Additive Manufacturing for Medical Education

The Noyce School of Applied Computing: Development of an Integrated System for Material Selection and 3D Printing of Lifelike Human Body Models

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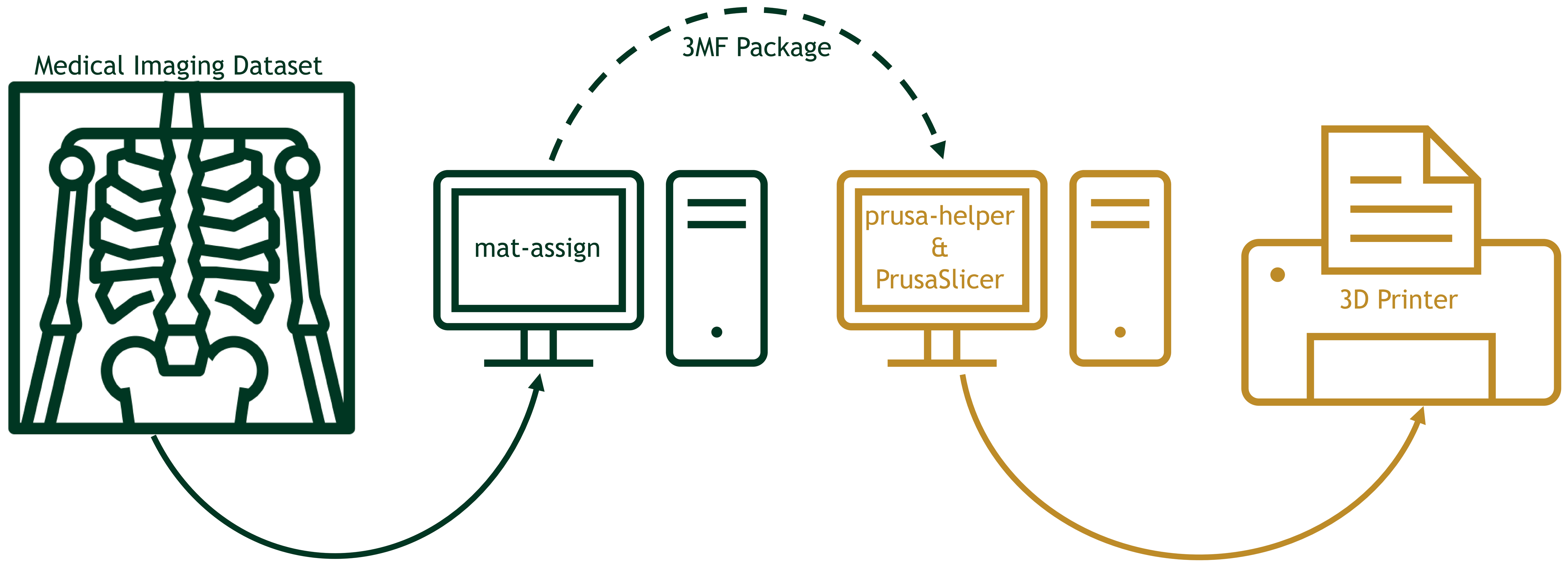


System Overview: General overview of stages of proposed workflow

Abstract

A growing body of evidence is suggesting that anatomical knowledge, the keystone of many medical specialties, is suffering among new graduates. While a host of reasons are provided, one common thread that many point to is the decline of cadaver dissections in the classroom. Many virtual audio-visual tools are used to address this gap, yet evidence has shown their ineffectiveness. Given this gap, the high degree of flexibility found in additive manufacturing (AM), and the many uses AM has already found in the medical field, we propose its use to fill this gap, allowing for students to learn with touch in addition to sight and sound among a host of other benefits. Our proposed system is a modular workflow that covers the generation of highly detailed heterogenous digital model representations and manufacturing said digital representations. In service of this, a basic framework of this workflow was implemented on Windows operating systems to show the viability of used standards.

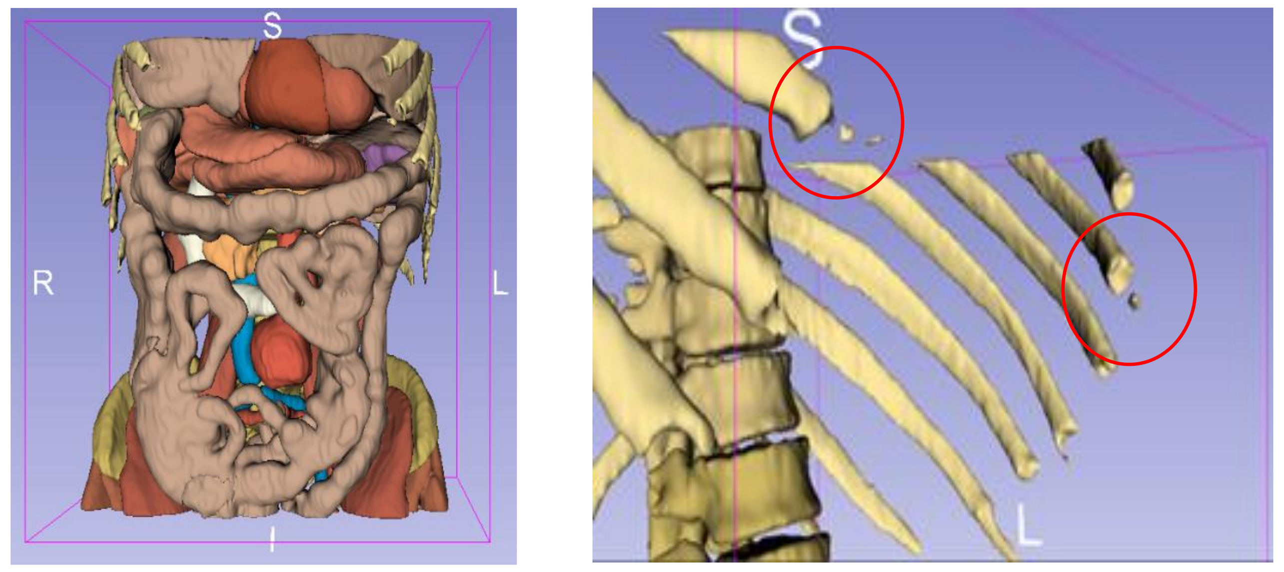
Motivation

3D printing is a highly diverse manufacturing method and is not new to the field of medicine. Some commonly used techniques in medicine include Fused Deposition Modeling (FDM) and Drop on Drop (DOD or PolyJet). DOD is extremely similar to FDM in that material is deposited on a plate layer-by-layer, with the only major difference being that DOD uses liquid ink-like polymers as opposed to solid thermoplastic filaments (Jamróz et al., 2018). DOD and FDM-like printers were chosen as the technology of choice due to their flexibility in material use.

Ultimately, the 3D Manufacturing Format (3MF) was chosen as the model representation of choice. 3MF files are triangular-mesh-based 3D models with a unified resource structure following the Open Packaging Convention (OPC) of which other notable members include .docx, .xlsx and .pptx (3MF Consortium, 2021). There are a host of benefits that using the 3MF package provides. First, there exists a standardized method for defining materials and assigning them to geometric features. Further, there is also planned support for functionally graded materials, best thought of as a custom and very specific material gradient. Moreover, there is considerable industry support behind this format, seeing support from companies like Microsoft in Windows and Prusa Research in PrusaSlicer project files. Given these benefits and the fact that it is the only standard with FGM support that is open source, it is clear to see why 3MF packages were chosen as the standard of choice.

System Overview

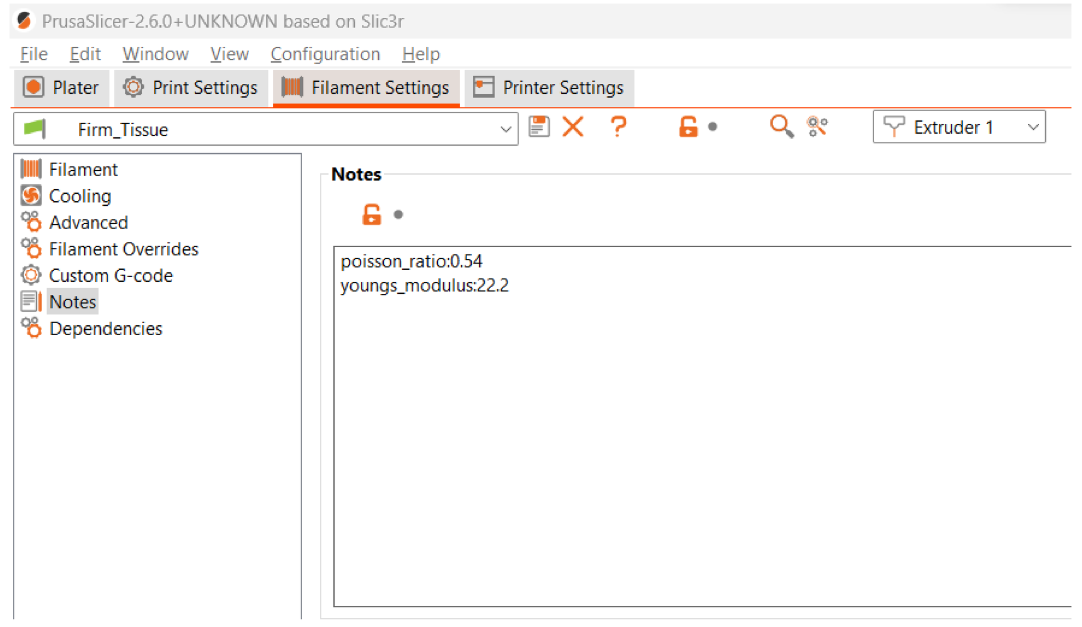
As previously noted, this system is organized into two stages: Model Generation and Model Manufacturing. During the Model Generation stage, a segmentation, or a collection of STL files in the same coordinate system whose material properties vary, is combined into a 3MF package that contains these material properties using the mat-assign script. Following the generation of the 3MF package, the Model Manufacturing stage is where the same 3MF package is opened and sliced in PrusaSlicer, during which each segment is assigned to an extruder using a material with properties matching those of said segment. This stage uses the prusa-helper script.



Using an example CT scan provided by the developers of 3D Slicer, a sample segmentation was developed, pictured above. This segmentation was generated using the default network provided by TotalSegmentator. While it is true the models generated by this network at this time do not meet the accuracy standards required for anatomical education, these segmentations are sufficiently detailed to demonstrate the effectiveness of the proposed solution and are only meant to act as a stand-in for more complex and accurate geometries. Following the generation of this segmentation, it was then fed into the mat-assign script which combined the segmentation into a single 3MF package. To generate a multi-material 3MF package, mat-assign requires three inputs. First is an input segmentation, represented as a folder containing STL files exported from 3D Slicer. Second, is an excel file within the folder containing material information. Finally, the script must also know the name of the resultant 3MF package. Detailed instructions for installing and using this tool can be found on our GitHub.

```
{
    "hardware_requirements": {
        "build_volume": {
            "x": 282.55413818359375,
            "y": 187.1318817138672,
            "z": 323.533203125
        },
        "extruder_count": 1
    },
    "print_materials": {
        "[Material Name]": {
            "density": 1178,
            "poisson_ratio": 0.63,
            "youngs_modulus": 21
        },
    }
}
```

Unfortunately, 3MF packages are not able to describe physical material properties using released standards. Thus, a new standard for the PrintTicket portion of the 3MF package was implemented. The custom PrintTicket is based on the JSON file format and follows the above example. There are two top-level objects within the PrintTicket that describe the type of information stored. The hardware requirements object stores general printing requirements like build volume and total number of unique materials, denoted as extruder count. The materials object stores each material name as appears in the 3MF model file and maps said name to three properties: Poisson's Ratio, Youngs Modulus and Material Density, in units of unitless, MPa & gcm^{-3} respectively. Units were chosen based on typical values found in a collection of studies and databases discussing the properties of various structures in the body (Choi & Zheng, 2005) (Katsamanis & Raftopoulos, 1990) (Lloyd, 2010)



At this point, the first half of the workflow has been completed, and the 3MF package can be freely transferred, followed by slicing which is guided by the prusa-helper script and PrusaSlicer application. Using prusa-helper with our custom version of PrusaSlicer requires some preliminary setup. First, custom filament profiles are created based on materials that can be used by the printing hardware. To define our 3 properties, two fields in a filament profile are used. The density field for the filament profile is provided by PrusaSlicer and, conveniently, is specified in gcm^{-3}. Having defined the necessary filament profiles, prusa-helper takes two inputs. The first input is the absolute windows path to the multi-material 3MF package produced by mat-assign, followed by the absolute windows path to the directory containing PrusaSlicer configuration files. When executed, prusa-helper will read the PrusaSlicer configuration files and will attempt to match material properties of each segment within the 3MF package to those of materials assigned to extruders in PrusaSlicer. Concurrently, a separate process will start PrusaSlicer and wait for it to open. If not all materials in the package can be mapped to an extruder, the user is notified that required materials are missing and what properties those materials hold. After notification, the user can reconfigure PrusaSlicer, and press enter to try again. Conversely, if all materials can be mapped, the package is opened in PrusaSlicer with extruder assignments for each segment. With the segmentation open in PrusaSlicer having correct extruder assignments, all that remains is to slice the segmentation. While we have tailored our solution for use with a tool-changing multi-material 3D printer, it should function using any multi-material printer that uses firmware supported by PrusaSlicer, some of which include RepRap, Marlin and Repetier among others.

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