NON-LAMINATED MACHINE DESIGN

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Abstract

Purpose - The Non-Laminated Machine Design (nLMD) is a Rapid Prototyping and Manufacturing (RP/M) technique developed to solve several problems related to the design and construction of special robots and machines.
Design/methodology/approach - The nLMD is based on the product design methodology "Design for Manufacture and Assembly" (DFMA), the rapid prototyping method "Laminated Object Modeling" (LOM), and good manufacturing practices involved in LASER cutting of metals sheets and welding. The nLMD starts with the DFA optimization of the machine concept to minimize the number of parts followed by the breaking down of every part into two dimensional shapes of the same thickness using DFM, and ends by building the whole machine on a single LASER-cut metal sheet. These sub components are welded together with autogenous TIG welding.
Findings - This technique has been successfully used since 2004 for the construction of several machines, including welding robots, CNC mill and plasma table, welding jigs, and other manufacturing machines. Since it is based on simple rules, it is easy to learn and has been adopted by a growing number of other designers.
Originality/ Value – In some cases, the price reduction was over 80% when compared to conventional CNC milling of stock to manufacture a prototype. The technique lets all the components be manufactured in one step, allowing for hundreds of different parts to be build in a couple of hours from one metal sheet using LASER cutting with one G Code. This provides simplified logistics, low cost and an excellent turnover for the development of industrial machines.

Keywords: Welding, Metal cutting, LASER, LOM, DFMA, nLMD

1. Introduction

Prototyping has always been an important step in the development process of a new product, especially when there is a lack of time or a tight budget. The 3D CAD systems with the virtual prototype and the rapid prototyping techniques are good tools for the design process, and can help to make important decisions. However, the costs of these rapid prototyping machines are very high and these machines can work only with a narrow selection of materials, usually resins or thermoplastics, which may not be suitable for a working part, just a non functional concept model. Nevertheless, these machines can build a complex shapes in a matter of hours, allowing designers to evaluate geometrical features. When designing for a consumer goods market, appearance and usability are both key components, and prototyping is critical because parts require some hands-on iteration.

The prototyping of complex machines is more difficult. Although there are many standardized parts and very few complex shapes, there are often hundreds or thousands of parts necessary. Even a rapid prototyping technique that takes only a couple hours for each part would require several weeks to build the whole machine, and the cost would be high. To improve this traditional machine building methodology, product design techniques like DFMA and DLM (Design for Layer Manufacturing) were studied and Layer Manufacturing (LM) technologies, allowing for the proposal of a completely different approach to the development of machines. The rapid manufacturing method proposed in this paper is based in product design techniques and not in a novel manufacturing process.

2. Design for Manufacture and Assembly

The DFMA is a product design technique that allows for the streamlining of the design. It starts with using DFA (Design for Assembly) that aims to minimize the number of machine parts through 3 simple rules. These rules state that two parts should always be merged, except under the following circumstances: (a) when the parts are made of different materials, (b) when the parts move in respect to each other or (c) when the parts should be separate to allow for maintenance or disassembly. Although a simple procedure, the results are extremely significant and sometimes reduce the number of parts in the assembly up to 60% by merging the parts that do not comply with the rules of the DFA (Boothroyd, G. et al, 2002).

After using DFA the designer should apply DFM, or Design for Manufacturing, that traditionally is used to minimize the diversity of materials and processes used to manufacture all the parts of the project.

The concepts of Design for Manufacturing (DFM) and Design for Assembly (DFA) have been used as an integration tool between design and manufacturing in a simultaneous engineering context (Giudice, F., et al, 2009; Gilligan, J. and Dewhurst, N., 2009). DFM encompasses the manufacture's challenges in the design, providing communication among all the designers of a manufacturing system, and allowing the design to be adapted at each stage of the product creation. The DFA is a tool that evaluates products according to their easiness of assembly, and indicates to the designer which parts can be used or may be eliminated (Boothroyd, G. et al, 2002 and Whitney, D., 2004).

The objective of a design focus in manufacturing is to identify, during the conception phase, the means by which to obtain an easier way to manufacture the product, thus emphasizing the integration between the manufacturing processes and the product design. This allows in an efficient manner the union of the needs and requirements of the product, simplifying and improving the manufacturing of the components that will compose the product after assembly. This idea brings us to the definition of production design as: "the activity of defining the specific means to be used by the operational forces to achieve the product quality goals" (Juran, M.J. 1992), which involve the definition of procedures and work sequence, and also the necessary stock material, machinery, tools and components.

Although the origins of DFA go back to the 1970's, history shows that there were some alternatives for efficient assembly since the turn of the twentieth century. An example is Henry Ford who, in 1908 was able to develop a design for his car that used fewer, more easily adjustable parts, which in turn made the cars easier to assembly, reduced cost and increased productivity (Womack, J.P. et al, 2007).

The integration of the manufacturing process planning to the product development, according to Huang (1996), presupposes the systematic contribution between the product development and manufacturing teams, which promotes efficient feedback in order to accommodate the needs and requirements of the client on the early stages of the product development. This integration allows for the reduction of the total cost of the product life cycle and the project time, because it can eliminate reworking cycles, since every problem is evaluated during the design phase (Stoll, H.W. 1988). The author reinforces that the concept of DFM emphasizes the importance of developing simultaneously products and processes for the integration and global optimization of the product's production cycle.

According to Romeiro Filho (2009), during the application of DFMA it is necessary the integration between the different designers on the initial phases to allow for a concept and definition of parameters that will simplify the manufacturing and assembly process. It's important to use the assembly of a multidisciplinary design team with the use of appropriate methods of design for production, which will allow for the creation of designs with solutions and detail levels compatible with the development of the execution phase.

3. Rapid Manufacturing (RM)

Since the late 80's, many additive processes that generate parts in a layered way have been developed, and are often refered as Rapid Prototyping (RP) technologies. The value of prototyping concept models for design validation is well defined and justified in the Rapid Product Development cycle according do Bernard et al (2002). The Rapid Tooling is also well stabilished for the manufacture of casting and metal forming tools, providing near net shape and cost savings (Levy, G. and Schindel, R., 2003).

Rapid Manufacturing on the other hand, have hundreds of examples in niche applications, like aeronautical and medical industry (Hessel, H. 2002; Master, M. and Mathey, M. 2002) but have not so far become mainstream mainly due to the high costs involved on the material and processing. Rapid Manufacturing is defined by Rudgley (2001) as "the manufacture of end-use products using additive manufacturing techniques", and this means that the product has to comply with real world demands of the product and compete with other well stabilished and more conventional manufacturing technologies.

To achieve the optimal results for a given rapid manufacturing technique, the design has to be optimized taking in account the process constraints, in a Design for Layer Manufacturing (DLM).

For the rapid manufacturing is necessary to take special consideration to the material due to the necessity of long term consistency and fulfilling the physichal, mechanical and geometrical properties, and keeping a reasonable manufacturing cost (Levy, G. 2003). This is the reason that the Laminated Object Manufacturing (LOM) is interesting, since it can work with almost any material as long the sheets can be laser cut and then joined in a stack.

Laminate object Manufacturing was initially investigated by Nakagawa, T (Nakagawa, T and Kunieda, M. 1984, and Nakagawa, T. 1993) for the development of laminated metal sheet tooling, and the process is suitable for medium and large parts made from paper, plastic or metal. The 3D design is modeled, sliced, LASER cut, joined and then milled to obtain the final net shape. This process has the benefit of being able to create complex shapes, but often leaves a staircase-like surface that has to later be machined or filled with additional material. To date, is mainly used as a Rapid Tooling for sheet metal forming (Himmer, T. et al, 2002) and metal casting (Wang, W. et al, 1999), and plastic injection tools being developed (Dalgarno, K. and Sterwart, T, 2001) .

4. Non Laminated Object Modeling

Although LOM is a well-established as a rapid prototyping or tooling technique, it has not been explored as a way to Rapid Manufacture parts. One of the reasons is because it does not provide a complete solution for building all the structural parts of a complex machine in a cost effective way. To achieve the desired results, a review of designing and building techniques was necessary. These 3 techniques together (DFA, DFM and LOM) led the development of a new prototyping method, the Non-Laminated Machine Design - nLMD.

In this technique, the concept shape of the machine is translated to steel plates instead of building a design by stacking sheets of material. Figure 1 gives side-by-side examples of the construction of a hollow box with LOM and with nLMD to allow for a comparison. Although the latter consumes far less material, it requires an extra step to assemble. Additionally, precision is difficult to achieve without a proper jig and tools.

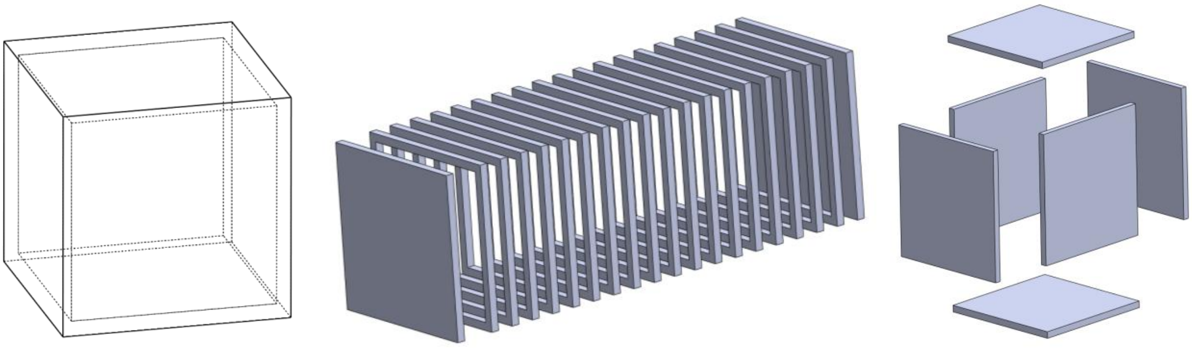


Figure 1: Concept shape of a hollow box and two different approaches for building it.

5. Metal Cutting and Welding

To build with this technique, the number of different parts in the machine must be minimized with the Design for Assembly (DFA) rules and then every part is subdivided in two dimensional shapes that can be cut from a single steel plate (DFM). These sub components are assembled through unique male-female slots which will position them properly for the welding.

To cut the material plates, there are five commercially available processes, OxyFuel, Plasma, Laser, Waterjet and Electrical Discharge Machining (EDM). Oxyfuel can be considered only for very thick steel parts, but not for general machine construction, and EDM is too expensive to be used with this technique, although suitable. Table 1 shows a qualitative comparison between LASER, plasma and waterjet cutting. Although steel can be cut with waterjet or plasma, the best results are achieved with LASER process, since it gives the highest quality at a reasonable price for the most common steel gage in machine construction (3, 5 and 6.35mm). The only problem with LASER cutting is the dross accumulation depending on the combination of material, thickness and machine parameters, resulting in extensive cleaning, especially in aluminum. In this case and when warping is severe, waterjet is preferred.

Table 1: Qualitative comparison between LASER, plasma and waterjet cutting based on manufacturers specifications (Flow 2011, Hypertherm 2011 and Trumpf 2011).

	LASER	**Plasma**	**Waterjet**
Manufacturing Cost	*Medium*	*Very low*	*Medium- High*
Precision	*Very High*	*Low*	*High*
Finishing / Dross	*Very Good / Poor*	*Medium / Poor*	*Good / Good*
Squareness	*Very Good*	*Poor*	*Medium*
Heat warp	*Medium*	*High*	*None*
Kerf size	*Very Small*	*Medium*	*Small*

One of the biggest problems with LASER cutting is warping due to thermal stress, especially on long parts. The warping can be more severe depending on the alignment of the part in respect to the plate and its lamination direction. During the programming and nesting of the parts, similar parts should be cut in the same direction. To completely solve the problem, however, it is necessary to properly place the steel sheets. Every part should have at least one plate in each axis, allowing the assembly to self-correct any warping or welding thermal stress.

The welding of the structure cannot add additional stresses or warping, and it cannot modify the final shape of the structure. In order to achieve that, the structure should use mechanical inserts that hold the structure together while an autogenous TIG welding fuses the heads of those tabs in order to avoid disassembly. These tabs have to be placed away from borders in order to avoid fusion during the welding. This minimal impact approach not only is fast and economical, but provides satisfactory structural performance and does not change the final shape of the part.

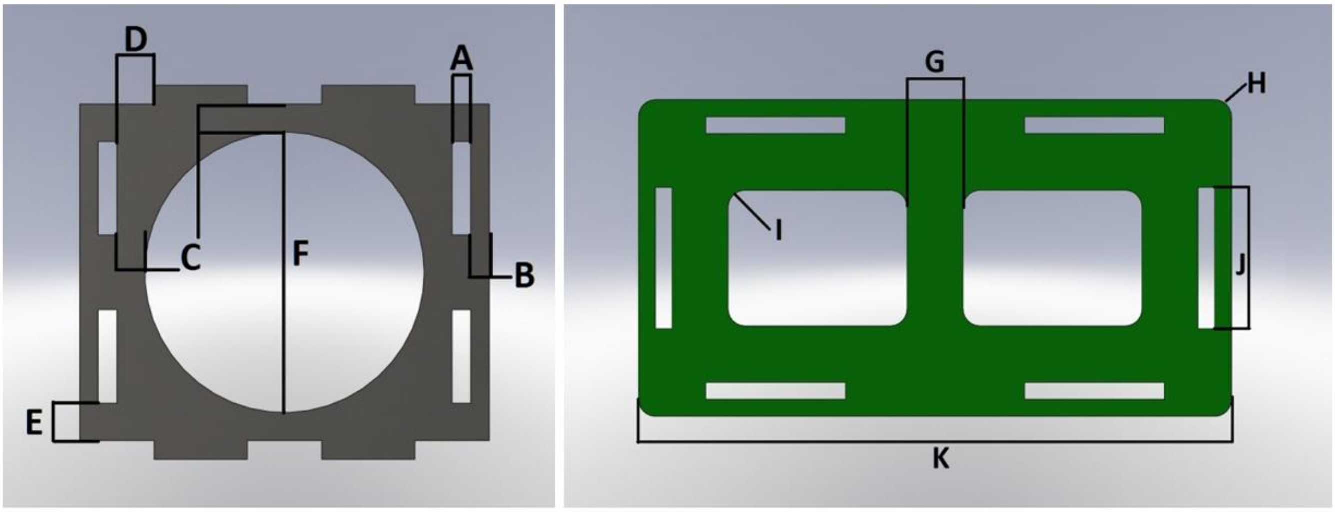
Another advantage is that the welding of the part can be easily automated without the need of a jig, since the tight fit in the tabs keeps the joints in place during the whole operation. This is also very practical for low volumes and manual welding, since the welder doesn’t have to open and close jigs to allow access to different sides of the part. Eventually, if a JIG is needed, this same manufacturing technique has been successfully used to build welding jigs and can be used as a rapid tooling for higher manufacturing volumes

6. Non Laminated Machine Design (nLMD)

A design is based on three factors: material, process and geometry. For this type of prototyping technique, the material chosen is metal plates, and the process is LASER cutting. Now, to achieve optimal performance in the construction, the part has to be simplified and built according to a set of rules that are determined by the constraints of the process and the characteristics that are being pursued in the final part. There are two sets of rules, one for part construction, which are mostly dependant on the process used, and other set of rules for assembly, which will compensate for manufacturing flaws, like warping, and provide a functional, structurally sound and easy to build part.

6.1. Part Design Rules for nLMD

The choice of the metal cutting process and the material thickness (*thk*) will influence the design rules to be used. On Figure 2, different parameters are shown that should be respected in order to achieve optimal results with this technique using LASER cutting and carbon steel sheet between 2 and 10mm, and it can be summarized as follows:



A = thk	*C > 2thk*	*E ± 2thk*	*G > 2thk*	*I > thk*	*K < 100thk*
B > thk	*D > thk*	*F > thk*	*H = thk*	*J > 2thk*	*2mm < thk < 10mm*

Figure 2. Design Rules for nLMD with LASER cutting

- [A = thk] The inserts should be the exact thickness of the metal plate, in order to achieve a tight fit during assembly, making the part very strong even before the welding.
- [B > thk] Although external inserts can be used, only internal inserts provides a self-locking assembly. The external border width should be at least equal to the thickness.
- [C > 2thk] A hole inside the part may be needed for weight saving or to provide access to an internal component. It cannot be too thin because of the pressure applied during a tight fit assembly might deform the part.
- [D > thk] The insert on one side should not be in the same line of the insert on the order side, otherwise the assembly might end with two inserts in the same place (which would result in a fragile T shaped insert on the all female insert part).
- [E ± 2thk] The female insert must not be placed too far away from the border. If the insert is placed too far, it will not provide a good locking effect. If it is placed too close, it may create a fragility point.
- [F > thk] Holes, indentations or other small details have to be bigger than the plate thickness, The precise limit depends only on the LASER machine used, and modern equipment can easily give features with half this size.
- [G > 2thk] Longer parts should divide the weight in order to minimize warping and to support the middle inserts during assembly (especially male inserts);
- [H = thk] All female insert parts should have the sides smoothed in order to avoid sharp edges. The radius should be equal to the thickness so it doesn’t interfere with nearby female inserts or expose the corner of the mating part.
- [I > thk] The weight saving internal radius should be as big as possible in order to provide better structural resistance (Note that a bigger radius results in smaller weight savings)
- [J > 2thk] The female insert should no be bigger than 60% of the side, and can be divided in multiple inserts if needed.
- [K < 100thk] Long parts will always warp. If a long part cannot be avoided, it is possible to use thinner plates. A warped plate with more than 5mm can be very difficult to assemble.

6.2 Assembly Design Rules for nLMD

The rules shown above provide a strong guideline to build any two-dimensional part with LASER. However, to create a three dimensions part that is structurally sound, easy to assemble and will have proper performance, it is necessary to design according to the following configurations.

The construction of mechanical components like gears, cams, pulleys and others various parts with LASER is possible, as long they don't have very demanding performance targets. The superficial finish is a little rough and the mechanical properties may not be optimal, but using this technique may be beneficial since it leaves one less part to manufacture or buy. Others parts, like adapter plates, spacers, special washer etc, can be easily built using the rules above (with special attention to warping) so these components have to be designed as small as possible. On Figure 3, some of these one-plate components are seen. The gear was successfully built and used a 5mm steel plate (Z40, M1,5), although it had small teeth for a plate this thick.

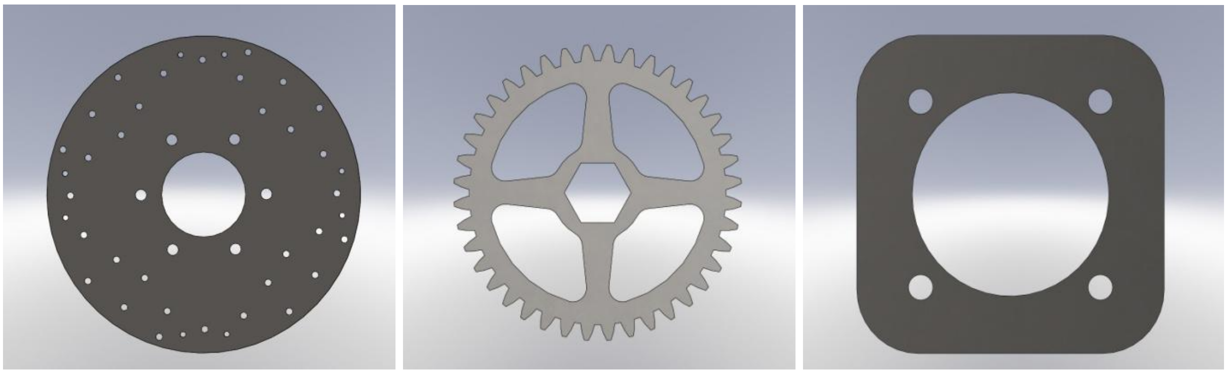


Figure 3. nLMD example with 1 plates (Adapter, Gear and Spacer).

To make a three dimensional structural parts, at least four plates are needed. Although it is possible to make parts with 2 or 3 plates, these parts will not be able to provide a self locking assembly and warp compensation and are thus incapable of providing reliable results. Figure 4 shows an example of a 4 plate structure, in which a pass-through is needed in order to assemble the two parts together. This kind of feature should be avoided because it weakens the part, and configurations with 5 or more plates should be preferred.

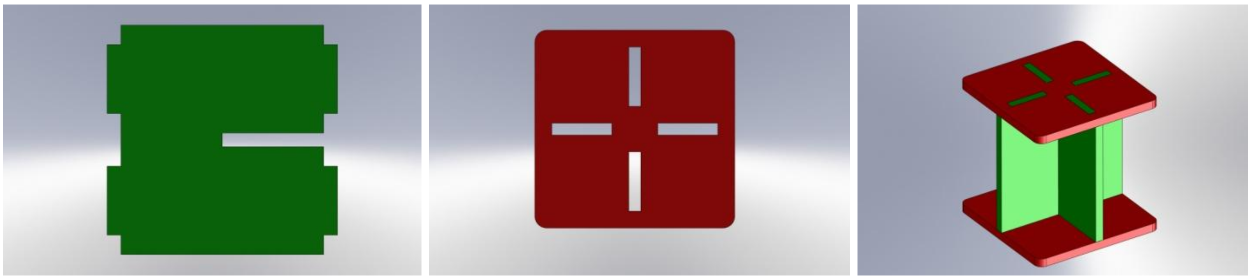


Figure 4. nLMD example with 4 plates (2 in X, 1 in Y, 1 in Z).

Configurations with five plates provide an open box architecture ideal to hold inside OEM parts while maintaining good structural properties along with self locking and warp compensation. Figure 5 shows an example of a five plate configuration.

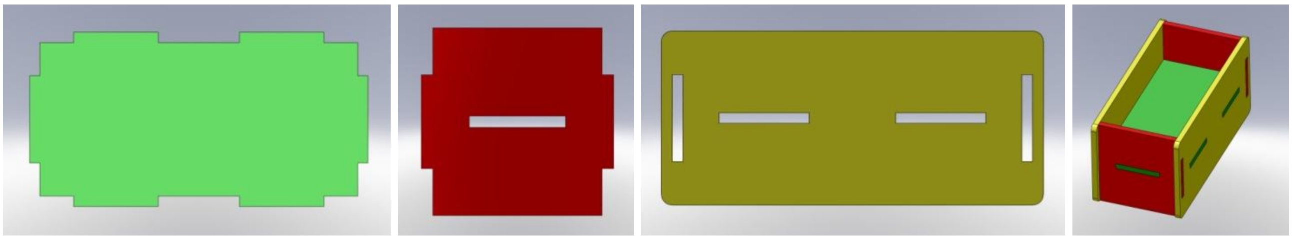


Figure 5. nLMD example with 5 plates (1 in X, 2 in Y, 2 in Z).

The six plates configuration, shown in figure 6, is ideal for longer structures or lighter parts, since the closed assembly allows bigger weight savings. The problem with this configuration is accessibility to internal components or assembling OEM parts inside it, and in those cases a five-plate configuration should be preferred.

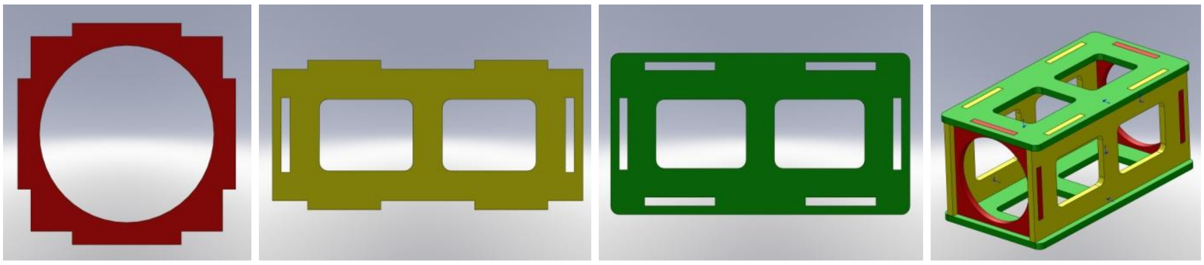


Figure 6. nLMD example with 6 plates (2 in X, 2 in Y, 2 in Z).

For longer parts, like the one show in figure 7, additional reinforcements should be added but ideally in only one axis so it does not impact negatively on the assembly. Reinforcements in more than one plane is possible but increases the assembly time significantly because it is much harder to negotiate several tabs in different direction at the same time.

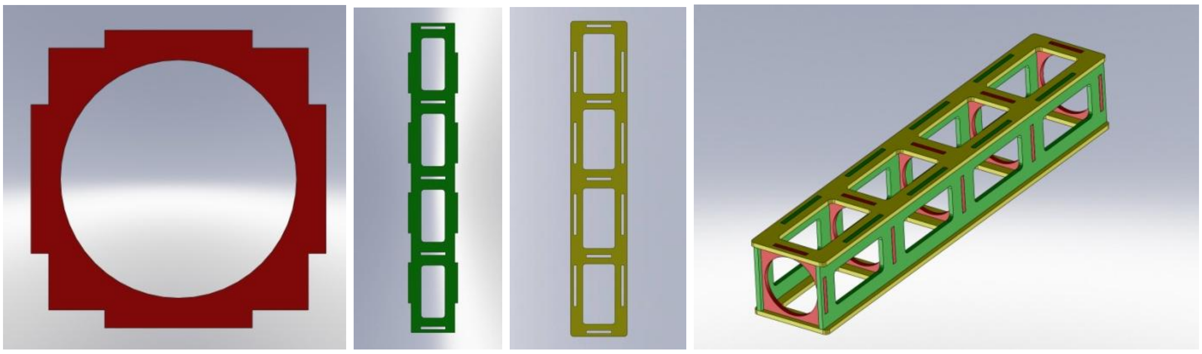


Figure 7. nLMD example with n plates (n in X, 2 in Y, 2 in Z).

7. Examples

These examples are from projects developed beginning in 2004 (shown in chronological order) as consultancy projects or for internal use. In these examples, it is not only possible to see not the evolution of the nLMD, but also the use of the DFMA and LOM techniques. In Figure 8, on the left, is seen the first attempt to build a structure with LASER, and on the right the following structure that has been optimized to minimize part count and to be completely build from a single steel sheet (except the axis).

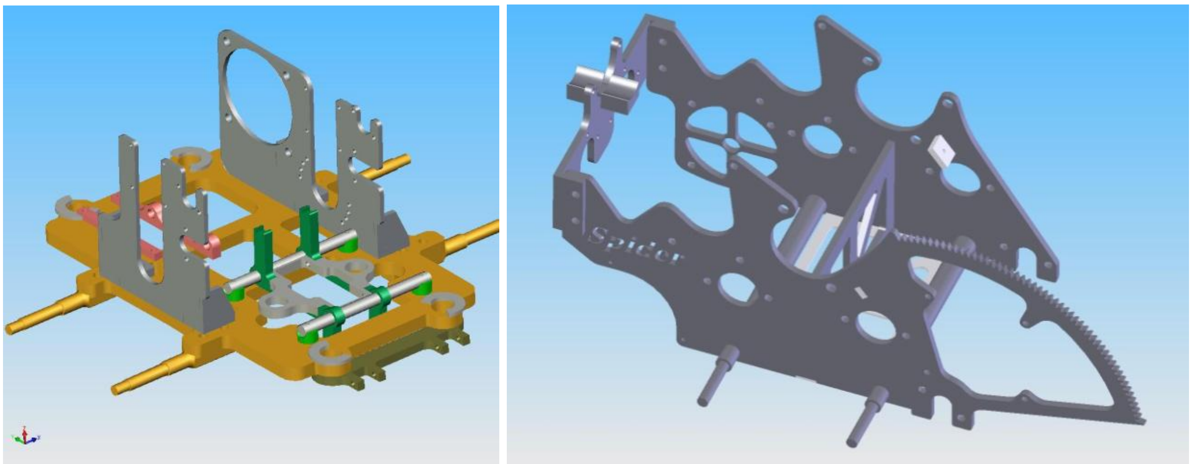


Figure 8. Comparison between the first and the second prototype structure: minimized part count and only one manufacture process and raw material

Other parts for this same welding robot could be built in a mix of the traditional LOM, but combining it with other parts to help the assembly and to achieve self locking and better structural stability, seen on figure 9.

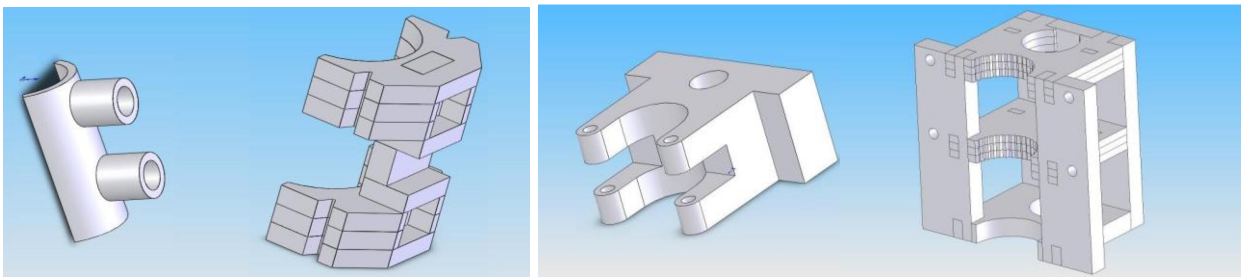


Figure 9. Two different tool holders and their LOD version

Another example of the nLMD application (seen in Figure 10) is the development of a pipeline ultrasound robot, where this technique allowed a complete development cycle from design to prototype in less than 30 days with very low costs.

Figure 10. Design, Manufacture and Assembly of the ultrasound Robot.

It was built for internal use a series of CNC machining with this technique, and in figure 11 it is quite easy to see how the four main structural parts on the system were developed and built according to the nLMD design rules, even the clamps to hold the stock part.

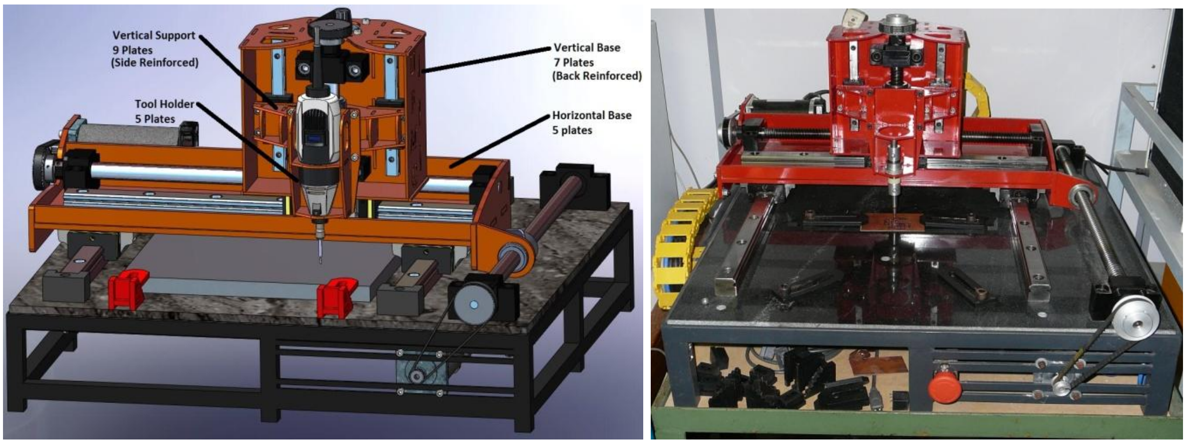


Figure 11. Design and result of a small CNC mill

8. Results

These and many other structures were built recently, providing the lab with a powerful technique to rapidly build any machine structure needed. Although it cannot be directly compared with other kinds of manufacturing, since the design optimizes for LASER manufacturing, the costs can be compared with the most conventional process for manufacturing machine prototypes: CNC machining. In Table 2 is presented not only the necessary time to manufacture and assembly different projects, but also a cost comparison against the CNC milling of a similar structure.

Table 2. Estimated savings with the LOD technique on the examples shown.

	Manufacturing Cost of the Structure	Manufacturing Time (total/ LASER cutting)	Assembly Time (Fit and Welding)	Estimated Economy
Orbital System 1	U$1400,00	30 days / 120 minutes	50 hours	50%
Orbital System 2	U$390,00	7 days / 90 minutes	20 hours	71%
Ultrasound Robot	U$610,00	2 days / 110 minutes	8 hours	82%
Robotic Arm	U$500,00	6 days / 80 minutes	5 hours	Not Available
Welding Jig	U$780,00	10 days / 200 minutes	80 hours	72%
Mini CNC Mill 1	U$250,00	3 days / 30 minutes	4 hours	80%
Mini CNC Mill 2	U$200,00	3 days / 20 minutes	2 hours	90%

Since these projects were built only with Rapid Manufacturing, the cost evaluation of a conventional prototyping through CNC milling was made by redesigning 10 parts from some of the projects shown above to be constructed with the same dimensions and material as their RM siblings, as shown in Figure 12. An average of those examples was taken and applied to all parts, allowing the cost saving estimation. In the example below, the set up, programming and tooling cost was at least 80% smaller (CNC mill U$150,00 vs. U$30 for LASER), used 85% less stock material and only 43% was scrapped, compared to 92% of milling. The machine time was almost 4 hours for milling both sides, compared to less than 3 minutes for LASER cutting, and although this machine hour cost 5 times more, still a 90% reduction in machine hour costs. For a part like that, it is expected 2 minutes per tab for assembly and welding, and for 38 tabs the cost is around U$30,00. The total for the machined part was estimated in U$584, and the rapid manufactured cost less than U$90,00, an 85% reduction. In practice, this cost is significantly smaller, since one third of this cost was for set up, and making all the machine parts from the same plate will dilute this cost significantly, and the parts nesting will improve material use efficiency even more.

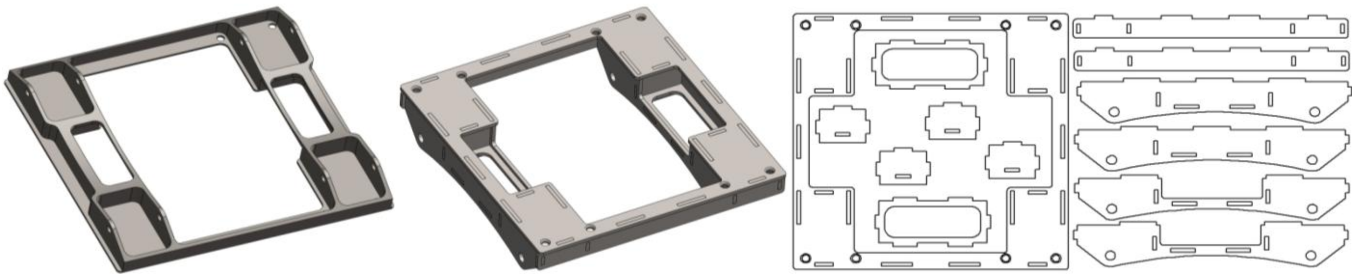


Figure 12. Milled version, Rapid Manufactured version and part nesting

9. Conclusions

The nLMD technique is a powerful development tool, based only on very simple and clear design rules that can be easily learned by any designer, leading to a faster development cycle, cheaper prototype and manufacturing with smaller time to market.

Although the proposed rapid manufacturing technique cannot build complex shapes, specially curved surfaces like other RP/M techniques, when it comes to building simple machines, especially machine tools and robots, the nLMD can be used with excellent results, fast manufacturing and cost savings, and even the extra cost to assemble and weld cannot offset the savings in the building process.

The proposed technique can also be used with a diversity of materials, like plastic, wood, aluminum, stainless and carbon steel, and different cutting technologies as plasma, LASER, EDM and waterjet, allowing extra flexibility to the designer.

New approaches complementary to the nLDM are being studied, like foam and resin reinforcement of hollow sections for extra rigidity, mixing different materials in one assembly and RP of the shell or case for the finished product. Also further studies on the part strength need to be made, but initial results show that the part has the same stiffness of a machined part.

The nLMD still in development, but is another tool for the machine designer that allows for an easy, precise, reliable and inexpensive construction, with great freedom of choice for material and process.

10. Acknowledgements

The authors would like to acknowledge the partners Rotech, BC-Trade, ISEL and FAR-X Technology for allowing publication of the examples illustrated in this paper.

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