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# Part Consolidation for Additive Manufacturing Demonstrated in the Design of a 3D-Printed Harmonic Drive

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## ABSTRACT

The goal of this project is to establish a novel design approach for the additive manufacturing of mechanical transmission systems. Our focus is the design and 3D printing of a harmonic drive. Harmonic drives use the elastic dynamics of metals to create an elliptical rotation, which is what conceives the reduction of speed of the outer piece. Additive manufacturing is used to achieve more complex and precise mechanical structures. Components of less complexity will be 3D printed with polymer and commercial parts will be purchased. There is a need for the creation of new plastics manufacturing processes that define and simplify the decision methods involved in the production. With this project, we will establish the process we consider best for plastic additive manufacturing. The decision of which parts are 3D printed or machined affects the harmonic drive's cost and lead-time; therefore, several alternatives are systematically analyzed. The final bill of materials contains the list of commercial parts and 3D printed parts. When assembled, a functioning harmonic drive is produced. The final harmonic drive is experimentally tested to determine the life of its components when subjected to working loads. The methods used in this research include the part consolidation for the optimization of the system, transcription of 3D models to STL files that can be printed, polymer additive manufacturing and traditional quality control techniques to improve the design. Material models utilized in this project are commercial aluminum parts, 3D printer and plastic, and a low-voltage power motor. The complete set of results will give torque and speed reduction ratios that will be compared to those previously obtained by electronic simulations. This locates us a step ahead in the creation of an optimal process for additive manufacturing.

**KEYWORDS:** 3D printing, harmonic drives, additive manufacturing, mechanical transmission systems

## INTRODUCTION

The goal of this project is to establish a novel design approach for the additive manufacturing of mechanical transmission systems. Our focus is the design and 3D printing of a harmonic drive. Harmonic drives use the elastic dynamics of metals to create an elliptical rotation, which is what conceives the reduction of speed of the outer piece. Additive manufacturing is used to achieve more complex and precise mechanical structures. Components of less complexity will be 3D printed with polymer and commercial parts will be purchased. There is a need for the creation of new plastics manufacturing processes that define and simplify the decision methods involved in the production. With this project, we will establish the process we consider best for plastic additive manufacturing. The decision of which parts are 3D printed or machined affects the harmonic drive's cost and lead-time; therefore, several alternatives are systematically analyzed. The final bill of materials contains the list of commercial parts and 3D printed parts. When assembled, a functioning harmonic drive is produced. The final harmonic drive is experimentally tested to determine the life of its components when subjected to working loads. The methods used in this research include the part consolidation for the optimization of the system, transcription of 3D models to STL files that can be printed, polymer additive manufacturing, and traditional quality control techniques to improve the design. Material models utilized in this project are commercial aluminum parts, 3D printer and plastic, and a low-voltage power motor. The complete set of results will give torque and speed reduction ratios that will be compared to those previously obtained by electronic simulations. This locates us a step ahead in the creation of an optimal process for additive manufacturing.

## DESIGN FOR AM

*Considerations*

The process of designing a product has to be thoroughly revised before beginning the production. Our project, which consisted of developing a new design of a harmonic drive, involved the establishment of a design process appropriate for the case. First, to define a product there needs to be a product layout determined. Our layout consisted of a list of parts, which was then separated into multiple lists arranged by the different materials to be utilized or the distinct manufacturing methods. There should be specific measurements for each part already detailed. For our project, our harmonic drive had been electronically designed and simulated through SOLIDWORKS. Our electronic testing proved the harmonic drive yields the appropriate results. Second, there needs to be an evaluation of the force and tension the prototype will undergo, to make the decision of the materials to be selected. After the desired measurements were evaluated, guided by the testing previously done, the designs of the parts to be manufactured in polymer were then converted to STL files to be 3D printed. Using plastic rather than wood, aluminum, or steel will affect the shape, manufacture, cost, and end-use of the product (Kazmer, 2011). The selection of the appropriate manufacturing process for processing plastic has been studied by Ramkumar & Kulkarni (2014).

Measurements have to be verified and changes have to be made to the original design to achieve an optimized prototype. The differences in measurements are to be modified in the electronic files for further printing. Quality control has to be rigorous in this process. Digital caliper was utilized for these adjustments. The objective of designing a harmonic drive for 3D printing is taking advantage of the new technologies to improve designs that could later produce advances in the field of mechanical engineering. To obtain a better prototype part consolidation techniques were utilized. These followed processes like the Design for manufacturing and assembly guidelines (DFMA) and the Theory of Inventive Problem Solving (TRIZ). One significant benefit of DFMA is the considerable savings in assembly cost because of the reduced amount of parts. The general intent of DFMA is to consolidate as many discrete parts into fewer (but potentially more complex) parts (Kazmer, 2011). TRIZ initiates this method by using the "Principle of Fragmentation" to divide the prototype into independent parts and analyzing the functions of each to determine the best fit for the parts to be consolidated. This verifies which design will benefit the structure.

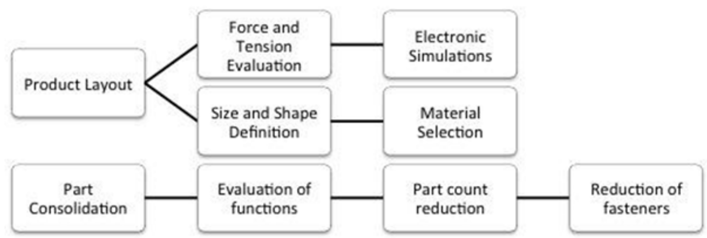


*Figure 1.* Part Consolidation Method

## HARMONIC DRIVE PART CONSOLIDATION

A harmonic drive (HD) is compact coaxial gear mechanism characterized by high reduction ratios (up to 300:1), no backlash, and a few number of components, which makes it popular in robotics and automotive applications (De Lucena, Marcelino, & Grandinetti, 2007; Gervini, Gomes, & Da Rosa, 2003). A typical HD consists of three main coaxial components: a circular rigid spline, a flexible spline, and a wave generator (Figure 2). The wave generator, which is usually an elliptic cam, runs inside the flexible spline and deforms it to engage the outer circular rigid spline along the major elliptic axis. When the wave generator deforms the flexible spline in such a way that there are two points of contact with the rigid spline, the mechanism receives the name of double wave HD.

HDs offer several advantages with respect to conventional spur gear transmissions, including better mass-to-torque ratio and smaller overall dimensions than a spur gear equivalent. Since HDs have a flexible component and several teeth engaging simultaneously during the transmission, there is damping factor that is four to five times better than the spur gear counterparts (Jeon & Oh, 1999). The flexible teeth gearing results in theoretically zero backlash.

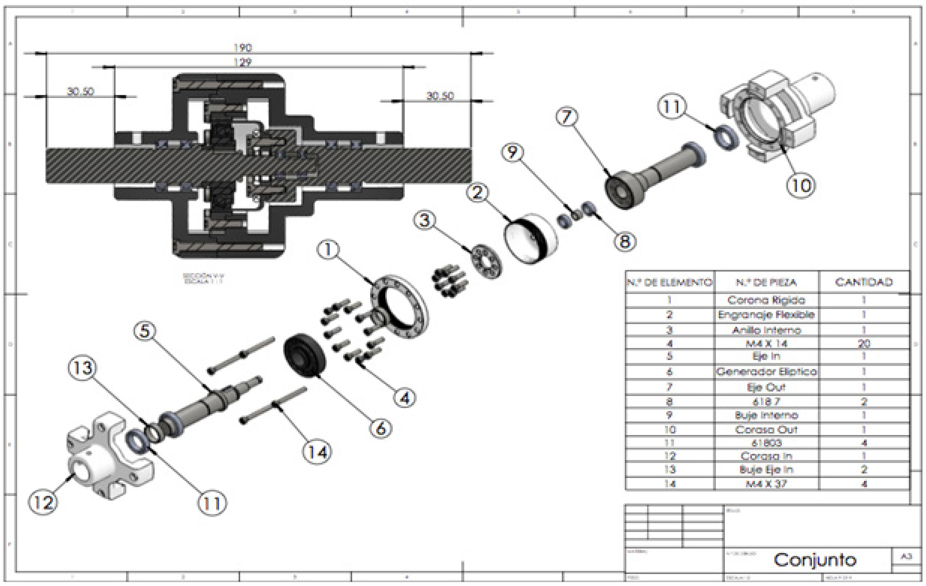


*Figure 2.* Initial design of a HD before part consolidation

A harmonic drive has to resist strong workloads, which means there were some parts that needed to be acquired in aluminum to resist the force. Parts that were going to be purchased commercially were searched for with the desired dimensions and specifications. These were mainly the bolts for the axes and the spheres used for the generator. The rest of the harmonic drive was manufactured in polymer. The shapes of the parts already designed were the ones used for the prototype. For a harmonic drive, the strength and flexibility of the material are key factors in its function. The tooth geometry of the flex spline has to be rigid and sustain the workloads, but flexible enough to acquire the elliptical motion necessary for the appropriate functioning of the transmission. After the first prototype is built, products undergo revisions and testing to verify their functioning. Measurements have to be taken to verify the impression has yielded the appropriate sizes for the prototype.

Due to conversion errors or 3D printer calibration, measurements that do not fit accordingly in the prototype have to be modified and edited.

One can optimize the harmonic drive by choosing to consolidate the parts with less dramatic effect in the function but most impact in the manufacturing process. Electronically testing needs to be carried on to choose with parts can be consolidated and allow the movement and resist the work force of a harmonic drive. The results provide conclusion about which parts will undergo more pressure as well as which parts serve for the same purpose and can be manufactured in conjunction. This is the third major step in our manufacturing process. Part consolidation will affect cost production, as well as lead time and efficiency. In our harmonic drive, one of the axes (Figure 3) required a key to lock the interior axis of the generator (Figure 4) around it. This was consolidated and made into one single part that improved the rotary composition of our structure.

*Results*

*Figure 3.* Input shaft (Part #5)

Assembly and production were more effective after the consolidation. Other minor parts were joined. This gave us the lead way for the second impression and new testing. One of the last steps mentioned in the Applied Plastics Engineering Handbook is fastening. Our harmonic drive required many bolts and snap rings, which are very convenient fasteners that are reversible and adjustable. This step is our fourth step in our manufacturing process. In our prototype, the bolts were bought in aluminum for a better and firmer hold of the components. The holes in the prototype were made to fit the size of these commercial bolts. The first impression had holes that were not big enough and had to be adjusted. This was also modified for the second prototype. Making the minor changes in the designed that were needed to fix some measurement errors, the prototype is printed again and tested to yield results regarding its function.

*Figure 4.* Wave generator shaft (Sub-assembly #6)

## DISCUSSION

Polymer products have special benefits in manufacturing. Their price is low per unit and they can be simply manipulated into complex designs. This includes all physical and chemical aspects of the structure. The primary challenge is the optimal decomposition of the overall system into a set of components that can optimize the capabilities of the materials. Primary design considerations in engineering design often include structural performance, end-use temperature, electrical and thermal conductivity, manufacturability, assembly time, material costs, and others (Frey, Palladino, Sullivan, & Atherton, 2007).

Our prototype is currently being tested and manufactured a second time. The parts consolidated have proven to contain a strong hold of the components and the necessary strength and flexibility. The four principal steps glossed previously (product layout, evaluation, part consolidation, and fastening) are very important steps involved in the manufacturing process of plastics. This way, the harmonic drive obtained can be optimized to produce better outcomes. The modified version proves to be better to print, as it contains fewer parts, although some have more complicated structures. This type of arrangements can be made in additive manufacturing because of its beneficial designing techniques and structures that provide unlimited possibilities of designs that can be produced.

Our project proves the benefits of this structural plastic manufacturing method that can be applied to optimize the structure being produced. With the great growth of additive manufacturing, especially plastics manufacturing, it is imperative to outline these guidelines and produce a uniform method to be applied. This organization will be very useful in this growing industry and will benefit the production of rapid prototypes or already-established products.

## CONCLUSION

The principal expected outcome is that the results given by the testing of the harmonic drive are very accurate with respect to the results obtained by the simulations. This will prove the design is successful. By creating a completely functional harmonic drive that was 3D printed we will be one step ahead towards creating devices with materials that are environmentally friendly and using advanced technologies that permit great rates of production, decrease the loss of material, and precision regarding the dimensions and design of the models. Also, it will support our established guidelines for plastics additive manufacturing.

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## REFERENCES

Ashby, M., & Johnson, K. (2013). Materials and design: the art and science of material selection in product design. Waltham, MA: Butterworth-Heinemann.

Corbett, J. (1991). Design for manufacture: Strategies, principles, and techniques. Boston, MA: Addison-Wesley.

De Lucena, S.E., Marcelino, M.A., & Grandinetti, F.J. (2007). Low-cost PWM speed controller for an electric mini-baja type vehicle. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 29(1), 21-25. doi: 10.1590/S1678-58782007000100004

Frey, D., Palladino, J., Sullivan, J., & Atherton, M. (2007). Part count and design of robust systems. *Systems Engineering*, 10(3), 203-221. doi: 10.1002/sys.20071

Gervini, V.I., Gomes, S.C.P., & Da Rosa, V.S. (2003). A new robotic drive joint friction compensation mechanism using neural networks. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 25(2), 129-139. doi: 10.1590/S1678-58782003000200004

Huang, G. Q. (1996). Design for X: Concurrent engineering imperatives. London, United Kingdom: Chapman & Hall.

Jeon, H.S., & Oh, S.H. (1999). A study on stress and vibration analysis of a steel and hybrid flexspline for harmonic drive. Paper presented at the 10th International Conference on Composite Structures, November 15, 1999 - November 16, 1999, Melbourne, Aust.

León, D., N. Arzola, & Tovar, A. (2014). Stochastic analysis of the influence of tooth geometry in the performance of harmonic drive. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 36(4). doi: 10.1007/s40430-014-0197-0

Kazmer, D. (2011). Design of plastic parts. In M. Kutz (Ed.), *Applied plastics engineering handbook: processing and materials*. Oxford, United Kingdom: Elsevier.

Milner, D. A. (2012). Computer-aided engineering for manufacture. London, United Kingdom: Springer.

Molloy, O., Tilley, S., & Warman, E.A. (1998). Design for manufacturing and assembly: Concepts, architectures and implementation. London, United Kingdom: Chapman & Hall.

Ramkumar, P.L., & Kulkarni, D.M. (2014). Objective-based multiple attribute decision-making method for plastic manufacturing process selection. *International Journal of Manufacturing Technology and Management*, 28(4), 184-199. doi: 10.1504/IJMTM.2014.066696

Wakil, S.D.E. (1998). Processes and design for manufacturing. Boston, MA: PWS Publishing Company.