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Top-Down Design Enables Flexible Design of Prosthetic Forearms and Hands

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Abstract

A service learning project where students learn and apply advanced CAD modeling techniques to the development of a parametric, fully customizable CAD assembly of prosthetic limbs is described. Engineering students, working with engineering faculty, designed and built prosthetic arms and hands using 3D printing for children in need within the local community. While existing CAD designs are available, customizing them to the very unique anatomy of users with missing or malformed upper extremities is a challenging process. One of the goals of this project was to streamline the customization process by customizing the prosthetic CAD models before the first part is printed. Top-down design is an advanced modeling approach that utilizes key parameters in a “skeleton” part to drive the size of all members of the prosthetic arm to greatly reduce customization time and allow nearly limitless customization. The educational goals of this project are to provide deep, applied learning of advanced CAD modeling (a key and broad mechanical engineering skill) techniques within the scope of a service learning project by harnessing the excitement and energy generated by this extracurricular project to amplify technical skill development. Project outcomes and perspectives from students and faculty are presented.

Introduction

Persons with malformed upper extremities have significant variation with some having functional wrist joints while other are limited to only elbow joint(s). Therefore, personalizing the fit of any prosthetic type device often requires significant modifications even if a proven design such as the UnLimbited Arm 2.0 - Alfie Edition [1] is available. These modifications are often done after parts have been fabricated and are an accepted part of the fitting process. It’s a general tenet of engineering that the sooner in the engineering process a change can be made, the quicker and cheaper it will be to fabricate [2]. For highly personalized/custom items such as prosthetics this effect is less pronounced but the effect remains. We detail here an extracurricular service learning project where students investigate, learn, and apply top-down design to the development of a highly flexible CAD design that will be used as the foundation for building customized prosthetics for community member having missing or malformed upper extremities.

This work was done at Eastern Washington University, a regional university primarily focused on undergraduate education with ABET accredited programs in Mechanical Engineering, Mechanical Engineering Technology, and Electrical Engineering. Most of our mechanical engineering courses are infused with hands-on learning opportunities and this extracurricular project maintains and expands this focus.

Background

The primary focus of the prosthetics utilized in this projects is for users who have missing or malformed upper extremities. As such, gripping and/or manipulating objects can be a challenge. A well designed and fitted prosthetic enables users to extend their reach; grasp or pick-up objects; and participate in activities (e.g. sports) that were unavailable or problematic before. A prosthetic arm, previously built and delivered by Eastern Washington University mechanical engineering students using an UnLimbited design [1] can be seen in Figure 1.

Figure 1. Prosthetic arm fabricated at Eastern Washington University using Unlimbited's design that inspired the current effort to develop a flexible, top-down CAD database

While additive manufacturing and 3D printing has been around since the '80s, the rise of affordable 3D printing got a kick start with Adrian Bowyer's open source RepRap project [3] and the expiration of some key Stratasys patents [4]. These events were foundational in bringing affordable, hobby grade extrusion-based 3D printers to anyone with as little as $200 and some patience. The design flexibility additive manufacturing enables is revolutionary but it is the low cost and relatively fast print speeds (for one-off items) that are key for our project. 3D printing frees users from many of the design constraints associated with injection molding (part draft), CNC machining (tool access), casting, etc. That said, like any manufacturing technology, there are still design rules that, when followed, will impact part strength, durability, build time, etc. The best practices for 3D printing part design are learned by students as they build, assemble, modify, and repair the prosthetics. Most additive manufacturing technologies continue to struggle with accuracy and repeatability but improvements continue to increase part quality. The 3D printer used for our prosthetic work is shown in Figure 2.

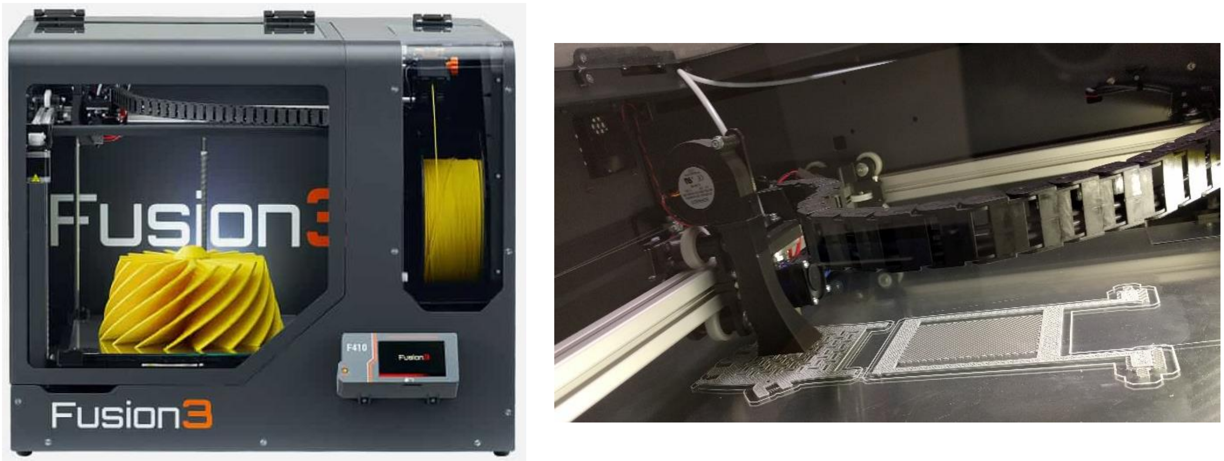

Figure 2. The Fusion3 F410 3D printer (www.fusion3design.com/f410-3d-printer/) and some prosthetic components printing in our lab

3D printing is a great fit for affordable prosthetics. The design freedom additive manufacturing technologies enables can simplify designs since multiple components can often be combined into a single component. The affordability and relatively short build time permits the ability to build and test several designs or replace parts quickly and cheaply if they break. The low tolerance of the parts is challenging but careful design choices can mitigate this. Foundational early work in realizing 3D printing potential when applied to prosthetics was done by Drew Murray and Stephen Davies of Team UnLimbited [1] and this project builds on their efforts.

Top-down design is an advanced design approach where a designer starts at the “top” (generally a top level assembly) and pushes design constraints down to lower level sub-assemblies and individual components [5], [6]. This technique enables highly flexible designs. For example, a designer could modify the overall size of the assembly and have all the underlying sub-assemblies and components automatically resize using carefully controlled/design parametric relationships (i.e. not simple scaling). Various top-level design techniques exist including skeleton models and assembly level features and each has its advantages and disadvantages. The primary top-down disadvantage is that inter-assembly and inter-part dependencies inherent to this approach can be cumbersome to create and maintain and you lose the ability to reuse components in other assemblies. Regardless, it’s a valuable design approach successfully used in many industries and a valuable skill for an engineer to possess.

Integrating engineering learning into projects that benefit the community is rewarding on many levels. Recipients get access to things that didn’t yet exist or they can’t afford while students develop new skills and gain valuable, resume building, experience. Further, students get real work experience working with “clients” while wrestling with balancing function, durability, fabrication time, cost, scheduling, planning, communication, ergonomics, user experience, etc. Finally, service learning projects build and reinforce strong relationships between educators, their administration, and their communities. From our experience, ideal service projects are ones that benefit the community or underserved groups, have challenging yet manageable design requirements, and modest budgets.

Project Objectives

While some existing prosthetic designs, like the one from Unlimbited, provide a somewhat customizable elbow actuated prosthetic forearm/hand design, there are many users needing prosthetics that are outside its narrow customization range. Thus, as an engineering university with access to commercial CAD programs, we will achieve extensive customization freedom by having full control of the CAD design. As such, the ability to measure potential user's specific forearm, elbow, and wrist geometry and more fully customize the prosthetic becomes possible. To leverage these resources, the primary goal is to create an easily modifiable design of a prosthetic forearm/hand that shortens the laborious fitting stage and can be used as a platform for the development of more radical designs.

Objective 1: Create a flexible design platform

A flexible platform will provide an elevated starting point on which future devices and projects can be based. The current prosthetic arm design is very functional but our engineering students are continuously wanting to customize it for users. Since the current design had limited digital customizability, most needed modifications are done in the shop or by designing and building separate add-on features. These manual modifications tend to be time consuming and necessarily limited in scope. Therefore, a highly flexible CAD design is a primary goal since this will both reduce customization time and increase the amount and complexity of possible customizations. To start, customization target ranges are 100 to 300 mm arm length, 30 to 150mm elbow width, and 135 to 255 mm hand length. Targeted range for wrist angles are -90° to +30° since at the -90° angle, the palm can rest on a table.

Objective 2: Teach students advanced CAD modeling techniques

As educators at a teaching institution, providing our students with growth opportunities, exposure to new/emerging technologies, and helping them develop engineering skills are among our top priorities. CAD skills continue to be highly desired by employers and teaching our students advanced CAD techniques better prepares them for entering the competitive engineering workforce.

Objective 3: Improve end user experience

Previous fit times were fairly long since some parts have to be modified (formed) after fabrication. The goal is to perform most of the customization at the CAD model stage and thus reduce fit times. Additionally, a flexible prosthetic design platform will benefit users by providing higher-quality prosthetics and potential reductions in fabrication and assembly time.

Project Details

For this project, students, who had experience with existing designs and prior CAD experience, were interested in developing their own design in order to improve customizability. Based on this goal, top-down design was suggested and an introduction to top-down design techniques was given. Students were challenged to research and implement this approach to reimagine a forearm-hand prosthetic that could be easily customized to wide range of sizes.

The prosthetic's primary function is to allow users to grip and pick up items and the hand size needs to be scaled appropriately so the user looks balanced. Additionally, the most challenging portion is often the prosthetic interfaces with the user since each user's extremities are very unique. The top-down design platform enables the designer to quickly size the arm length, hand size, wrist angle, and elbow width. For example, with this control, a person with larger hands but a shorter arm can still get a customized fit. The resulting size range could make replacement parts challenging but the ubiquity of 3D printers reduces this risk.

Due to the high variability in end-user body geometry, function, etc., being able to easily customize prosthetics is key to achieving quality results since an uncomfortable or nonfunctional device won't be used. Since this area is also the contact point between the user and prosthetic, fit is key to device comfort, limiting abrasion and pressure points, and utility. Therefore, the ability to add custom geometry to the base design will enable highly customized, fully functional solutions for almost any user.

Finding users who would benefit from these devices requires engaging with the local community. Reaching out to local elementary schools has been a primary approach. Children, since they are continually growing, often can't afford to get a new prosthetic every time they grow. Thus, a customizable, yet affordable, solution is very beneficial.

Results

After many hours of learning, investigation, and effort, the design shown in Figure 3 was produced in SolidWorks. The design, inspired by Unlimbited's foundational work, currently can be configured with an arm length of 250 to 300 mm, an elbow width of 30 to 100+ mm, a hand length of 135 to 235 mm and a wrist angle of -15° to +5°. Customizing the CAD database takes less than three minutes once the end user size requirements have been determined. The designer simply opens the assembly, creates configurations, edits 4 global variables, and rebuilds the newly sized parts. After some final tweaks, the build and validation phases will begin. Ultimately, it will be used as a foundation for more extreme customizations as it is used for various users in our community.

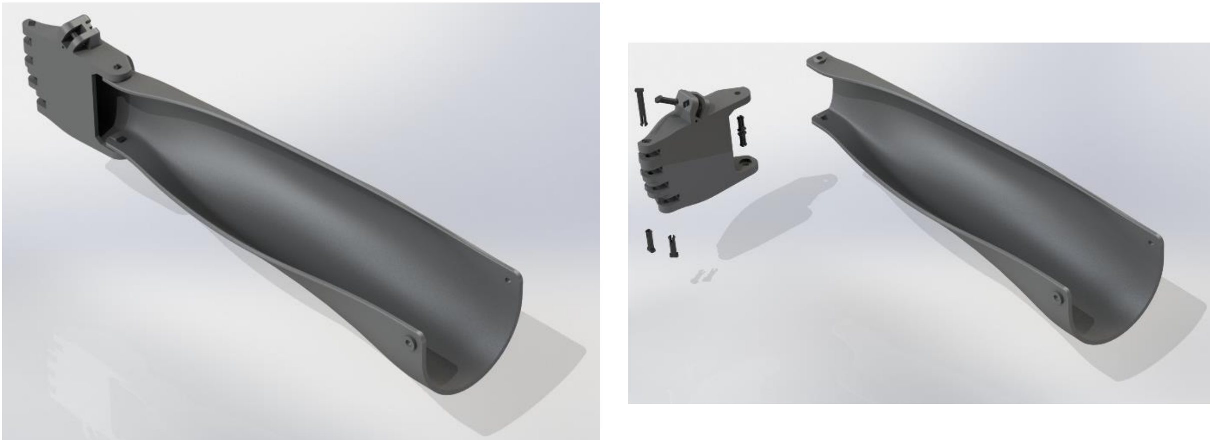

Figure 3. Top-down assembly of forearm, wrist and hand

While the top-down design process required a sizable learning curve, the student reported in a project evaluation that they found it to be a superior design methodology to the basic parametric bottom-up method. That said, they also feel the level of complexity and inherent instability of top-down models, if built incorrectly, could pose significant hurdles for inexperienced CAD users. As such, they felt it definitely qualified as an advanced modeling technique and found the experience invaluable.

Once the potential benefits of top-down design were articulated, it was exciting to see how quickly and thoroughly it was embraced for this project. Significant effort was spent exploring and learning the various top-down design approaches and the benefits and challenges were learned as the design unfolded. We feel this approach benefitted both the students and community members by adding advanced CAD techniques, better preparing starting engineers, and helping users gain access to quality of life altering prosthetics.

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