TECHNICAL DOCUMENT

SIMULATION-DRIVEN DESIGN OF A PORTABLE BASKETBALL HOOP SYSTEM – INITIAL STEPS

Written by Drew Burkhalter, Technical Manager. A simulation-driven design process is proven to generate improved, more robust and cost-effective designs within a shorter design cycle. Incorporating simulation and optimization early in the design cycle helps shape the concept designs so less iterations and rework is necessary as the design matures. This paper is intended to discuss the initial steps that can be taken when using a simulation-driven design approach to design and engineer products. Several of Altair's design and engineering tools will be coupled to achieve various design goals.

Introduction

For this case study, a portable basketball hoop system is chosen for several reasons. This is a product that is common in everyday life, easily understood and has several challenging design goals. Within Altair's software suite, HyperWorks, there are several programs that will be leveraged to tackle these challenges. Inspire and Inspire Motion are used to mock-up concept geometries and mechanisms as well as generate design spaces. OptiStruct is used to analyze and optimize the structure to meet certain user-defined criteria.

Design Goals and Challenges

Across the U.S., portable basketball hoop systems have become more and more common with community and homeowner's association restrictions on permanent basketball hoops as well as for the ease of use, installation and construction of these units. Typically, these systems have several key features and design goals. Ideally one of these structures will be very stiff to achieve good energy return during ball strike, have adjustable height for different skilled players and ages, maintain a minimum safety distance between the playing area and the base, have a low center of gravity to prevent tipping, injuries or damage, be easily folded up and transported into a standard garage, meet high performance and durability standards for outdoor use, and have relatively low cost to purchase. Currently there does not seem to be a portable basketball hoop system on the market which meets all these design goals.

Figure 1: Example of a portable basketball hoop system
(Spalding's "The Beast" Portable Basketball Hoop System)

Coupling Altair's topology optimization technology with Inspire Motion can provide a stiff and lightweight design that meets center of gravity constraints and considers various height and transportation load cases. Additionally, considering manufacturing and material options throughout the process will be important to generate a cost-effective design. We are using this portable basketball hoop system as an example, but the process can be applied to countless other products and designs. The focus is on meeting all the design goals, but some goals will require further analysis and optimization later in the design cycle. At these beginning stages of this simulation-driven design process, the focus is on structural and safety design requirements. All of the design goals in Table 1 are considered, but optimizing cost and manufacturability are only indirectly considered and are not incorporated into the simulation-driven design process at this time. These can be included in future studies as the design matures and the feasibility of the design is better understood.

Design Goal	Software
Adjustability (10 feet to 7 feet for various ages and skill levels)	Inspire and Inspire Motion
Playability (stiffness, stability, mass distribution)	OptiStruct
Safety (distance to base, low and rearward cg)	Inspire and Inspire Motion
Durability and Fatigue Strength	OptiStruct
Compactness and Portability	Inspire and Inspire Motion
Minimize Cost (minimize and optimize material usage)	OptiStruct
Manufacturability	OptiStruct

Table 1 Portable Basketball Hoop System Design Goals

There are many challenges with this design and meeting the various design goals. For this paper these challenges can be divided into three groups: geometrical, structural, and analytical.

Geometrical Challenges

Many of the design goals and challenges for this portable basketball hoop system are primarily geometry based. Designing a system which adjusts from 10 feet to 7 feet, keeps the plane of the backboard perpendicular to the ground at various heights, maintains a safe distance between the plane of the backboard and base, and folds into a compact structure that can fit into a standard garage are all geometrical problems. Even maintaining a low and rearward center of gravity can be solved partially based on geometry. Although sketching up 2D designs is the natural starting point, knowing how the various parts will interact with each other and how the mechanisms will work is paramount. Inspire and Inspire Motion are powerful tools in which a designer can do quick and easy iterations of conceptual designs.

Structural Challenges

Once there is a general idea how the system will work and how the various parts fit together, structural challenges will need to be overcome. The structural design goals will be to create a portable basketball hoop system that is very stiff in all configurations, minimizes the amount of material needed, has a low and rearward (as far from rim as possible) center of gravity and evenly distributes stresses throughout the structure. Engineering judgement and overdesigning (making the structures overly durable) might be how such a structure is typically designed, but tools like OptiStruct are specifically developed for tackling these types of challenges OptiStruct topology optimization analyzes the available volume the design can occupy and the various load cases to whittle away at the material until only what is necessary to carry the specific loading remains. Topology optimization is most powerful at the beginning of the design cycle when the design freedom is at its peak. OptiStruct 's strength is in optimizing and distributing material to locations that will efficiently and effectively support the various loads the structure will carry throughout its life. As the design matures, additional structural optimization techniques are used, but it is always best to start with topology.

Analytical Challenges

Lastly, several analytical challenges are present with a structure such as this. The portable basketball hoop system will have several load cases while in its various configurations. The system will have to withstand loads at various hoop heights, as well as transportation loads when folded up. Typically, just creating the different finite element (FE) models in their different configurations would be time consuming and difficult, but with Inspire and Inspire Motion it is very straightforward.

Additionally, once the FE models with the various load cases in different configurations are created all the models will need to be considered simultaneously during the optimization process. This will be achieved with Multi-Model Optimization (MMO) in OptiStruct.

Simulation-Driven Design Process

To start the simulation-driven design process of this portable basketball hoop system there are certain established "given" quantities. The rim and backboard have specific dimensions and will not be modified. The standard height of the top of the rim is 10 feet above the ground, although for some youth basketball it can be lower. On professional, college and high school basketball courts the distance between the baseline (the out-of-bounds line at the two ends of the court) and front plane of the backboard is 48 inches. The ASTM standard (ASTM F 1882-06) for the minimum operational height of the bottom of the backboard is 78 inches for a system like this1. For safety purposes, a clearance area of 48" x 78" will be used as the minimum "safe" area between the base, structure and backboard. Therefore, the starting point for the portable basketball hoop system will be a standard sized backboard and rim, with a rim height of 10 feet and a 48" x 78" "safe" clearance area between the base, structure, and backboard as shown in Figure 2.

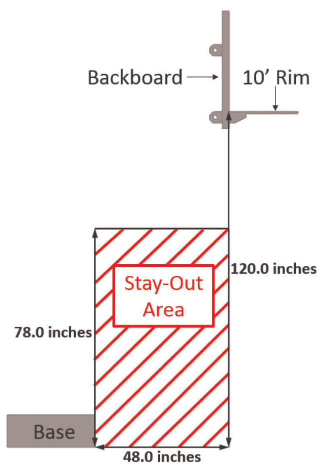

Figure 2: Base and backboard with a rim height of 120" (10 ft.) and "safe" 48"x78" clearance area

Ideation in Inspire

One of the first things that needs to be figured out when designing the height adjustment mechanism is how to keep the plane of the backboard perpendicular to the ground when adjusting the height while maintaining the 48" x 78" stay-out area. Additionally, when the portable basketball hoop system is folded up in the transporting/storing configuration it must have a height less than 84 inches (the standard height of a garage door) and ideally a length less than 96 inches.

Creating quick mock-up mechanisms and running an Inspire Motion model is a very quick and straightforward process. This process provides important insights into how the structure will move, how the parts should be joined, the clearances and interaction between parts and how compact it can be. Figure 3 shows a few initial design trials that did not end up meeting the geometric design requirements.

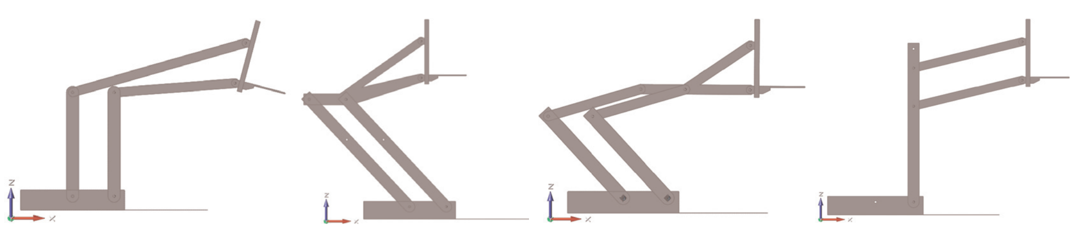

Figure 3: Backboard doesn't remain perpendicular (first), 48"x78" clearance not maintained (second), not compact enough when folded up (third) and center of gravity too far forward (forth)

Material Distribution of Design Spaces

Once the mechanism is designed and the clearances are well understood, the next step is creating design spaces for the topology optimization. Ideally the design space for each component will envelop all the available volume that the parts can occupy. Having a general idea of how the loads will be carried by the structure will help when generating these design spaces because it will help with deciding how to distribute the material. For example, if it is known that one of the components will carry more load than another and they will contact each other, then the contact interface could be skewed so that more material is available for the more heavily loaded component.

In Inspire Motion, the joint forces can be plotted after running a quick motion analysis. Additionally, these plots can be exported to CSV files so that a closer look can be taken if needed. Figure 4 shows a preliminary design with the joint numbers as well as a comparison between the resultant torque of the various pinned joints. At this point, actual magnitudes aren't important, but rather comparing relative magnitudes to one another to anticipate which areas may need more material to carry the loads. For example, the torque in joint 17 is relatively much higher than in the other joints and material can be prioritized to the parts connected at this joint. The 'Push/Pull' and other geometric tools within Inspire make the geometry manipulation of design spaces very intuitive.

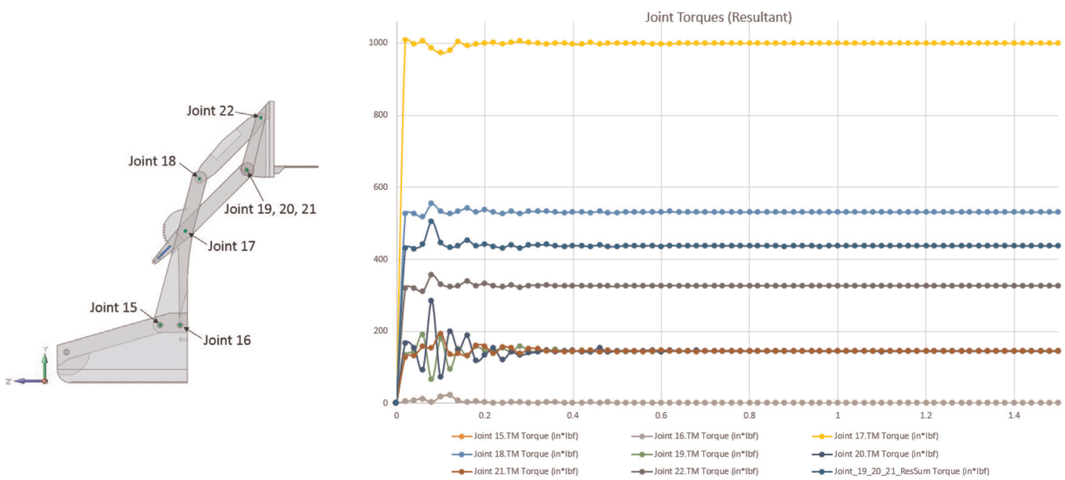

Figure 4: Plot of the torques of the different joints in the preliminary portable basketball hoop system design

Analysis and Optimization Set-Up in Inspire

To increase efficiency, as much as possible of the analysis and optimization is set-up in Inspire because it can be done very quickly and easily. Also, one model can be used to create multiple Optimization models in their various configurations. The material assignments, contacts, joints, loads, boundary conditions, and load cases can be set-up in Inspire.

For this example problem, all the design spaces are assigned a polycarbonate material.
The non-design rim, pins, and partitioned section of the base are assigned steel with the backboard being glass. Within Inspire, joints and contacts are automatically identified and easily created based on aligned holes and the proximity between parts.

The load cases for this structure are conservatively estimated. All load cases are simplified to be linear static. For the primary load case, a 400-pounds downward static load is applied to the end of the rim. Additionally, it is estimated if a full-sized basketball hit the backboard at 40 miles per hour it would exert a peak force of around 300 pounds. This force is applied at the upper left-hand corner in the x, y and z directions as three separate load cases. With all four of these load cases, the bottom, non-design section of the base is fixed. All four of these load cases are applied when the portable basketball hoop system rim height is at 10, 9, 8 and 7 feet. Since the backboard and rim are cantilevered out into space and have significant mass, gravity is included in all load cases.

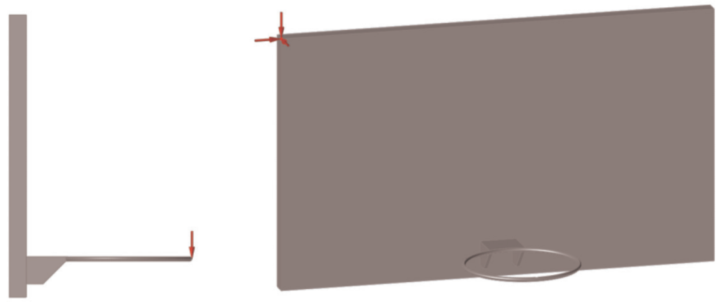

Figure 5: 400 pound static load at end of rim (1 load case) and 300 pound x,y,z load at upper left corner of the backboard (3 separate load cases)

Lastly, when the portable basketball hoop system is completely folded up in the configuration for rolling it to and from the user's garage, a 4g down load case is created to represent the system falling off a curb. The contact interfaces and locked joints are adjusted for this particular load case. Most of the optimization set-up can be done in Inspire. The optimization problem will be set-up where the objective will be to create a structure with the maximum stiffness for all configurations and load cases, while only using a percentage of the available design space. Many other design constraints could be included but this is a good first step when doing topology optimization. Running the optimization a few times with different percentages of available design space provides good insight into what the critical structural members are.

Design Details

Now that the design and design spaces are well defined, here are some details about the portable basketball hoop system. The assembly has five separate design spaces (this does not include the reflected pattern repetition symmetry design spaces which will be discussed later). The base is the largest design space and has a non-design plate at the bottom where the boundary conditions are applied. This volume is made large to help enable the center of gravity of the assembly to be low and rearward. Even if most of this volume is not needed structurally, the volume is available for adding counterbalance weight.

The vertical design space is pinned to the base in two locations. The forward-most location will need to be disengaged to allow for the assembly to fold up. The rear-most pin will act as the pivot point. The vertical design space also has features to allow for the height adjustment mechanism.

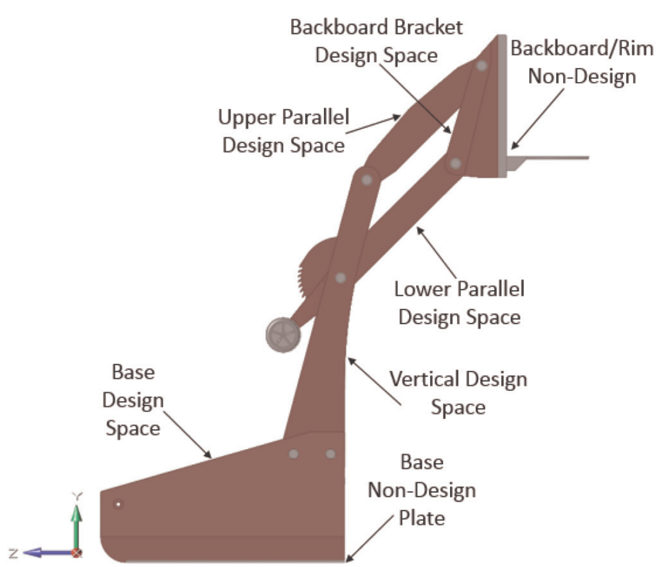

Figure 6: Portable Basketball Hoop System Design and Design Spaces

The two parallel design spaces are also pinned to the vertical design space. The lower parallel design space also acts as the height adjustment lever in conjunction with features on the vertical design space. A spring-loaded adjustment trigger mechanism at the adjustment lever will engage with teeth on the vertical design space and the height can be adjusted in six-inch increments. Also, at the height adjustment handle, a wheeled axle is included to help facilitate positioning the structure for play as well as moving it to storage.

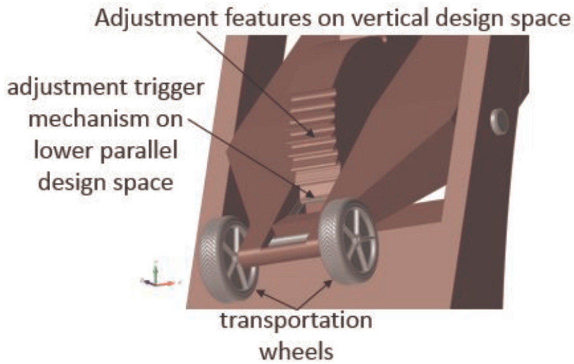

Figure 7: Portable Basketball Hoop System Height Adjustment Mechanism

The two parallel design spaces are pinned to the backboard brackets. This design space is also tied to the back of the non-design backboard. These brackets, along with features throughout the assembly are designed to "fit into" each other so that the assembly can be as compact as possible when in the folded configuration. More details about some design features for the folded configuration are given later in the paper.

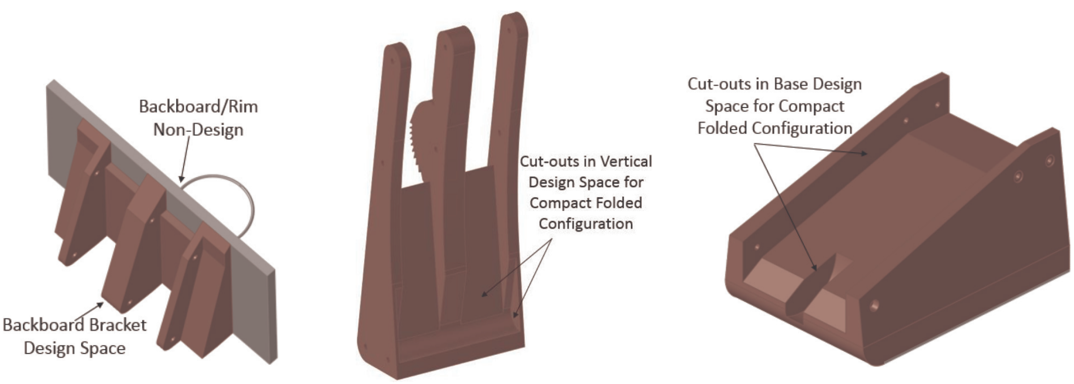

Figure 8: Backboard Bracket Design Space and Cut-Out Features for Compact Folded Configuration Preparing Models for MMO

Currently it is necessary to export the models from Inspire and import them into HyperMesh for two main reasons. Multi-Model Optimization (MMO) is not currently available in Inspire and symmetry constraints are not supported in MMO. The majority of the optimization set-up can be performed in Inspire, but it is necessary to do the final set-up of the MMO topology models in HyperMesh. There are plans to make MMO available in Inspire and symmetry constraints available in MMO, but no current timetable is set.

This export from Inspire and import into HyperMesh process will need to be carried out for all five models in the different configurations (10 ft., 9 ft., 8 ft., 7 ft. and folded). It is only necessary to export one half of the model from Inspire because the other half will be generated in HyperMesh so that the optimization will result in a left/right symmetric design using pattern repetition. Within Inspire Motion, an actuator attached to the basketball rim precisely moves the height to the new location. Inspire Motion provides a tool which allows the user to make the current frame of the motion simulation the new design position. This is an important and useful tool for this process because it would be difficult to do manually and accurately within HyperMesh.

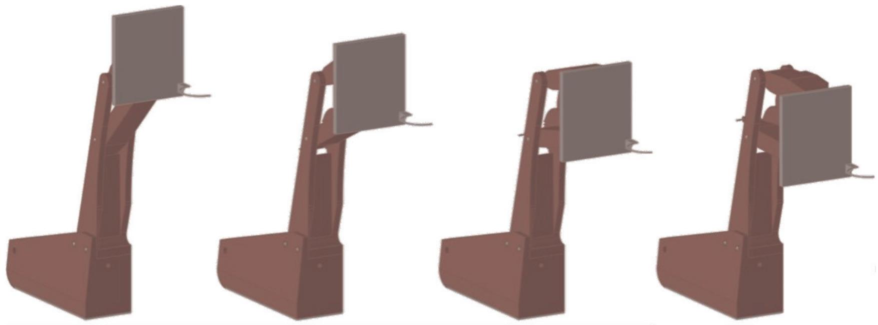

Figure 9: Different height configuration half models exported from Inspire

For the folded model, the portable basketball hoop system design is set up so that, once it is folded up, it is transported like a wheelbarrow. Like a standard wheelbarrow, there will be handles on one side and wheel(s) on the other. An additional locking pin is added to keep the assembly folded when transporting. For the "falling off a curb" load case, the ends of the handles are constrained in the up/down and fore/aft translational degrees of freedom and the wheel axle location is constrained in the up/down and right/left translational degrees of freedom. Lastly a 4g down load is applied to the full structure.

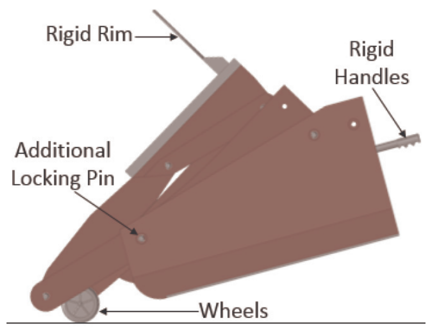

Figure 10: Folded configuration

Once all five optimization models are generated, an MMO master file needs to be created to link all the models together. It is important that all the design variables identification numbers match between models so OptiStruct can identify parts between models. This is another advantage of exporting the .fem files from one Inspire model because the ten (5 left and 5 right) design variables should have identical numbers between models.

```
SCREEN OUT
$
TITLE = MULTIPLE MODEL PORTABLE BB HOOP SYSTEM TOPO OPTIMIZATION
$
$---------Model_Name_User---FEM_File_Name
ASSIGN,MMO,H_10ft,PBHS_Topo_Full_10ft.fem
ASSIGN,MMO,H_9ft,PBHS_Topo_Full_09ft.fem
ASSIGN,MMO,H_8ft,PBHS_Topo_Full_08ft.fem
ASSIGN,MMO,H_7ft,PBHS_Topo_Full_07ft.fem
ASSIGN,MMO,H_6ft,PBHS_Topo_Full_06ft.fem
ASSIGN,MMO,Folded,PBHS_Topo_Full_Folded.fem
$
BEGIN BULK
$
DOPTPRM,DESMAX,150
$
ENDDATA
```

Figure 11: Example MMO Master File

Results

Before discussing the topology optimization results, it would be good to have an understanding of how OptiStruct topology optimization works. The optimization software was originally based on Wolff's law and simulating bone growth. Wolff's law generally states that bones will restructure themselves, over time, to become stronger to resist the specific loading applied to them. OptiStruct topology optimization analyzes a design space (the volume a part can reside in) and identifies the best load paths necessary to efficiently support the various load cases. OptiStruct uses a mathematical approach to iteratively optimize the material layout so that the resulting structure meets user-defined design requirements. The end results are typically organic-looking truss structures that are made of only the necessary material and the rest is removed. The results don't always illustrate exactly how much material is needed for the load paths, but that structure is needed in that location.

Individual Topology vs. MMO Topology

When complex loading or many load cases are applied to a design space it can be very difficult to intuitively determine what the structure should look like to support all the different loads. In this case, we not only have multiple load cases but also multiple configurations (10ft position, 9ft position, 8ft position, 7ft position and folded position) which makes it more complex. To try to understand how each configuration impacts the final multi-model topology optimization, an optimization analysis of each single configuration model is performed. Since the configuration of the portable basketball hoop system changes how individual parts within the assembly are loaded, the single configuration results are very different from each other as well as from the MMO results. It can be seen in Figure 12 how the configuration impacts the structure.

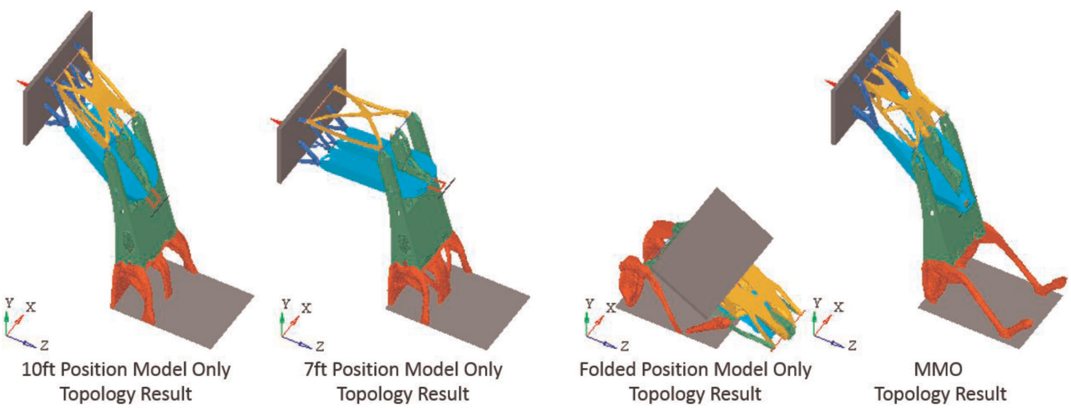

Figure 12: Comparing Individual Topology Optimizations with MMO

Two explanatory examples are the lower parallel and base design spaces. For the various height configurations, the lower parallel design space acts like a cantilevered beam in bending. It can be seen in Figure 13 that OptiStruct is creating hollow box beams. ince the 7 ft. position is more cantilevered than the 10 ft. position, OptiStruct assigns more material to this component in the 7 ft. configuration. In the folded position, this design space is acting like a beam in bending again, but between the wheel axle and the additional locking pin. In this configuration OptiStruct removes almost all the material which is kept in the other configurations. In the MMO model OptiStruct does its best to consider loads from each configuration to create the stiffest structure for all configurations.

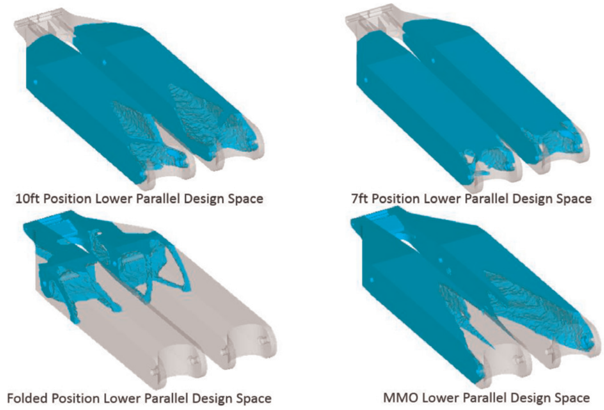

Figure 13: Lower Parallel Design Space - Comparing Individual Topology Optimizations with MMO

For the base design space, in the various height configurations the load path is directly under the footprint of the rest of the structure. OptiStruct determines the most efficient path from the pinned connections and contact to the boundary conditions. In the folded configuration, since there is an additional pinned connection transferring load at the rear of the design space, OptiStruct includes structure from this pinned joint to the location where the handles connect to the base.

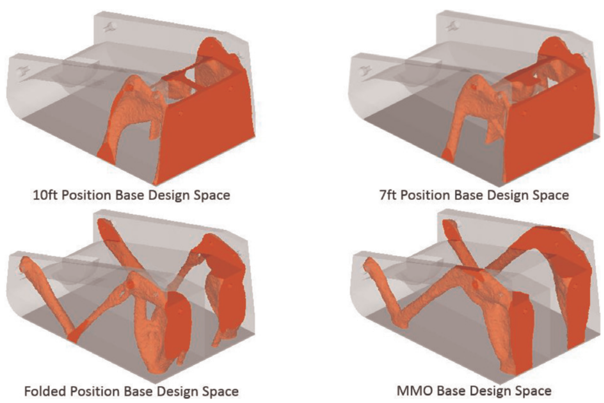

Figure 14: Base Design Space - Comparing Individual Topology Optimizations with MMO

Topology Results with Different Volume Fraction Constraints

As mentioned earlier, it is often good practice to analyze a topology problem with different optimization set-ups. In this case an adjustment is made to the volume fraction constraint from 15% of the total design space volume to 7.5% of the total design space volume. This will provide some insight as to which load paths are critical and where material really needs to be.

When comparing the upper parallel design space results, it can clearly be seen that the center connection to the backboard is less critical to a stiff assembly than the outer connection. In the vertical design space, it can be seen in Figure 15 that several of the solid members are hollowed out or reduced when less material is available, but the overall structure is similar.

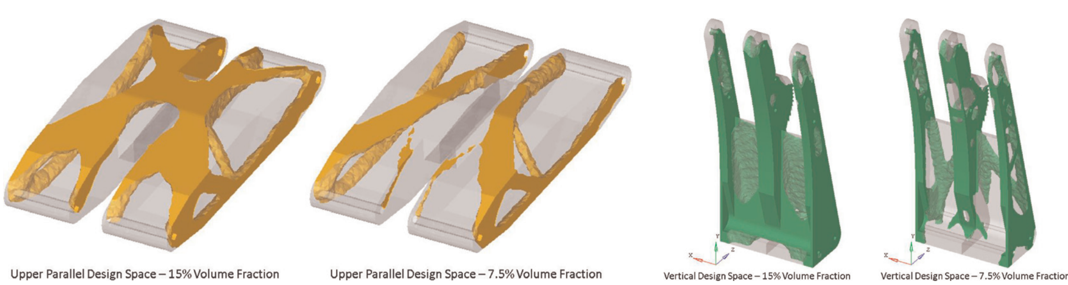

Figure 15: Upper Parallel and Vertical Design Space - Comparing 15% and 7.5% Volume Fractions

Topology Interpretation

Another advantage of having results from multiple optimization set-ups is that when interpreting the results into a design, structure can be added from multiple results. For instance, in the upper parallel results, the 15% volume fraction shows the two sides are connected in the middle, but in the 7.5% result they are not. To better meet the mass target for this design, most of the interpretation will be based on the 7.5% volume fraction results but adding a connection between the two sides should not increase the weight significantly so this connection could be added.

Within Inspire there is a very powerful tool called the PolyNURBs tool. It is possible to take the ragged, organic-looking topology results and easily interpret them into a smooth solid structure. Primarily the process consists of creating PolyNURB cages around the topology results and attaching them to each other. Figure 16 shows the initial interpretation of the topology results.

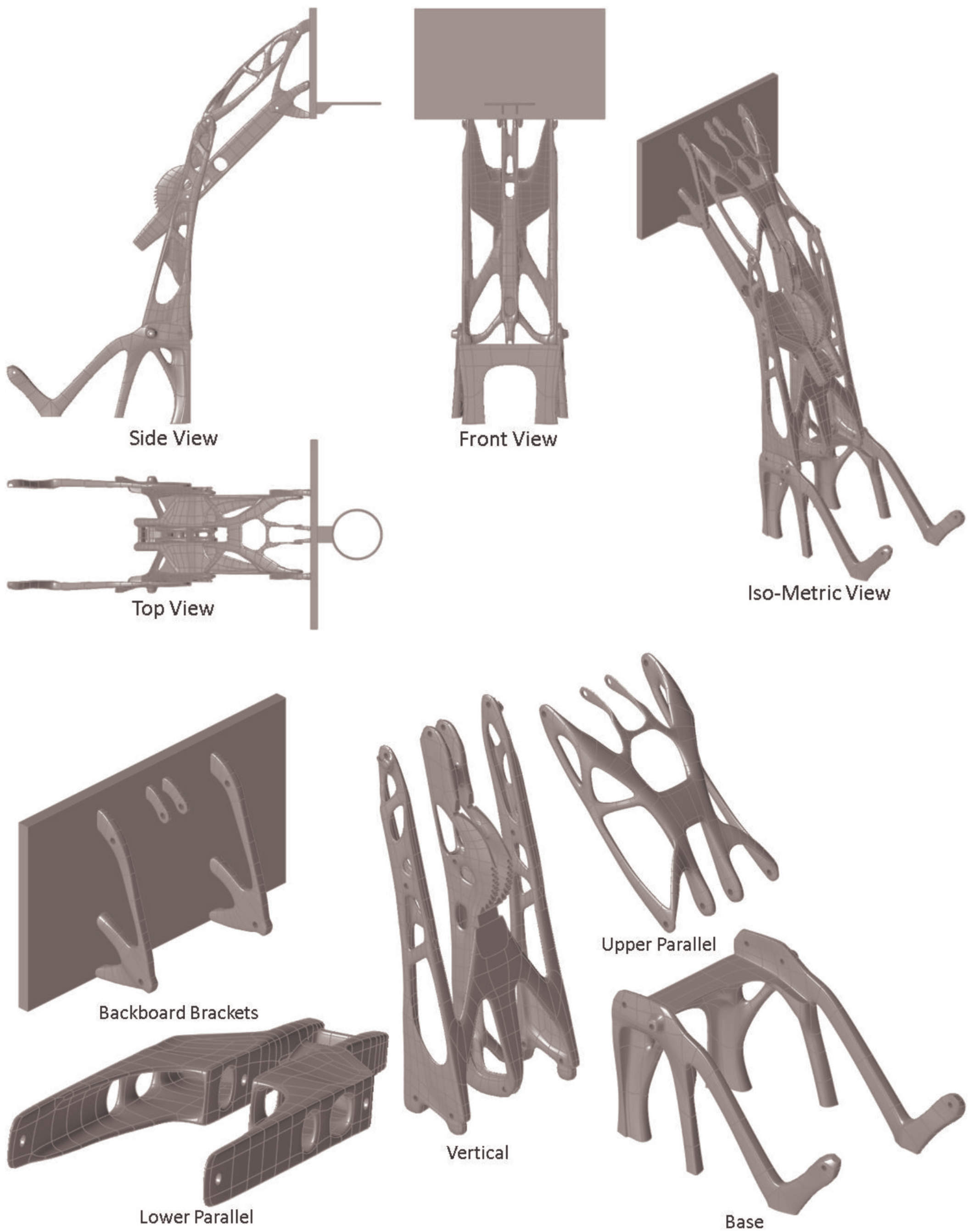

Figure 16: PolyNURB Topology Interpretation of Optimization Results

Verification Analysis

Now with an interpreted concept design, it is straight-forward to set-up the same connections, loads and boundary conditions from the optimization set-up and run an initial verification analysis in Inspire. For this initial phase, only the 7 ft. configuration is analyzed because it had the highest deflections and stresses when post-processing the optimization results. This being the worst loading position makes sense because in this configuration the rim is extended the furthest from the base.

The worst load case in this 7ft configuration is when the 400-pound downward load is applied to the end of the rim. This load caused the polycarbonate assembly to have a maximum displacement of about 3.5 inches. At this time, it is unknown if this amount of deflection is acceptable or not. Additional research and testing would be required to compare to similar systems. The stresses in the assembly appear to be well below the yield stress of the polycarbonate. Almost the entire structure has stresses below 2,000 psi, and the expected yield stress of the polycarbonate should be at least 4,000 psi. In some locations where rigid elements are attached to the structure, local artificially high stresses occur. These high stresses are ignored because they are not accurate.

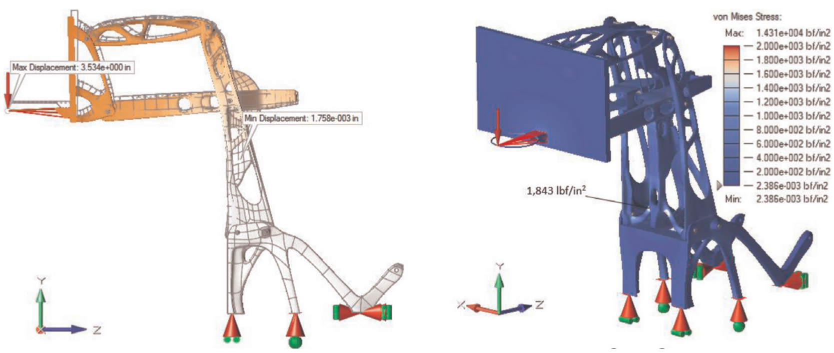

Figure 17: 7 ft. Configuration Displacement (left) and Stress (right) Contour Results

These initial analysis results are promising, but many improvements can still be made as the simulation-driven design process continues. Currently the weight of the support structure is about 775 pounds. Ideally, the mass of the support structure will be reduced, but additional weight will need to be added to the base to improve the location of the center of gravity. In all portable basketball hoop system designs, counter weight is added to the base. Often this is accomplished by having a large hollow cavity in the base than can hold water, sand or rocks. The next phases will focus on these types of details and improvements in the design. Additional optimization and analysis techniques will be performed to help improve the design and meet all the design goals.

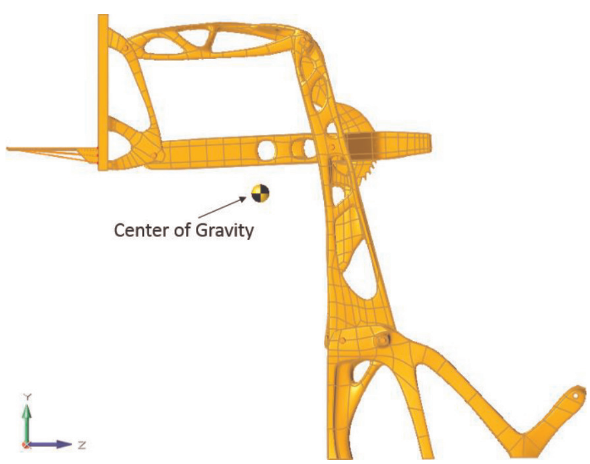

Figure 18: Topology Interpreted Design Center of Gravity for 7 ft. height configuration (worst case)

Conclusion and Discussion

This study was performed to illustrate the initial steps of a simulation-driven design process. A portable basketball hoop system was used because several clear design goals and requirements were identified. The design goals of having an adjustable height system that maintains a "safe" 48"x78" clearance area and can be folded up to be transported and stored in a standard size garage was achieved. The optimization was set-up to take the design spaces that achieved these geometric goals and create the stiffest structure possible for the applied load cases and allotted material.

Additional studies will take this simulation-driven design process to the next steps. These steps will include evaluating the stiffness, durability (stress analysis) and balance (center of gravity constraints) of the portable basketball hoop system in its various configurations under the different load cases. Selection of materials, consideration of manufacturability and evaluation of costs will also be included. Several additional optimization and analysis techniques will need to be executed to help achieve these design goals.

Acknowledgements

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