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Design for the Combination of Additive Manufacturing Parts With Products Already Developed – An Hybrid Design Approach

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ABSTRACT

The geometric freedom allowed by additive manufacturing (AM) has driven the development of products based on human-centric design through functional and aesthetic customization. The combination of personalised AM parts with products already developed is a disruptive and flexible approach that may create optimized product-user interactions. For this, critical comprehension on the manufacturing process is required to ensure appropriate mechanical connection between the new and existing components of the product. This paper addresses a method for product optimization based on this hybrid design approach. A specific case of a musical instrument that was redesigned for greater ergonomic compatibility with users was considered to describe the sequential development steps.

Keywords: Additive manufacturing, Hybrid method, Design rules, Musical instrument

INTRODUCTION

Additive manufacturing (AM) comprises a set of versatile manufacturing technologies that enable the design, development and production of parts with highly complex geometries that could not otherwise be obtained (Hajare and Gajbhiye, 2022). This flexibility is propelling its use in the production of daily consumer goods and technical functional parts for a variety of industries (e.g., automotive, aerospace) (Hajare and Gajbhiye, 2022). Additionally, the potential of AM for mass product customization has led engineers and designers to overcome technological obstacles and therefore reach innovative developments which enable new interactions. These new interactions were somewhat achieved by different strategies that created the possibility to personalized products that, therefore, enhanced the performance of the user. These strategies where centered in: (i) the development of new products that were design from the evaluation of the problems and needs of the user, in their relationship with the product; (ii) by the development of add-ons that could be enclosed in the existent product, overcoming the major issues in the interactions; (iii) and, by resorting to the development of parts of the product that could be replaced by new optimized ones. All of these strategies prescribed AM as the manufacturing process to achieve the required goal, mainly since AM enables design freedom, fast manufacturing and the product/part personalization. This paper focus on main topics of an ongoing research with the overall aim of describing a method for non-conventional design and manufacturing processes for the development of hybrid products. It is centered in the design and manufacturing of individual parts of the product, that could support enhanced interactions by product personalization and the production through AM technologies. Therefore, in this paper it is discussed and presented the definition of the concept of hybrid products, the main issues involved in the concept and the production by AM. It is also presented the specific case of a musical instrument, with the main requirements for the development and, the method that was employed to overcome the challenges imposed by the AM process characteristics.

HYBRID PRODUCTS CONCEPT

Hybrid products was defined as products composed by two or more materials produced in a single process or by embedding inserts, by means of AM (Lima et al. 2017, Sampaio et al. 2019). In general, this concept was dedicated to the strategy of embedding external components in an AM build process that involved, (i) the design of a part with a specifically designed cavity to accept the external component, (ii) pausing the print in the "middle" of manufacturing process, (iii) inserting the external component into the designed cavity, and (iv) restarting the manufacturing over the inserted component. Past examples can be seen in the work of Meisel, et al. (2014), Willis, et al. (2012), Lima et al. (2017) and Sampaio et al. (2019).

More recently it was introduced the concept of hybrid products as a result of the combination of a hybrid manufacturing process based on the combination of AM processes with conventional injection moulding through overmoulding steps (Sampaio et al. 2022). This concept is related to the innovative aspects of AM processes which, when explored, can increase and augment conventional manufacturing an facilitate the next generation of customized products. The combination of processing technologies or hybrid manufacturing is a solution to overcome obstacles by combining processes advantages and overcoming product limitations (Sampaio et al. 2022).

The possibility of combining AM parts with products already developed also emerged on a hybrid approach. It supposes the redesign and production of individual parts of the product, taking advantage of the geometric freedom of the additive fabrication, for effective integration into existing products. This concept is a modern solution for the production of spare parts needed for repair and maintenance operations. Through this method, a more flexible and efficient supply chain is guaranteed avoiding logistical constraints of physical inventories. The integration of AM parts into conventional products also enables personalization and, therefore, the adaptation and optimization of the product to specific users, which is particularly important for tangible interactions, where multiple pushing, grabbing, and holding movements are implicit. This personalization gives added-value to products, which is considered a differentiating factor for most companies (Torn and Waneker, 2019).

One particular characteristic of all these concepts is that the need to think on design for assembly is presented. These non-conventional procedures require in-depth understanding on the mechanical connections and fittings existing between the AM parts and the product already developed to ensure aesthetics and functionality in the end. Comprehend the geometric and dimensional accuracy enabled by AM, which is dependent on the technology, equipment and manufacturing parameters is, therefore, a fundamental topic addressing the hybrid method (Roth et al. 2022). Of all AM technologies, Selective Laser Sintering (SLS) was elected for this study due to the higher geometric flexibility it allows (Ben et al. 2017).

SELECTIVE LASER SINTERING

Based on the Powder Bed Fusion concept, SLS was one of the first AM technologies available on the market (Gibson et al. 2010; ASTM, 2012). In SLS, a laser source is used to fuse powder particles that are successively deposited over a building platform to create parts from a digital CAD file (ASTM, 2012; Lopes et al. 2021). In regions of the powder bed where no sintering or fusion is programmed, the powder particles remain loose to support the parts being produced, which gives SLS high design flexibility and consistent surface quality comparing to other fabrication processes (Ben et al. 2017). To enable designers to take full advantage of such inherent geometric freedom within the process capabilities and constraints, several design guidelines for SLS are being established and updated over the years (Allison et al. 2019). For laser-sintering of conventional polymeric materials, such as polyamides, standard guidelines suggest the design of parts with minimum wall thickness of 0.7 mm, minimum holes diameter of 1.5 mm, minimum features size of 0.8 mm and minimum clearance of 0.3 mm for moving parts (Ben et al. 2017; Minetola et al. 2020). In turn, as this technology resorts to powder material that is exposed to successive heating-cooling cycles and complex energy phenomena, the manufactured parts are prone to shrinkage and warpage and, consequently, they depict dimensional inaccuracies in most cases (Singh et al. 2019). Studies in this field have shown that there is a series of printing characteristics in SLS which prevents the production of parts with desired dimensional and geometric characteristics, being necessary to in practice adjust theoretical design guidelines (Allison et al. 2019; Minetola et al. 2020). Trial runs using test artifacts with various features with different sizes are often necessary to ultimately fabricate parts with a tolerance suited to their application, depending on the settings defined for each building job (Weiss et al. 2018; Singh et al. 2019). The geometry of the part is a critical issue in SLS with well-known impact in the manufacturing process. The geometry of the part defines the cross-sectional area in each layer which influences the duration and number of times that the laser beam acts on the surface of the powder bed, and, therefore, the thermal gradient created during the manufacturing. Undesired dimensional deviations are mostly observed in thicker parts, i.e., with larger cross-section, as they retain more energy during the manufacturing process, as opposed to thinner parts that guarantee greater energy dissipation (Ben et al. 2017). For instance, the clearance needed to design moving parts is dependent on their geometry, as the value needs to be gradually increased with the increasing of the wall thickness due to the phenomenon of secondary sintering observed in surrounding powder particles (Ben et al. 2017). Owing to the complex dependence of the dimensional accuracy on a variety of factors, more research to understand the tolerances enabled by the manufacturing process in each building job is necessary as it is of key importance to produce near-net shaped parts by SLS (Minetola et al. 2020). Based on exploratory research, methodologies describing fundamental development stages may be established with the objective of helping engineers and designers to conceive products with dimensional and geometric accuracy suited to the application purpose. As aforementioned, this is essential condition to create hybrid solutions by combining AM parts with others produced with different fabrication processes.

METHOD FOR PRODUCT OPTIMIZATION

This section presents the method involved in the design, development and production of hybrid products obtained through the combination of optimized AM parts with products already developed. The method consists of six main steps, from preliminary product and user needs understanding until prototyping, testing and final assembling (Figure 1). A specific case-study was used to in detail describe the development steps, highlighting the sequence of activities embracing each one.

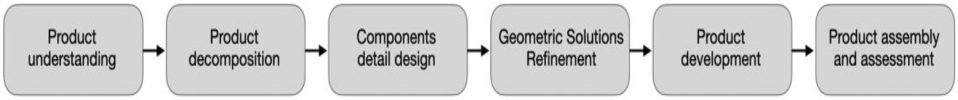

Figure 1: Steps of the product optimization method.

Case-Study – Background

Musical instruments are products in which additive manufacturing has a major field of applications. Although some developments have already been done, optimized solutions to overcome interaction difficulties have not yet been fully researched and achieved. Interaction difficulties are ergonomic incompatibilities that increase users' efforts to push, grab, hold, and therefore play the instrument. This is the case of optimizations, or customizations, to instruments to be used by people with non-conventional usage (e.g., disabilities), thus this case-study is centered on the design and development of a trumpet that can be played differently from the conventional use (i.e., with a different hand or with just one hand). A trumpet is an instrument of force, whose air pressure and speed, embouchure force, and tube length are fundamental pillars of its personality. The instrument is played with both hands, where the right hand is responsible for the musical notes and the left is used to support the instrument. In terms of design, although the major advances in terms of manufacturing processes, very little evolution has been made to the instrument. A trumpet is a musical instrument of wind, generally produced in brass, with a pipe of 1 to 2 meters, being the smallest instrument in the metal family, but the one that has the most acute and penetrating register of all instruments. The instrument is a cylindrical metal tube three-quarters of its length, becoming conical along the length and ending in a bell.

In the next sections the main issues and objectives concerning the design of an optimized trumpet based in the concept of hybrid products and produced by SLS is presented and discussed.

First Step – Product Understanding

The first step of the method is focused on a complete understanding of the product, both in terms of form and function. Comprehension on these topics can be achieved by resorting to physical or digital models of existing products and by collecting information from users' perspective and experience. In the specific case of the musical instrument, main targets included understanding the functionality of the trumpet, typical interaction with the users, main components and its function (e.g., mouthpiece, pistons, tunning slide, valves), and requirements for sound production. Through a comprehensive analysis and critical observation and interaction with the instrument, some potentialities for product optimization were identified. In this regard, it was found that standard geometric configurations are ergonomic for players who press pistons for the musical notes with the right hand and hold the instrument with the left hand. For left-handed players, holding the trumpet with the right hand is a difficult task as the second valve restricts a comfortable interaction with the instrument. This interaction may also be hindered by a more difficult access to the pistons. The development of a new design concept enabling the use of the trumpet with just one hand, either right or left, would therefore overcome such typical limitations of players, through the generation of novel inclusive design solutions. In this initial step of development, a commercial trumpet was measured (main body and accessories) and a digital model was created using CAD software, accordingly.

Second Step – Product Decomposition

The second step comprises the definition of the architecture of the product, through its decomposition in various functional components (Ulrich and Eppinger, 2015). This enables to, in detail, understand the individual components and their relative contribution to the functionality of the product, and also allows for the possibility of a modular, multifunctional or multi-material production, minimizing common manufacturing constraints. In this activity, all components composing the trumpet were identified and analyzed separately and as part of an assembled product. Some mandatory conditions for the proper functioning of the instrument were identified, namely (i) critical dimensions of functional constituents and (ii) the need to use metallic materials in the mouthpiece and pistons. The decomposition of the production in several parts demonstrated that the optimization of the product would involve redesigning the central region of the pistons with which the user directly interacts.

Third Step – Components Detail Design

The design of various geometric solutions with different tolerances is performed in the third step of development. The main purpose of this analysis is to identify adequate tolerancing for the mechanical connections established between the new and existing components of the product and the capacity of the manufacturing process for accurate reproducibility, depending on the processing settings (i.e., part orientation, process parameters, material, etc). Considering that the main goal of the work is to redesign the central region of the trumpet maintaining the existing metal pistons, it was necessary to identify the tolerances allowed by the AM process in order to ensure proper sliding between the components while ensuring acoustic insulation. Thus, real-scale tubes with clearance varying between 0.25 - 1.25 mm were designed and produced by SLS with Polyamide 12 in an EOS P 396 equipment (Figure 2).

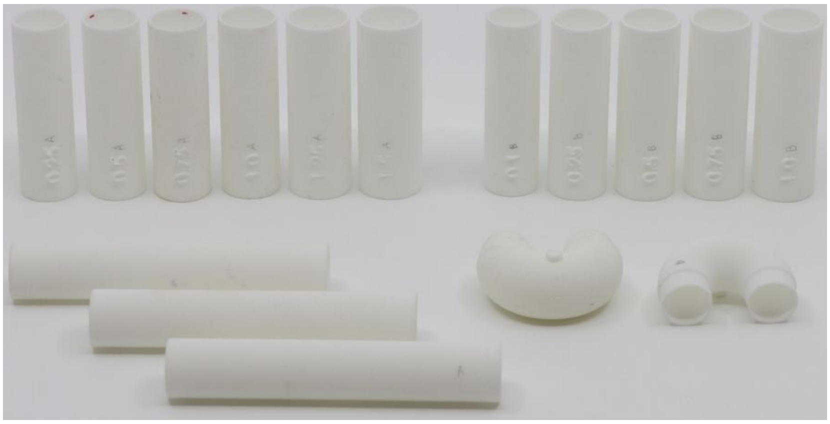

Figure 2: Real-Scale tubes with different tolerances.

Fourth Step – Geometric Solutions Refinement

This activity involves the testing of various geometric solutions of the product, in order to infer reliability and identify necessary changes and new design iterations. Assembled components of the trumpet were evaluated and the most appropriate geometric solutions were identified, resorting to draft versions of the instrument manufactured by AM. The fitting between the polymeric prototypes and the existing metallic parts was evaluated by testing the trumpet in real conditions (Figure 3). The sound produced by the trumpet, conditioned by the clearance of the sliding components, was also evaluated in this stage.

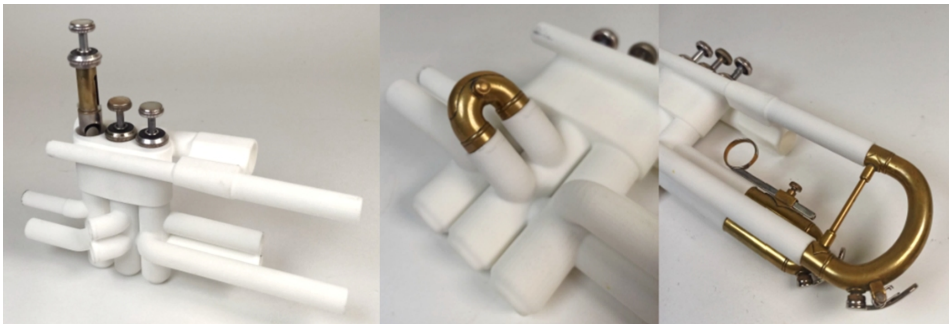

Figure 3: Hybrid product test assembly.

Fifth Step – Product Development

This activity consists in the development of the 3D model of the product to be produced. The model should contemplate data acquired from the previous activity with regard to clearance and tolerancing of mechanical connections and standard design rules for the specific AM technology. Thus, once established the tolerances between sliding elements and functional connections, new design versions of the product were developed focusing on the identified optimization purpose, viz., the adaptability of the trumpet for disable people and for both left and right-handed players. With a draft version of the main body of the instrument manufactured by AM, usability tests were performed to identify ergonomic problems in the interaction with the user (Figure 4).

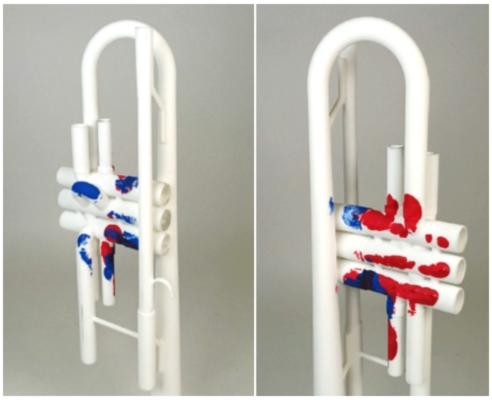

Figure 4: Usability tests (blue: right hand; red: left hand).

Based on the results obtained from the usability tests, there was developed a product with a support surface for holding the trumpet avoiding the direct contact of the palm of hand with the second valve and a smoother tubes profile providing greater fingers grip and enhanced handling comfort (Figure 5). The trumpet finger hook was also redesigned aiming to ensure greater adaptability to different users. By implementing these modifications, it was possible to reduce the mechanism from four individual parts to just one functional unit.

Figure 5: Details of the developed hybrid trumpet (3D CAD render).

Sixth Step – Product Assembly and Assessment

The assembly of the product by combining optimized AM parts with the existing components is the final step of the hybrid method. The assembly process allows to validate the previous development activities with the obtention of a functional product in its complete form. In this stage, the final version of the hybrid trumpet was assembled and compared with intermediate design solutions (Figure 6). The developed musical instrument was produced by SLS and integrates several original parts (e.g., mouthpiece, pistons, etc.) to ensure mechanical functionality and quality sound production. By including an optimized hand support structure and an adapted trumpet finger hook, it was created the possibility to hold the instrument with just one hand, contradicting ergonomic incompatibilities of conventional solutions.

Figure 6: Intermediate (black) and final (red) versions of the developed hybrid trumpet.

CONCLUSION

The implementation of a hybrid design approach as a means of adding value to existing products was demonstrated in this work by combining AM parts with conventional trumpet components, with the aim of ensuring an optimised instrument user experience. The methodology employed to understand the problem and user needs, identify solutions and develop new concepts follows six sequential steps that have been described in detail. Fundamental activities are the product decomposition and designing of mechanical connections with appropriate tolerancing, which depends on the manufacturing process and part geometry. Once defined an appropriate clearance between the casing and pistons, the main body of the trumpet was redesigned in order to create a comfortable area for handling and playing the product with just one hand, either left or right, and a more ergonomic trumpet finger hook. The novel hybrid trumpet that was developed and produced evidences higher adaptability to different users, even people with disabilities, while minimize the hands tension that is felt by players after long periods of use.

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