DESIGN TOOLS FOR DEVELOPING LOW COST CNC MACHINES

Jordano Fernandes Cordeiro, jordano.f@gmail.com
Kássio Maciel Kienitz, kassio.kienitz@gmail.com
Frederico Allevato Ramalho Filho, fcnc05@gmail.com
Eduardo José Lima II, eduardo@demec.ufmg.br
Alexandre Queiroz Bracarense, bracarense@ufmg.br
Universidade Federal de Minas Gerais, Departamento de Engenharia Mecânica, Av. Antônio Carlos, 6627 – 31270-901, Belo Horizonte, MG, Brazil

Abstract. *The CNC machines are precision equipments that normally have a very high price. The use of design tools, like Design for Manufacturing and Assembly (DFMA) and Laminated Object Modeling (LOM) can create a rapid manufacturing method that reduces prices without scarifying quality. This study shows how these techniques works and brings examples of machines designed for rapid manufacturing and having very low costs as result. With exception of motors and axis, these CNC machines are entirely constructed with parts projected using the DMFA and LOM techniques.*

Keywords*: DFMA, LOM, CNC, Rapid Manufacturing*

1. INTRODUCTION

The machining of stock materials is largely used at the industry to obtain characteristics in a part that other manufacturing processes cannot give. Two characteristics that can serve as an example are surface quality and dimensional tolerance.

The machining of parts started a long time ago with fully manual processes, and with time became mechanized and fully automatized with the development of the process and the working material. To obtain complex parts with minimal time and reasonable cost, it was developed numerical control machines that could deliver parts with reliability, good quality and precision.

With further development in computer and electronics, it became possible to design small machines to do other manual jobs that weren't in the original CNC market, like jewelry, engraving and toys. On the market today, there are available several different options of small CNC milling machines, but they are too expensive for small company or artisans to buy it.

So a small CNC milling machine with low cost has a good market among handcrafters that wish to automate some of their work, or make small batches or even explore their creativity on shapes that cannot be made by hand.

The objective of this paper is to demonstrate, based on 2 study cases, the economical feasibility of the project and to identify the consumer market of this product. Based on that information, design techniques like DFMA (*Design for Manufacturing and Assembly*) and LOM (*Laminated Object Modeling*) will be used to lower the cost and improve the product to the market that is being constructed for, improving the cost/benefit ratio of the final product.

2. DEVELOPMENT

2.1. Advantages and Disavantages of CNC Machines.

According to Amic (1996), CNC machines have several advantages over conventional machines, among them:

- Doesn't need specially shaped tooling to do uncommon surface, since this can be achieved with syncronyzed movement of the axes;
- Easy to incorporate design changes in a CAD/CAM environment;
- Good repeatability with statistical significance;
- Production Increase.

The biggest disavantages of the CNC machines are:

- Higher initial cost;
- Highly trained operators are needed to make the programs, make adjustments and maintenance;
- The CNC programming language is low level and unfriendly, making harder to double check for programing errors;
- New programs might generate high rejection rates of the parts;
- The stock material has to be prepared to the exact dimensions of the program.

In this work, the aim is to design a system that keeps the most part of the advantages and tries to minimize some of the disadvantages with cost reduction and working with a market that doesn't build complex parts and doesn't need tight tolerances, making the inherent disadvantages of CNC machines less noticeable.

2.2. Product Design Tools

The design tools 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 (Boothroyd, 1996), 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.

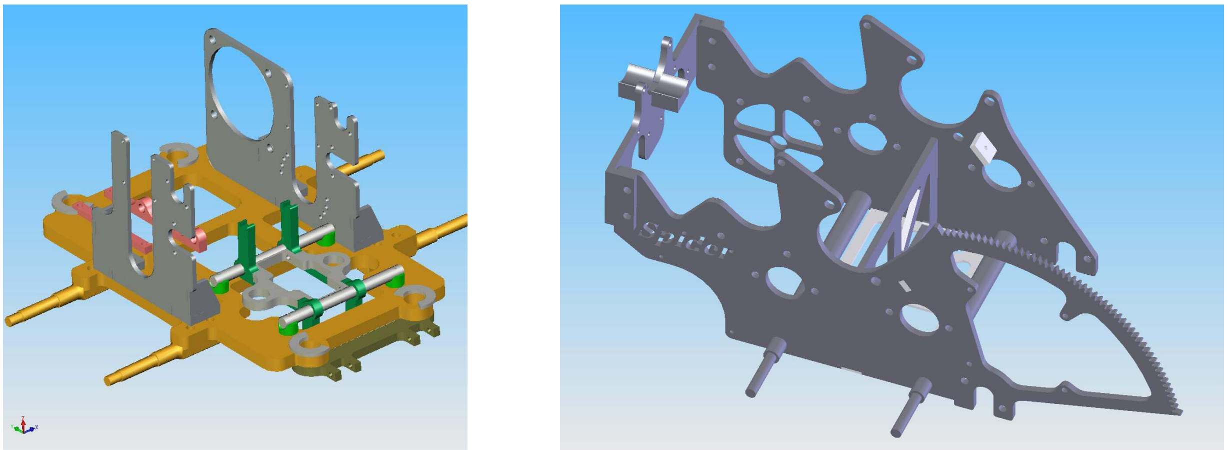
2.2.1. Design for Assembly (DFA)

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



(a) (b)

Figure 1: Example of DFA use: 22 parts before (a) e 7 parts after.

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

2.2.2. Design for Manufacturing (DFM)

The design for manufacturing is a design 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, 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, in this case, a rapid manufacturing process achieved with the use of LASER cutting of steel plates and assembled with welding

2.2.3. "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. 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.

2.3. Price x Value map

To conquer the attention of a market segment, three characteristics are the most important to obtain some advantage in the market: Smaller price, technological novelty and design novelty. This small CNC mill were design to be small and simple, so it could be cheaper. But to be cheaper than other small mills, new technologies were used, in the form of rapid manufacturing techniques with streamlined assembly and manufacturing processes. Since this product can be easily manufactured to any shape and size wanted, with the rapid manufacturing techniques, it obtains a design advantage in the market since it can be easily tailored to any given application with no significant increase in the final cost.

These three advantages will bring the value of the product, for a given market, and keep price reasonably low. For machines, value is mainly based on functionality, and a machine that is customized for the customer need has higher chance in obtaining the highest price/value ratio.

3. Market Analysis and competing products

Small milling machines today have two different kinds of manufacturers, the big industries that already manufacture full size machines and are able to scale down their machine with good quality but high prices. The second type of manufacturers are small companies that build these machines on demand or in very small batches. Alternatively, some companies work converting manual mills to CNC, with less than optimal results.

Researching among small manufacturers that sells on eBay, it was found a machine that is a good example of what is being sold by these companies, like the machine built in aluminum profiles seen on Figure 2.

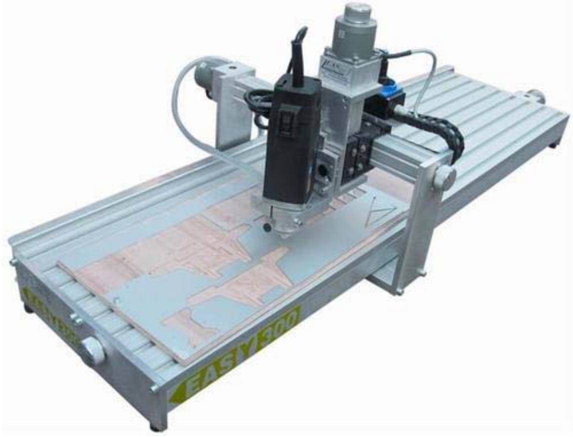


Figure 2 – Small customizable CNC mill (LASERCNC)

In every product researched, it was emphasized that the system came with a software control system capable of importing drawings from several drawings packages, like CorelDraw and AutoCAD. This is a good indication that the product had to be a complete system package with mechanics, software and hardware assembled to cover the needs of the client, and the final value of the product is not only the quality of the system, but the compatibility with external software packages.

3.1. Target Market

With technical data of several possible competitors in the market, it was researched what should be improved to improve value to the target market, and for that, discover what kind of business normally buys small milling CNC machines. With interviews with actual and potential buyers, it was possible to gather data about their needs.

These machines were normally sold to 3 different kind of people: hobbyist, handcrafters and small business. Hobbyists are normally a person that uses the equipment at night or weekends, do custom jobs with low precision, sees the CNC mill as a mean to develop other hobbies and wants a simple and low maintenance machine. Since it is used at home, normal problems involves noise, footprint, health hazards and the amount of garbage that it may generate.

Handcrafters uses a CNC mill for personalized small batch production, with low precision requirement and in soft materials. The size and ease of assembly and maintenance is important, since the equipment is often taken to fairs, events and parties. Engraving and woodworking is a considerable market for this type of user.

Small industries uses this type of equipment specially for prototyping parts and equipments for their main business. They require high safety requirements for the operator and standard parts for ease of maintenance and making possible a stock of spare parts.

Another market that uses small CNC milling machines is the manufacturing of electronic printed circuit boards (PCBs). These kind of machines are needed to drill the holes to insert the components, independent of the production scale, and was found used in this application by individuals and by small and large industries. The CNC machine can also be used to mill the traces in the cooper of the board, or to deposit acid resistant ink where the traces should be, so a printed circuit board can be prototyped with a very small cost.

4. RESULTS

The results will be presented in two study cases, were prototypes were developed according with the proposed design tools to achieve maximum value with a minimum cost and fulfilling the demands of the potential market.

4.1 Study Case A: CNC mill for PCB Routing and Drilling

The first prototype was designed to be the cheapest possible, in order to determinate the absolute minimum cost for a complete system. The market focus would be PCB routing (milling the cooper to form the traces) and milling, since the requirements for rigidity, speed and torque is very low, and the system could be small since a working area of 200x200mm is enough for most needs. The final construction price with material, welding, painting, assembly, components, hardware and the free open source software was R$1.500,00, excluding only the price of a PC, required for controlling the system. Even considering all the taxes, profit margins and other costs, the final price was much lower than similar machines with prices ranging from R$8.000,00 to R$15.000,00. With a price so much lower than what is actually found in the market, hobbyist and artisans can afford such technology, that was before confined only to small industries.

The design, shown in the CAD simulation in Figure 3 proved that with proper design techniques the costs could be reduced in a dramatic way. The structure, once a major cost in several projects of machines, was reduced to only 20% of the construction cost. This was possible because every part, with the exception of the axis and the screws, were made from a single 3mm steel sheet that was LASER cut and TIG welded.

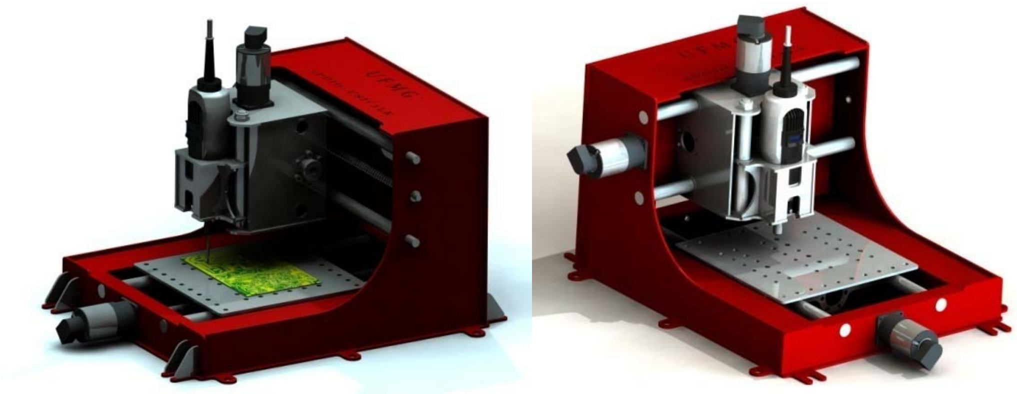
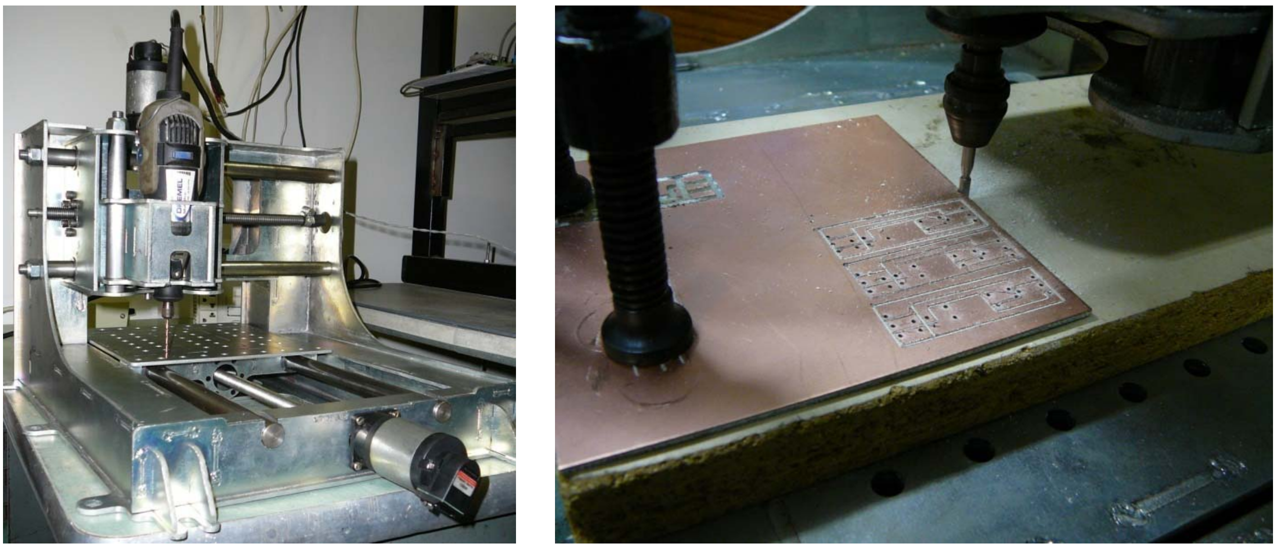


Figure 3 – CAD model of the first prototype using DFX/LOM technique.

After some tests with PCBs (Figure 4) and prototyping, it could be concluded that this system could not be used for milling even soft materials, like aluminum or plastic, and wasn't suitable for the prototyping market. With PCBs, on the other hand, the results were considered good, with enough precision and repeatability for manufacturing a PCB prototype. Some problems were detected with this first prototype, mainly the extremely low quality screw showing uneven results and the low power (8W) servos used, delivering a final speed too slow for practical use.



(a) (b)

Figure 4 – First prototype and PCB manufacturing tests.

So although the results were considered satisfactory, the system is not market ready. Some adjustments in the quality of the components need to be made, which might increase the final price of the system, but even so will be much cheaper than any other system currently in the market.

With these results and trying to design a machine capable of doing machining in soft materials, a second prototype was built with four times the working area, high quality ball screws and linear ball guides and 100W servo motors. The results are shown in the study case B.

4.1 Study Case B: CNC mill for Prototyping

The second prototype developed had a different philosophy, but the same design techniques. This time, cost wouldn't be the primordial factor, but quality, in order to obtain the best possible Value/Price ratio. The use of high precision ball screw and guides would alone double the price, and the bigger servos also increasing costs in power supplies and electronics. The other characteristics would have to be improved to keep the construction price under the established R$4.000, 00 which would allow a final price under any competitor but with a much higher quality.

To make the design simpler, it was adopted a moving portal configuration, over a fixed table. The tables, four times bigger than the previous version, needed to be perfectly flat but at the same time low cost, and for that was used commercial granite stone, cut to size and drilled to fix the ball guides in place. Another important economic change was the use of oversized ball guides, allowing the use of 2 cars, were normally 4 would be used, and one where should be 2. This was made because the cars are the most expensive part in the ball guide system, while a 15mm guide is only 20%

cheaper than a 30mm guide, so the costs in precision equipment could be cut in 40% without sacrificing to much of the quality. The first and the final CAD design are both shown on Figure 5.


(a)

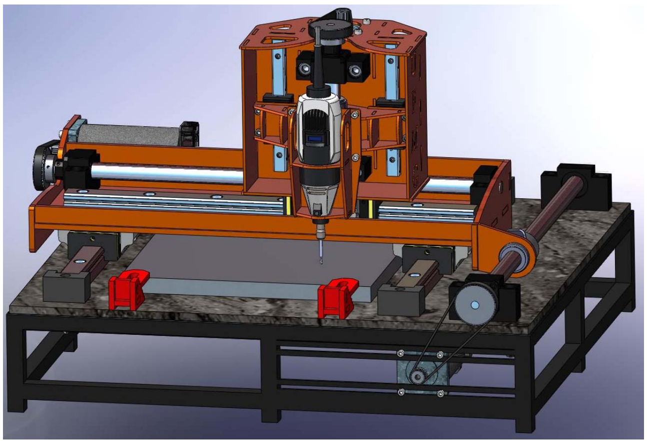
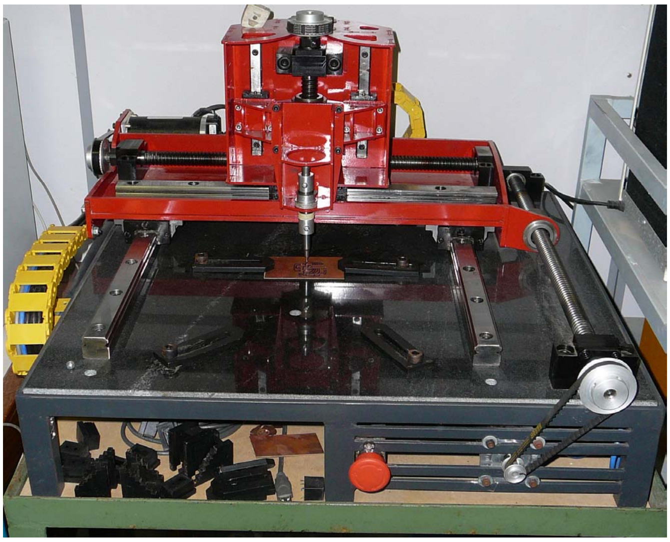

(b)

Figure 5 – New system conception (a) and the finished design (b).

The structure was also designed with the rapid manufacturing technique, this time mixing 3 and 5mm steel sheets (Figure 6). The control box was also built with the same technique on the 3mm steel sheet, also seen in Figure 7.


(a)


(b)

Figure 6 – Prototype of the new system (a) and control box (b).

This system was capable of delivering extremely high speed and also a very good quality in the manufactured parts, limited only by the power of the spindle. The higher cost, although comparable to some other systems in the market, came with a much better quality, that is found only in systems over R$20.000,00. The power and precision opened the possibility to explore multiple types of usages, with only the exchange of the tool.

5. TOOLS

To give the equipment enough versatility, several types of tools can be mounted to do different kinds of jobs. For prototyping, a DREMEL hand tool (Figure 7b) was used with carbide cutters to mill soft metals and plastics with good results. Special tools could be fitted on the DREMEL to route the cooper of a PCB, but the results were uneven, with every island needing to be checked for shorts from swarfs. A new tool holder was developed to hold a pen with a permanent marker (Figure 7a), that draws over the copper with acid resistant ink, and after that the tool is changed for a drill that make all the needed holes. After that, the cooper is corroded in acid, making a PCB prototype in minutes.

Another option is assembling the system with a fused material deposition (FMD) tool, that melts plastic wire in place and build the prototype in an additive manner. Many others tools can be made and adapted to the system in order to satisfy the customer needs.

(a)

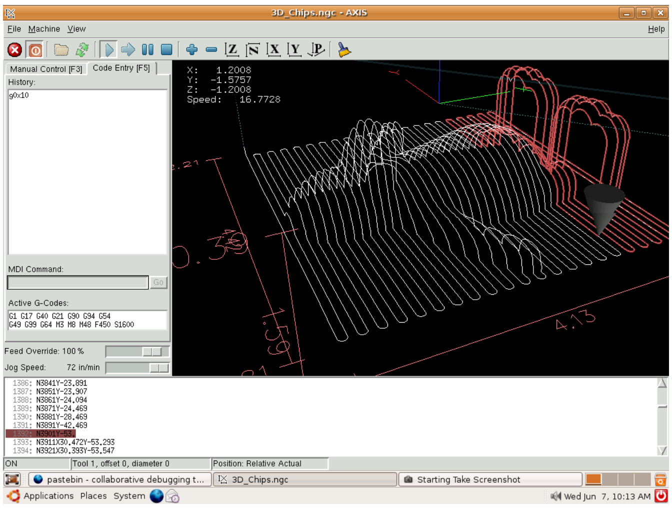
(b)

Figure 7 –Tool holder with pen on a spring loaded support (a), and with the DREMEL tool (b).

6. HARDWARE AND SOFTWARE

The hardware and the software for the CNC systems had a sever price reduction after the year 2000. The software, including some CAD/CAM projects can now be found for free, like the EMC2 project in the Figure 8a, initially funded by NIST and now supported by volunteers all over the world. Other CNC control programs can be found from U$50 to U$200.00, with different functionalities.

Hardware have different prices depending on the type of motor used (step motor or AC and DC servo motor), but has a price around U$150.00 for each axis, for driving up to 1500W, in the case of DC brushed servo motors. Step motors can be driven for under U$50,00 for a motor with less than 200W, that is more than enough for small servo mills. A typical servo driver, by Geckodrive Inc. can be found on Figure 8b.



(a)

(b)

Figure 8: Open source CNC controller (a) and low cost motor driver (b).

7. CONCLUSIONS

With the first prototype it can be concluded that it is possible to construct CNC equipments with an extremely low cost, taking advantage of free software, low cost electronics and rapid manufacturing techniques that provides structures with low cost and good quality. The second prototype could be built with improved functionality and excellent performance through the use of expensive but good quality parts, the ball screws and guides, but this modification further improved the price to value ratio.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

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10. RESPONSIBILITY NOTICE

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