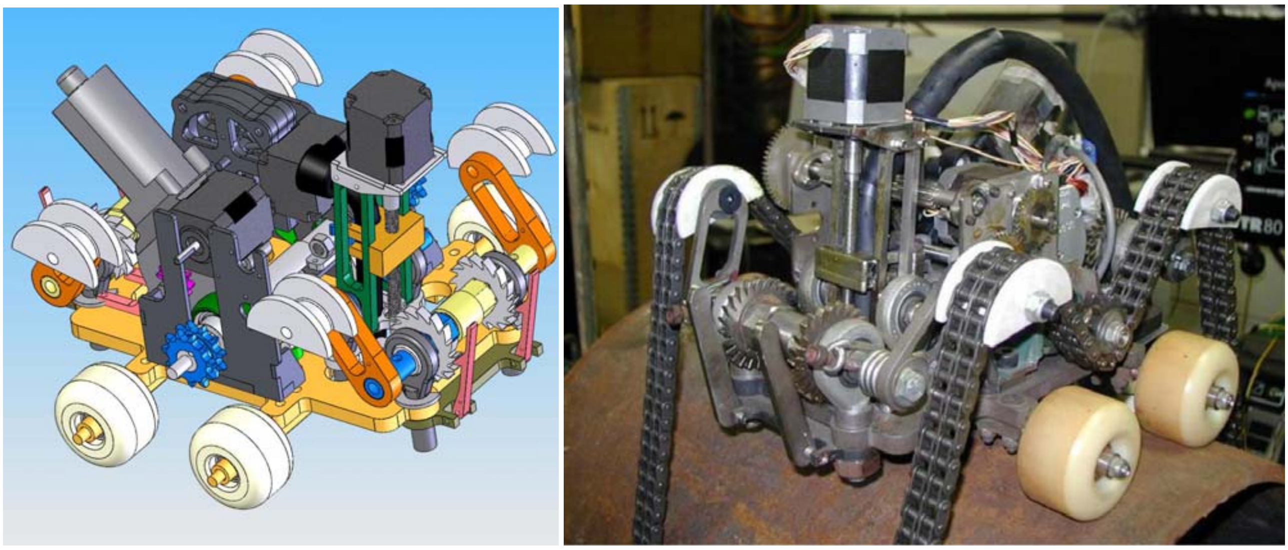

Figure 4: First design and prototype.

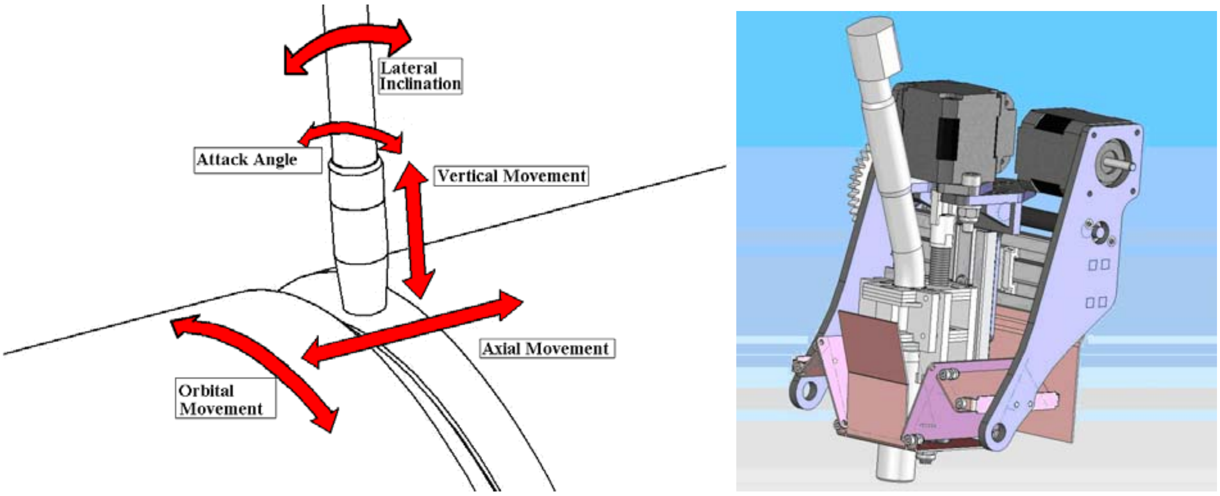

Figure 5: Possible degrees of freedom and torch modularization

The second change indicated was joining the different components fixtures in a single structure. In the first project, the main base was horizontal, and when new electrical and mechanical components were added, it was noticed that it was a mistake, since most of these has vertical mountings. A new vertical structure that had all the mountings, and also had functions as transmission and load bearing should be incorporated developed as soon as possible. Also, it should mate with the newly redesign torch manipulator. The results are shown in Figure 6, where the part count was reduced from 24 to 9 with better results, featuring more functions and a fraction of the cost.

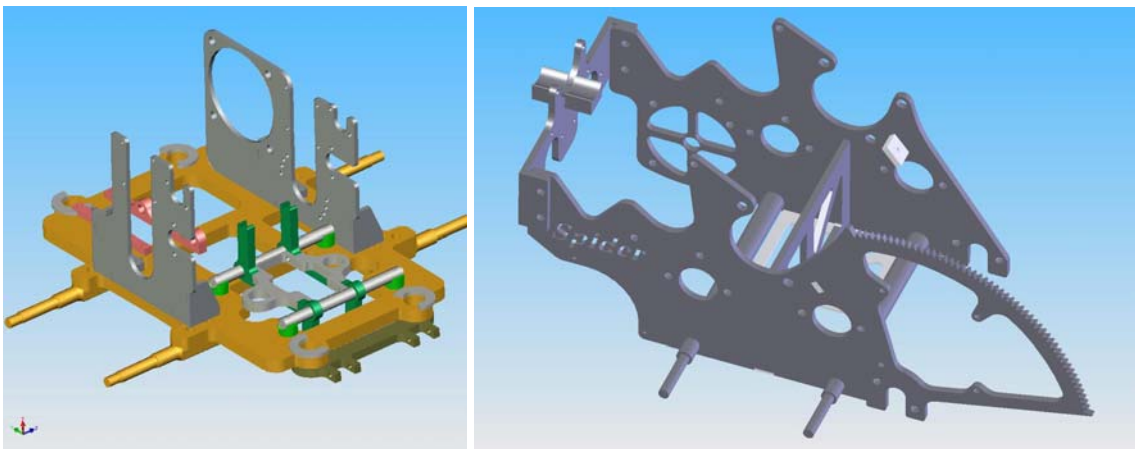

Figure 6: The original and the redesigned main structure.

With the mains structure altered, other simplifications like eliminate intermediary gearing and incorporate other transmission parts in structural parts were made, along with the elimination of milled and turned parts, as shown in Figure 7.

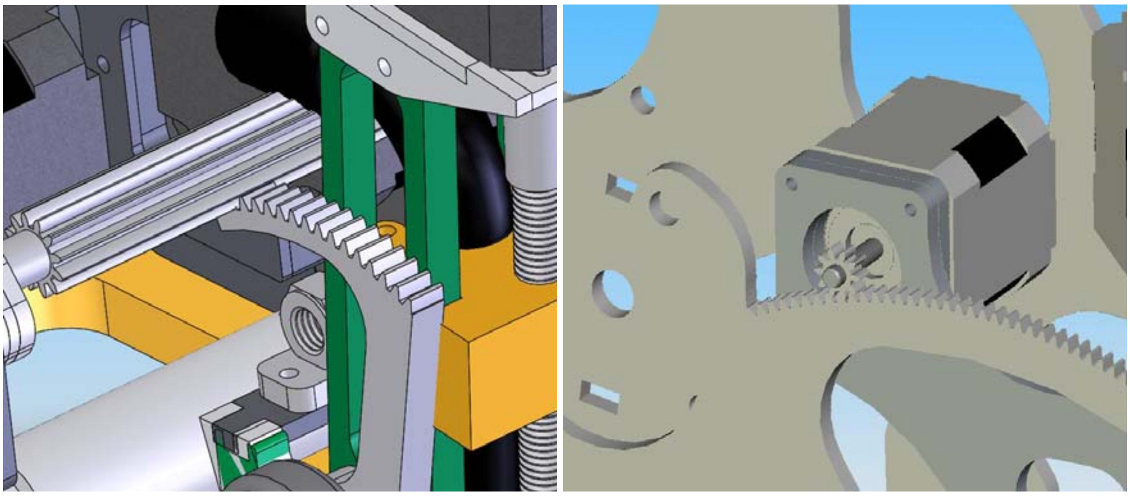

Figure 7: Intermediate gearing of the angular movement and the second version with direct drive.

With the main problems solved, attention were given to small parts that were hard to build, and that could be easily adapted to be LASER cut and weld through the DFM techniques. For example, a coupling made by three small tube parts that were sawn and weld, but it was very hard to attain the necessary tolerances between the tube centers, seen on Figure 8. To reproduce this three dimensional structure with the LASER, it was modeled in sheets to be joined in a self oriented structure, assembled vertically and welded with GMAW in the lateral chamfer developed for this reason.

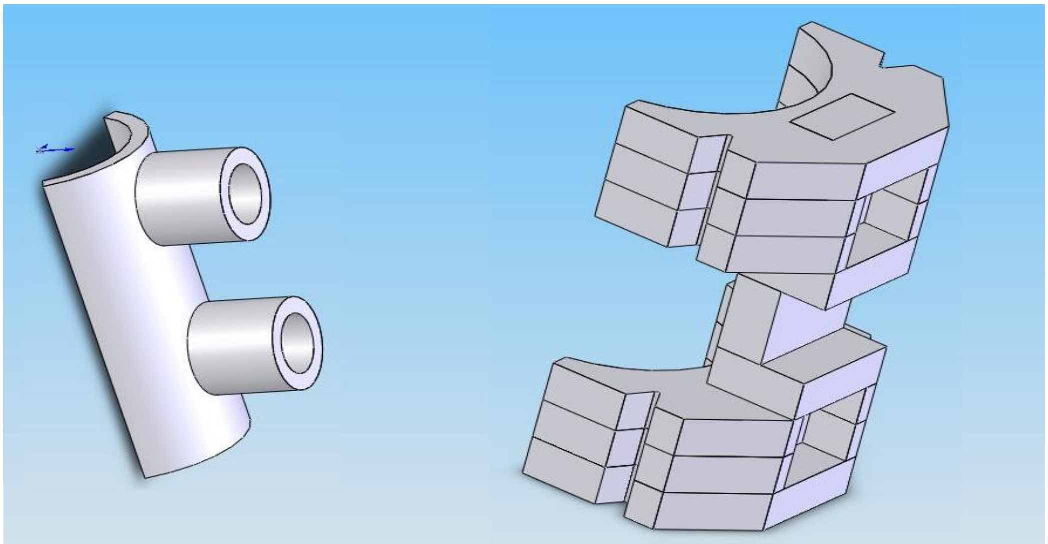

Figure 8: The torch coupling and the LOM version.

Another interesting example, shown in figure 9, is of another part used for welding torch coupling, in which a milled part was substituted by a LASER cut part, to fulfill the same needs. It is also important to mention that this exchange was made with benefits, because the LASER could make the splines that improve the contact with the torch without any additional costs, and the same feature in the milled could double the part cost. The size difference is due to the rail, with no impact in functionality. This part was made only with 3 and 5mm metal sheets, the same that is used for the entire robot. It is also important to note that the self orientation of the pieces allows a rigid assemble even before the GTAW welding. Although both solutions increase the sub-components part count, the final result is cheaper and easier to manufacture.

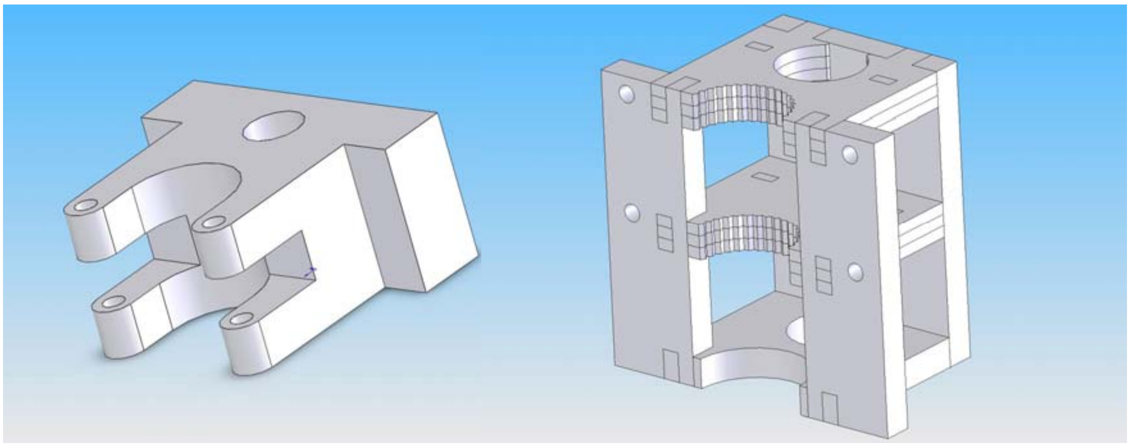

Figure 9: Torch fixture system and the LOM version.

The final result was a robot with enhanced features, more space for future changes, and capable of receiving new equipments inside. The need for close tolerances was eliminated along with assemble adjustments. The number of bolted joints also diminished, because the parts were welded when disassembling wasn't necessary. The robot in its final configuration can be seen on Figure 10.

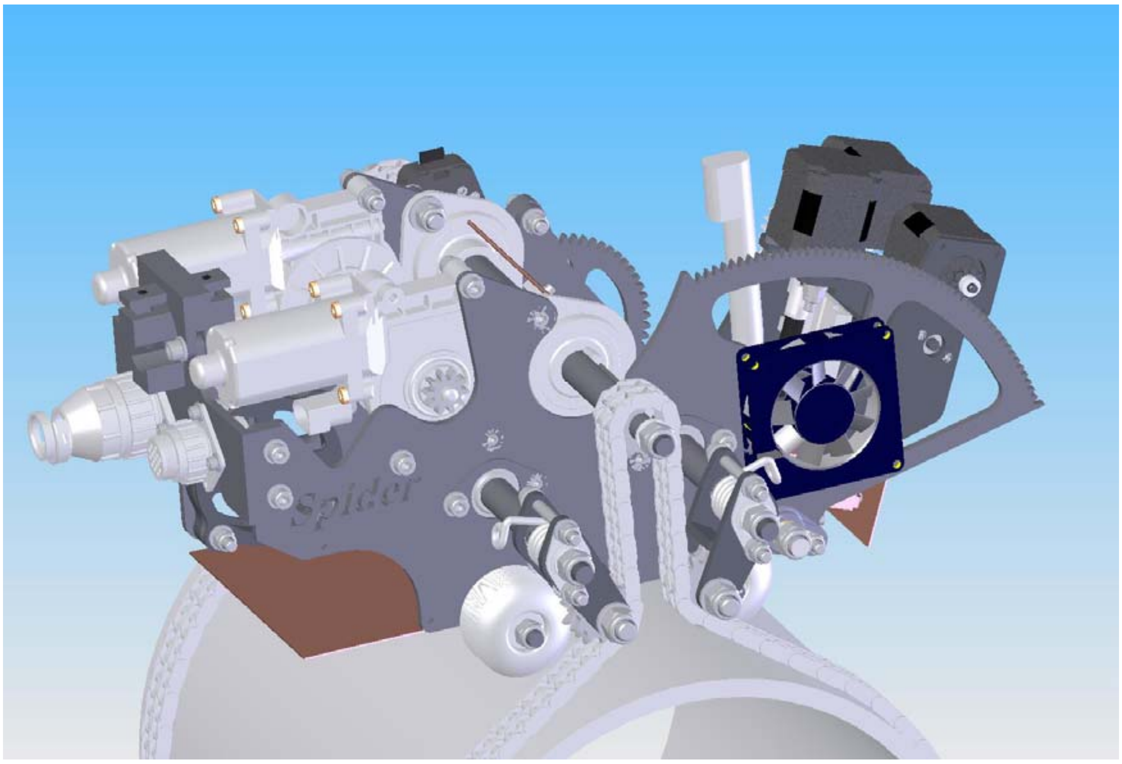

Figure 10: Orbital welding robot in its second version.

4.1 Results of study case A

A simple and objective manner to analyze the conception success is the hierarchy structure, a representation developed by Bonsiepe (1978) that shows how the product is made. It is a fast and non-geometric display of the product organization. In that manner, it is easier to observe which items have to be modularized, grouped or eliminated. For that, the pattern language proposed by Alexander (1994) should be used, to separate the groups according to the affinities, symmetries and sub assemblies, and these directly affect the size of the tree.

The structure doesn't take very long to be built even in complex products like this robot. Some new CAD programs can even generate automatically this tree, for monitoring the development of the project. On Figures 11 and 12 it is possible to see the difference between the two robots, although they develop the same function, move and fix in the tube the same way, the trees are very different, being the second much simpler.

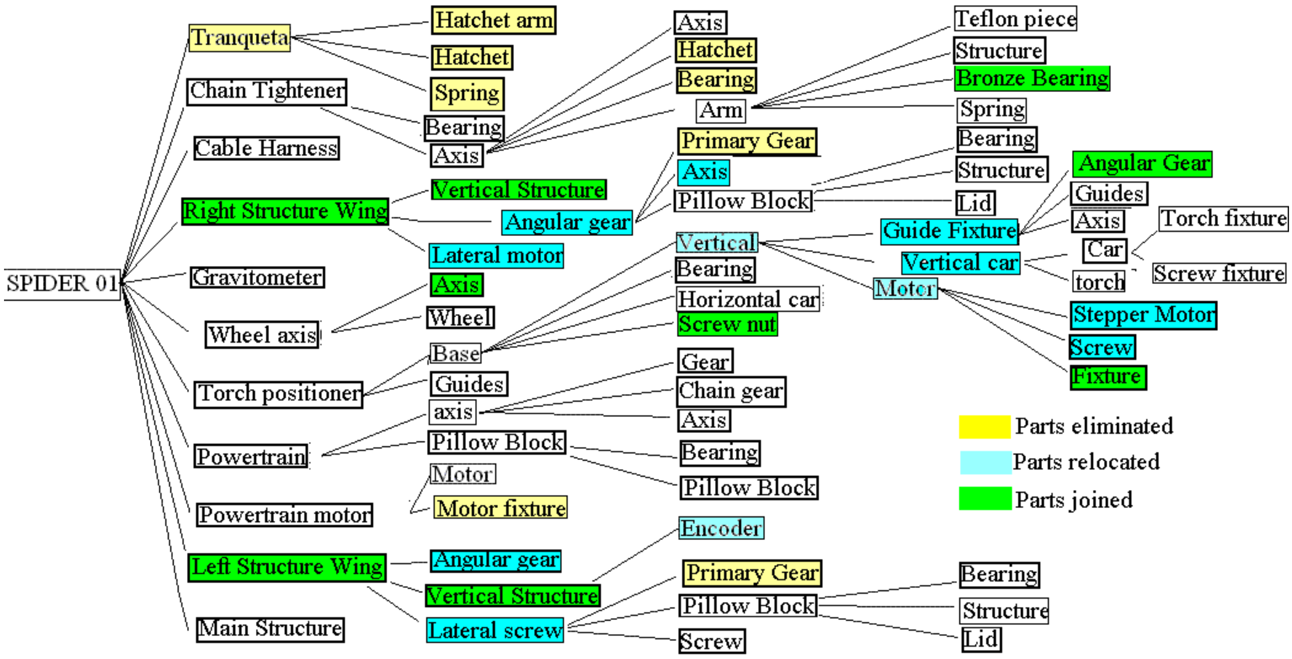

Figure 11: Hierarchy tree for the first robot.

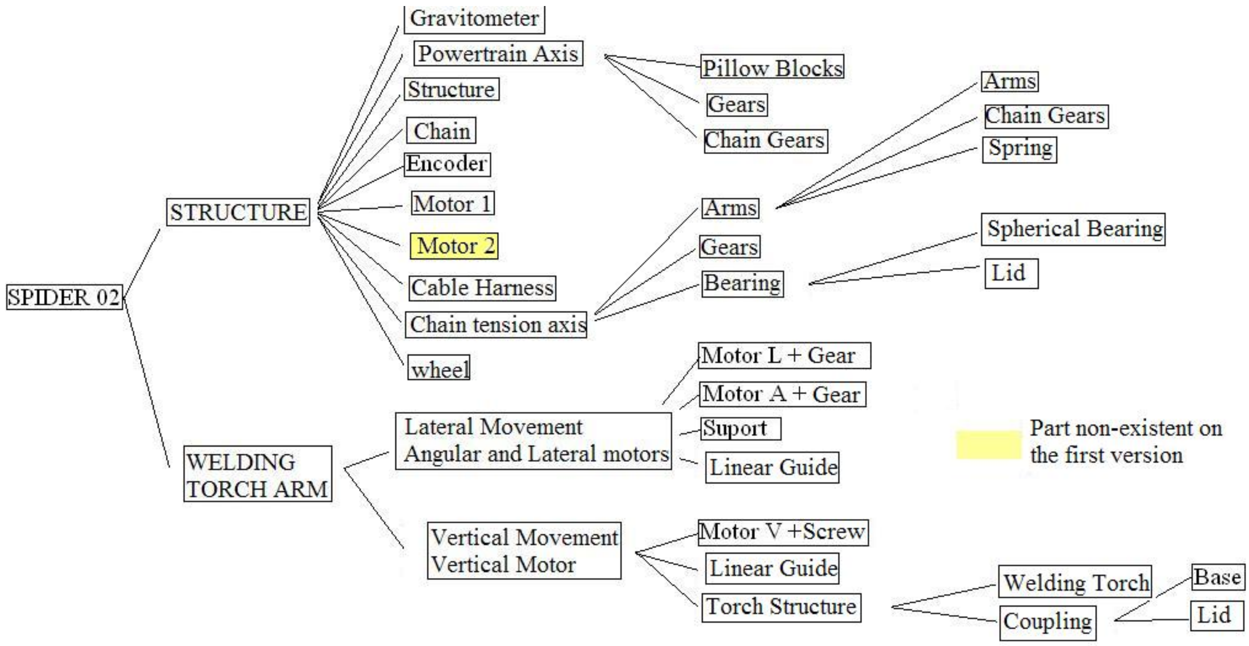

Figure 12: Hierarchy tree for the second robot.

4. CASE STUDY B – ORBITAL INSPECTION ROBOT

This robot was developed to automate the ultrasonic inspection of welded oil and gas pipes. The equipment was developed to adapt with an existing ultrasonic inspection system.

Although this project is derived for the study case A design, due to the different functionality other characteristics are necessary, like being weatherproof. For that reason, it was necessary to make a proof of concept prototype, and the time frame demanded by the client was extremely short, only thirty days, and for that not only rapid manufacturing was necessary, but also very low cost so a disposable conception prototype could be made. For that, it was applied the same techniques described in study case A. Also, the design needed a four degrees of freedom transducer carriage that also needed to be tested, and would also be validated in the proof of concept prototype, seen on Figure 13.

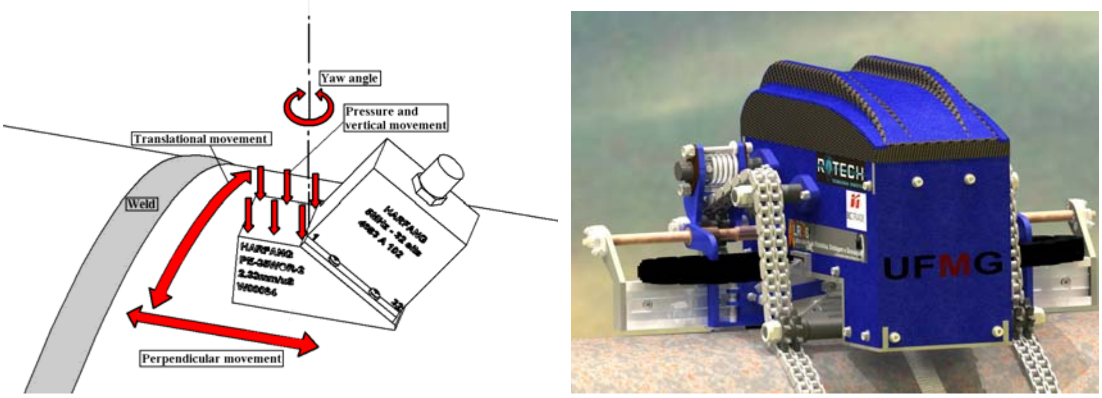

Figure 13: Necessary degrees of freedom and the robot CAD model.

All the design was optimized to have only two manufacturing process, the turning of the axis (3% of the parts), and LASER cut of the sheets (97%). All the parts cut were made with only two sheet gauges, 1/8” and 3/16”. The DFA also pointed out that were redundant axis and wheels, and that’s why this robot have one axis less and no wheels, as seen on Figure 14.

With the rapid manufacturing, the CAD drawings were given to the LASER cut company and the manufactured parts arrived two days later, with one more day to assemble and weld, and one more to assemble the external components, like motors and bearings. The proof of concept tests was made in the same day.

Figure 14: Conception, four axis design and proof of concept tests.

5. CASE STUDY C – AUTOMATED WELDING JIG

Another study made by the Robotics, Welding and Simulation Group (GRSS) of the Federal University of Minas Gerais (UFMG), Brazil, was the development of a automated welding jig to provide auxiliary axis for a anthropomorphic robot for up to four different parts at the same time, with a total of five additional axis . These welded parts had to be weld on all the sides, and the table have to turn to allow new parts to be assembled in the jig in one side, while the robot welds on the other.

The client also required that the system had very low cost and easy operation. Due to the amount of sparks and weld droplets, and technical difficulties involved in welding the part, it was necessary that the jig was small and cheap enough to be disposable every time it would get to dirty or loose the needed tolerances due to the thermal cycles. This would reduce personnel cost in maintenance. In Figure 15, the part to be welded is in red, the disposable jig in blue and the complete automated jig for four parts is on the right.

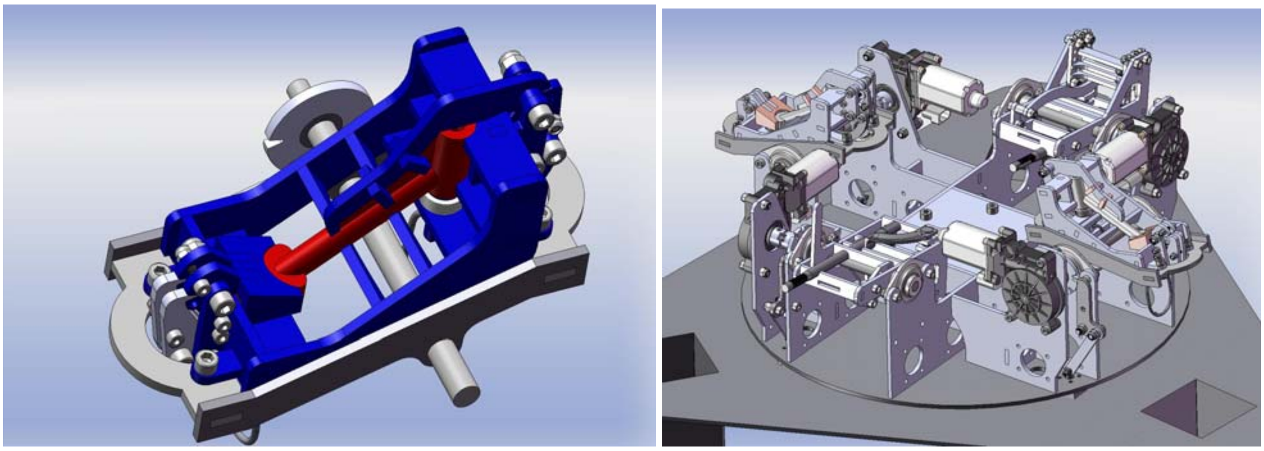

Figure 15: Part fixture and complete automated welding jig.

5. CONCLUSION

The use of methodological tools was extremely useful for the redesign of the orbital welding robot, and the use of these techniques didn't mean in more time spent in designing. The use of the latest CAD software allowed a fast and efficient creation of solutions, allowing a fast learning process of the problem.

The low manufacturing cost and testing were also important, breaking the trend to do prototype less projects to cut costs. Using the techniques, a prototype was made and accelerated the discovery of the problems involved, also allowing simultaneous engineering, which is very important in a multidisciplinary field.

Most important, the very low cost allowed disposable jigs and proof of concept prototypes, bringing to the manufacturing equipment field a new horizon.

6. ACKNOWLEDGEMENTS

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