OPTIMIZATION OF A WORM GEAR ASSEMBLY DESIGN FOR ADDITIVE MANUFACTURING

D. Borstell*, M.-C. Georg*

* Research Laboratory for Additive Manufacturing, Koblenz University of Applied Sciences, 56075 Koblenz, Germany

Abstract

Worm gears are widely used to transmit power at predominantly low speeds and high-speed ratios. Their self-locking characteristic makes them unique to many drive applications. Industrial power requirements are causing forces and tensions mostly prohibiting thermoplastic materials in worm gear drive trains.

Double basses are tuned using a worm gear assembly made from machined steel and brass or cast bronze. Neglectable power requirements, few hours of operation, esthetic expectations and the classic luthier's approach to making such an instrument by hand have excluded the double basses' tuning assembly from all engineering approaches regarding optimal design, efficiency and costs.

Manufacturing the traditionally designed double bass worm gear assembly using Additive manufacturing processes requires the application of general design rules and the rules of Design for Additive Manufacturing (DFAM) resulting in an optimized gear assembly regarding weight, costs and design properties.

Introduction

Double bass tuning assemblies are available in different qualities, resulting in retail price ranges between € 30 and € 500 for a set of four. Individually handcrafted sets reach ranges of € 2000 to € 3000. Add 20% - 25% for basses with five strings. Prices for double basses start at about € 500 and go up to more than € 100.000 for original old instruments.

Economically the price of the tuning set should remain within a certain percentage of the instrument´s price. Georg [1, p. 1] sets a limit of about 7%. Most of the instruments sold, are for students or beginners, i.e. in the lower price ranges. Often these basses are equipped with tuning gears with compromised quality due to price issues. An average quality gear assembly retails for about € 100 for a set of four. The double bass tuning gear assembly has never been in the focus of engineers or accountants and therefore holds a treasure trove of potential for improvement. It is an ideal object to demonstrate the benefits of additive manufacturing. It is the goal of this study to design an additively manufactured tuning gear with the same or better quality than average for less than € 25 apiece.

State of the Art

Tuning of string instruments is done by tensioning or relaxing individual strings in order to get a higher or a lower tone. The strings are rolled up on tuning pegs which are then turned by hand to tune up or down. Smaller string instruments (violins, violas and celli) have conically shaped wooden pegs which together with the conical bores in the pegbox form a conical press fit. Sliding friction determines the torque requirement when turning. It is most important to reach a defined rotational position of the peg and to hold the peg at exactly the same position to tune to a specific tone. The peg's position, i.e. the tuning of the instrument, is then held by static friction. I order to turn the peg again torque has to be applied by hand to overcome static friction. The size of the double bass prohibits usage of frictional wooden pegs, because their

sheer size is too large for precise manual handling of the conical press fit. The worm gears' high transmission ratio and the self-locking characteristic allow precise manual tuning independent of frictional issues. The gradients of shaft cone and pegbox bore cones have to match exactly. Luthiers use a reamer with a 1:25 gradient to get a perfect match. Precise manufacture and correct assembly of the shaft and the bores is laborious task.


Figure 1: Pegboxes of Violin (left) and Double Bass (middle and right)

The elements of an average quality gear assembly are mounted on a base-plate (1) which is fixed to the side walls of the pegbox with wood screws. The worm-shaft (2) (machined steel) is held to the base-plate with two bearing-brackets (3) which are lightly greased. Disassembly is not possible. The worm wheel (4) (brass) is connected to the brass-shaft with a metric screw (5) and positioned in the side walls of the pegbox in two conically shaped bores.
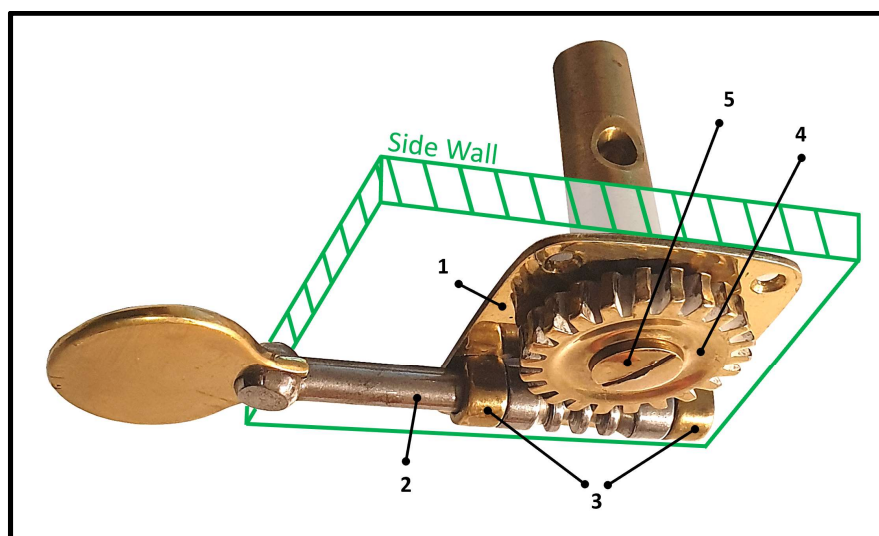

Figure 2: Tuning Gear Assembly [1]
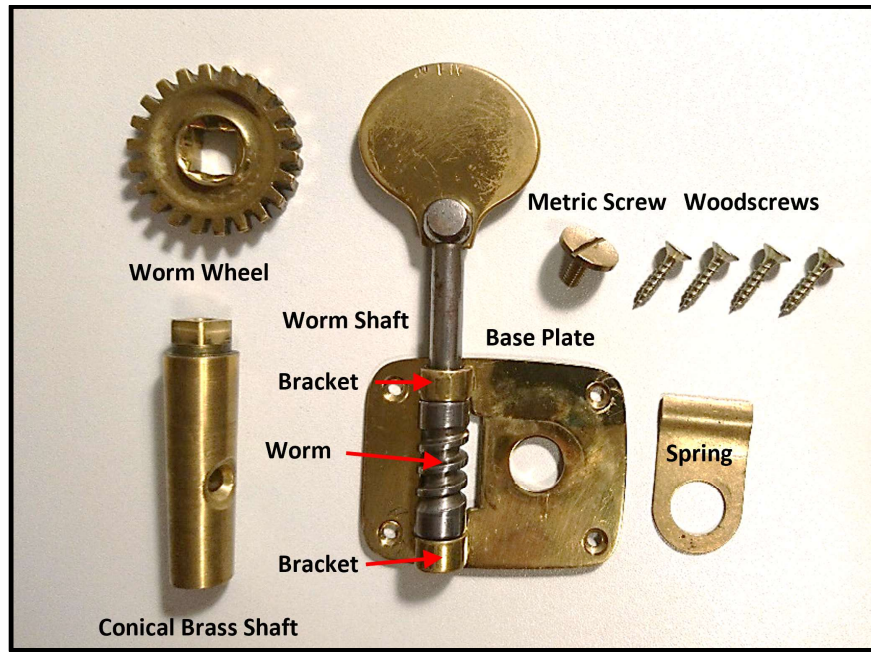
Figure 3: Tuning Gear, Individual Parts [1]

Torque is transmitted by a square hole in the wheel matching the square end of the conical brass shaft. It also has a drilled hole to catch the end of the string. The spring is not visible from outside. It is positioned between base-plate and worm wheel with the lip under the worm to arrest the axial position of the brass shaft in the conical bores.
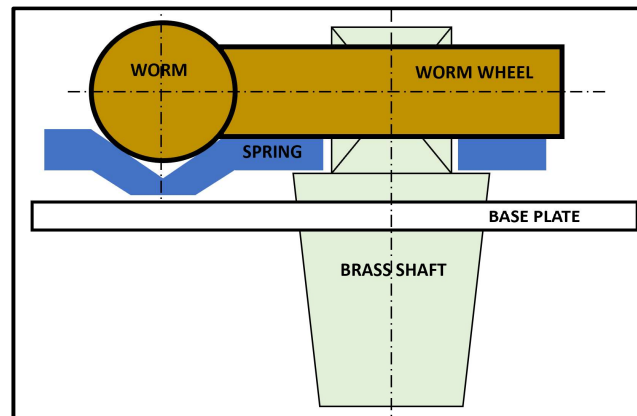
Figure 4: Spring Position

Design strategy

Simpson [2] [3] [4] describes the possible options between simple replication (crawl or restrictive DFAM), adaption (walk) or optimization (run, opportunistic DFAM). Replication will use exactly the same geometry as the given part. No benefits will be generated except for speed. Parts will have a non-optimal geometry for AM and suffer from manufacturing defects resulting in a worse quality than the original part. Optimization is based on the given geometry but allows modifications to avoid the restrictions resulting from the AM process (e.g. overhangs, wall thicknesses). Applying design tools such as topology optimization, lattice structures or biomimicry to create a specific AM-geometry will result in a totally different part.
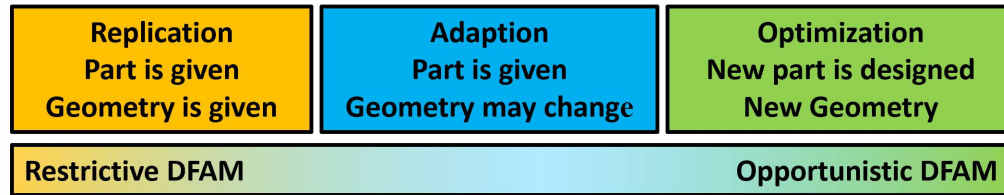
Replication Part is given Geometry is given	Adaption Part is given Geometry may change	Optimization New part is designed New Geometry
Restrictive DFAM		Opportunistic DFAM

Figure 5: Design Strategy [4], [3]

The tuning gear is used in a very conservative and non-engineering environment. Carving curved wooden structures manually has been the predominant manufacturing method for a double bass for centuries. Introducing innovative manufacturing methods may not be welcomed by all luthiers, users and customers. Sound posts for string instruments made from carbon are available since many years, but have yet failed to penetrate the double bass community in large numbers [5]. Topology-optimized structures or advanced materials like carbon or thermoplastics may be therefore not be perceived as absolutely desirable.

Costs issues are driving our decision towards inexpensive FDM-printers and therefore the application of thermoplastic materials like PLA, PETG, or Nylon will have to be accepted. Two steps will be taken:

- Explore replication by studying the mechanical feasibility of using thermoplastic materials:
  - o Calculation of the Hertz Pressure between the gear flanks
  - o Scan and print the worm wheel
  - o Assess the expected wear
  - o Evaluate results and in case of complications take the
- Adaptive approach by
  - o Defining case-relevant design rules
  - o Apply these rules to create an improved 3D CAD model
  - o Print the improved tuning gear assembly
  - o Evaluate the improved model

Simpson however refers to a single part. The tuning assembly requires the expansion of our design horizon from a part to an assembly. Analysis of the structure, i.e. considering all possible interfaces between the individual parts and their interactions will increase complexity, but also the number of possible starting points for optimization.

Replication

The mean Hertz Pressure between the gear flanks and the wear rate have been identified as the critical issues.

Applying the classic engineering formulas for worm gear flank pressure [1, p. 16ff] [6, p. 792ff] will allow to determine the Hertz Pressure. Input force is the maximum pull of the string, the String Force F_S. String manufacturers publish maximum string pull of their strings. Georg [1] has evaluated the published forces by two string makers (Thomastik and Pirastro) and calculated the resulting maximum forces:

| Maker	String Pull - Given Values	Factor	Resulting Maximum String Force F_S in [N]
Pirastro	13,8 kp – **35,1 kp**	1 kp = 9,806 N	344,2 N
Thomastik	24,5 kg – **39 kg**	F = m g, g = 9,81 m/s²	382,6 N

Considering a safety factor of 1,15 a Maximum String Force of $F_{Smax} = 450$ N will be applied. The diameter of the brass shaft is $d_s = 14$ mm and the diameter of the worm wheel is $d_p = 30$ mm resulting in a force at the gear flank of $F_P = 210$ N.
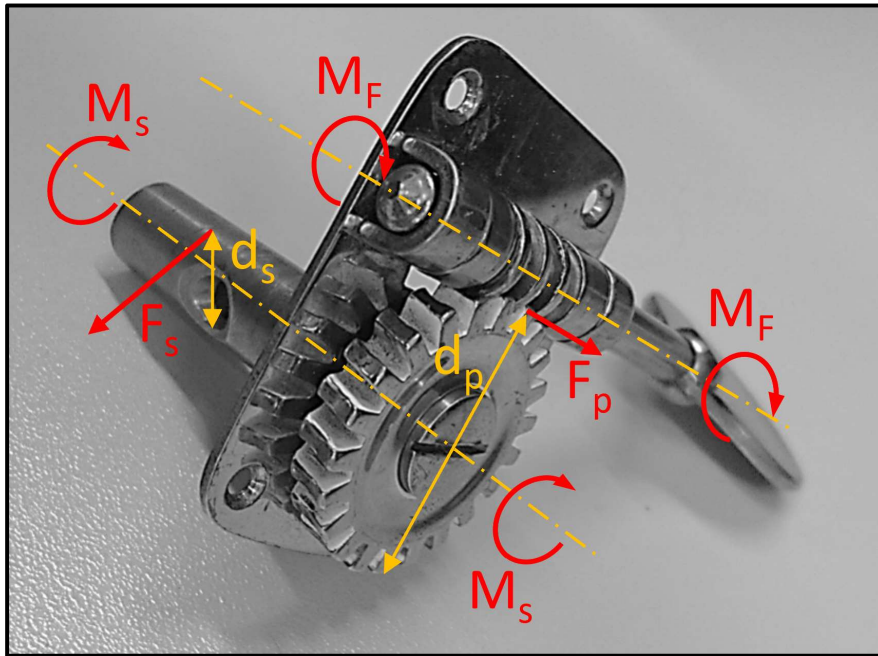

Figure 6: Diameters, Forces and Moments [1]

The resulting mean flank pressure is now calculated to be $P = 33,84$ N/mm². This is within the permissible compressive strength ranges of most thermoplastic PLA filaments. Wear properties now have to be assessed in a practical test using a scanned wheel. The scan of the worm wheel is done using an GOM ATOS Core 3D scanner.
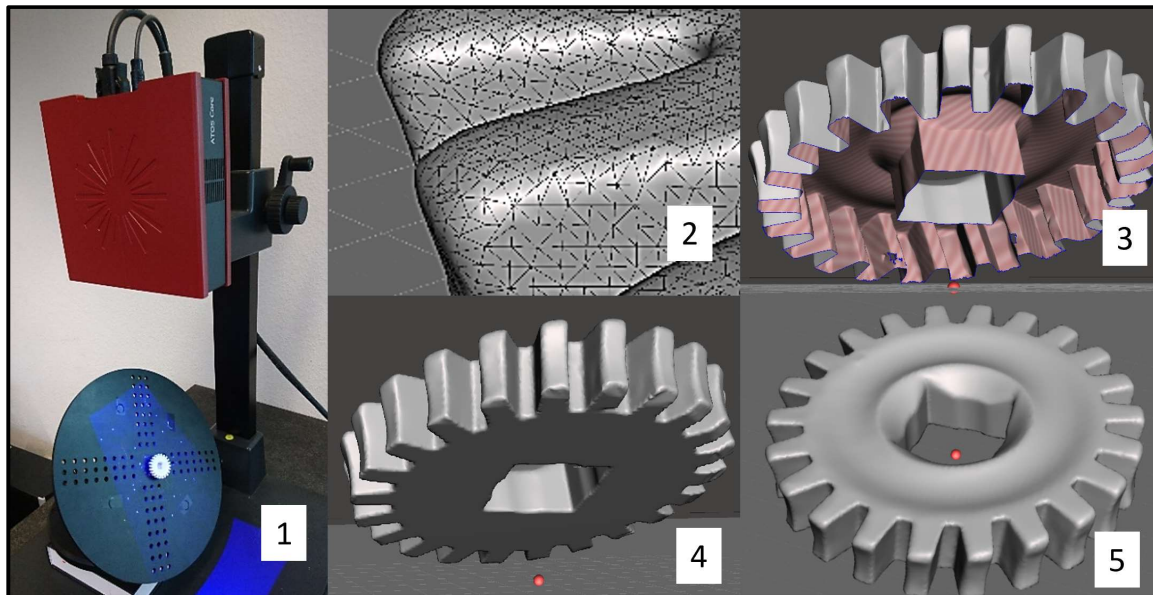

Figure 7: GOM Scanner (1), Triangulated Surface (2), Shell (3), Filled Model (4), Smoothed Model (5)

The scanned triangulated surface (2) is cured of faults and filled (4) using "Autodesk Meshmixer". Slicing of the smoothed model (5) with "IdeaMaker" reveals the disadvantages of replication by scanning: the symmetry of the scanned model is not exact and the shapes of the individual teeth are not identical as they would have been with a newly generated CAD model.
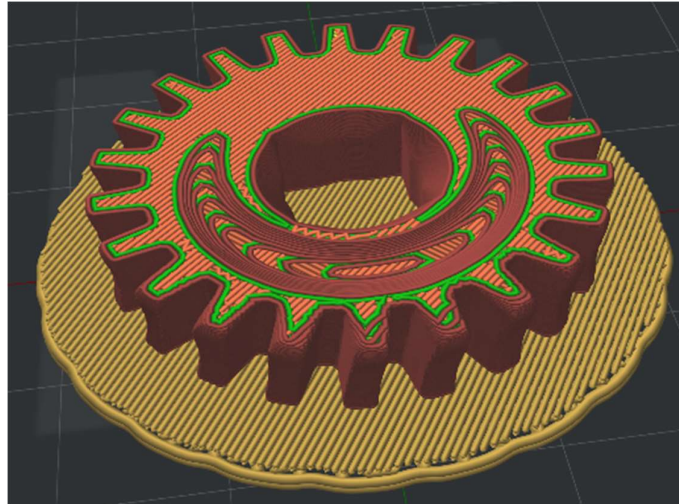

Figure 8: Non-Symmetric Sliced Scan-Model

The wheel is printed on a RAISE 3D Pro 2 printer in PLA (layer thickness 0,05 mm, speed 60 mm/s, filling 100%) and then mounted into the original gear assembly.
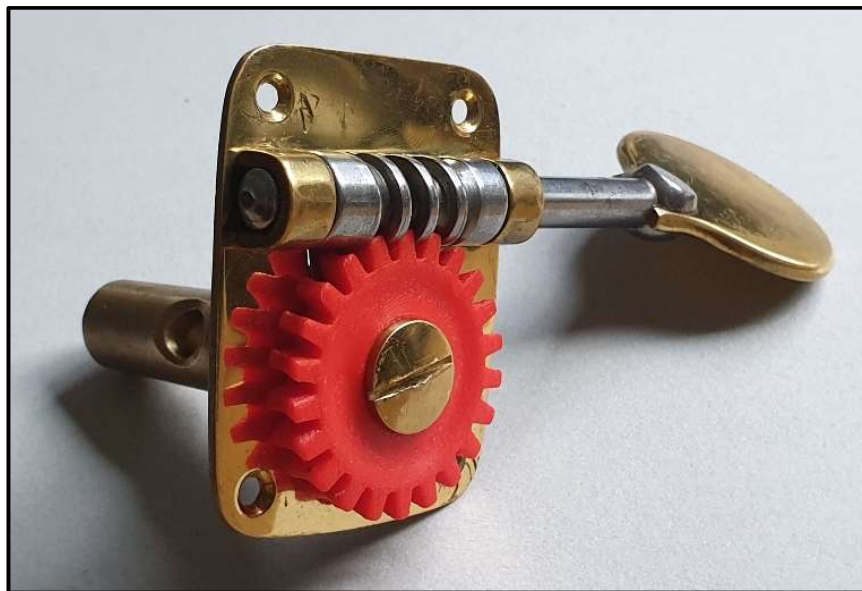

Figure 9: Rebuilt Assembly

First handling experience is smooth. Play between the flanks is not detectable and full turns show no variation in friction between wheel and worm. The rebuilt assembly is tested at 450 N simulated pull using a simple mechanical setup with a lever and a water filled bucket creating the desired load levels.
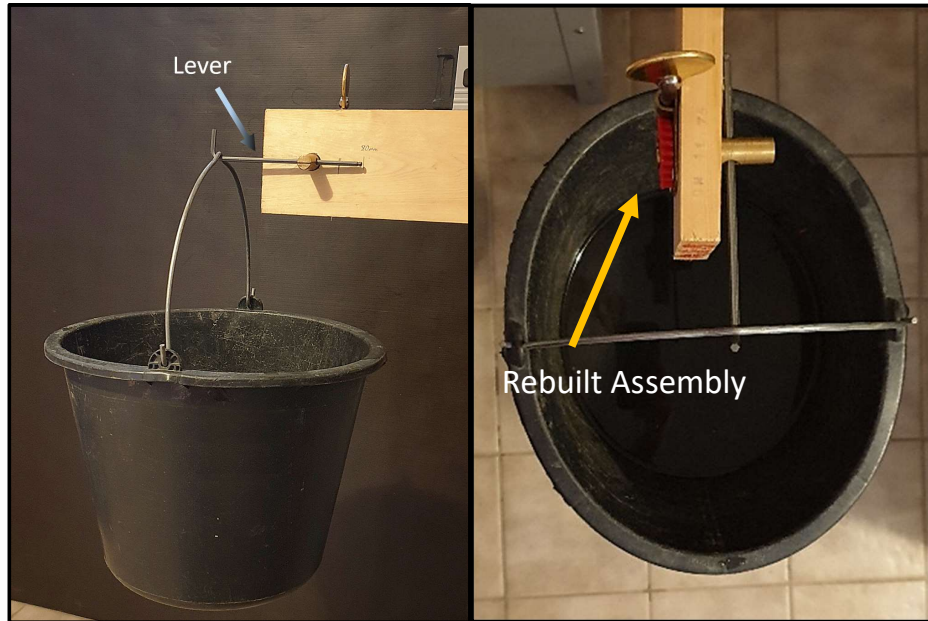
Figure 10: Mechanical set up

After application of a static load with the equivalent of F_S = 450 N no visible damage was detected. Elastic deformation started at approximately 250 N. Reducing the load back to zero revealed a permanent plastic deformation starting at approximately 335 N. Handling was checked by turning the handle twice in each direction by 180° at 450 N. Handling was smooth and even. After disassembling the wheel, a visual inspection reveals clear wear marks on the flanks of the teeth.
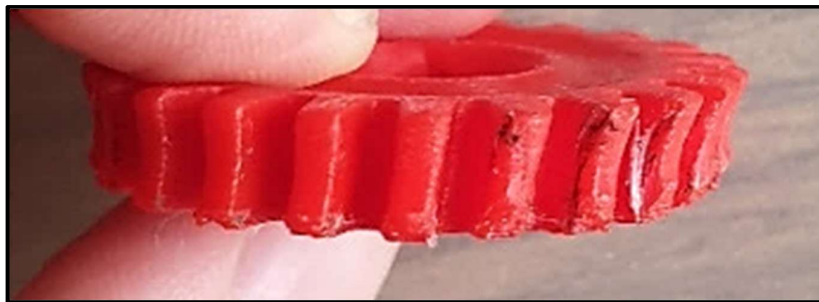

Figure 11: Wear Marks PLA [1]

Considering multiple daily tuning operations, the replication using a PLA wheel and a steel worm does not promise the necessary wear resistance and as next steps alternative materials are evaluated for all parts and the adaptive approach is taken.
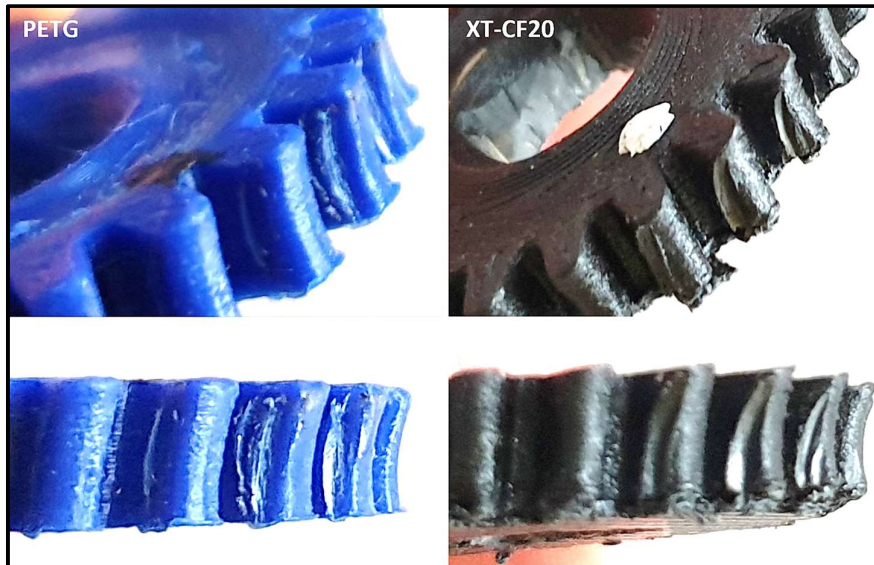
Alternative Materials

Two alternative materials are tested: PETG and XT-CF20. PET is known to be very durable from plastic bottles. PETG is a PET modified with glycol in order to improve printing characteristics. XT-CF20 is a carbon fiber filled filament for extreme loads. Wheels from both materials are printed on a Prusa Mark 3 (PETG) and on an Ultimaker 2+ (XT-CF20). Different printers were used due to availability of printers and filament.
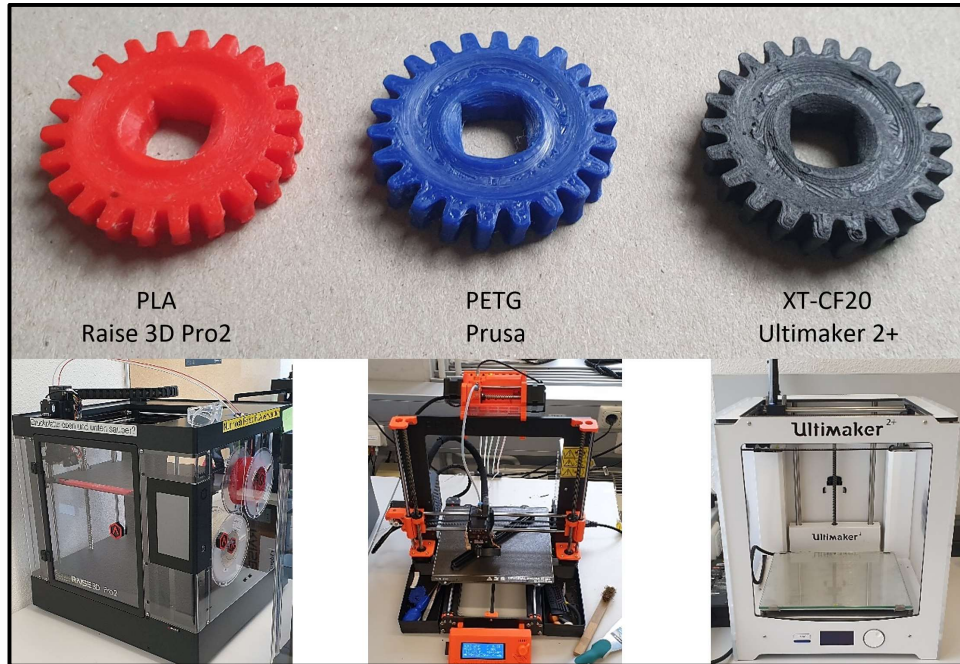
Figure 12: PLA Wheel and Alternative Materials and Printers

Both wheels were mounted into the gear assembly and subjected to the same tests as the PLA-wheel.

Figure 13: Wear Marks of PETG and XT-CF20 Wheels [7]

In a close visual inspection PETG shows by far the smallest wear marks of the three materials and is therefore selected as alternative material.

Design Rules

Design rules and methods have always been part of any engineering efforts and have formed the basis for effective designing. Gericke [8, p. 50] lists design rules, such as analysis, abstraction, synthesis, specific questioning, negation and redesign, forward and backward stepping as universally applicable rules.

More specific rules refer to the design's suitability for manufacturing processes, assembly and of course for operation according to the part's specification. Such rules have been taught to many students and are anchored in the thinking of generations of engineers. The introduction of AM as a new manufacturing technology did have an impact on these rules. Consequently, many existing parts and assemblies - like the worm gear assembly - which have been designed before AM, have been designed using partly obsolete sets of design rules. In our case the difference between "crawl" and "walk" also means an upgrade to the set of applied design rules by taking AM into account. Out of the many strategic design rules, three basic rules have proven to be very effective when applied to the overall design of the tuning gear assembly:

- Integrated Design, [8, pp. 338, 343]
- Elimination of Useless Parts,
- Negation of Assemblability [8, p. 51].

Integration is a design procedure which will enable an individual part to fulfill as many functions as possible thus reducing the number of parts. Differential design in contrast usually requires many parts, as each individual part fulfills one function only. The first step to integral design is the reduction of the number of parts. Fewer parts have a direct impact on costs and weight. Integral design has always been used as a means of reducing costs but at the disadvantage of creating a complex geometry, sometimes too complex for conventional manufacturing processes. Additive manufacturing enables further integration, lower costs and lower weight due to the simplified possibility of manufacturing complex geometries. "One part only" is the goal.
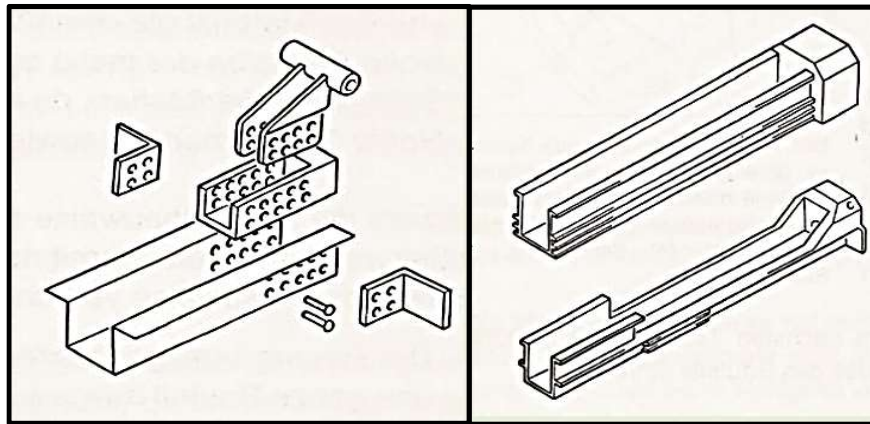
Figure 14: Differential Design vs. Integrated Design [9]

The Elimination of Useless Parts is possible if a part's function is not needed. The part improves the quality of the assembly but omitting the part will not seriously effect operation of the assembly in a negative way. These parts can be eliminated without integrating their function into other parts. Such parts are typically found in designs which have not been subject to engineering and commercial optimization.

Assemblability (Mountability) has been one of the most common rules to be observed. AM has set new standards which allow us to widely negate this rule. The build-up in layers and undercuts allows structures which cannot be assembled but which can be manufactured additively.
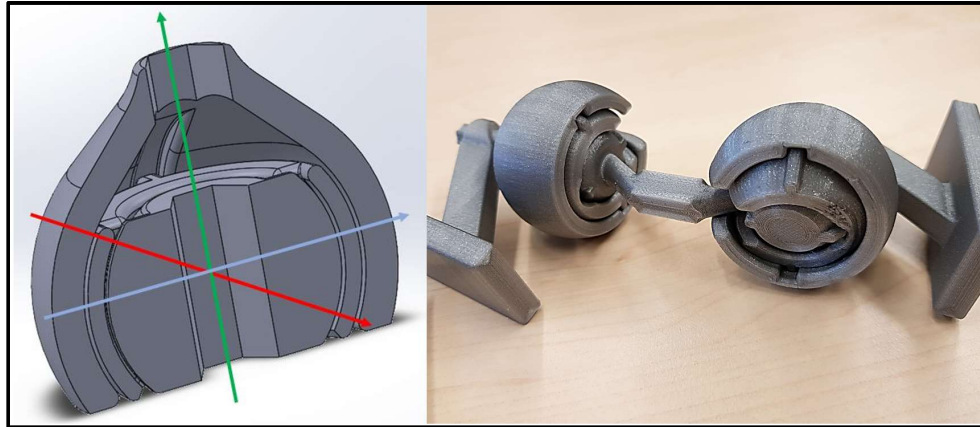
*Figure 15: Drive Train with two „Non-Mountable" Universal Joints [10]*

Application of these rules will simplify the structure of the assembly, but increase the geometric complexity of the (fewer) parts. It is the goal of this study to increase the parts' complexity to an extent, that subtractive manufacturing processes will not be applicable anymore and AM will be without alternative.

Figure 16: Assembly: Complexity vs. Manufacturing Process

Structural Analysis and Application of Design Rules

Abstraction of the existing gear assembly results in identifying seven parts (P1–P7), 10 internal interfaces (INT1-INT10) to other parts and four external interfaces (EXT1-EXT4). External interfaces connect the gear assembly to the bassist's hand or to the double bass. Modifications to the double bass and the human hand are undesirable. Therefore, redesign of these interfaces will not be feasible. Consequently, the internal interfaces between the individual parts will be the starting points for the adaption to the AM manufacturing process.
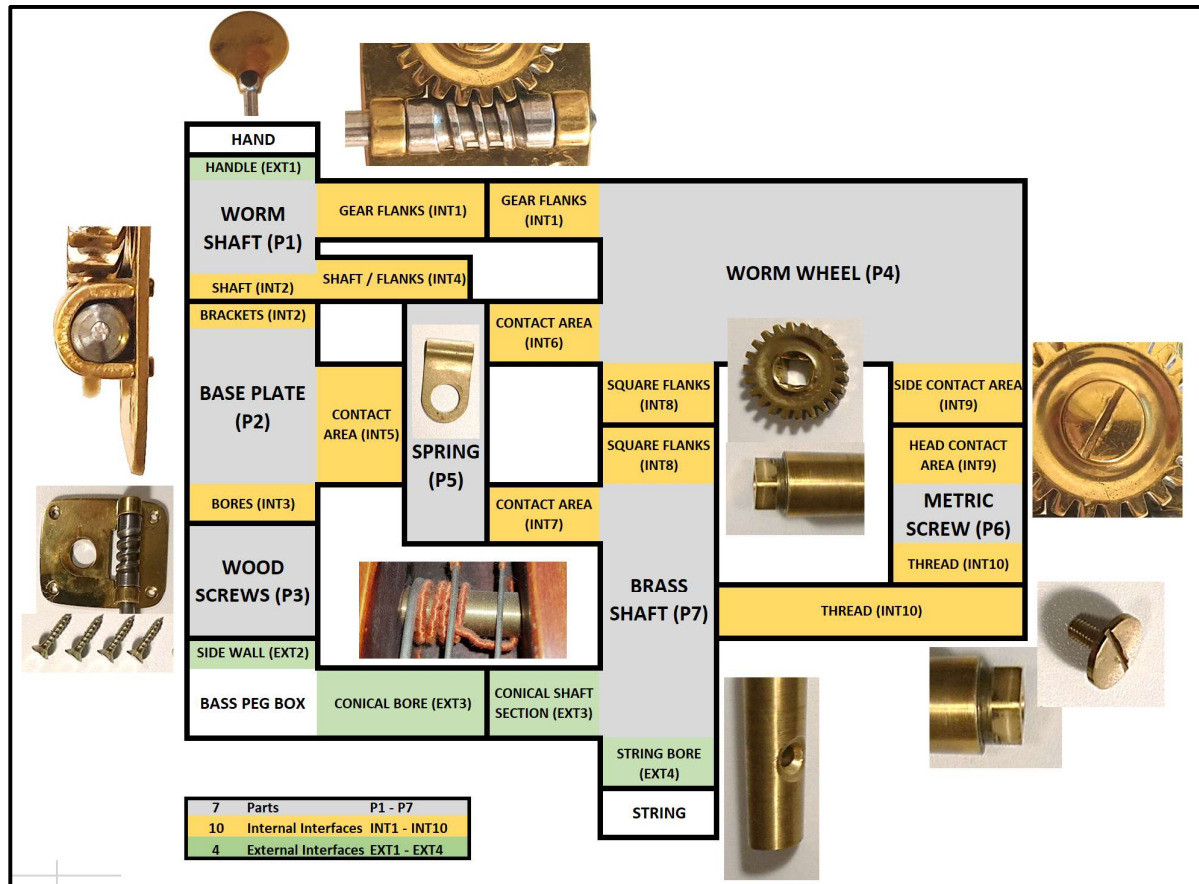
Figure 17: Structure of Existing Gear Assembly

Elimination of useless parts usually results in the integration of their functions into remaining parts. Eliminating and integrating therefore can rarely be applied separately. Knowing that we may neglect assemblability will make room for an even higher degree of integration.

Step 1: Fixing the axial position of the brass shaft must not necessarily be achieved using a spring. We can integrate this function into other elements later. The spring (P5) becomes obsolete and is eliminated.

Step 2: The metric screw (P6) can also be eliminated. Conventionally manufacturing a gear wheel and a shaft is done by turning with minimized chip volume resulting in two separate parts: wheel and shaft. Additive manufacturing allows shaft and wheel to be manufactured as one part resulting in the elimination of the screw and its functions as well as eliminating the square flanks between shaft and wheel. The contact area for the spring is lost, but serendipitously the spring was already eliminated in step 1.

Step 3: Integration of the base plate (P2) into the worm wheel / brass shaft will further simplify the assembly reducing the number if parts to three and the number of internal interfaces to three.
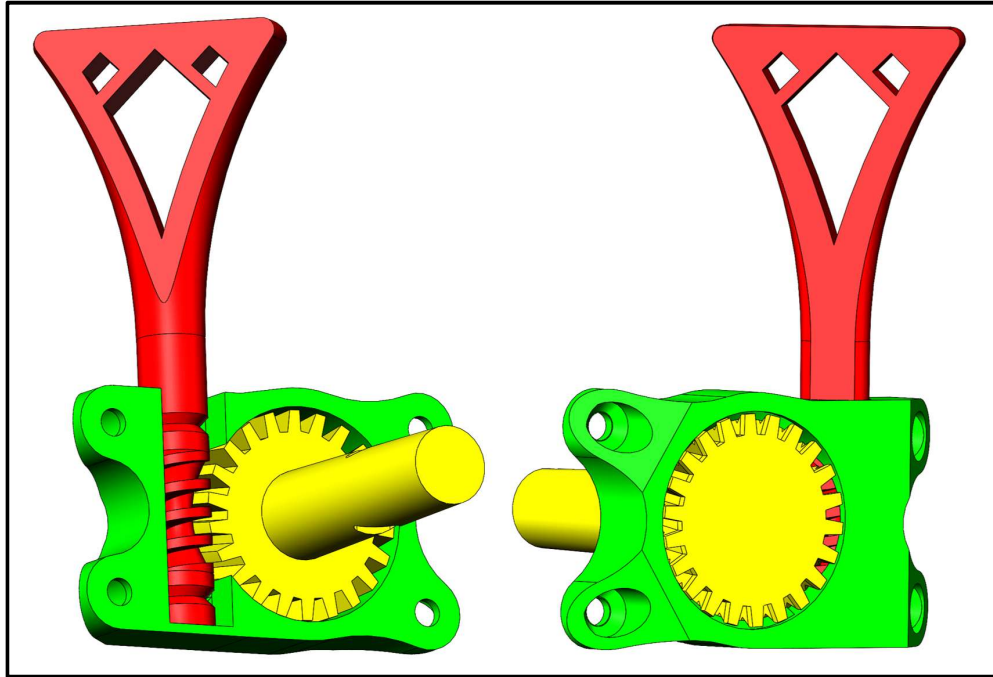
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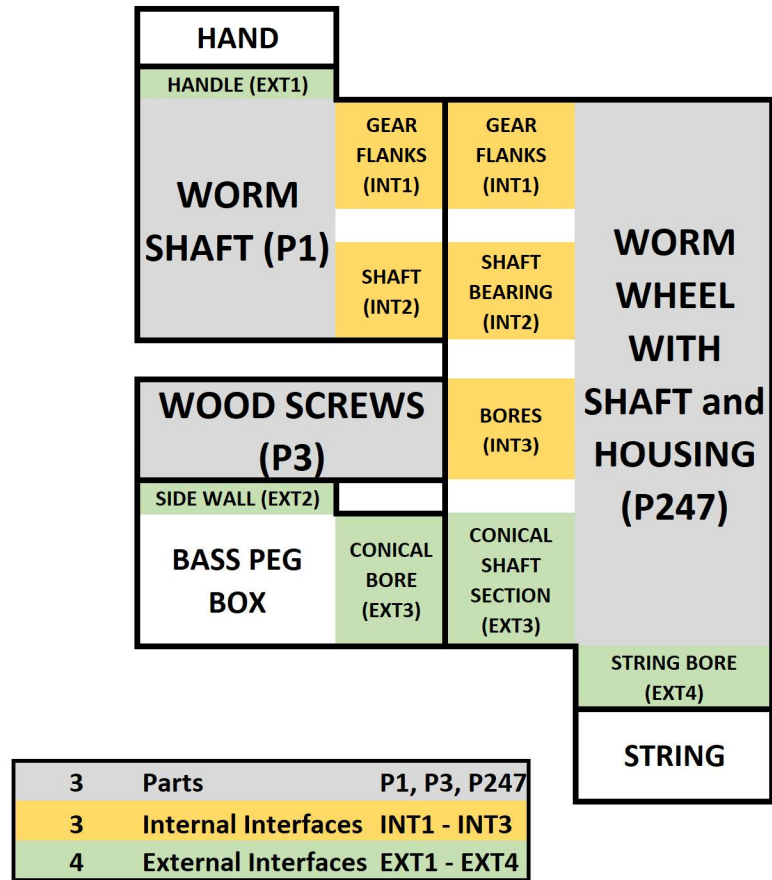
Figure 18: Final Simplified Structure

Adapted Design

Excluding the wood screws the adapted design features three parts of which two are printed together in a single sub assembly:

- Worm shaft with integrated handle (red)
- Worm wheel sub assembly consisting of housing (green) and integrated worm wheel with attached shaft (yellow)

Figure 19: CAD Model of Adaptive Design

The interface to the pegbox side walls using the wood screws is not changed. The worm wheel is held axially by a radial outcrop and radially by the inside diameter of the housings opening, effectively eliminating the spring and all parts connecting wheel and shaft. The once spherical bore in the shaft becomes triangular to enable printing without support. The teeth of the worm shaft are flattened on the underside because printing direction requires a larger contact area to the build plate and at the same time it eases assembly with the worm wheel gear.
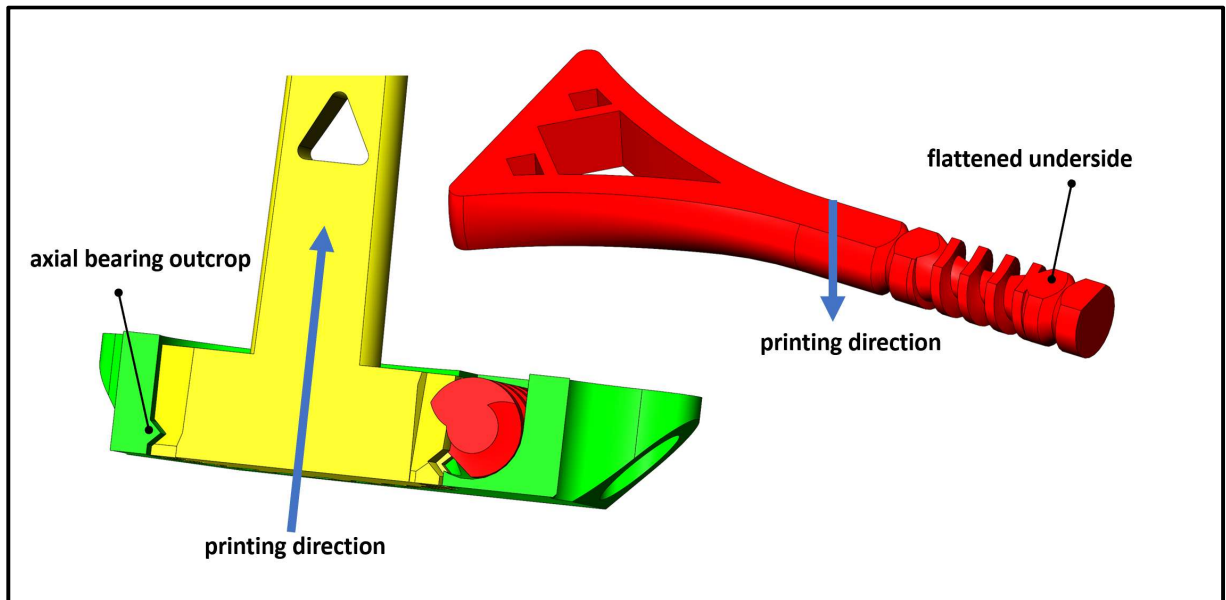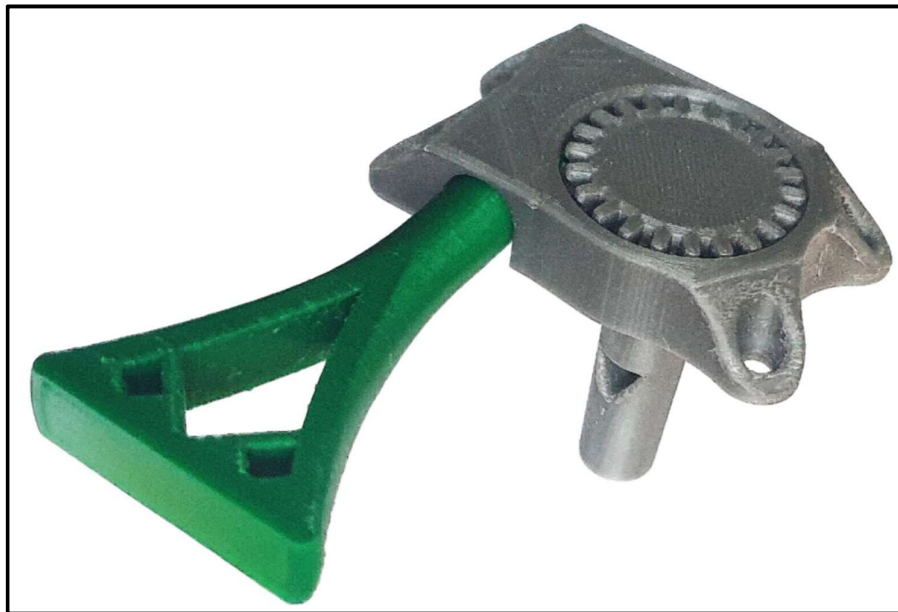

Figure 20: Details of Worm Wheel Assembly and Worm Shaft

The worm shaft also features the axial bearing outcrop. Radially it is held in position through the conformal bore in the housing.
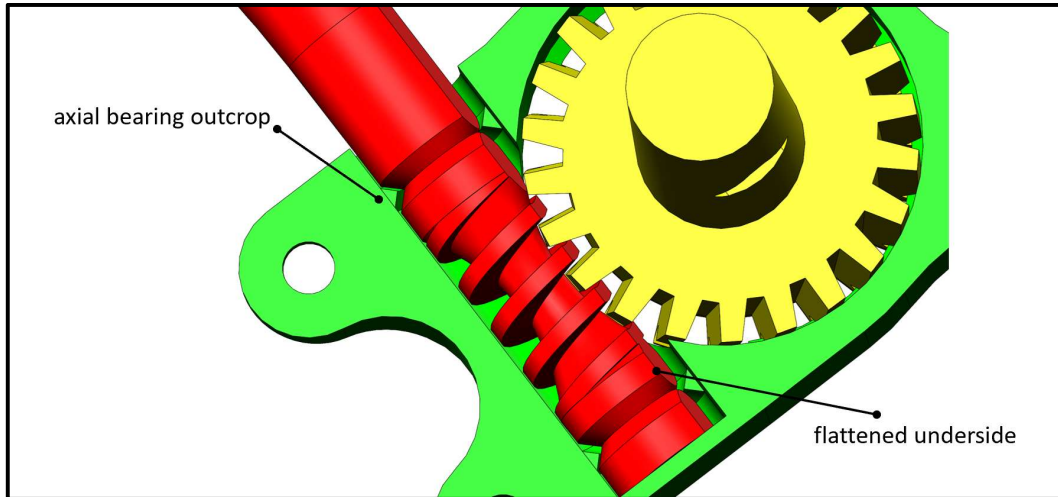
Figure 21: Shaft – Wheel Assembly Details

Figure 22: Assembled Prototype [7]

Integration, Elimination of Parts and Negation of Assemblability have resulted in a large reduction of the number of parts. Structural complexity was widely reduced whereas geometrical complexity increased significantly necessitating an additive manufacturing process.

The prototype was printed in PLA using an Ultimaker 3 with a 100% filling and a layer height of 0,06 mm for the worm wheel assembly and 0,04 mm for the worm shaft. Total printing time was approximately 20 h using 24 g of filament resulting in material costs of 0,40 € for one assembly (PLA). Even using PETG the goal of 25 € or less has been achieved.

Outlook

The prototype is currently evaluated in the field by a luthier and preliminary feedback suggests that the overall functionality is good. Accuracy of dimensions and quality of surfaces need to be improved to enhance precision. Therefore, an improved CAD model with a precise

globoid gear will be created and dimensional precision and wear characteristics using an SLA model will be evaluated.

Acceptance of thermoplastic material and functional design will have to be evaluated with users. To improve acceptance, it will be helpful to provide individualization of the handle design, allow for specific transmission ratios for each string to achieve tuning up or down by one half tone in pitch with a 180° degree turn of the handle, use various colors for children's basses or brass colored filament.

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