Final Project Report

MECH4860: Engineering Design

Vidir Solutions

Self-Balanced Vertical Shelving Carousel

Report Prepared For:

Vidir Solutions: Dimitri Caldeira
Delmer Plett
Chris Hamm

University of Manitoba: Paul Labossiere

Report Prepared By:

Group 9: Alina Toidjanov
Braden Ganetsky
Dylan Ondracek
Jordan Mitchell

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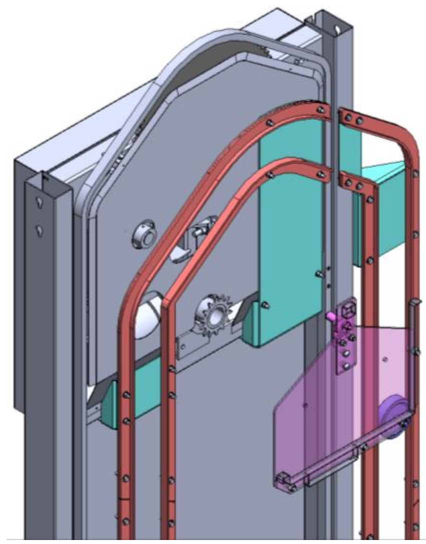
Executive Summary

This report presents the final design of the Self-Balanced Carousel project facilitated between Vidir Solutions and the University of Manitoba. The goal of the project was to design a self-balancing upgrade to Vidir's vertical shelving carousel, such that each carrier maintains its inclination at any given time or position. This would prevent issues caused by uneven shelf loading.

The final design presented in the report is broken down into four major components. A guide track, pictured in red, was added to both side towers of the carousel. Each track requires a set of mounting brackets, shown in cyan. On either side of each shelf, we added a wheel, shown in blue. Finally, we redesigned the shelf-chain connection, pictured in pink, to be compatible with the track. The strength of the components was evaluated with a preliminary finite element analysis, as applicable.



MAJOR COMPONENTS OF THE FINAL DESIGN

The tracks and wheels work together to constrain each shelf, preventing swaying and tilting. The guide tracks constrain the position of the shelf's wheels, which in turn constrains the rotation of the whole shelf. The tracks allow the wheels to move in tandem with the shelf's pivoting axis, as driven by the carousel's main chain system.

Beyond solving the main problem, our design addresses key concerns discovered over the course of the project. By putting guide tracks on both carousel towers and not having mirror symmetry, the two superimpose to provide total coverage for the entire carousel rotation. A reworked shelf-chain connection facilitates shelf installation with a much smaller overall profile, minimizing the effect of necessary gaps in each guide track. The lower portion of the track is adjustable to accomodate the carousel's chain tensioning mechanism.

The design satisfactorily meets the project specifications. Notably, we performed a motion simulation and determined that the design limited the shelf's tilt to ≤2.5° in both clockwise and counterclockwise motion around the carousel. Our design comes in below budget, with a total material cost estimate of $687.19. We recommend Vidir manufacture a prototype to test impact between the track and wheel where gaps in the track exist, a specification we were unable to conclusively model.

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1 Introduction

Vidir Solutions is a leading manufacturer of vertical motorized storage carousels and display systems, offering storage solutions for a variety of industries. Compared to conventional fixed shelving, powered solutions optimize vertical storage space, ergonomics, and storage density [1]. Mounting shelves to a chain-driven vertical carousel allows the height of the carousel to be adjusted, making items easily accessible. One such carousel is pictured in Figure 1. Each shelf is typically two feet deep and as wide as 15 feet. The carousel can range from 8 feet to 20 feet in height.

On a standard vertical shelving carousel, each of the carousel's shelves can be loaded with up to 1000 lbs of contents. Ideally, the weight of the loaded goods is centered with respect to the depth on each shelf. Our project is concerned with non-ideal shelf loading.

FIGURE 1. PROMOTIONAL MATERIAL FOR A VIDIR SHELVING CAROUSEL.
SOURCE: ADAPTED FROM [2].

The carousel's drive system is powered by electric motors, which can turn both clockwise and counterclockwise. This mechanised system is what allows shelves of goods to be accessed quickly and easily despite being stored at a height. There is a single pivot point on each end of the shelf that pins the shelf to the chain.

Vidir has presented the team with a process improvement project for a vertical shelving carosuel. The carousel utilizes a chain and sprocket drive system to rotate shelves for easier user acess. The objective of the design is to upgrade the unit to keep shelves stable despite uneven loads. This design report presents the final design developed by the team to meet this objective.

The project was broken down into three separate phases, consisting of a project definition phase, a concept generation phase, and a detailed design phase. In the project definition phase, we gathered background information through research and meetings to create the design needs and requirements. We used this information in the concept generation process to produce various designs and come up with selection critieria.

At the end of the generating concepts, the selection process identified two close variations of an "asymmetric" guide track concept as the set of best options with which to move forward. The "asymmetric" specification was used to distinguish this design's lack of mirror symmetry between the two side towers of the carousel. This design utilizes both sides of the carousel in an elegant matter, so that the left and right sides would combine to create an overall effect greater than the sum of its parts. A concept generation sketch of a precursor to this concept is pictured in Figure 2 below.

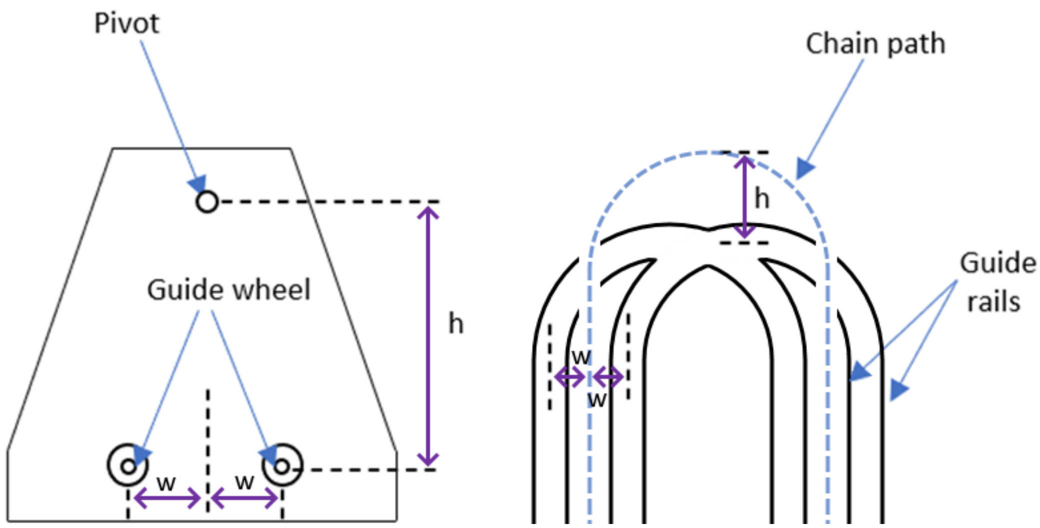


FIGURE 2. CONCEPT GENERATION SKETCH OF A PRECURSOR TO THE ASYMMETRIC GUIDE TRACK CONCEPT.

When we brought our selection to Vidir, they asked us to give further consideration to one of the designs we had scored significantly lower in the selection process, which used magnetic wheels. After a week of research and consultation with Vidir, we concluded that we would move forwards with the guide track and not the magnetic wheels. We were most confident in our ability to create a good design with regular wheels, and our design paves the way for a magnetic wheel option, should Vidir consider another modification to their carousels in the future.

This report presents all the details developed for the final model. For clarity, the problem is definition is restated, and our identifed design needs, specifications, and design space are presented. Section 2 presents the final design broken into its major components: the track, shelf wheels, the shelf-chain connection, and the mounting brackets. After the components of the final design are described, Section 3 discusses the design functionality and features. In Section 4, we provide a detailed description of the engineering decisions and analyses that defined our final design. Following that, Section 5 estimates the material cost of our design via a rudimentary bill of materials. In Section 6, we present a motion study of the carousel with and without our design implemented, a required client-specific delieverable. Next, Section 7 summarizes the finite element analysis we performed to verify our design is capable of performing under its expected loads. Finally, we conclude in Section 8 by comparing our design to our target specifications and highlighting our recommended actions for Vidir to pursue after receiving our completed project.

1.1 Problem Definition

The project problem can be defined in two parts, which are the shelf's levelness and stability.

Ideally, shelves are evenly loaded along the shelf's depth. In this case, weight is centered underneath the axis of rotation created by the free pivot points on each end of the shelf. When a shelf's center of gravity is not directly under its pivot axis, the shelf tilting to vertically align the two. A tilted shelf's contents are less stable, which possibly leads to items falling. Vidir wants to improve the design to address this load balancing concern and improve overall safety.

Shelf stability is important for safe carousel operation. When the carousel is activated to move its shelves, the shelves which experience any horizontal acceleration will sway because of the inertia of the carried load. The contents of an unstable shelf can unexpectedly fall, posing a hazard to anyone nearby and damaging product. An unstable shelf also sways further than expected when being rotated through the carousel, which can result in collisions between the shelf and its surroundings, such as the floor, the carousel structure, or the carousel's protective mesh. A lesser stability concern is that of ergonomics. An unstable shelf can shift as its load is modified, causing it to sway during manual loading and unloading. A swaying shelf constantly deviates from its ideal position and makes it more difficult for the operator to load and unload items. This compromises operator safety and can result in injury with heavier loads.

1.2 Objective

The objective of our project is to design an upgrade to the shelving carousel that will keep the shelves stable and level despite uneven loads. A successful design will limit a shelf's tilt to within 5 degrees of vertical when a load of 1000 lbs is applied at a 5" offset from the shelf centerline, as shown in Figure 3 below.

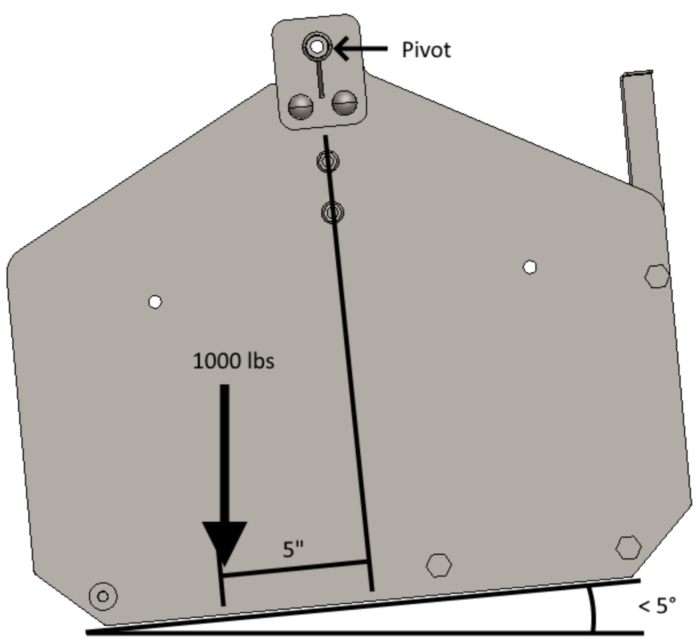


FIGURE 3. DESIRED EFFECT OF DESIGN

To accomplish this within the given timeframe, manufacturability was considered in the design process, but the actual manufacturing process is outside the scope of the project.

1.3 Deliverables

The project deliverables and their recipients are summarized in Table I below.

TABLE I. DELIVERABLES

Deliverable	Vidir	U of M
Final Design Report	Yes	Yes
CAD Model	Yes	No
Motion Simulation	Yes	No
Oral Report	Declined	Yes
Poster	No	Yes

The client-specific deliverables are a CAD model and a motion simulation.

The CAD model is a full model of our design integrated into an existing carousel. Vidir provided us with a STEP file of an existing carousel on which to base our model. Notably, Vidir has said that they intend on fabricating our design from the CAD model we are providing them. As such, they are not asking for a formal bill of materials or engineering drawings of the components in our design.

The motion simulation is an animation and motion study of the full carousel rotation, to show that our design is functional. To model the problem description, a load is applied along the length of the shelf, offset from the centerline of the shelf. We are providing motion simulations of both the original carousel model and our design.

For the University of Manitoba, we are delivering an oral report and a poster highlighting our design. The poster and presentation slides for our oral report are due to be delivered on December 9th, the same date as the final design report. We will give the oral report on December 10th.

1.4 Design Needs

After considering our background information and problem, we identified the design needs in consultation with Vidir.

1.4.1 Summarized Needs

We broke down our list of needs into primary needs, which are absolutely required for the design, and secondary needs, which would be nice to have but are not strictly required. These are categorized, named, and explained in Table II below.

Table II. Design needs

		Need	Explanation
Primary Needs	**A.**	The shelf rotates smoothly.	To ensure the safety of carried goods, the shelf must move and rotate about its pivot smoothly. Abruptly starting or stopping rotation could cause contents to fall over.
	B.	The shelf does not wobble in steady state.	Aside from the unavoidable acceleration wobble caused when starting and stopping the carousel, the shelves should quickly reach a resting position.
	C.	The shelf stays level over its entire revolution around the carousel.	It would be relatively easy to ensure that the shelves stay level over the front and back of the carousel, but it is essential that they remain level around the top and bottom of the carousel.
	D.	The shelf does not contact the floor or other shelves.	Collisions between swaying shelves and their environment can cause falling products, damage to the environment, and damage to the carousel unit.
	E.	The total design integrates into the given existing carousel and shelf.	At a minimum, the design must be viable for one particular model of carousel, supplied to us by Vidir.
	F.	The design is safe.	A carousel already comes with safety features that will adequately protect against most potential safety hazards, but we need to be sure that this is the case.
Secondary Needs	**G.**	The total design is inexpensive.	The design must be affordable, but the definition of “affordable” varies between customers. An expensive design may still be worthwhile.
	H.	The total design integrates with existing power supplies.	On all current carousel models, there is no way to get electrical power to the individual shelves. Vidir believes that this may be possible, but ideally the design does not require it.
	I.	The carousel can fully operate in all modes of motion.	Carousels operate most efficiently if they can rotate both clockwise and counterclockwise.
	J.	The total design is easy to assemble and install onto existing carousels.	Preferably, the design can be sold as an upgrade to carousels already in the field, for whichever models it supports.
	K.	The design integrates with other models of carousels and shelves.	Vidir offers a wide degree of customization in their carousels. The design may not be able to be adjusted to fit every model, but the more the better.

1.4.2 Generation of Needs

We generated our needs in consultation with Vidir. We first had an initial project kickoff meeting, after which we drafted a preliminary set of needs, and we then refined them based on further conversation with Vidir to reach the needs listed in Table II on the previous page.

Needs *A* and *B* are both about the motion of the shelves, but they are about fundamentally different things. The shelf must rotate smoothly, which refers to the maximum values of acceleration and jerk of the rotation. To be rigorous, we included the need of the shelf not wobbling in steady state, meaning that it eventually comes to a resting position. It is possible for a design to satisfy one of these needs without satisfying the other, even though they are related. Need *C* is critical, the shelf must stay balanced and upright. If this need is not satisfied, then the project has failed, even if we create a design that satisfies all the other needs.

Needs *D* and *E* are a physical consequence of the carousel operating properly. The carousel cannot operate properly if the shelves contact anything other than the pins on which they rest, and the carousel cannot operate if the design does not integrate effectively with the given carousel. Lastly, need *F* brings in the human aspect. The carousel absolutely cannot harm any person in any way that is the fault of the design, and we must make it difficult for injuries to occur if they cannot be eliminated.

In the conversations with Vidir, we deemed need *G* as not being essential to the success of this project. They want something that works, at the lowest cost we can make it. The cost itself is not of particular concern. Need *H* considers the fact that we are mechanical engineering students, with very limited exposure to electrical design. A successful design could add new power supplies to the carousel, possibly onto each shelf, but due to the complexity of adding electrical components, it is ideal that we do not do this.

Vidir would rather have something that works partially as opposed to something that does not work at all, which led to need *I* If we can make a design that only works perfectly in one direction of motion, this will still be considered. As well, they mentioned the ease of assembly and installation, which need *J* references. A successful design could be difficult to assemble and install, and could be preinstalled at Vidir's plant, but these are not preferable. Lastly, this project is focused on creating a design for one specific carousel and shelf model, which was already expressed in need *E*. Need *K* expands on this, and explains that it would be preferable if the design worked on other models as well, but this is not strictly required.

1.5 Target Specifications

After developing the list of needs, we developed a list of specifications, also known as the metrics, that are based on the needs. These are concretely described and given measurable and testable units. Some of these can be answered with an answer of "yes" or "no", but others require checking if a value is above or below a certain threshold. We relate these specifications back to our identified needs.

1.5.1 Design Requirements and Ideal Specifications

To match with the design needs, we separated the specifications into the design requirements, which correspond to the design's primary needs and must absolutely be met, and the ideal specifications, which correspond to the design's secondary needs and are only nice to have. The requirements are described with relevant measurable units and target values in Table III, followed by the ideal specifications in Table IV.

TABLE III. DESIGN REQUIREMENTS, WITH MEASURABLE UNITS

	Description	Measurable unit	Target value
1.	The design allows shelves to rotate smoothly on their pivoting axis.	Smooth motion	Yes
2.	The design causes shelves to have a vibrational settling time of no more than 5 seconds after excitation.	Seconds	5
3.	The design causes shelves to stay within 5 degrees of rotation, forwards or backwards, from the upright position.	Degrees	5
4.	The design stays within the bounded volume (design space) with our additions, including shelf movement.	Within design space	Yes
5.	The design does not increase the weight of a shelf by more than 50 pounds.	Pounds	50
6.	The design allows for safe management of hazardous energy.	Can be locked out	Yes
7.	The design minimizes and then identifies all pinch points, abrasive surfaces, sharp points, and other physical hazards.	All hazards marked	Yes

TABLE IV. IDEAL SPECIFICATIONS, WITH COLUMNS CONTINUED FROM ABOVE

	Description	Measurable unit	Target value
8.	The design stays within a budget of $5,000.	Canadian dollars	5000 (ideal) 20000 (max)
9.	The design's powered sections (if any) are separate from the carousel's shelves and thus stationary.	Powered sections are stationary	Yes
10.	The design meets all primary needs during both clockwise and counterclockwise operation of the carousel.	Operates in CW and CCW motion	Yes
11.	The design can be assembled separately and then attached to a pre-existing carousel.	Can be assembled then attached	Yes
12.	The design can be assembled and attached to a carousel: by no more than 2 people;	People	2
13.	and in 8 working hours per person.	Hours of assembly	8
14.	The design meets all primary needs when installed on other carousel models.	Fits with other models	Yes

1.5.2 Need-Specification Relationships

The target specifications in Table III and Table IV were developed based on the project needs. These relationships are summarized in Table V.

TABLE V. RELATIONSHIPS BETWEEN NEEDS AND SPECIFICATIONS

Specification	Satisfies need(s)	Explanation
1. Smooth Rotation	A. Smooth Rotation	It will be visually evident if the shelf has abrupt motion, as stored items will shift or fall.
2. Settling Time	B. No Wobble	Vidir provided a settling time of 5 seconds, which will be when the shelf is within 5% of the resting position. This ensures minimal wobble.
3. Angle	C. Shelf Stays Level	Vidir provided a maximum angular deflection from upright of 5 degrees in either direction, which ensures that the shelf stays level.
4. Design Space	D. No Collisions	If we add too much bulk onto the shelf or the structure, then the shelves will collide with each other, the structure, or the ground. The design space is the volume in which we can add onto the shelf or carousel without any collisions occurring.
	E. One Carousel Model	Designing only within the bounded volume will help to integrate the design into the existing carousel and shelf.
5. Added Weight	E. One Carousel Model	Vidir provided a value of 50 lb of allowable added weight per shelf, which will also help to integrate the design into the existing carousel and shelf.
6. Lock Out	F. Design is Safe	Any power that we use must be managed properly and have safety mechanisms in place.
7. Hazards Marked	F. Design is Safe	All physical hazards must be eliminated where possible, or else clearly marked if they remain.
8. Budget	G. Inexpensive	Vidir provided values for the ideal budget and the recommended maximum budget, of $5,000 and $20,000, respectively.
9. Stationary Power	H. Existing Power Supply	The existing power supplies are all stationary.
10. CW/CCW	I. Full Range of Motion	A full range of motion is achieved when all primary needs during both clockwise and counterclockwise motion of the carousel.
11. Pre-assembly	J. Easy to Install	Vidir would prefer if the additions can be assembled and installed on site, as opposed to requiring installation at the Vidir plant. This reduces possible travel and makes things easier.
12. Assemblers	J. Easy to Install	Vidir would prefer if the installation can be done by two installers;
13. Assembly time	J. Easy to Install	and in one 8-hour workday. These conditions limit the complexity on assembly, making things easier as well.
14. Transferrable	K. Other Carousel Models	Proper integration with a carousel model is determined by the design meeting the primary needs

1.6 Design Space

To evaluate whether a design will physically fit in the system, we determined the design space. This term refers to the volume in which we can safely place additions to each shelf without the shelves colliding with the ground, the carousel structure, or any of the other shelves.

The design space has two portions. First, there is the volume around the structure where is it safe to add components. Secondly, there is the volume around each shelf where it is safe to add components.

For simplicity, we evaluated the design space based on the simplified model in Figure 4. It was created based on the original dimensions provided by Vidir but only contained extruded silhouettes of the 10 shelves, along with thin extruded representations of the chains. Since only overall dimensions were required to determine the design space, excluding the details made this visually easier to comprehend.

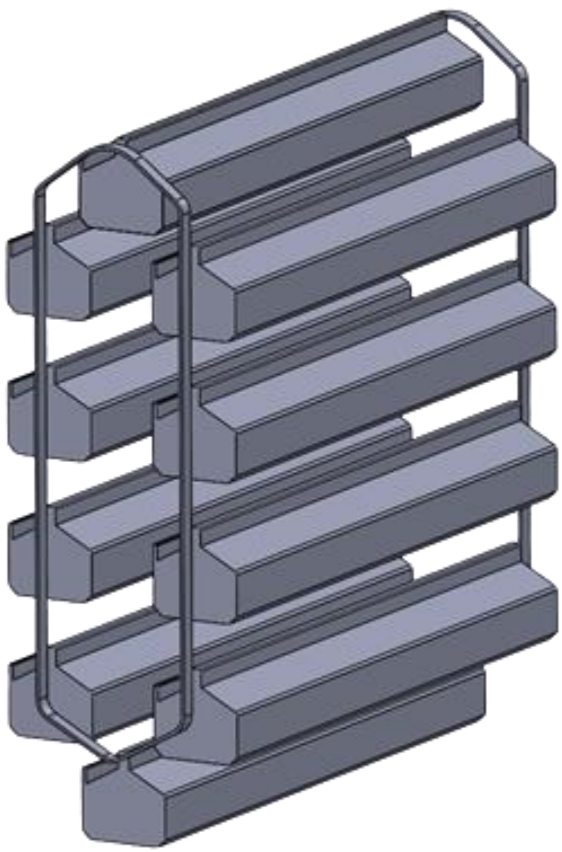


FIGURE 4. SIMPLIFIED MODEL OF THE SHELVES AND CHAINS.

1.6.1 Design Space for the Structure

Figure 5, below, shows a crude outline of the design space for the structure, shown as the flat, transparent bodies. There is one on either side of the shelves. We cut out portions for other structural elements, like the cross beams, which are not shown in the figure. Because the shelves connect to the chain using a pin, there can be nothing placed in the pin's path, which cuts each extrusion into an inner and an outer portion.

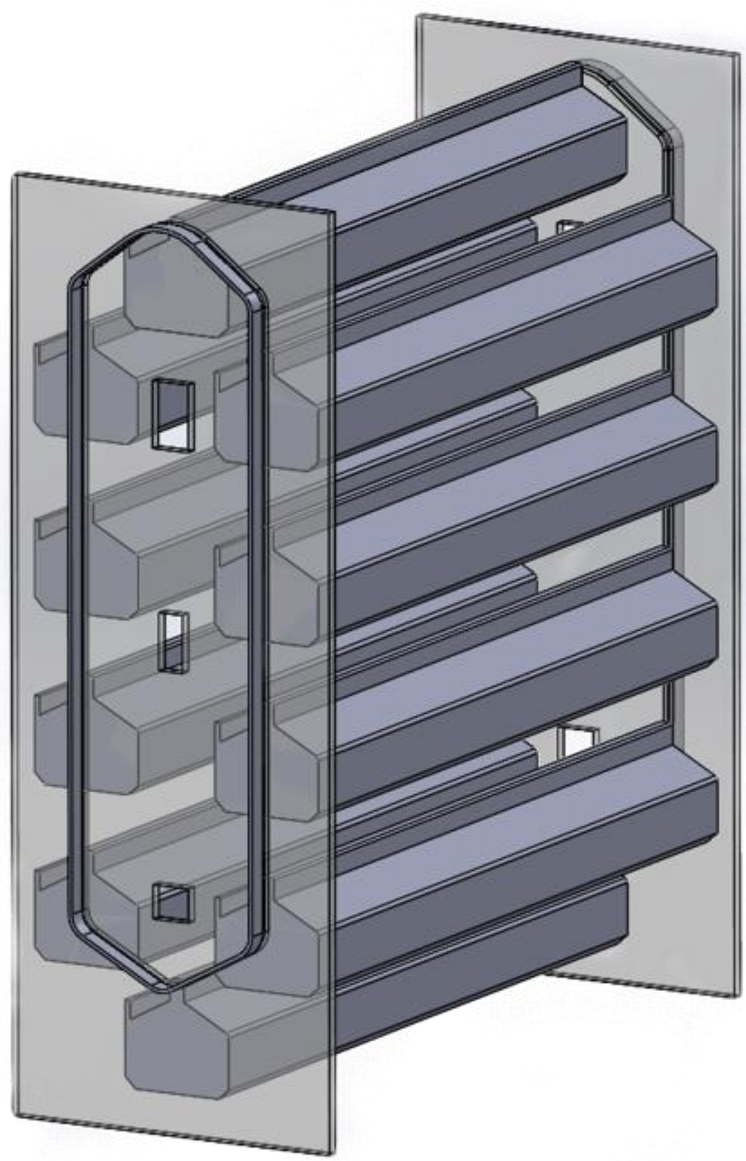


FIGURE 5. DESIGN SPACE FOR ADDING COMPONENTS ONTO THE CAROUSEL STRUCTURE

1.6.2 Design Space for the Shelf

This section gives a summary of the steps we took to find a crude design space for the shelf. First, we transformed the shelf silhouettes into their convex hull, which simplifies the process with very little loss of accuracy. From there, we extended the surfaces of each shelf until they met the other shelves, took the intersection of every resulting shelf shape, and patterned that around the carousel, shown in Figure 6.

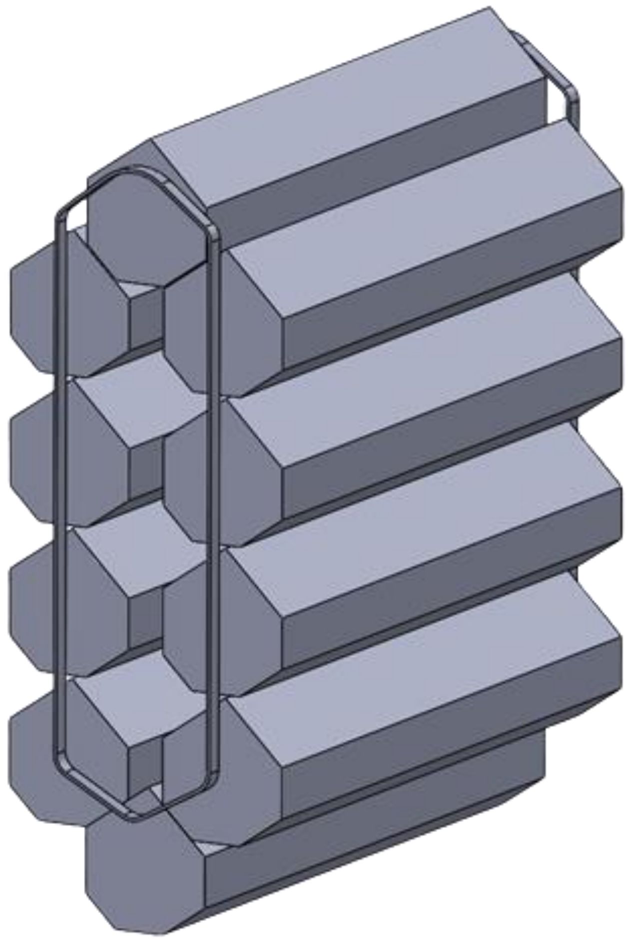


FIGURE 6. ISOMETRIC VIEW OF THE EXTENDED SHELF VOLUMES USED TO GENERATE DESIGN SPACE.
THE SHELVES ARE REPRESENTED AS IF THEY WERE AS LARGE AS POSSIBLE IN ALL DIRECTIONS, WITHOUT NEEDING TO MOVE AROUND THE CAROUSEL.

Each shelf was moved along the arc length of the chain in small, equal segments and any portions where the shelves intersected were cut away. This process was repeated until each shelf moved into the position of its neighbouring shelf. Then, we put every shelf in the same spot, took the intersection of all the shelves, and distributed them back into their own spots. By doing this, we considered the movement around all portions of the chain, embodied in one shape. Finally, we took the convex hull of this end shape as our design space. The result is shown in Figure 7 below as the transparent bodies.

A small part of the original shelf silhouette is sticking out of the final design space shape, seen on the top right of Figure 7, which shows that this design space is not the entire volume that is safe. There are places outside of this volume that are safe to add material. However, this final shape is the volume that is conclusively determined to be safe.

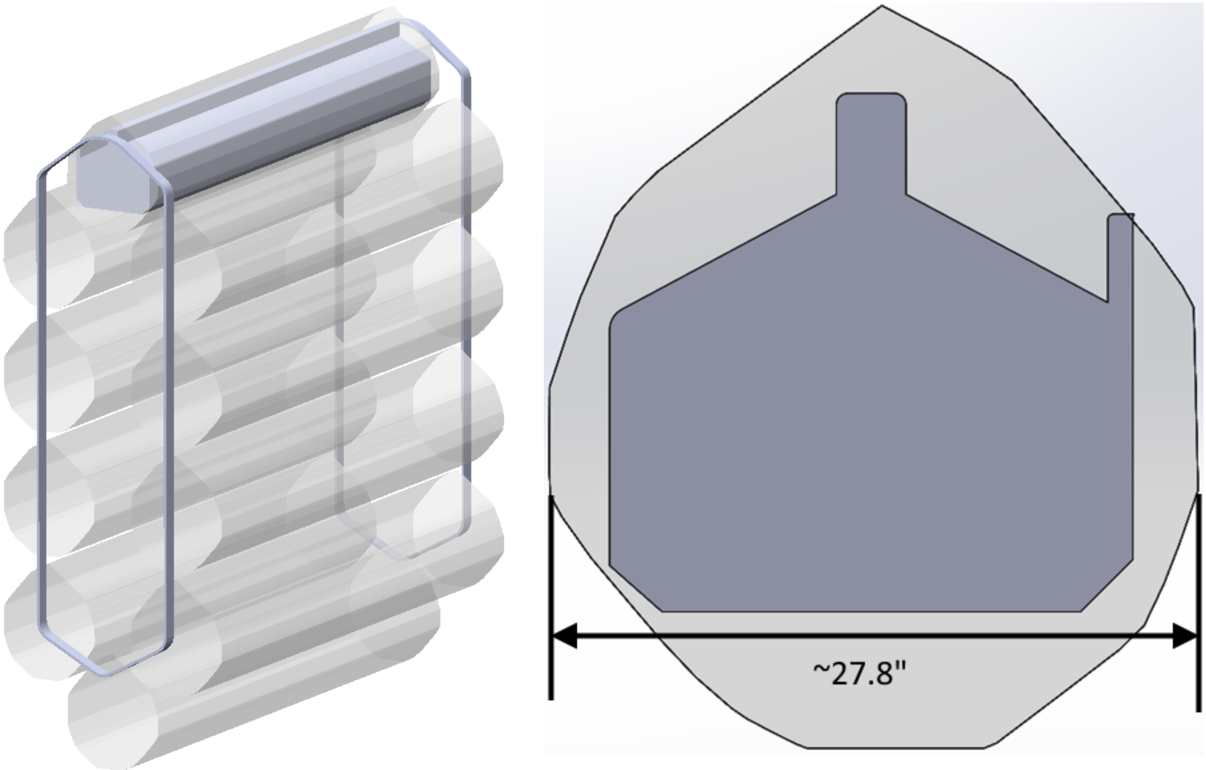


Figure 7. The final shape of the design space for adding components onto the shelf, as part of the entire carousel without outlines (left), and compared to the shelf silhouette with outlines (right).

2 Overview of Design

Our design can be described by breaking it down into its major components. To help convey the broader context of our design, a render of the full carousel is shown in Figure 8. This model of carousel holds ten shelves, as are shown in the render, distributed evenly along the length of the chain. On the next page, we identify what parts of the carousel are designed by us for this project.

FIGURE 8. RENDER OF THE FULL FINAL DESIGN.

Our design is in four parts, which are highlighted in Figure 9 below. To both side towers of the carousel, we added guide tracks (red) and their mounting brackets (cyan). On either side of each shelf, we added a wheel (indigo) and redesigned the chain-shelf connection (pink).

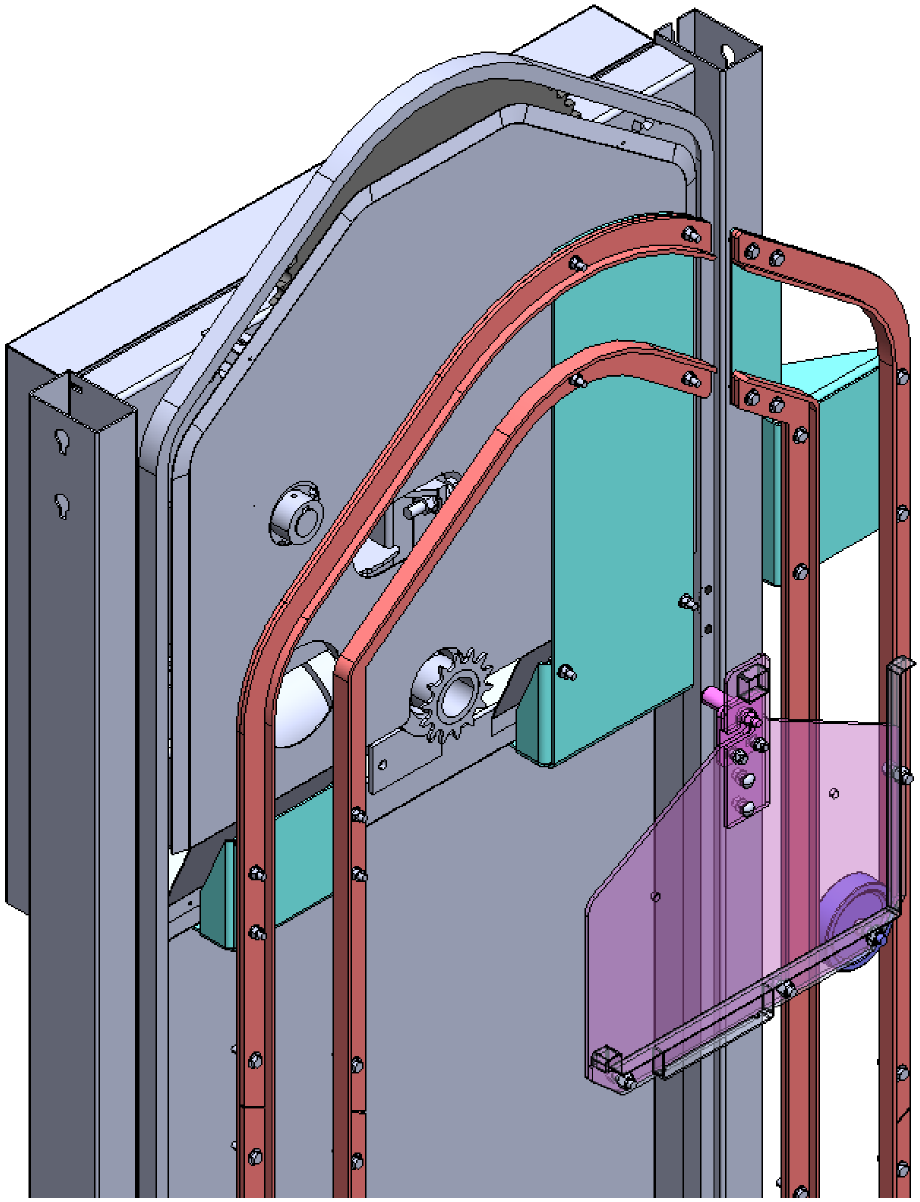


FIGURE 9. ISOMETRIC VIEW OF THE HIGHLIGHTED COMPONENTS OF THE DESIGN.

The guide tracks are presented first, as they are the core component of the design. They are followed by the wheels, the self-chain connection, and finally the track's mounting brackets. Each section provides a breakdown of each component's self-contained features, supported by visuals.

2.1 Guide Tracks

The core component of our design is the series of guide tracks, highlighted in red in Figure 10 below. One set of guide tracks is attached to each tower. The drive chain of the carousel is coloured yellow as well, to expose the similar shapes of the chain and the guide track.

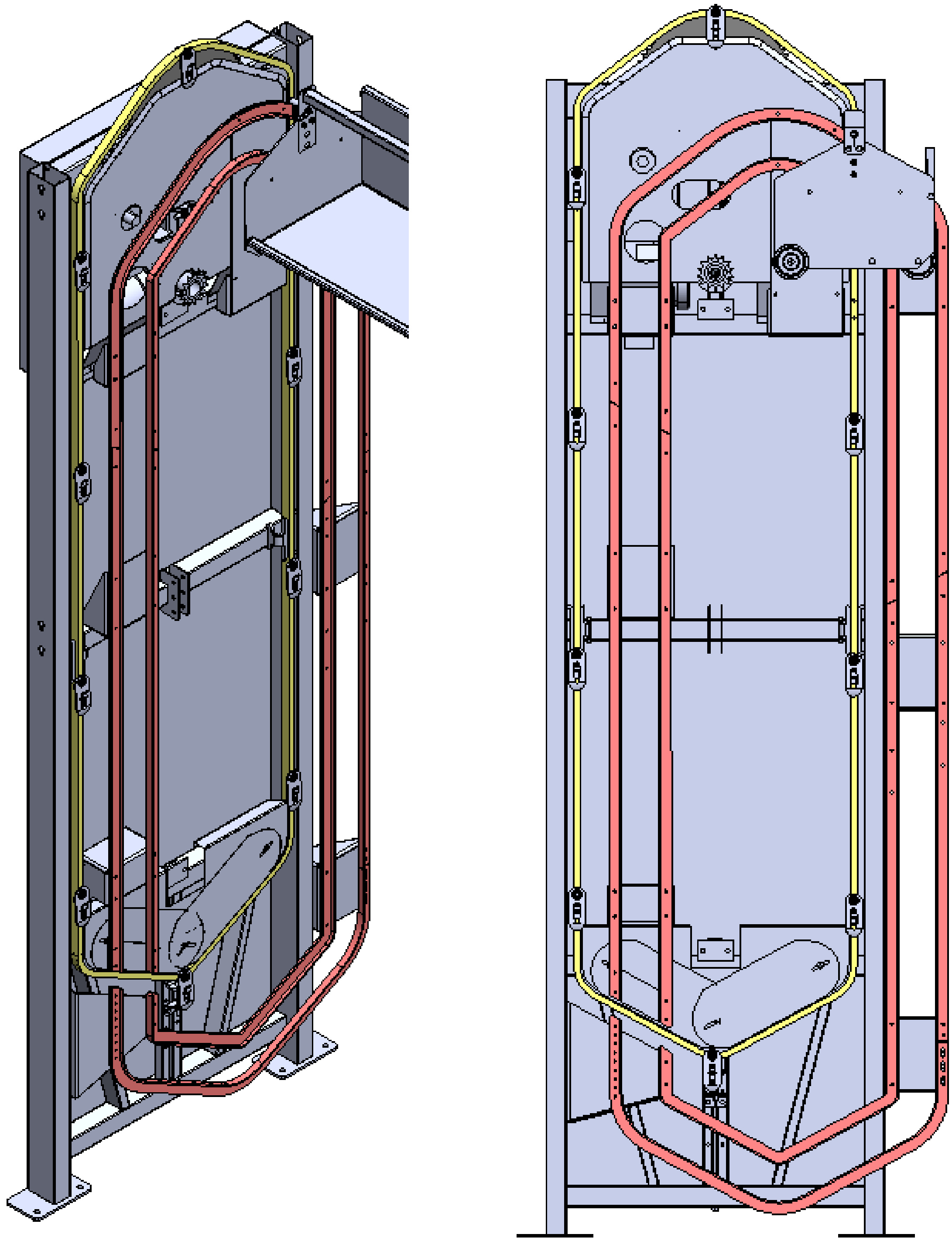


FIGURE 10. GUIDE TRACKS ON LEFT CAROUSEL TOWER, IN ISOMETRIC AND SIDE VIEWS. GUIDE TRACKS ARE COLOURED RED, WHILE THE SIMPLIFIED DRIVE CHAIN IS COLOURED YELLOW.

2.1.1 Relation Between Guide Tracks

An important feature of the design is that the guide tracks are copied exactly for each of the two towers of the carousel, not mirrored. This is shown in Figure 11 below by showing the tracks from both towers, with one in red and the other in green. The two sides are identical except for orientation and position. This is easy to see when the tracks are overlaid as they are in Figure 11.

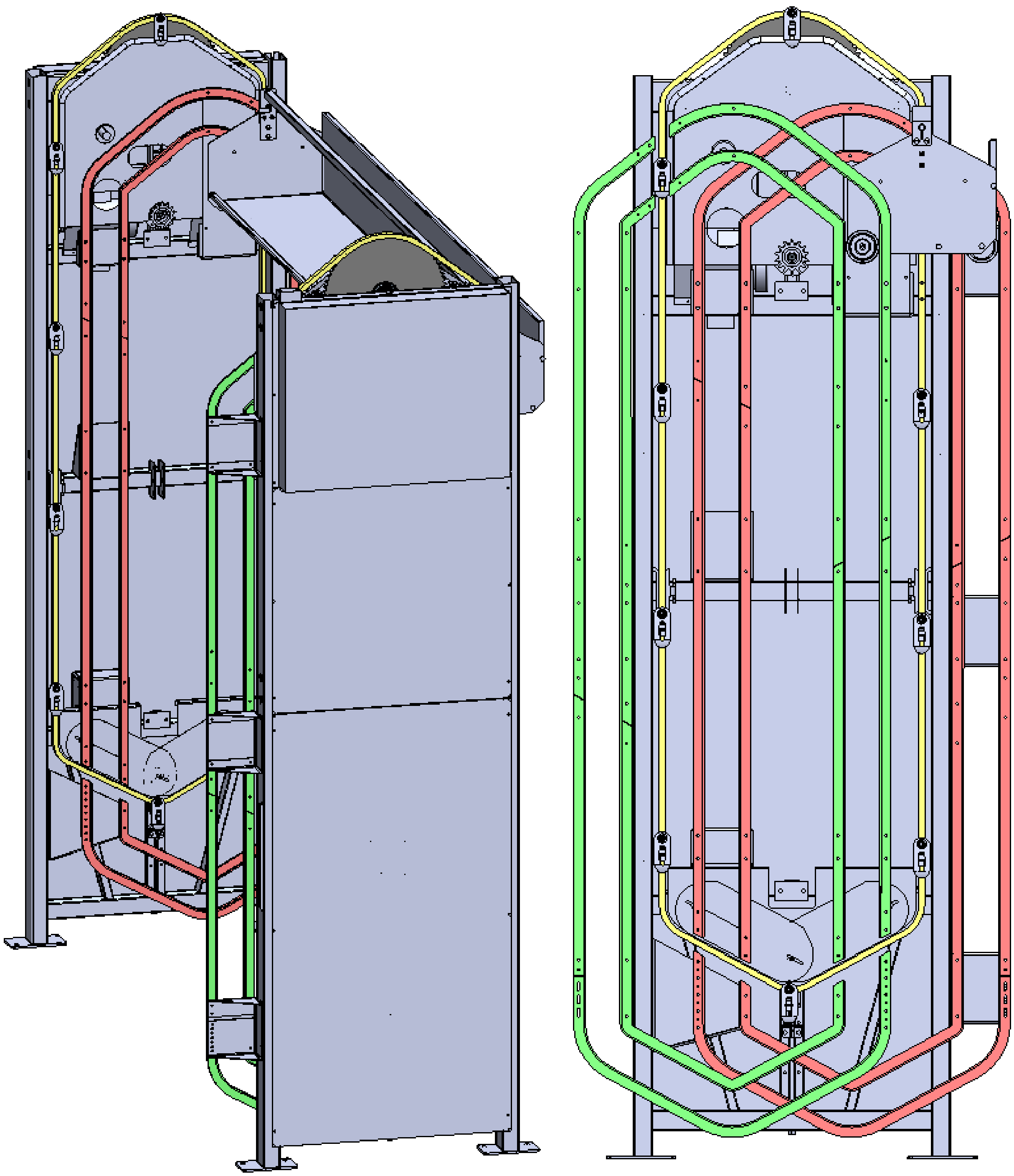


FIGURE 11. GUIDE TRACKS ON BOTH CAROUSEL TOWERS, IN ANGLED AND OVERLAID-SIDE VIEWS. IN BOTH VIEWS, THE GUIDE TRACKS BELONGING TO THE LEFT TOWER ARE RED, AND THOSE BELONGING TO THE RIGHT TOWER ARE GREEN. THE SIMPLIFIED DRIVE CHAIN IS YELLOW ON BOTH TOWERS.

2.1.2 Track Shape

The shape formed by each set of tracks is directly derived from the carousel's chain. The tracks are formed around a path identical to the chain, but wider, and translated 18" down and 9" horizontally. Effectively, the tracks set the boundaries for the path of a wheel located that 18" vertically and 9" horizontally away from the chain-connection of the shelf. This is shown in Figure 12 below.

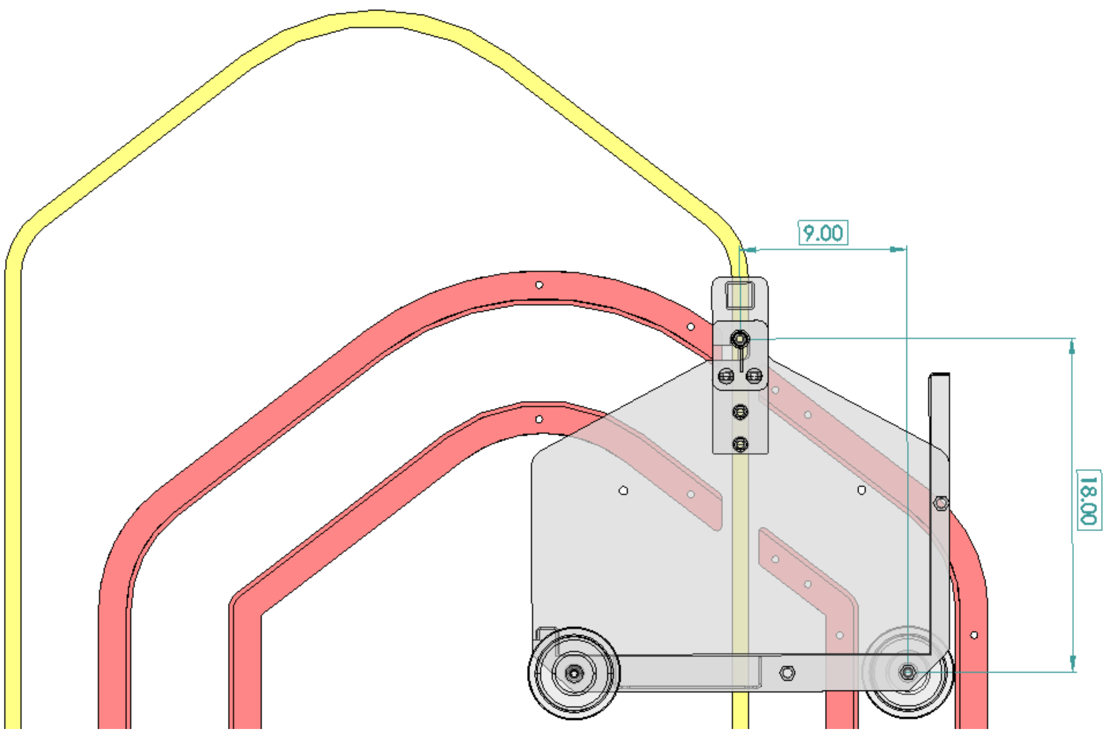


FIGURE 12. SIDE VIEW OF GUIDE TRACKS AND CHAIN TOP PORTION, SHOWING KEY DIMENSIONS OF HOW THE CENTERLINE OF THE TRACKS' INNER SPACE IS GENERATED. THE SET OF GUIDE TRACKS IS RED, AND THE SIMPLIFIED CHAIN IS YELLOW.

The difference between the tracks on each tower is the direction that the horizontal translation occurs when generating the track paths. In the pictured left tower's tracks, the tracks are translated 9" back depth-wise with respect to the shelf, or to the figure's right. For the right tower's track set, it would be translated left in the figure plane, so that the second set of tracks would hug the left wheel in the same manner as the tracks do on the right, for the right wheel.

2.1.3 Track Cross-Section

Each track section is comprised of ¼" thick pieces of laser cut steel, welded to a ¼" thick piece of steel which is wrapped around the shape of the laser cut pieces. The wheel contacts the exposed surface of the wrapped piece. The laser cut pieces are 1-½" wide, while the wrapped pieces are 1" wide. These dimensions are shown in the figures on the next page.

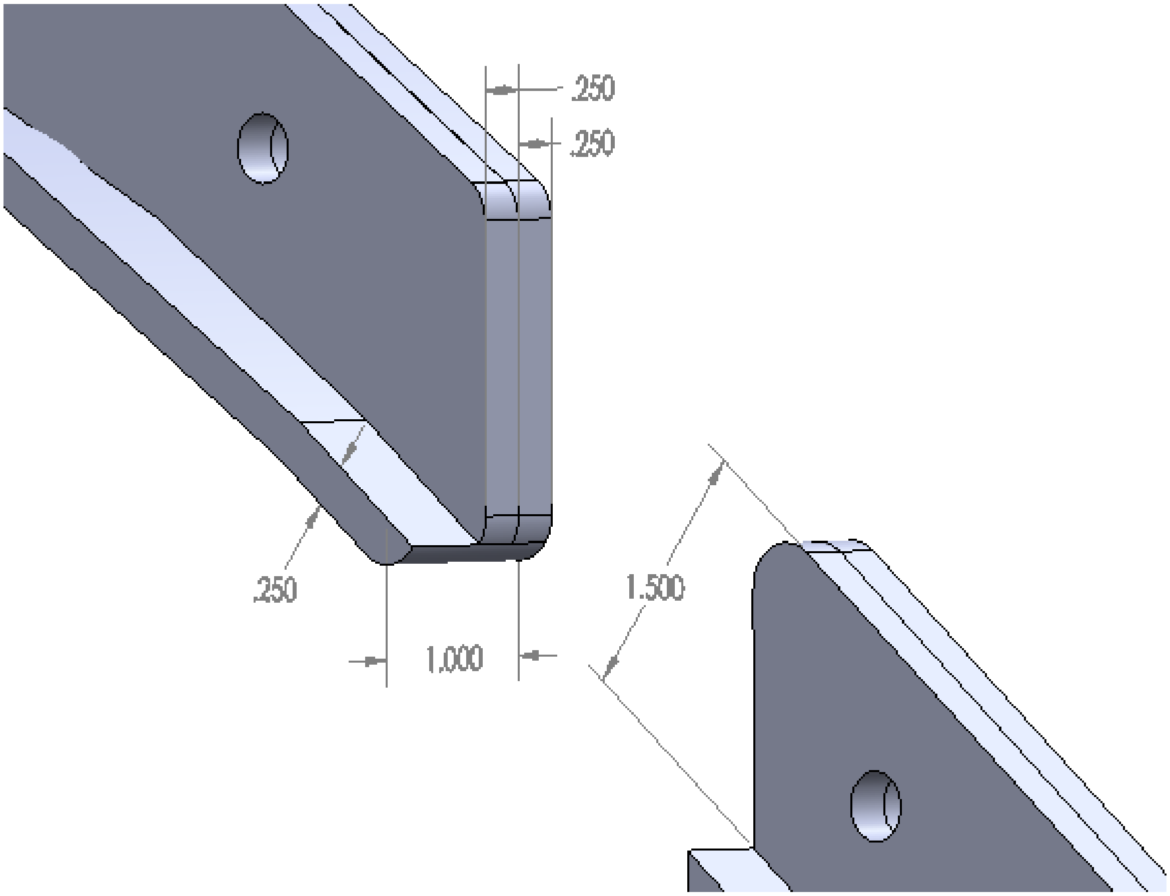


Figure 13. Dimensions on the laser cut and wrapped pieces of the track, shown at the gap between the left inner and right inner section.

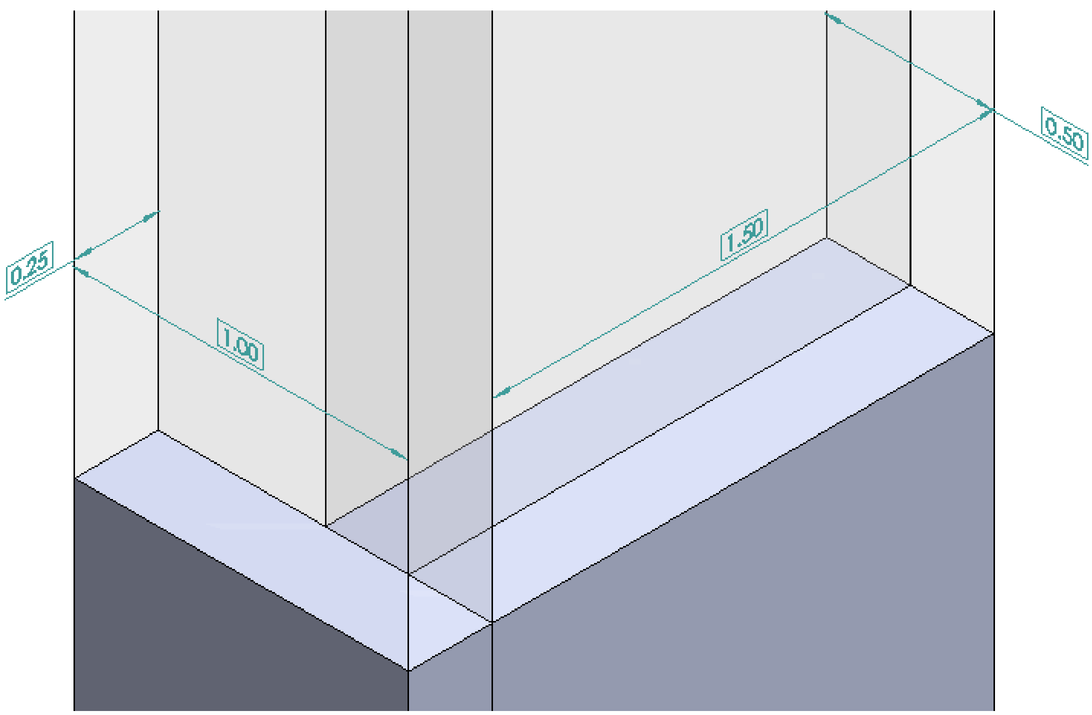


Figure 14. A cross-sectional view of the dimensions of the pieces of the track.

2.1.4 Naming Convention

Each track set is split into four sections, based on two dividing factors. First, there is an inner/outer split, as the tracks bound the inside and outside of the shape. Secondly, there is a left/right split, as the tracks are bisected by the chain. We will use the labels given in Figure 15 to refer to the individual sections of each track set.

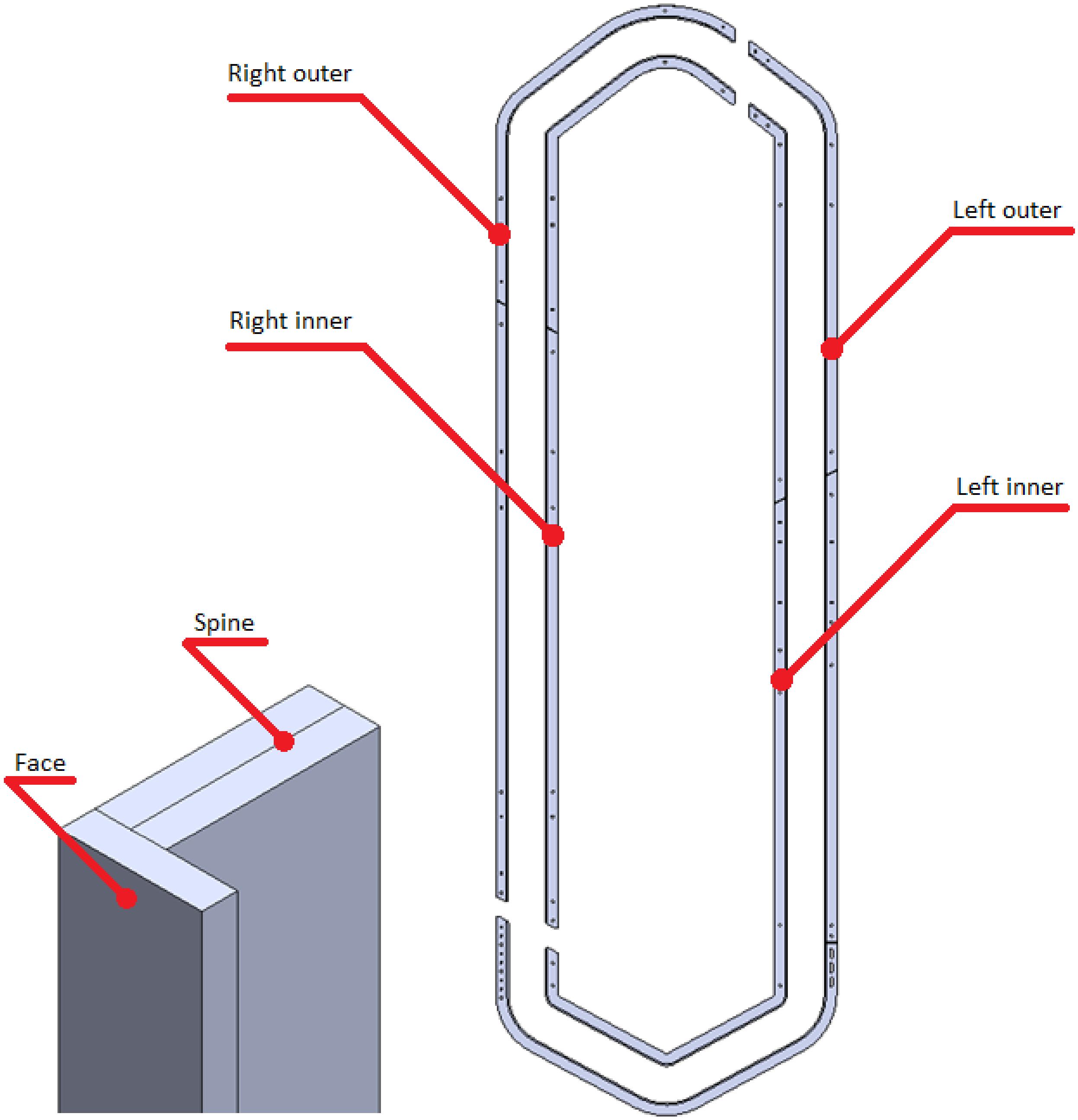


Figure 15. Terminology of track cross-section (left) and major track sections (right).

2.2 Wheels

The wheel shown in this section is used to support smooth motion along the guide track. There are two identical wheel assemblies on each shelf. This assembly consists of the wheel, bearing, bolt and fastening components. Each assembly uses one flat head socket cap screw, one general purpose washer and three thin nylon insert locknuts. Figure 16 shows the details of the assembly.

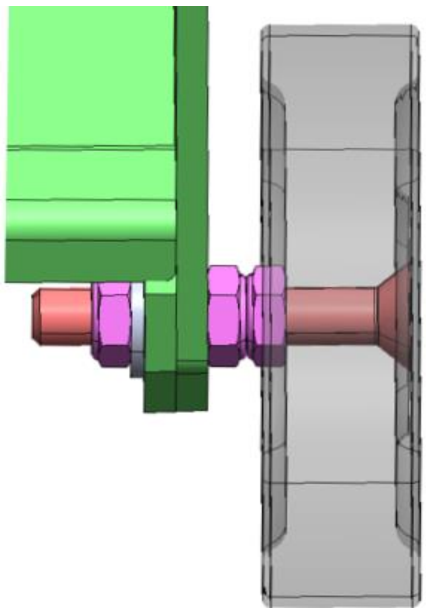


Figure 16. Colour-coded wheel subassembly.

Transparent	**5” Diameter wheel** An off-the-shelf part machined to work for the requirements. Includes an integrated plastic sleeve. Width of 1.25”.
Red	**1/2” Flat head socket cap screw** 3” in length. A countersunk hole is machined into the side of the wheel facing the shelf to avoid interference with the brackets.
Purple	**Thin nylon-insert locknut** 5/16” in width. Inserted against wheel side and on both side of the shelf.
Grey	**1/2” ID Washer**
Green	**Shelf** Total of 1/2” width where it is intersected by the screw.

The wheel in Figure 16 is shown as transparent. It is an off-the-shelf design that has been modified to fit the design needs. The key features include a countersink hole and a bearing sleeve.

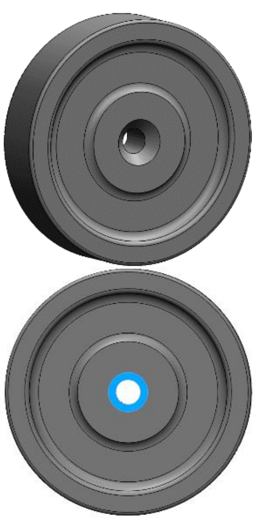


Figure 17. Wheel in two views.

Countersink hole Diameter: 0.938” countersink angle: 82° Length: 0.251”	A countersink hole is machined into the side of the wheel to ensure the bolt does not extend past the wheel.
Sleeve bearing ID: 0.5” OD: 0.8” Length: 0.73”	The highlighted wheel portion in the bottom figure corresponds to the sleeve bearing. It was modified to begin after the countersink hole for the remaining width of the wheel.

2.2.1 Shelf Wall Modification

To install and access the wheel assembly, the original holes located on the shelf wall must be moved. In Figure 18, the holes are at a vertical distance of 18” away the center of the hook, which is the connection point to the chain. The left and right holes are 9” away from the centerline and the middle hole is 2.50” away from the centerline. These dimensions allow the wheel assembly to be mounted symmetrically on left and right-side holes without interfering with the horizontal shelf sections above the holes. This design is the same for both ends of the shelf. The wheels are mounted one per side, at opposite depth-wise offsets.

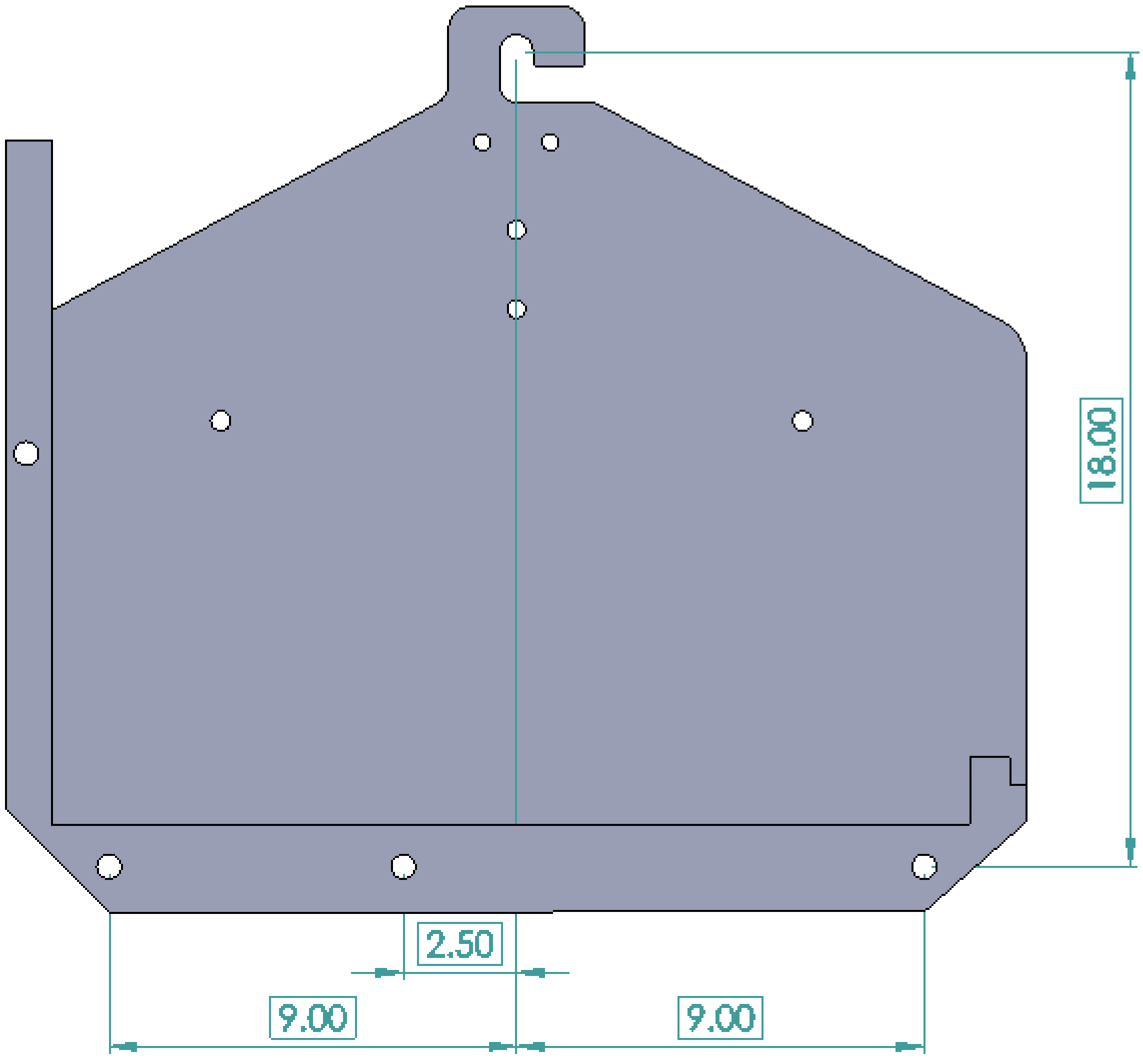


FIGURE 18. MODIFIED DIMENSIONS OF SHELF END-WALL PIECES.

Also pictured in Figure 18 is the L-shaped piece of shelf end-wall, which also has its holes modified to match the large shelf end-wall.

2.3 Shelf-Chain Connection

Our design reworks the connection between the shelf and the chain of the carousel. This section of the report describes the subassembly's parts and how they fit together.

Figure 19 shows the general area where this component is located on one of the ends of the shelf. Only the shelf, connecting assembly, and simplified chain are visible.

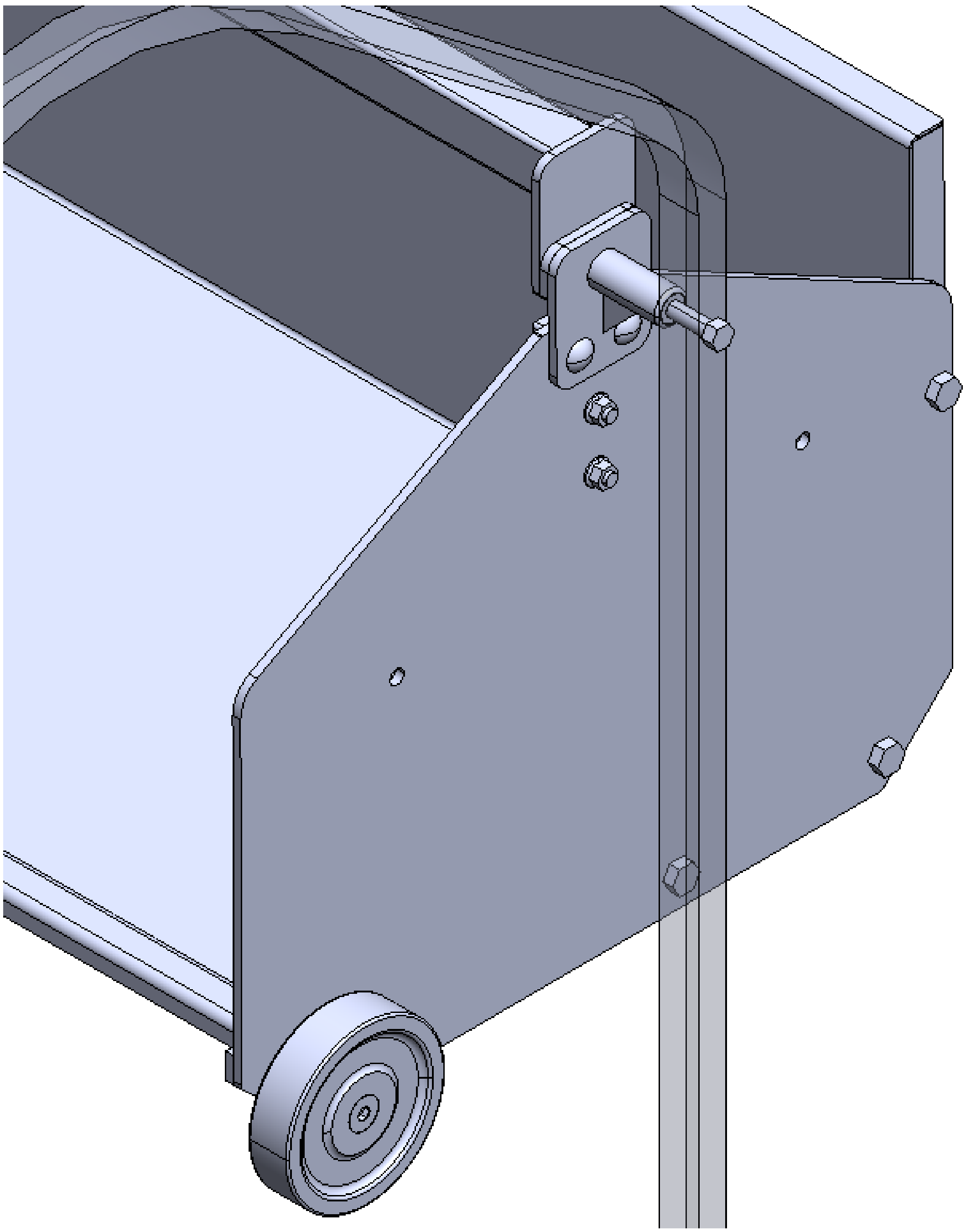


Figure 19. Shelf with full connecting assembly, isometric view. Frame suppressed. Chain simplified and transparent.

2.3.1 Connection Components

The connection subassembly cleanly splits into a chain-mounted portion and a shelf-wall portion, held together with fasteners. These are shown in Figure 20 below.

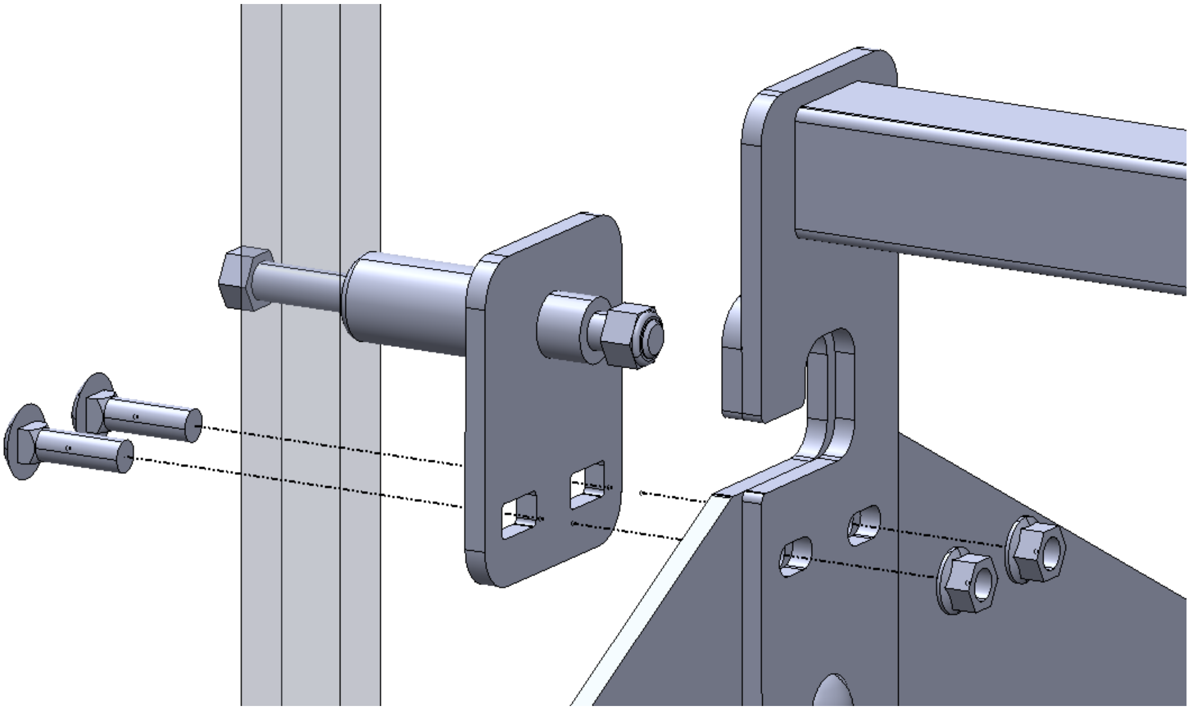


FIGURE 20. EXPLODED VIEW OF THE TWO HALVES OF THE SHELF-CHAIN CONNECTION SUBASSEMBLY AND THEIR FASTENERS.

The chain-half of the subassembly is installed integral to the carousel's chain. The chain will have these evenly spaced, placed at all points where a shelf could be installed. It would be prohibitively difficult for the 5" long bolt to be installed when shelves are being added, which is after the remainder of the carousel is in place.

The shelf-half of the subassembly is built into the shelf wall.

The fasteners are 3/8" diameter carriage bolts. They are 1-¼" long measured from the head, and one is each held on with a nut identical to those holding other carriage bolts onto the shelf.

2.3.2 Details of Connection Halves

The chain-half of the subassembly is made of entirely new parts. Some of them are commonly available, others are sheet metal, and one custom made.

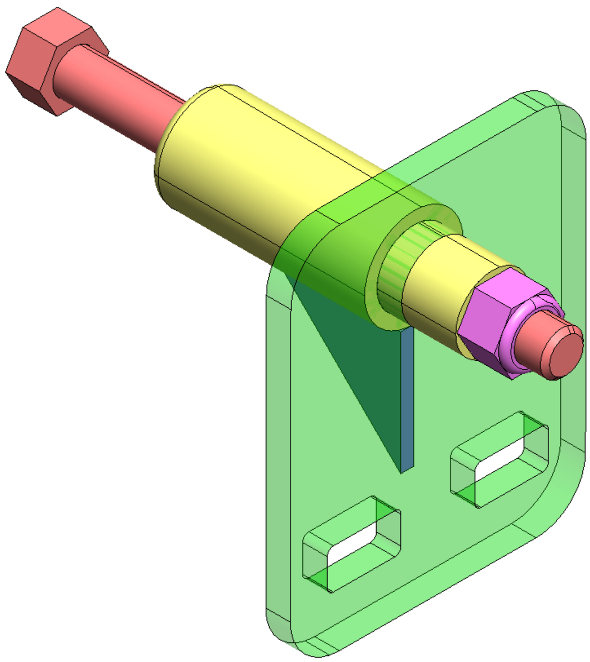


FIGURE 21. COLOUR-CODED CHAIN-HALF OF THE SHELF CONNECTION SUBASSEMBLY. THE GREEN PIECE IS TRANSPARENT.

Red	**7/16" Bolt** About 5" long; enough so that the nut doesn't rub against the sleeve.
Yellow	**Connection Sleeve** Rotates freely on the 7/16" bolt. Is thicker on the far side of the plate, to better resist bending.
Green	**Bolting Plate** Is welded to the sleeve. Visible face is 2.45" from the sleeve's far face.
Blue	**Gusset Plate** Welded to the sleeve and plate for additional support.
Purple	**Nut** Keeps it all from falling apart when the shelf-half is not installed.

The shelf-half of the assembly is made by modifying the original shelf wall pieces.

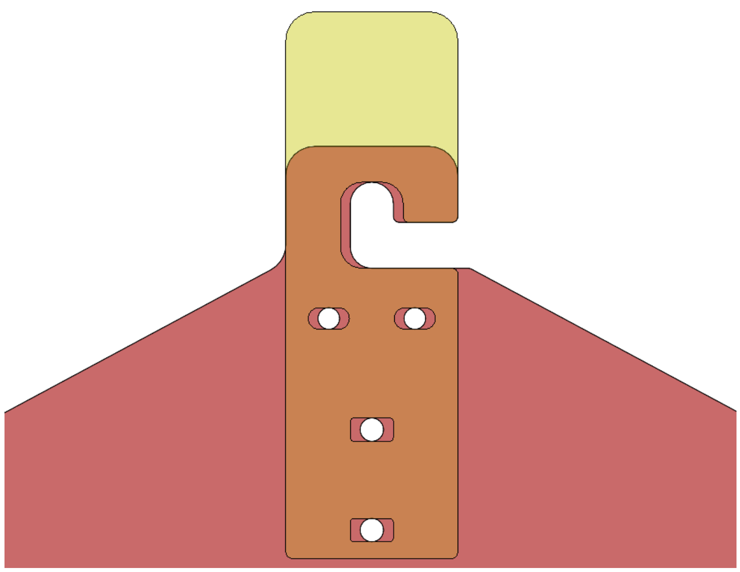


FIGURE 22. COLOUR-CODED SHELF-HALF OF THE SHELF CONNECTION SUBASSEMBLY. THE YELLOW PIECE IS TRANSPARENT, CREATING ORANGE WHERE IT OVERLAYS RED.

Red	**Shelf Wall** The clothes-hanger shape allows the shelf to be hooked onto the 'sleeve' of the chain-half when installing the shelf. The inner circle of the hook fits onto the outer diameter of the chain-half's sleeve.
Yellow	**Pipe Plate** All the holes in the pipe plate have an equal 11/64" of allowance horizontally for easier assembly.

2.4 Track Mounting Brackets

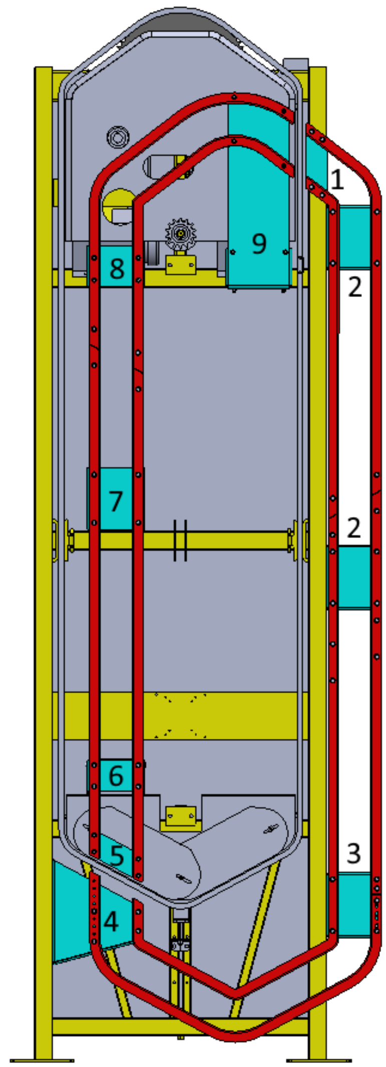


FIGURE 23. COLOUR-CODED RIGHT TOWER, HIGHLIGHTING THE GUIDE TRACK, FRAME, AND BRACKETS, IN RED, YELLOW, AND CYAN, RESPECTIVELY.

Shown in Figure 23, we designed the brackets to mount the track sections onto the frame of the tower. They are coloured in cyan, red, and yellow, respectively. We numbered the brackets clockwise around the track, starting at the vertical gap on the right sections.

Bracket 1 and Bracket 5 are back plates that brace the hanging portions of the track. They are grouped in with the other brackets because they are made with laser cut sheet metal as well, even though they are completely flat. The other brackets all bolt to the back of the track on one surface, and bolt to a piece of the frame on another surface.

Most of the brackets are made from 10-gauge steel. The exceptions are Bracket 6 and Bracket 9, which are made of 6-gauge steel for additional strength.

The track is fastened to the brackets using hex head ⅜" bolts and nuts. The exception is for Bracket 8, which uses ⅜" carriage bolts as to only require access to one side of the bolt to fasten. These are the same bolts that the brackets use to fasten to the frame.

Brackets 2, 3, and 4 fasten to a vertical face of a frame piece, and require the bolts to be slotted in from above. Brackets 6 and 7 fasten to the top face of a frame piece, and Brackets 8 and 9 fasten to the bottom face of a frame piece. These bolts are slotted in from the back, in the perspective of Figure 24, and are pulled out of the page. The brackets that are within the frame require the sheet metal covers to be removed from the bracket in order to be installed.

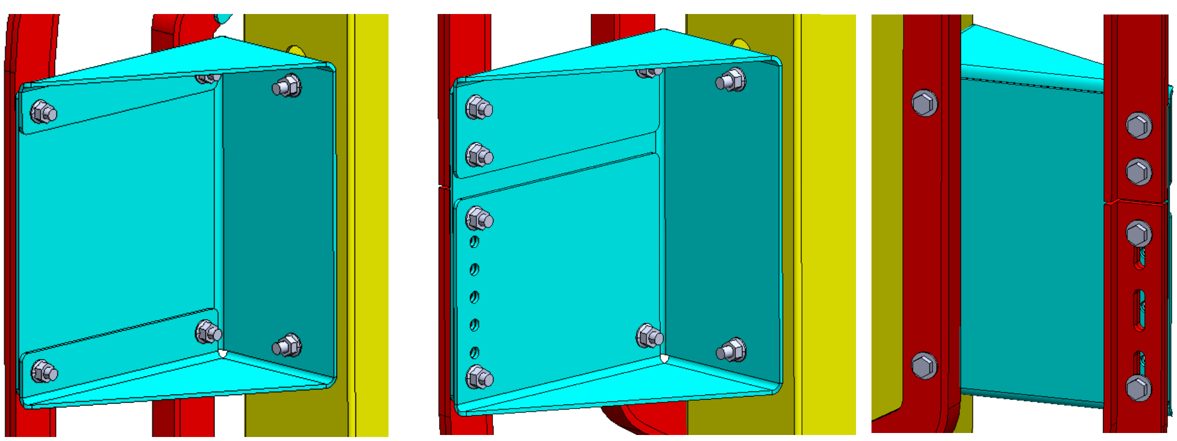


FIGURE 24. BACK VIEW OF BRACKET 2 (LEFT), BACK VIEW OF BRACKET 3 (MIDDLE), AND FRONT VIEW OF BRACKET 3 (RIGHT)

On the previous page, Figure 24 shows Brackets 2 and 3. Bracket 2 is the only bracket that is used twice in this design. Bracket 2 and Bracket 3 are almost identical, but Bracket 3 has larger inner folds to accommodate its increased number of holes. These extra holes are used to connect to the slots in the track, shown in the front view. This is a separate piece that can move vertically and requires more holes.

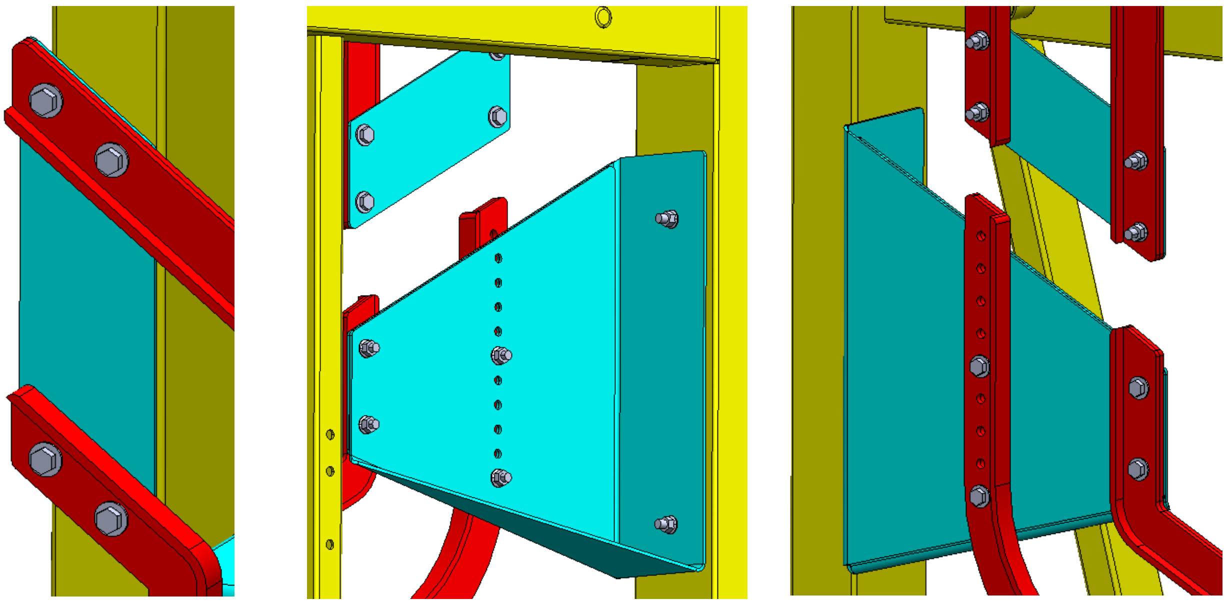


FIGURE 25. FRONT VIEW OF BRACKET 1 (LEFT), BACK VIEW OF BRACKETS 4 AND 5 (MIDDLE), AND FRONT VIEW OF BRACKETS 4 AND 5 (RIGHT).

Figure 25 shows Brackets 1 from the front and Brackets 4 and 5 from the back and the front. Bracket 1 and Bracket 5 are just back plates to brace the hanging portions of the track. The back view in the middle image of Figure 25 can only be seen with the tower covers off and with an angled frame piece removed. This angled frame piece is in the right image. Similarly to Bracket 3, Bracket 4 requires many vertically spaced holes to allow adjustment of the track, discussed in detail in Section 3.4.

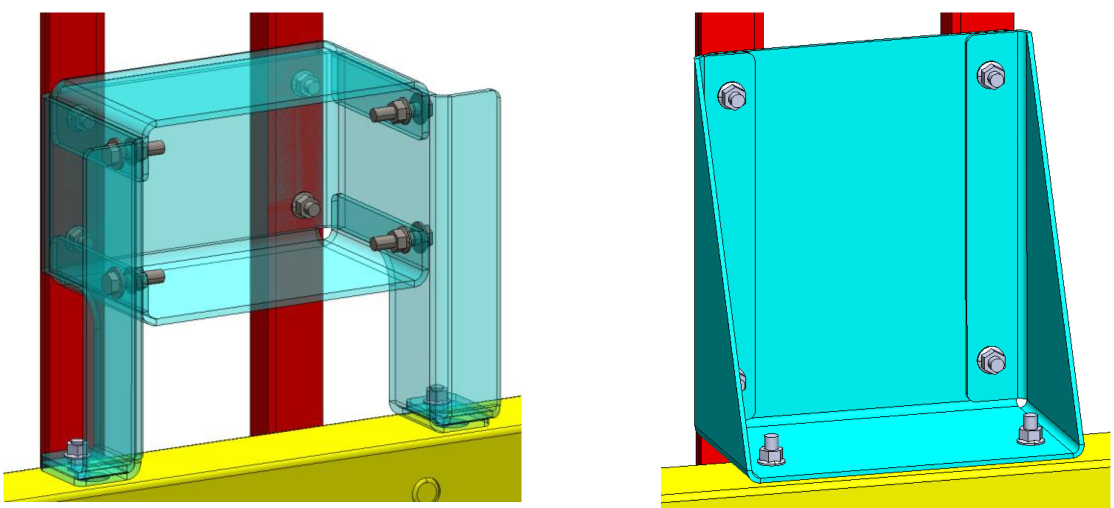


FIGURE 26. TRANSPARENT VIEW OF BRACKET 6 (LEFT), AND BACK VIEW OF BRACKET 7 (RIGHT).

Figure 26 shows Brackets 6 and 7 from the back view, with Bracket 6 as transparent in order to see all the required bolts. Brackets 6 and 7 are the two brackets which bolt down onto the top surface of a frame piece. From the view in Figure 26, the brackets get placed down further towards the reader, and then pushed into the page to be tightened.

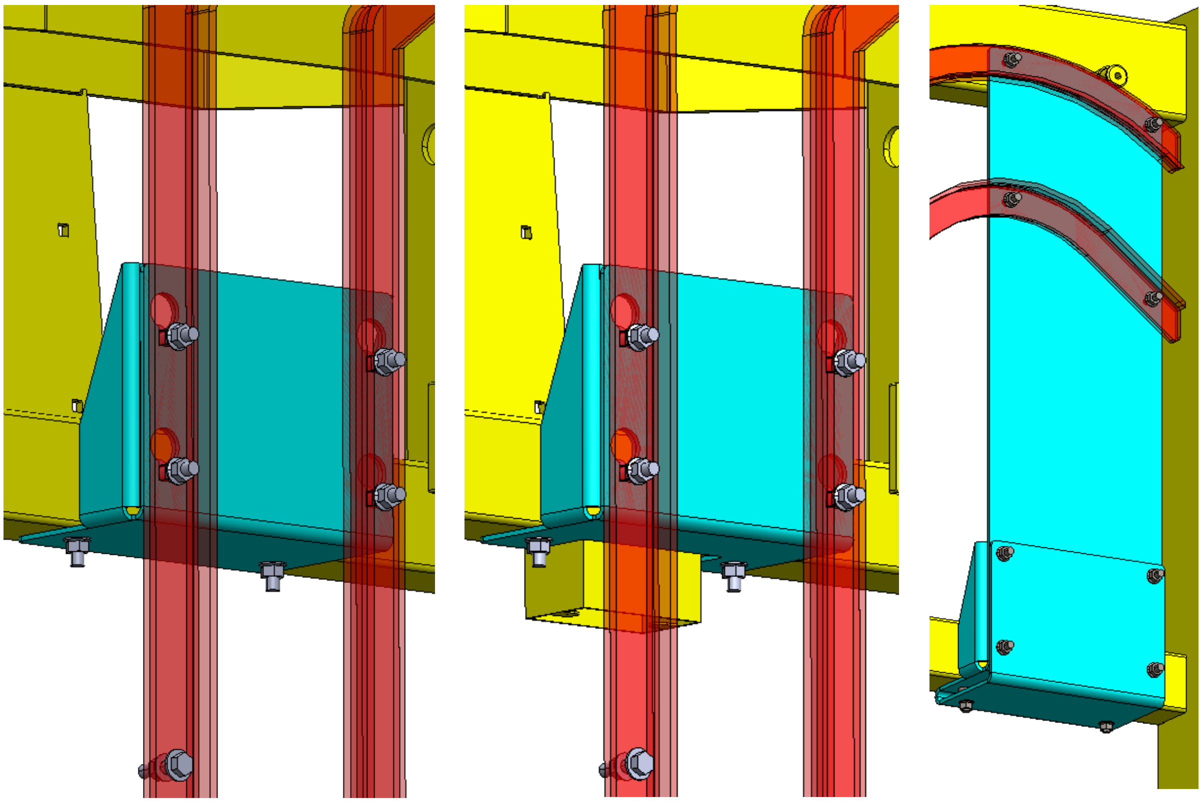


Figure 27. Front views of Bracket 8R (left), Bracket 8L (middle), and Bracket 9 (right).

Figure 27 shows Brackets 8 and 9 from a front view, which bolt in similarly to Brackets 6 and 7, but instead they bolt up onto the bottom surface of a frame piece. From the view in Figure 27, the brackets get placed further away from the reader, and then pulled out of the page to be tightened. The left and middle images show the difference between the two types of Bracket 8. The “L” version of Bracket 8 allows for the small junction box located under the frame piece on the left tower. Bracket 8 is the only bracket to bolt to the track using the same carriage bolts that the brackets use to bolt to the frame.

Bracket 9 is in the right image of Figure 27 to show that the contour of the bracket matches that of the track. Bracket 9 is one of two bracket made with 6-gauge steel. The bottom part of Bracket 9 is similar in size and shape to Bracket 8, but is reinforced with a bent double-layer to support how it extends far upwards to meet the track. The bolts that fasten Bracket 9 to the track are the only bolts connecting the track that are turned around. However, these bolts are the same normal ⅜” hex head bolts, which all the brackets use to fasten to the track other than Bracket 8.

3 Design Functionality

The components of the design work together to achieve the functionality that we set out in our problem description and overcome the challenges that we encountered during our design process.

3.1 Tracks and Wheels Constrain Shelf

The primary requirement of the project was that the design must prevent shelves from swaying, tilting, or otherwise deviating from their upright position. To accomplish this, the guide tracks constrain the position of the shelf's wheels, which then constrains the rotation of the whole shelf. Figure 28, below, illustrates how the wheels fit inside the tracks by overlaying the tracks and shelf.

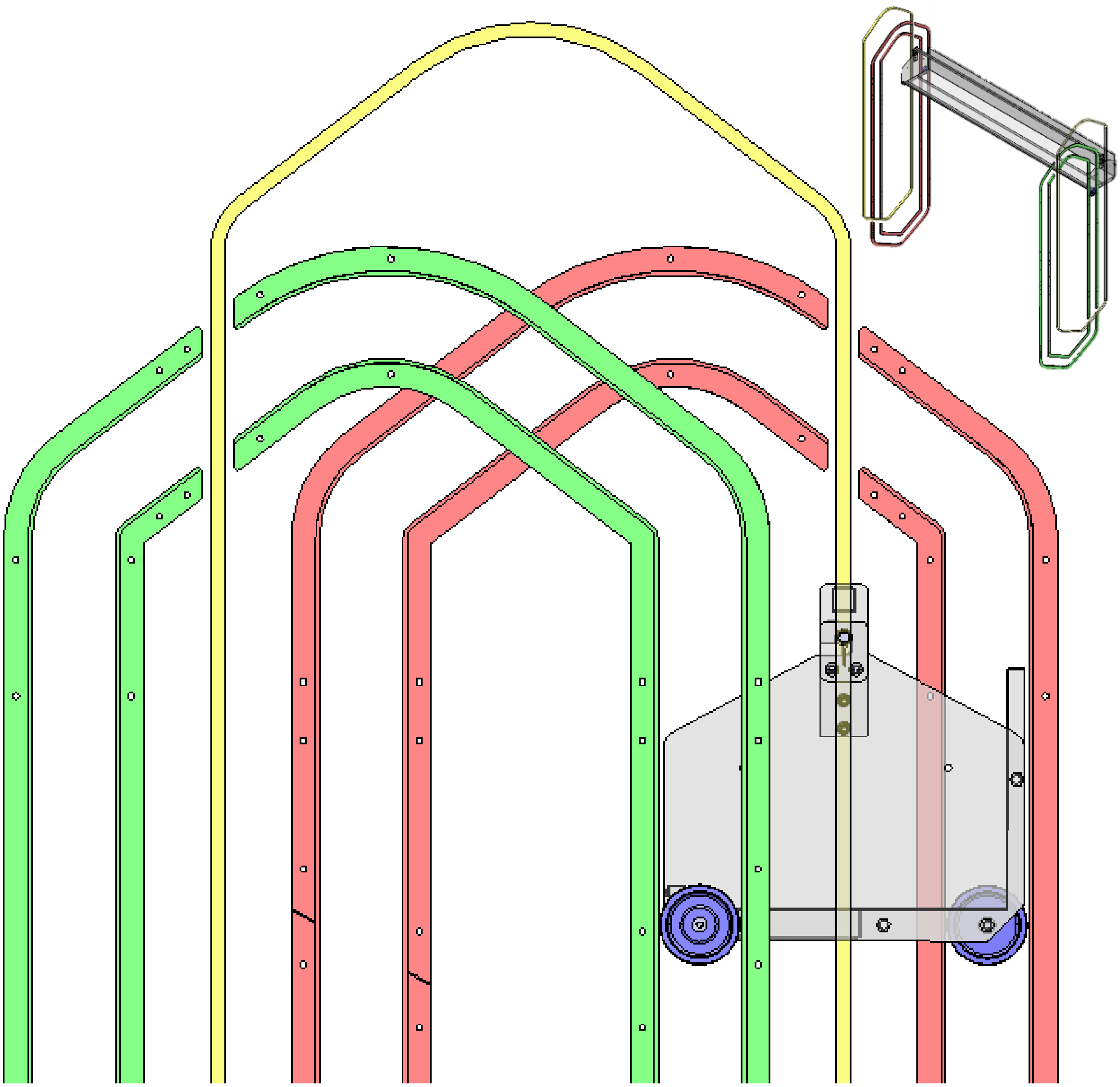


Figure 28. Side view of shelf and overlayed guide tracks. The guide tracks are red (left tower) and green (right tower), the chain path is yellow, and the wheels of the shelf are blue. In the top-right corner, an isometric view shows how the guide tracks do not intersect.

3.2 Two-Track Design Prevents Flipping

Many preliminary designs had the fatal flaw that they had the potential to flip the shelf at the top bend of the carousel. The two figures below illustrate how that could happen if the red guide track were not there, and how the additional guide track's additional constraint protects the design.

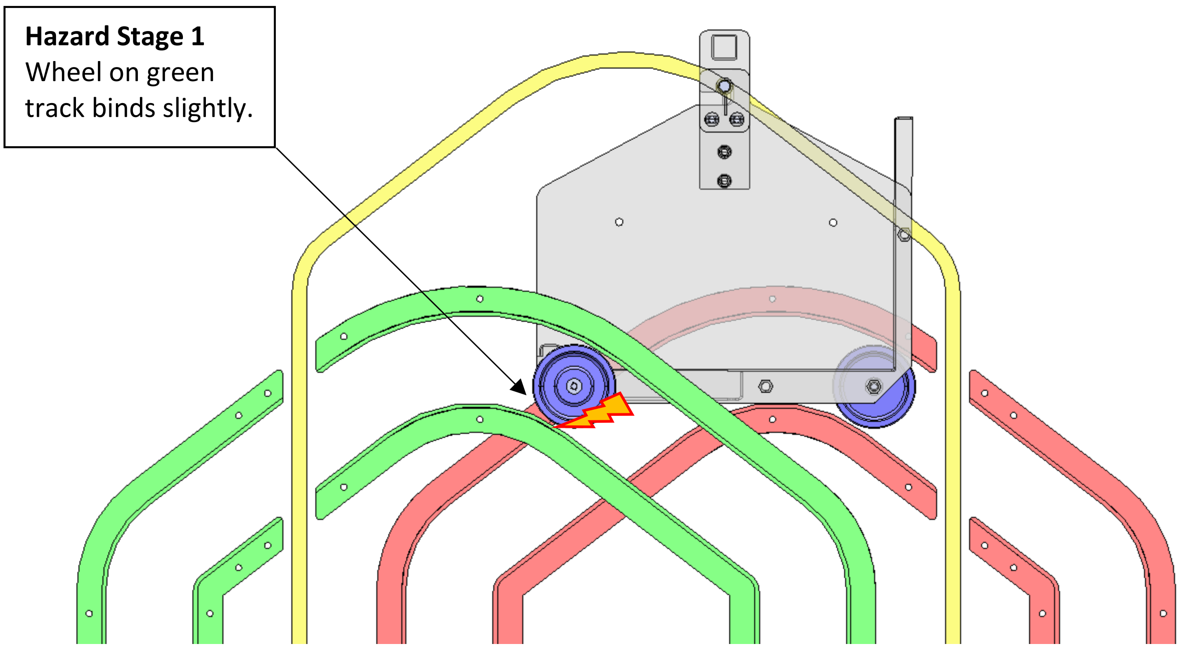


FIGURE 29. AVOIDED FLIPPING HAZARD ILLUSTRATION, PART 1.

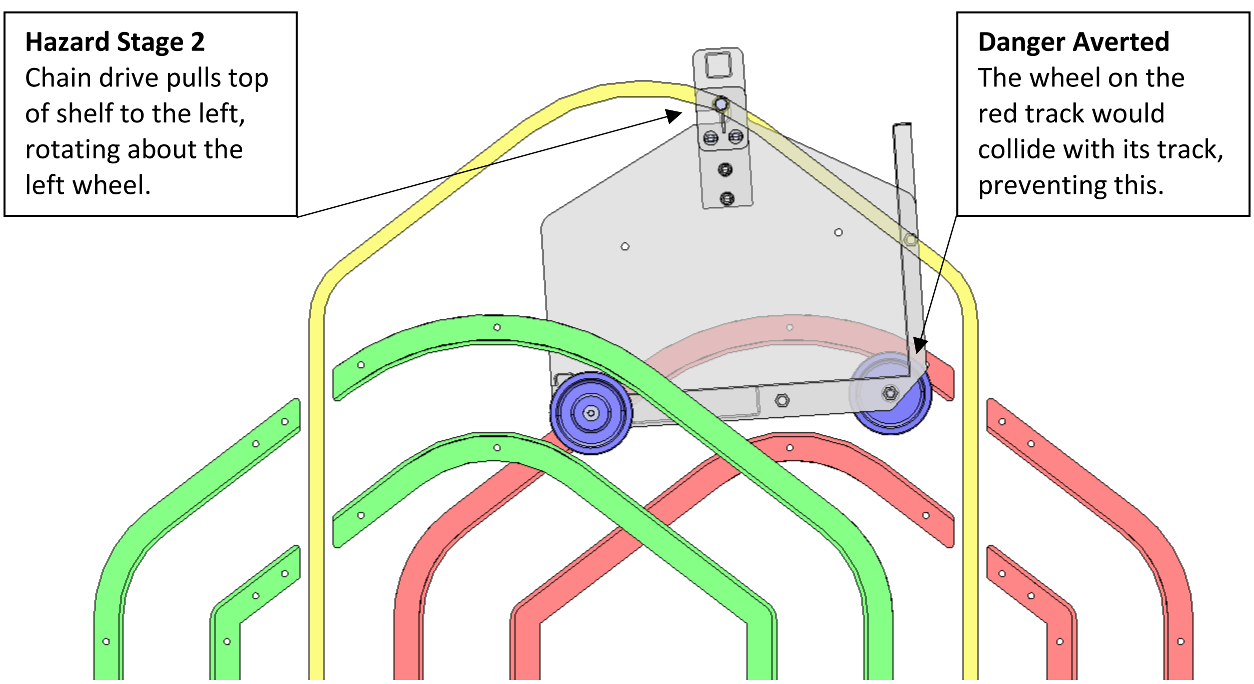


FIGURE 30. AVOIDED FLIPPING HAZARD ILLUSTRATION, PART 2

The addition of the second track prevents the shelf from flipping, a critical improvement from our preliminary designs.

3.3 Reworked Connection Passes Through Tracks

During our design process, we faced the challenge that the chain's path is inviolable. Our design space could not include anywhere where the shelf-chain connection passed through.

By reworking the shelf-chain connection down to just a sleeved pin, the connection can pass cleanly through gaps in the track from all angles. Below, Figure 31 and Figure 32 show the pin passing through the gaps at the two intersections between the tracks and the chain.

The vertical intersection near the top of the tracks is relatively easy to picture.

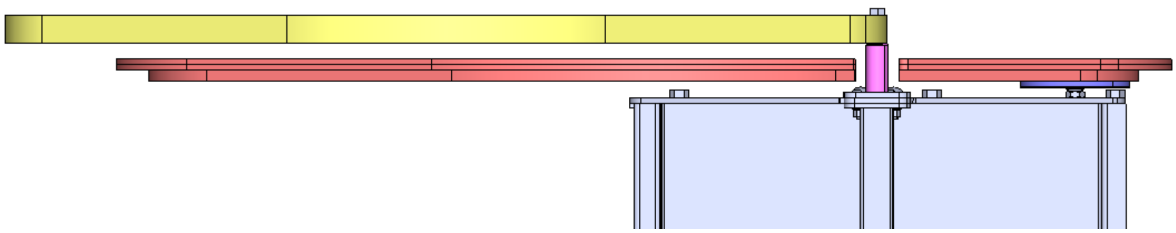


Figure 31. Top-down view of shelf-chain connection sleeve (pink) passing cleanly through the top gap in the left tower's tracks.

The side intersection benefits from seeing in the side view, before considering it in the view normal to the chain's path. The gusset plate of the chain-shelf connection is visible in the normal view but does not contact the tracks.

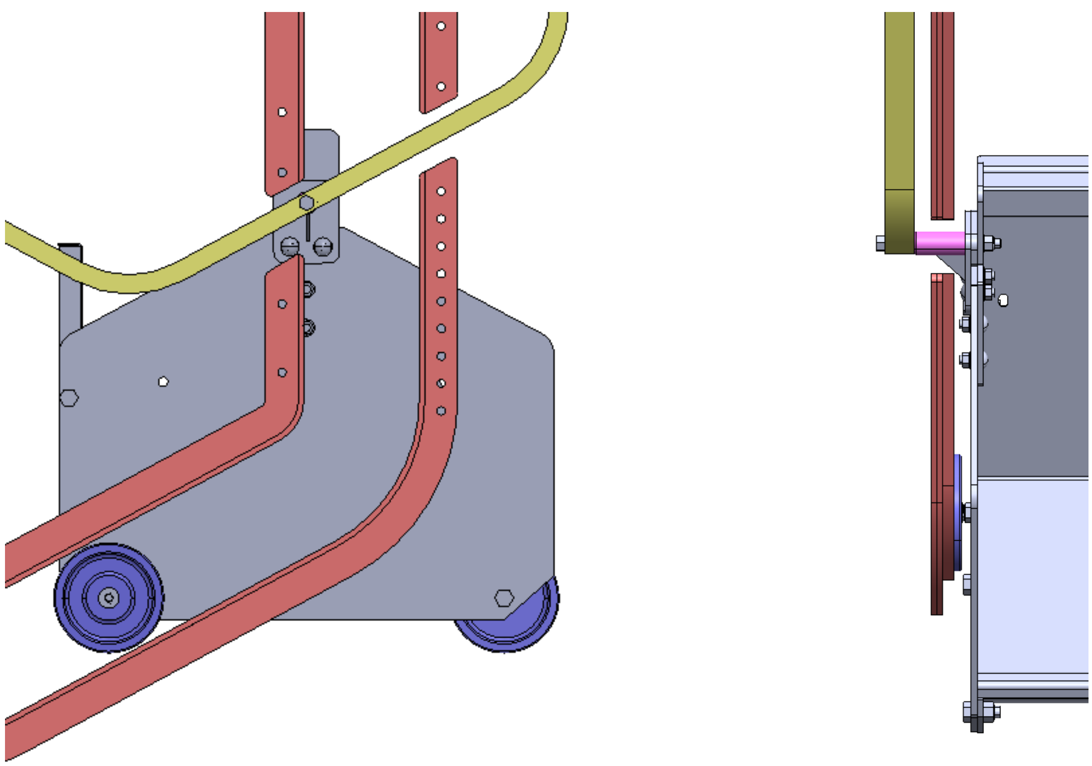


Figure 32. Side and normal views of shelf-chain connection sleeve (pink) passing cleanly through the side gap in the left tower's tracks.

3.4 Adjustable Lower Track

The chain on the shelving carousel is tensioned by moving the bottom-most sprocket vertically, independently of the other sprockets. These sprockets are shown in red in Figure 33 below, with the movable tensioning sprocket in a bolder hue.

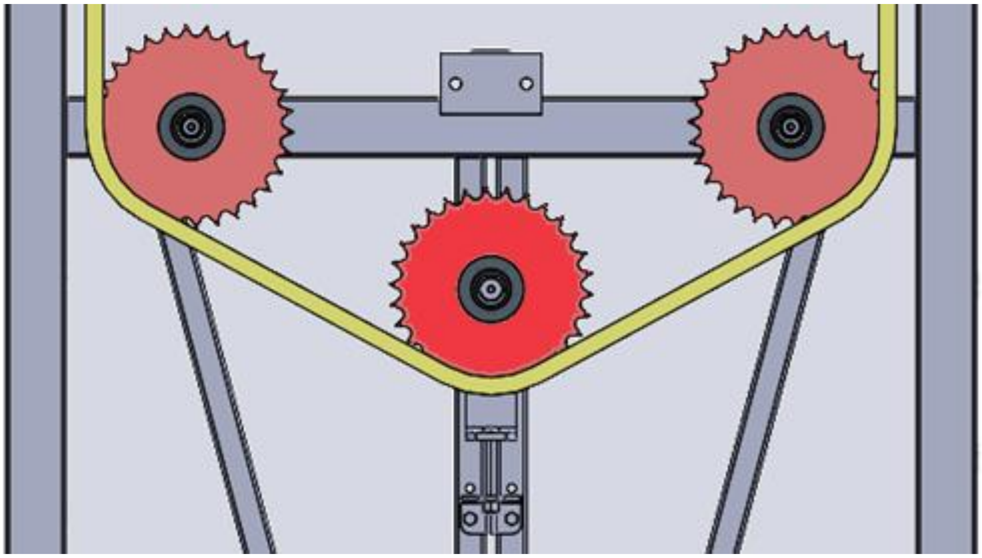


Figure 33. Sprockets at lower area of chain, with guide tracks and sprocket housing hidden. The sprockets are highlighted red, and the simplified chain yellow.

The tensioner can change the path of the chain by up to 1" at the bottom bend. In addition, the angle that the chain can take is variable, because the bottom sprocket moves independently of its neighbours. Since the guide tracks are based on the chain path, this means that the guide tracks must also be adjustable. To accommodate the possible variations in chain path, we split off a portion of the right-outer track section to make it adjustable separately from the rest of the track. This piece is highlighted in blue in Figure 34 below.

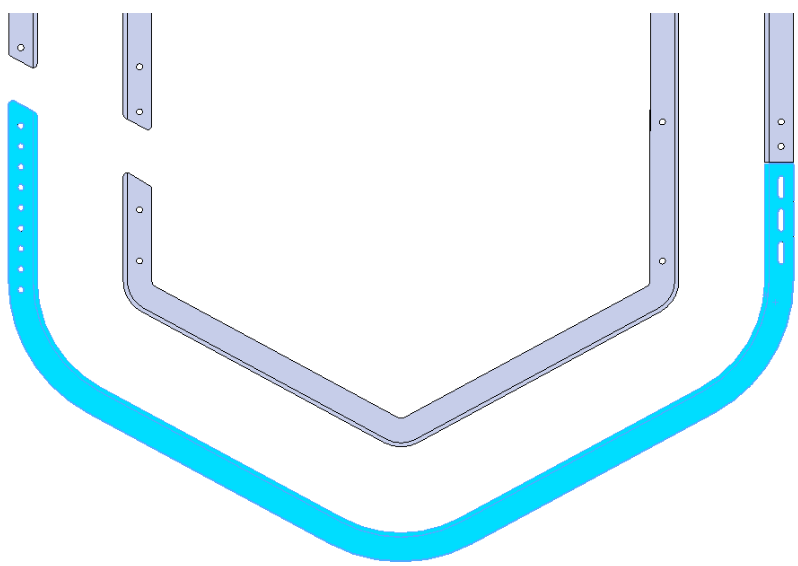


Figure 34. Adjustable portion of outer-right track section highlighted in light blue.

The usage of the adjustable lower section is shown in Figure 35 below. In both pictures, the expected path that the shelves' wheels will take is shown in blue. In the left figure, the tensioning sprocket and the adjustable track are both in their highest position. The tracks completely bound the expected path of the wheel. On the right figure, the tensioning sprocket and adjustable track are both lowered by a full 1". The track still bounds the wheel's expected path, but because the angle of the path changed, it does not do so quite as cleanly as it did on the left.

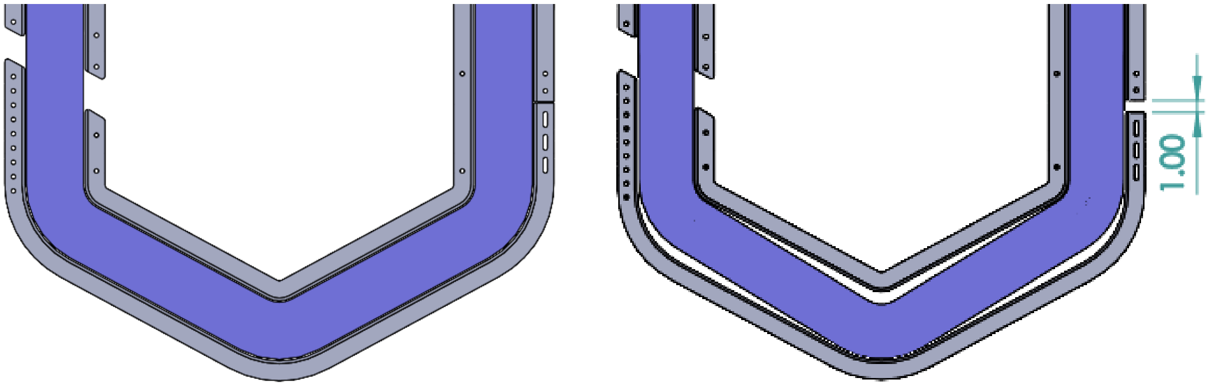


FIGURE 35. COMPARISON BETWEEN ADJUSTED HEIGHTS OF LOWER TRACK SECTION, WITH EXPECTED WHEEL PATH SHOWN IN BLUE.

To minimize the amount of extra gap the adjusted bottom portion would create, we made it movable in ¼" increments. It should be moved in tandem with the tensioning sprocket to ensure the outer track has clearance.

We used a Vernier-like scale to make the track move in ¼" increments. On the left half of the track portion, holes are spaced 1-¼" apart. Behind it on the bracket, holes are spaced 1" apart. The result is that as the track is lowered, every ¼" a different pair of holes is aligned. There are nine holes on the track and ten holes on the bracket, so that there are two pairs of aligned holes on that side. This is shown in Figure 36 below, rotated 90° clockwise.

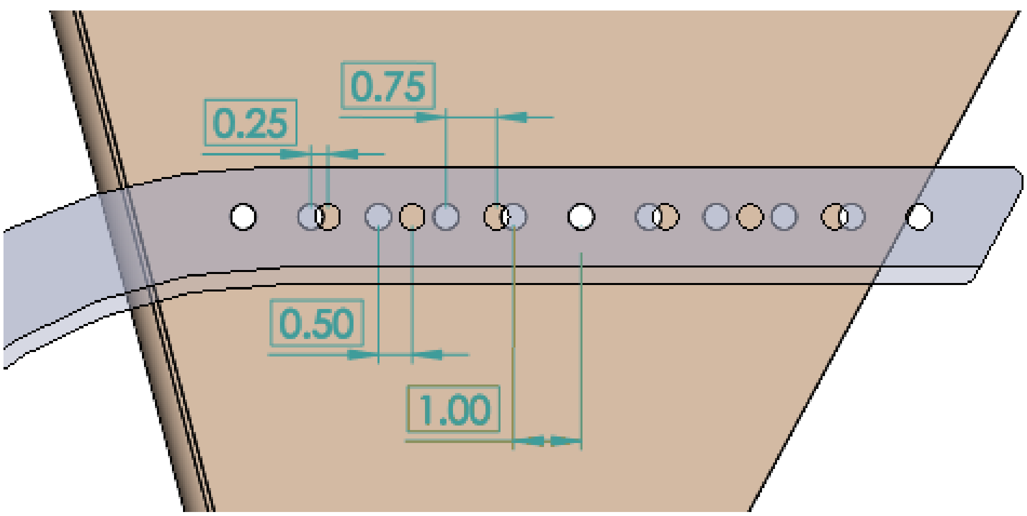


FIGURE 36. VERNIER BETWEEN BOTTOM TRACK AND BRACKET 4, ROTATED 90° CLOCKWISE.
THE BRACKET IS COLOURED BROWN INSTEAD OF CYAN TO MAXIMIZE VISIBILITY OF HOLES AGAINST THE TRANSPARENT TRACK.

The right side of the split bottom track has three 1” vertical slots which are spaced 1” apart from each other. Its mounting bracket has a configuration of seven holes which allows each discrete vertical location of the piece to have multiple holes available at all times, with one of these holes lining up with the top of a slot on the track piece.

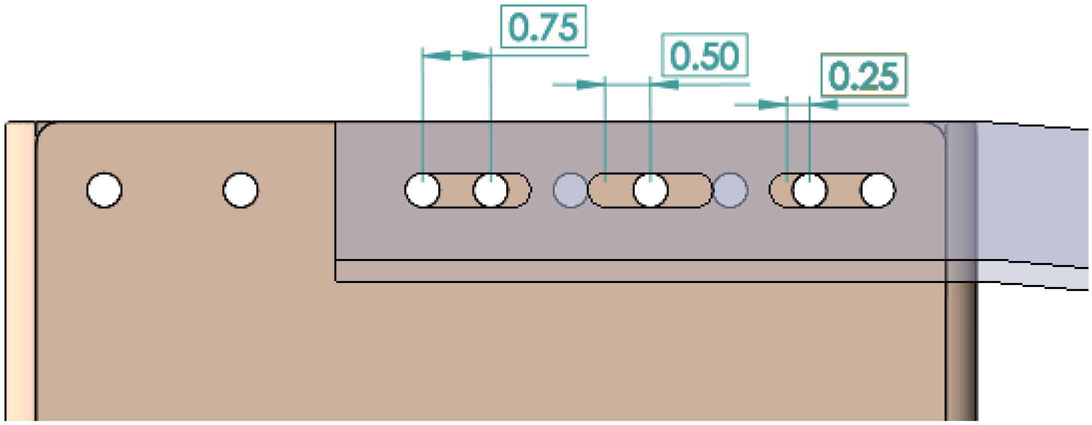


FIGURE 37. VERNIER BETWEEN BOTTOM TRACK AND BRACKET 3, ROTATED 90° COUNTERCLOCKWISE.

In both Figure 36 and Figure 37, the track is shown in its uppermost position, as befitting the sprocket also being in its uppermost position as given in the supplied CAD model.

Finally, the adjustability of the bottom portion can make the left-most intersection of chain and track’s gap wider than the others. When the movable piece is moved down by the full 1”, the gap becomes larger than 3-½”. Fortunately, when the wheel is passing over this gap, the wheel on the other tower of the shelf is not passing over any gap, so we are confident it can keep the shelf stable enough that the wheel on this side will not get stuck.

3.5 Shelf Installation

The carousel's shelves can be easily installed and removed. The clothes-hanger shape built into the shelf walls allows the shelf to be hung in place on the 7/16" bolt connecting the shelf to the carousel before it is bolted to the plate. The figure below illustrates how the shelf is attached before being bolted into place.

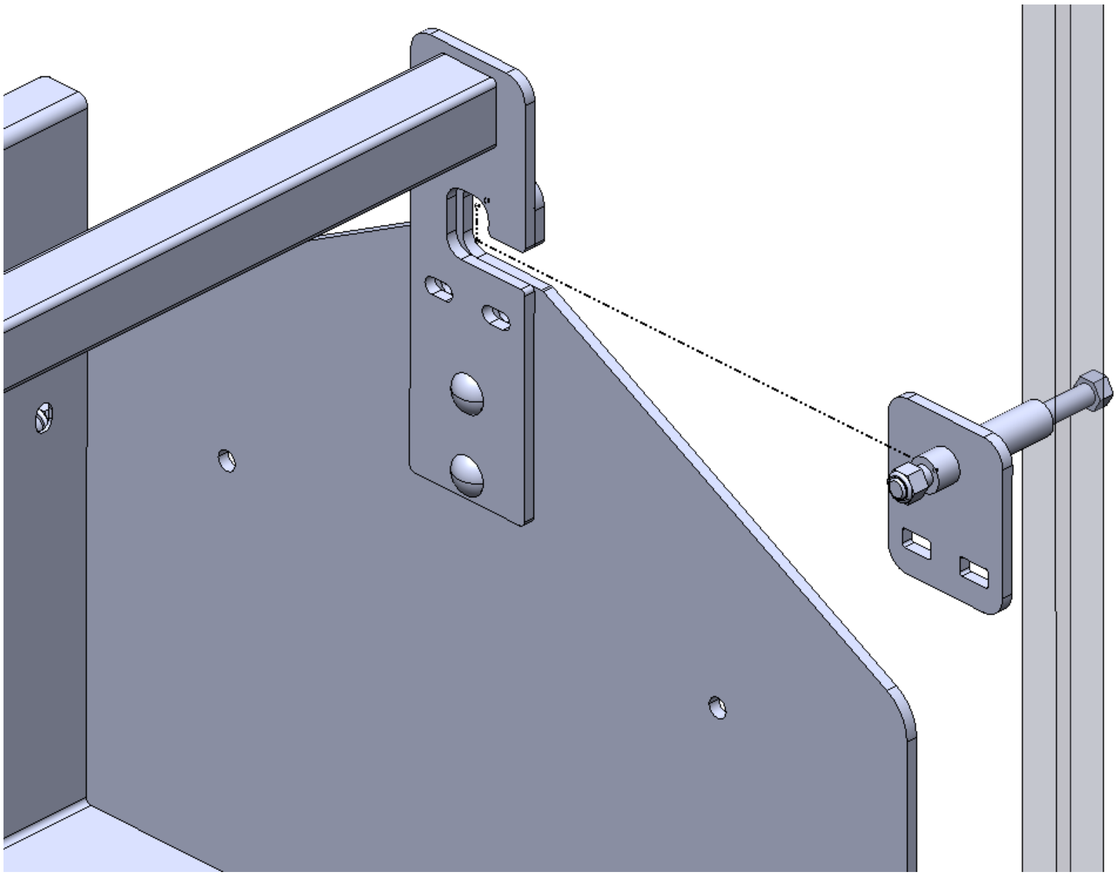


FIGURE 38. SHELF BEING INSTALLED ONTO THE CAROUSEL. THE BLACK DOTTED LINE SHOWS THE PATH THE SHELF FOLLOWS DURING INSTALLATION. THE CARRIAGE BOLT FASTENERS THAT LOCK THE TWO HALVES OF THE CONNECTION TOGETHER ARE PUT IN AFTER THE SHELF IS IN PLACE, AND SO ARE NOT PICTURED.

This is less slightly convenient than the original installation method, which required no bolts, but it remains an easy operation. To remove an installed shelf, simply follow the installation steps in reverse order: remove the two bolts attaching the shelf on each side, lift the shelf straight up, and finally pull the shelf away.

4 Design Analysis

In this section, we describe the key decisions that shaped each major component of the final design, and the analytical engineering work we performed in reaching those decisions. Where detailed analyses were not performed, we justify the decisions we made.

4.1 Track Design

The guide tracks were designed based on a set of driving dimensions and the geometric relations of parts of the carousel model and our design elements. We also chose design elements to make the track manufacturable by Vidir.

4.1.1 Choosing Driving Dimensions

As stated in Section 2.1.2, the track was designed based on the carousel's drive chain being translated 18" vertically and 9" horizontally. We chose those driving dimensions based on where they would place the wheels on the shelf. The further away from the shelf's main pivot point, the larger the lever arm the wheels would have available to resist an off-balance load's torque with. These are shown in the context of the shelf in Figure 39 below.

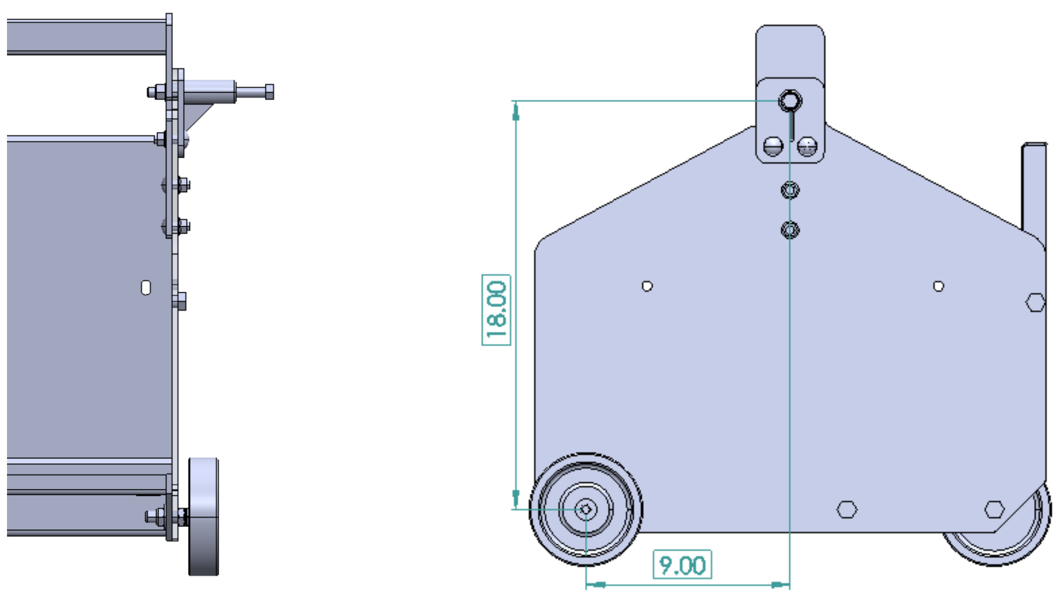


Figure 39. Front and side views of shelf to show origin of driving design dimensions.

The exact distances were chosen to be rounded values for simplicity. These chosen dimensions went on to be the foundational assumption for the guide tracks. In hindsight, we should have been more exacting when selecting these dimensions. As was shown in Section 2.2.1, we modified the location of two structural bolt holes for the shelf and repurposed them into the wheel fastening locations. We had to modify their locations because of our requirement of exactly 9" horizontal spacing and 18" vertical spacing from the shelf pivot axis. By the time we realized that we could have used those holes without any modifications by shifting our wheels by less than an inch, too many parts were dependent on this assumption to feasibly change in our project's timeframe.

4.1.2 Distance Between Tracks

The distance between the inner and outer track sections is based on the diameter of the wheels. In our design, we chose a 5" diameter for the wheels. We decided to use a 5" wheel so that it can easily pass over the necessary gaps in the tracks, discussed in the next section, without falling through or getting stuck. We then added an additional ⅛" tolerance on all sides of the wheel, to combat the issue of a possible misalignment of the two towers, which Vidir said is typically within ¼". Therefore, the total distance between the inner and outer tracks is 5-¼". This tolerance also helps with tolerances in the track faces. Figure 40 shows how this dimension also applies around the corners of the tracks' path.

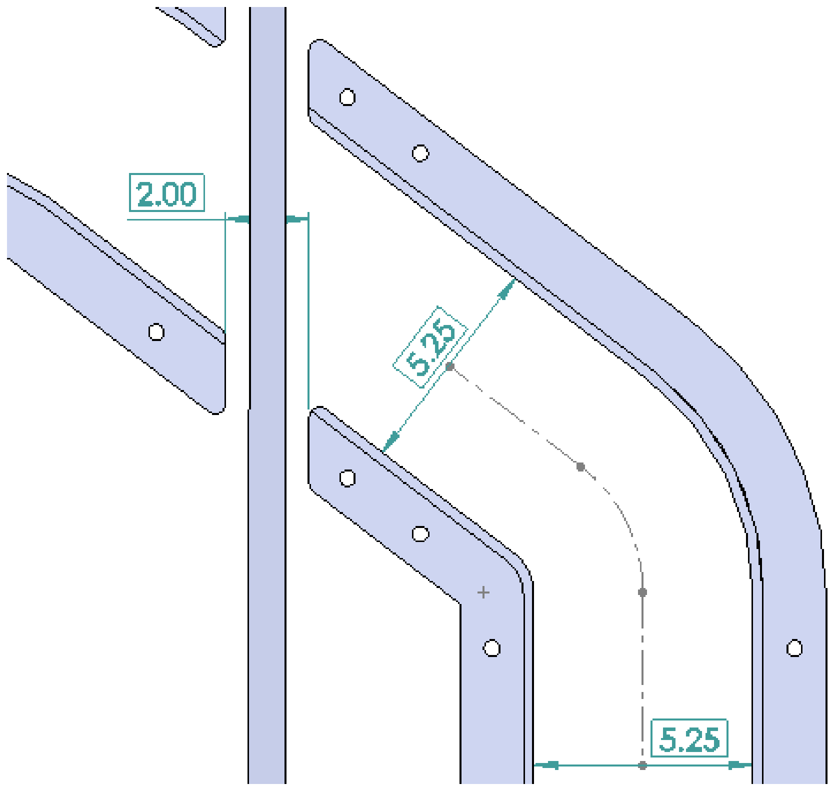


Figure 40. Side view of guide tracks near the top intersection with chain path. The span between the inner and outer sections of guide track is dimensioned in multiple places, and the gap for the track-chain intersection is dimensioned as well.

4.1.3 Track-Chain Intersections

One of the functional features of the design is that the reworked connection can pass through the gaps in the track at the track-chain intersections. The dimensions of those gaps were chosen specifically to be small enough for the connection to pass through, and large enough to prevent the wheels from doing the same. In Figure 40, the gap at the top intersection between the chain and track is shown and is dimensioned as 2" wide. This gives a clearance of 0.5" to either side of the shelf-chain connection as it passes through, which should be plenty. At this intersection, we expect little deviation in chain location.

However, there was another requirement at the lower-left intersection. Each of the 6 circular arcs in the chain represents a sprocket at that location. The central sprocket on the lower half of the chain has a tensioner, which moves it up to 1" down from where it lies in the model, which changes the angle of the chain in that lower portion. In addition to the tensioning changing the angle, the chain can also sag. To accommodate this chain tensioning, we designed the left inner and left outer sections to be cut at the angle of the chain when the sprocket is in its uppermost position, and the right inner section to be cut when the sprocket is in its lowermost position. We found the new angle by recreating the mock chain model, but with the moving sprocket translated down by 1”. The distances from the chain to the track are enough that any sagging will not cause the chain to touch the mounting bracket.

4.1.4 Resistance to Bending

When supporting the load of a shelf’s wheel, the track acts like a cantilever beam. We selected dimensions for the cross-section of the track with this cantilever-like behaviour in mind. The full calculations can be found in Appendix A.

Using the dimensions described in Section 2.1.3, we calculated the track’s resistance to bending in the direction of loading, summarized in Table VI below.

TABLE VI. TRACK RESISTANCE TO BENDING

Intrinsic Track Property	Value	
Face width	1.00	[in]
Face thickness	0.25	[in]
Spine width	1.50	[in]
Spine thickness	0.50	[in]
Centroid, measured from face	0.78125	[in]
Second moment of area	0.28548	[in^4]

We then estimated loading conditions for the track. We approximated that the track had fixed connections to its mounting brackets, constraining track angle and deflection at both ends of its cantilever-like body. We arbitrarily picked loading conditions of 44” between ends, and an applied force of 500 lbs applied exactly halfway between the ends. This overstates the effect of the loading, because more accurately that much load would be spread between two points of contact and closer to the cantilever fixtures. We used the material properties of A36 steel from [3]. The conditions and results of this analysis are summarized in Table VII below.

TABLE VII. TRACK BENDING ANALYSIS

Track Loading Property	Value	
First end type	Fixed	
Second end type	Fixed	
Distance between ends	44	[in]
Applied force, at halfway	500	[lbs]
Maximum deflection	0.0674	[in]
Max stress	16249	[psi]
Factor of safety	2.22	[---]

We find that even when using higher-than-actual loading conditions, our chosen track cross-section lets the track maintain a factor of safety >2 with about 1/16” deflection.

4.1.5 Fabrication Considerations

Vidir's laser cutting equipment can comfortably accommodate up to ¾" thick steel sheets, with an area of up to 60" by 120". We split each section of the guide track's spine into two pieces, so that they would not be larger than the allowable area. We chose to design the spine of the track as two ¼" sheets despite the laser cutter's ability to handle ½" to increase stability where the laser-cut pieces get joined. The join happens at a different place in the front laser cut piece ¼" that the back laser cut ¼". This means that no seam goes all the way through. A front-facing seam is shown in Figure 41 below.

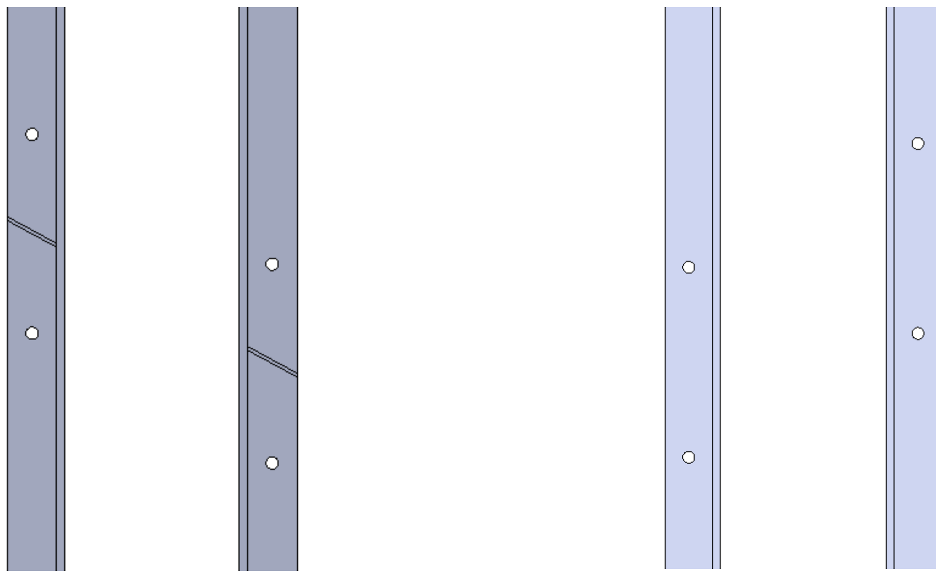


FIGURE 41. FRONT AND BACK VIEWS OF A SEAM BETWEEN TWO LASER-CUT TRACK PIECES.

There are bolt holes on either side of all seams to properly secure each piece, so the front and back pieces do not have to be welded to each other. Some of these seams are placed across bracket locations, so that the bolts used in the brackets also secure the seam. This track is mounted onto specially designed laser cut brackets, using regular ⅜" bolts in most places and ⅜" carriage bolts on one bracket.

The face of the track is made of bent ¼" sheet metal. As designed, there is a ¼" tolerance between the two faces of the set of tracks to accommodate tower misalignment and tolerance in bending. As calculated in Appendix A, the face provides relatively little stiffness to the track, so it would not be unreasonable to reduce the thickness of this part of the track to ease manufacturing. However, we would start to be concerned about the face possibly deforming on the half of its width that is not directly supported by the spine.

The spine and face of the track are to be welded together. This way we avoid putting fasteners in the path of the wheels.

To assemble this design, first each bracket should be attached to the tower frame. Then, each track section should be individually assembled and attached to the brackets. The special bracket with the carriage bolts holds the left track sections, so they should be attached to this bracket first. Otherwise, the order in which brackets are added does not matter.

4.2 Wheel Design

This section describes the development of a wheel that rides along the track, minimizing friction and ensuring smooth motions for the carousel cycle. An analysis was undertaken in Appendix A.3 to determine appropriate wheel dimensions. This included determination of materials, their properties and force and moment calculations to determine the minimum allowable dimensions.

After the minimum allowable dimensions are determined, we investigated both manufacturing and off-the-shelf choices. Vidir's preferences leaned strongly towards an off-the-shelf model that could be used as is or modified to meet the design needs. Since we found the latter choice feasible, we ruled out in house manufacturing. The selected off-the-shelf model and the required modifications are covered in this section.

4.2.1 Wheel Selection

To reduce in-house manufacturing, we investigated using off-the-shelf wheel that could be easily modified to fit our exact needs, instead of making wholly new wheels.

We based our wheel selection on the following criteria, in decreasing order of importance, as shown in Table VIII below.

TABLE VIII. CRITERIA FOR OFF-THE-SHELF WHEEL SELECTION, IN DECREASING IMPORTANCE

Criteria	Value	Reasoning
Diameter	5"	Our design assumed a wheel diameter of 5" to create the tracks and minimize the risk of the wheel escaping or being stuck in the gaps at the chain-track intersections.
Width	<1.5"	There is an available space of 1.75" between the end of the shelf and the carousel tower. We need at least ¼" of tolerance, if not more.
Axle diameter	1/2"	The existing bolts that we are re-purposing into wheel axles are 1/2" diameter. Decreasing this will reduce the strength of the shelf.
Load capacity	≥250 lbs	In our analysis, we calculated each wheel to expect up to ~250 lbs of load.
Hub length	Minimal	Like with width, we need our wheel to fit inside the available space between shelf and carousel.

We were not able to find an off-the-shelf wheel that would satisfy every desired criterion, so some degree of machining would be required. We decided not to search for custom-manufactured wheels, because we expect in-house modifications will be fully effective and more economical.

We ended up selecting the following rubber wheel from McMaster-Carr [4], pictured in Figure 42 below with its relevant specs on its right.

FIGURE 42. RUBBER WHEEL, 5" DIAMETER X 1-1/4" WIDE. SOURCE: ADAPTED FROM [4].

Wheel/tread material	Rubber
Wheel dimensions	
Diameter	5”
Width	1 ¼”
Hub length	1 ½”
Axle diameter	3/8”
Capacity per wheel	290 lbs
Wheel bearing	
Type	Sleeve
Seal Type	Open
Material	Acetal Plastic

We could not find a wheel that satisfied all three criteria of diameter, width, and axle diameter. Our chosen wheel meets our desired diameter, width, and capacity. Its hub is made of plastic and rubber, which should be relatively easy to mill down (compared to a steel-cored wheel).

4.2.2 Wheel Modifications

The rubber wheel met the required diameter and wheel width. However, the hub length and axle diameter had to be modified. Table IX outlines the steps that need to be taken to modify the wheel to match what we have in the CAD model.

TABLE IX. WHEEL MODIFICATIONS FOR SELECTED OFF-THE-SHELF MODEL.

Step	Modified Feature	Original Dimensions	New Dimensions
1	Total hub length	1.500”	0.975”
2	Sleeve inner diameter	0.375”	0.500”
3	Countersink hole on one face	-	Diameter: 0.938” Countersink Angle: 82° Length: 0.251”

The first modification step is to mill down the center hub, on both sides. On the tower-facing side of the wheel, the hub is milled down until it is inset compared to the outside rim of the wheel. This guarantees that in the case of an unwanted collision, the rubber outer rim will contact and not metal on the axle. On the shelf-facing side of the wheel, milling down the hub creates room to place locknuts to keep the wheel in position and resist vibration. This amount could be changed, depending on the choice of fasteners and the space that is required for them.

The second modification step is to expand the inner sleeve to accept a 1/2” axle. This meets the minimum allowable dimension for the bolt as calculated in Appendix A and matches the other fasteners holes on the shelf wall. This was a necessary step because there were no good choices available for 5” diameter wheels with a ½" axle diameter. The width of the available options where not suitable and they came with either a ball or roller bearing. Which made them harder to modify and increased the price about 3 times.

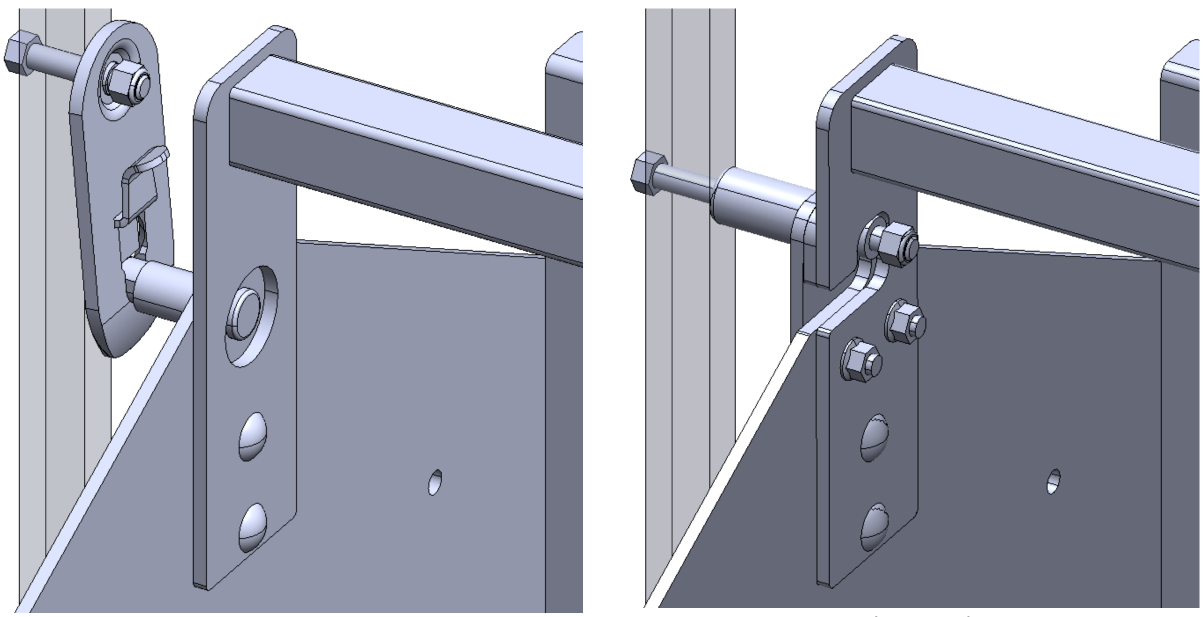
The final modification step is to countersink a hole into the tower-facing end of the expanded axle. This allows the flat head cap socket to be concealed inside the wheel, saving space and minimizing interference with the track and tower support panels.

4.3 Shelf Connection

This section covers the design decisions and calculations that went into the reworked connection between the shelf and carousel chain.

4.3.1 Comparison to Original

The connection between the shelf and the chain had to be modified smaller to let it pass through its designated gaps at our design's chain-track intersections. The existing connection was approximately 5" tall, which would have required an equally-large gap in the guide track to pass through. The redesigned shelf connection is only as large as its 1" diameter connection sleeve, at the cost of some of the installation convenience of the original. The original and redesigned connections are pictured side by side in Figure 43 below.



Original Redesigned

Figure 43. Comparison of original and redesigned shelf-chain connections. Chain is simplified and transparent.

4.3.2 Estimated Resistance to Shearing

The connection on the chain side was not changed between the original and redesign. Both use a 7/16" bolt through the chain. We can be sure that the shear strength of the redesign is equal to that of the original.

On the shelf side of the connection, the shelf attaches to the welded chain-half of the subassembly by two carriage bolts and the top hook. Each carriage bolt is 3/8" diameter, and the inner sleeve at the top hook is ¾" diameter. Again, comparing to the original design, if a 7/16" bolt is sufficiently strong against shear, the ¾" of the inner sleeve over the bolt is more than enough on its own. As well, the two 3/8" bolts together have more cross-sectional area than a single 7/16" bolt.

We are reasonably confident that the redesigned connection is at least equally strong as the original design against shearing.

4.3.3 Design of the Connection Sleeve

The sleeve is the most critical part of the connection subassembly, as it carries most of the bending stresses caused by the shelf load. The portion of it that spans between the carousel's chain and the connection assembly's bolting plate must be resistant to bending. The dimensions we decided on for the sleeve are shown in Figure 44, below. These dimensions are also what the bending-resistance calculations of Section 4.4.4 are based on.

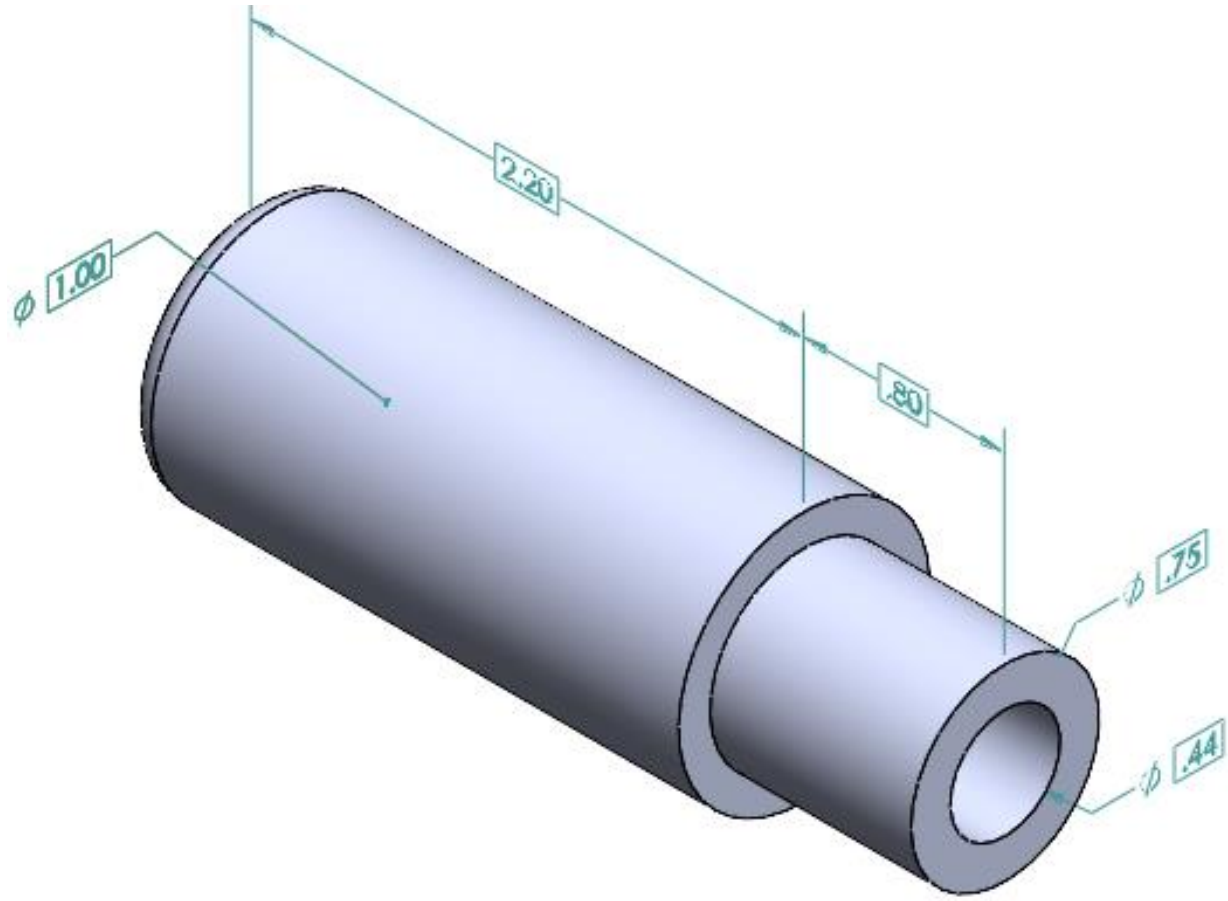


FIGURE 44. DIMENSIONED ISOMETRIC VIEW OF THE SHELF-CHAIN CONNECTION SLEEVE.

However, this has resulted in a more complicated part to manufacture. It is neither formed sheet metal nor a combination of off-the-shelf components. It could likely be machined out of 1" steel rod stock. Based on some of the parts in the original CAD model, we are confident in Vidir's ability to make or acquire custom parts like the above sleeve as needed.

We acknowledge that Vidir may wish to consider modifying this part for ease of manufacturing. Below, Table X describes the key relationships between the dimensions of the sleeve and the rest of the carousel, so that Vidir is able to make informed alterations as desired. Modifications for manufacturing that affect any of the "critical" marked dimensions should be carefully considered to ensure that the design remains fully functional.

Table X references the dimensions shown in Figure 44 to refer to those features.

TABLE X. DIMENSIONS OF THE CONNECTION SLEEVE AND THEIR IMPORTANCE

Dimension	Key Relationships	Critical
***Φ* 1”**	○ Determines resistance against bending. ○ Must fit comfortably between the intersection gaps in the track.	Yes
2.20”	○ Distance between chain and bolting plate, which is flush to the shelf wall. ○ Decreasing this increases the range of motion for the shelf along its longitudinal axis.	Yes
.80”	○ Width of available space (less 0.25”) for the hook-shape of the shelf-half of the connection assembly to rest on. ○ Should be at least 0.75”. ○ Must leave room for the nut on the end of the 7/16” bolt.	No
***Φ* .75”**	○ Fits inside the hook-shape of the shelf-half of the connection assembly. ○ Needs to resist shear, but not bending.	No
***Φ* .44”**	○ Is the surface that touches the 7/16” bolt. ○ The sleeve must be able to rotate on the bolt.	Yes

It would be acceptable for the sleeve to be made in two overlapping pieces, one inner and one outer. In this case, there would be two sleeves, one 2.2” long with OD 1” ID 0.75” and the second 3” long with OD 0.75” ID 0.44”. This would not significantly impact bending strength.

Finally, Vidir should do their own tests on what size of innermost diameter gives the best fit and rotation on the 7/16” bolt. It is possible that an inserted bushing would greatly improve rotation, in which case the modeled ID of 0.44” dimension would need to be increased.

4.3.4 Estimated Resistance to Bending

Vidir expressed concern over the connection's resistance to bending because the new design is a cantilever, whereas the original connection's weak point would fail in shearing. The figure below will be referenced for the calculations.

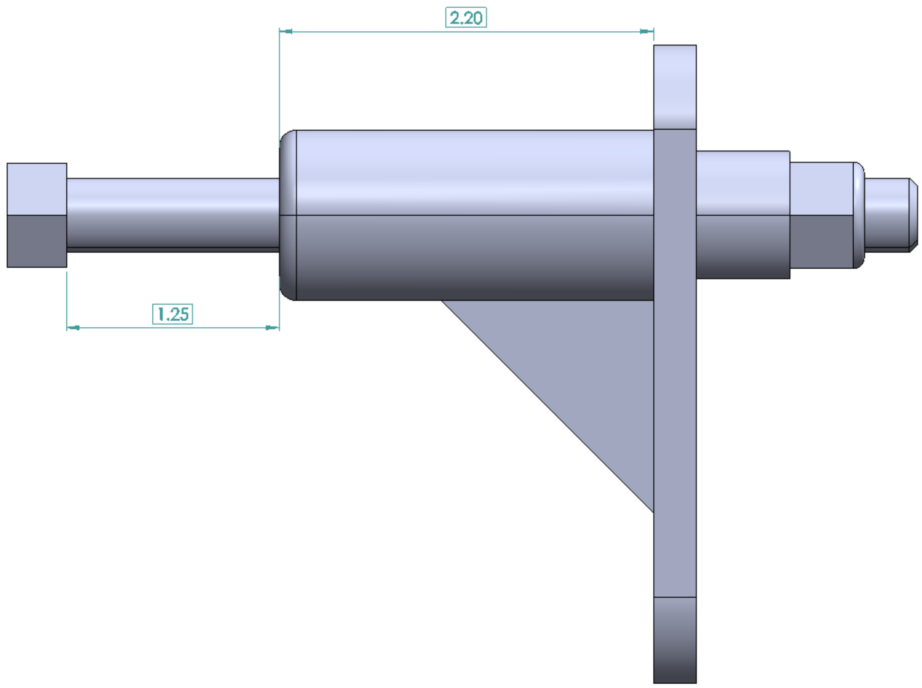


FIGURE 45. SIDE VIEW OF CHAIN-HALF OF SHELF-CHAIN CONNECTION.

To ease analytical analysis, we will leave out the effects of the gusset plate. Since the gusset plate increases the bending strength of the assembly, the actual strength of the connection will be greater than what we calculate. Rr

We apply the following conditions: the exposed section of the 7/16" bolt may rotate (about the section's midpoint), but not translate; the bolting plate may translate, but not rotate; 750 lbs of force are applied downwards at the bolting plate; the chain connection applies half the moment it would take to counter rotation at that end (425 lb-in).

Using the properties of A36 steel from [3] and applying standard cantilever beam calculations, we calculated the following results:

TABLE XI. EXPECTED CANTILEVER PERFORMANCE OF SHELF-CHAIN CONNECTION, NEGLECTING GUSSET PLATE

Total deflection	0.024	[in]
Angle at chain	0.037	[deg]
Factor of Safety	2.86	

Earlier in the design process, the connection had only a ¾" thick sleeve and no gusset, resulting in an unsatisfactory factor of safety. This prompted us to reinforce the sleeve to 1" thickness to achieve a factor of safety >2. We added the gusset plate on top of that for additional certainty.

4.4 Mounting Brackets

The simplest and most versatile way to make these brackets is by using laser cutting, which is already being used to make some of the track pieces. The numbering of the brackets was shown in Figure 23 in Section 2.4. All brackets are mounted to the frame using the same nuts and bolts that mount the cross grid in the supplied model, which are ⅜" carriage bolts. We did this so that Vidir would only be using parts they already have, so that this addition would feel natural and consistent with the rest of the carousel.

Most of the brackets use 10-gauge sheet steel with a bending radius of 0.2". The two exceptions, Brackets 6 and 9, use 6-gauge sheet steel with a bending radius of 0.25". We chose 10-gauge for most of the brackets so that they will be strong enough, without being too heavy and overdesigned.

4.4.1 Back Plates (1 and 5)

Bracket 1 was originally meant to bolt directly into the frame piece behind it, however this is unnecessary due to the upper copy of Bracket 2 being a few inches away. However, Bracket 1 remained in the model, but now as a back plate, in order to still properly brace the outer and inner sections of track against each other. Bracket 5 was based on Bracket 1, but this time it was more important. There was no option to mount Bracket 5 directly to the piece behind it. Rather, with the condition that Bracket 5 would need to mount to the frame, it would simply merge with Bracket 6. This way, as a back plate, Bracket 5 can be a lightweight supplement to Bracket 6.

We decided to give all brackets the dual usage of mounting the track to the frame and bracing the outer and inner sections of track to each other as back plates, which drastically increases the stiffness and resistance to deflection. This effect of reduced the number of brackets required to fully support the track.

4.4.2 Brackets 2 and 3

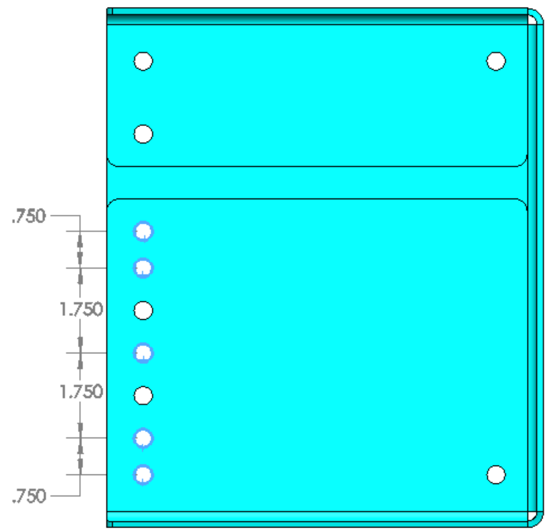


FIGURE 46. CLOSE-UP OF BRACKET 3, SHOWING ITS HOLE PLACEMENT.

Bracket 2 and Bracket 3 were originally intended on being only one type of bracket, but they diverged when we designed the portion of the right outer section of track that lowers. Bracket 3 is the same design as Bracket 2, except it has more holes to support more bolt configurations.

The five holes highlighted in Figure 46 have a necessary placement, but the other two holes can be any distance between its neighbouring holes. The five key holes correspond to the three 1” slots in the track at the same location, which are each spaced apart with 1” in between. This totals 5” vertically, which is the same as the sum of the measurements in Figure 46. Because the movable piece of track is meant to lower in discrete intervals of ¼” up to 1” total, the holes are set to always have one bolt at the top of a slot for each stop. The other holes ensure that each discrete position have at least two accessible bolt holes.

4.4.3 Bracket 4

Other than the pure back plates, all brackets have inner folds which allow bolts to pass through two different layers of sheet metal. This configuration properly stiffens the brackets in 3 dimensions, instead of each bracket simply being a flat piece of sheet metal. Originally, we thought that the angled frame piece behind Bracket 4, shown in the left image of Figure 47, would interfere with the stiffening triangle and inner fold. To resolve this issue, we initially designed a complex and confusing bracket. Then, we realized that this frame piece would not interfere, as seen in the left image of Figure 47, so we redesigned the bracket. The ten vertical holes are each spaced apart by 1”, shown in the right image of Figure 47, interact with the nine vertically spaced holes on the track piece, which spaced apart by 1-¼”. This configuration uses a Vernier scale, which allows ¼” adjustments, and ensures that two bolts can be used on this bracket for each discrete location of the moving track piece.

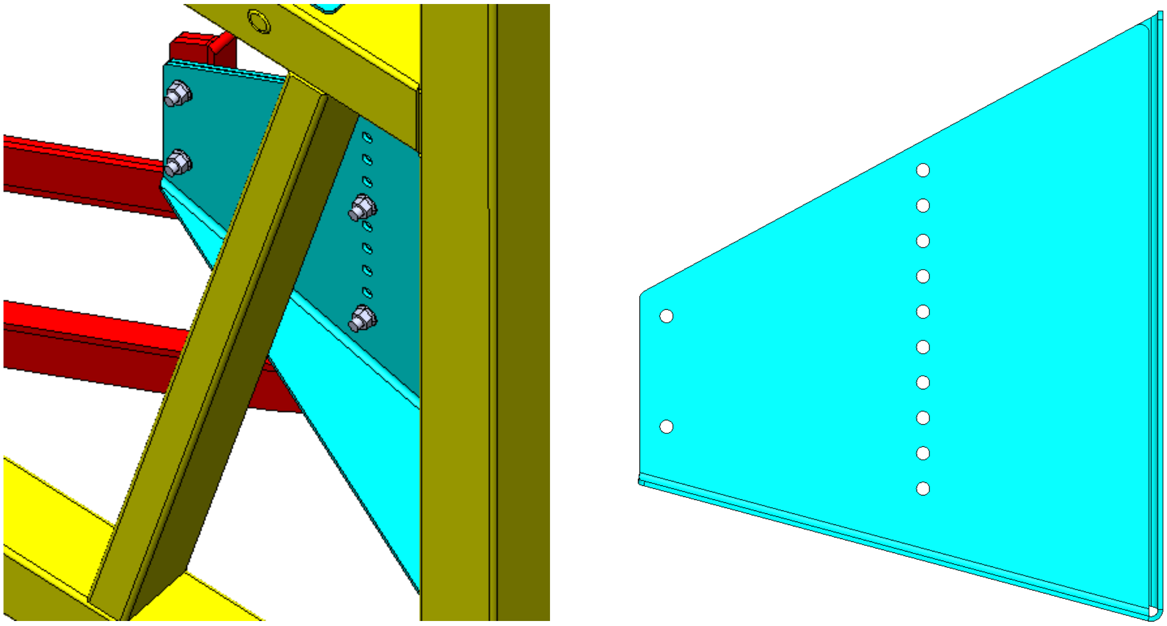


FIGURE 47. VIEW OF BRACKET 4 WITH THE ANGLED FRAME PIECE (LEFT), AND FROM THE BACK (RIGHT).

4.4.4 Bracket 6

Bracket 6, shown in Figure 48, is designed to attach to the track at the closest point possible to the gap without touching the sprocket guard. The folds on the back offer extra support against bending, which helps mitigate the stress, and shows the limitations given the design space. This bracket is made of 6-gauge sheet metal, as opposed to 10 gauge, for additional strength. The four 3/8" bolts greatly increase the stiffness of the protruding box-like structure of the bracket.

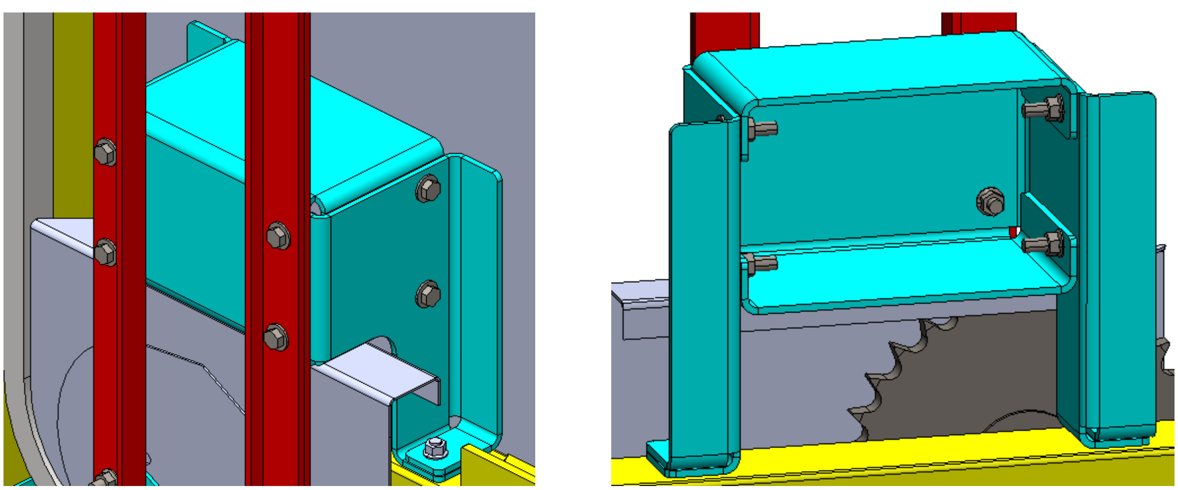


FIGURE 48. FRONT AND BACK VIEWS OF BRACKET 6.

4.4.5 Bracket 8

As was shown previously in **Error! Reference source not found.**, Bracket 8 mounts the track using c arriage bolts instead of the regular hex head bolts, which can be explained by Figure 49 below. Once the bracket is mounted onto its proper frame piece, the back is inaccessible. The cover behind it cannot be removed, as the cover guards the sprockets and other moving components. Therefore, we used carriage bolts to mount the track from the front, which eliminates the need to access it from the back.

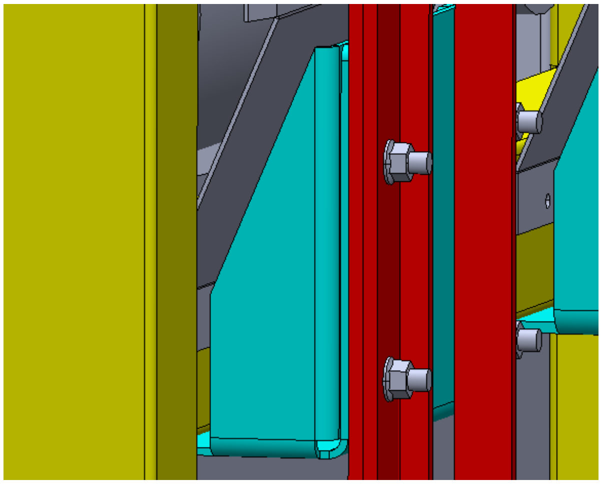


Figure 49. Side view of Bracket 8.

4.4.6 Bracket 9

For Bracket 9, we chose to use 6-gauge to increase its strength because of its large overhanging vertical portion, as shown in Figure 50. From its bolts into the frame up to its highest point, it measures over 32” in height, so the 6-gauge steel provides extra stiffness where we lack room for structural components. Our original idea was to mount the bracket over the top of the chain onto the top of the uppermost frame piece, but this would intersect the chain path and was therefore not possible.

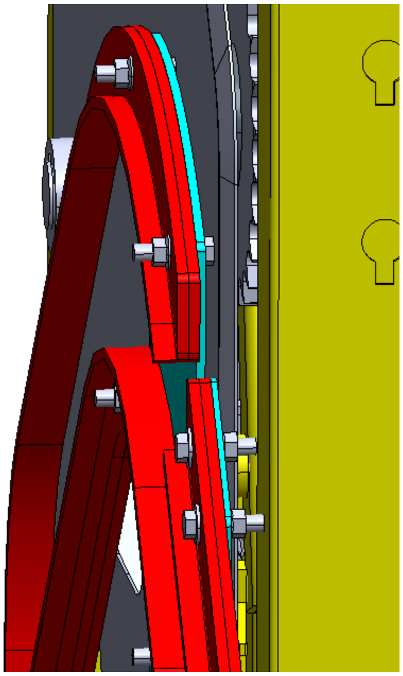


Figure 50. Side view of the top portion of Bracket 9.

Bracket 9 also mounts the track using bolts in the reversed direction, with the bolt head at the back, as shown in Figure 50. This is the only bracket that does so, because there is not enough space between the bracket and the components in the tower.

4.4.7 Mounting to the Frame

Brackets 6, 7, 8, and 9 all mount to a horizontal surface of a frame piece, meaning that the slots for the carriage bolts can no longer be aided by gravity to maintain the bolt's position as they would on vertical surfaces. Therefore, we placed the slots such that installation consists of the bolts first being placed closer to the tower cover and then slotted inward towards the shelves. Once the tower covers are in place, a bracket's possible movement is obstructed by the cover, meaning that the bracket cannot come out of its placement even if the bolts loosen slightly.

5 Bill of Materials and Cost Estimate

Vidir said that the CAD model would be satisfactory for their purposes, but if we summarize the parts that we used and modified, we can reduce the effort Vidir needs to put in to manufacture our design. We can also use this to estimate the material price of our design.

5.1 Standard Fasteners

We used a large quantity of fasteners in our design. From our CAD model, we identified the fasteners that were not original to the CAD model Vidir provided to us and counted them in Table XII below.

TABLE XII. FASTENERS USAGE AND COST

Part	Parts Per Tower (x2)	Parts Per Shelf (x10)	Total Quantity	Price Per Unit	Cost	Ref.
Hex Bolts						
3/8” X 1-1/2”	57	-	114	$0.25	$26.16	[5]
7/16” X 5”	-	2	20	$2.41	$48.16	[6]
Carriage Bolts						
3/8” X 1”	14	-	28	$0.26	$8.30	[7]
3/8” X 1-1/4”	-	4	40	$0.32	$12.77	[8]
3/8” X 1-1/2”	6	-	12	$0.30	$2.43	[9]
Socket Cap Screws						
1/2” X 3”	-	2	20	$1.83	$36.60	[10]
Washers						
3/8”	53	-	106	$0.05	$5.59	[11]
1/2”	-	2	20	$0.13	$2.50	[12]
Flanged Nuts						
3/8”	73	4	186	$0.11	$19.83	[13]
Locknuts						
7/16”	-	2	20	$0.12	$2.49	[14]
1/2”	-	6	60	$0.59	$35.10	[15]
Unthreaded Spacers						
3/8” X 1/2”	2	-	4	$1.96	$7.84	[16]
TOTAL COST					$209.92	

Our price estimates for the fasteners in Table XII were drawn from McMaster-Carr’s website. In our references, we have included links to the exact parts we priced out for the listed dimensions. If Vidir chooses to use different surface finishes or material grades for parts, this will naturally affect their cost. At the unit prices we picked, fasteners contribute $209.92 to our design’s total material cost.

5.2 Sheet Metal

Nearly all structural components of our design are made of sheet metal. The following table is of post-processed sheet metal area. This understates the used material due to holes and unreclaimable space when manufacturing but makes for a fairly accurate cost estimate.

TABLE XIII. SHEET METAL USAGE

Part	Thickness	Area [in²]	Quantity	Total Area [in²]
Track				
Spine (total)	1/4”	1993.4	2	3986.8
Face (total)	1/4”	669.8	2	1339.7
Brackets				
#1	10-gauge	38.8	2	77.6
#2	10-gauge	216.0	4	863.9
#3	10-gauge	270.6	2	541.1
#4	10-gauge	447.6	2	895.2
#5	10-gauge	38.8	2	77.6
#6	6-gauge	301.1	2	602.2
#7	10-gauge	226.5	2	452.9
#8 (Left)	10-gauge	143.5	1	143.5
#8 (Right)	10-gauge	147.1	1	147.1
#9	6-gauge	403.2	2	806.5
Connection				
Bolt plate	1/4”	10.0	20	200.0
Gusset	10-gauge	0.8	20	16.4

We asked Vidir for their standard costs for the sheet metal thicknesses we used [17]. Together with the area calculated above in Table XIII, we estimated the cost of our sheet metal, calculated below in Table XIV.

TABLE XIV. SHEET METAL COST

Thickness	Area [ft²]	Price [$/ft²]	Cost
1/4"	38.38	$5.51	$211.46
10-gauge	22.33	$2.50	$55.82
6-gauge	11.68	$4.05	$47.32
TOTAL COST			$314.60

Altogether, sheet metal contributes $314.60 to our design’s total material cost.

5.3 Other Components

Most of the components we used in our design were either fasteners or sheet metal. The remainder are few: the rubber wheel for the wheel subassembly, and the sleeve for the connection subassembly.

The rubber wheel is available off-the-shelf. Its specifics are listed in Section 4.2.1, sourced from McMaster-Carr. Here, we consider its price, and add it to Table XV.

The sleeve is not an off-the-shelf component. The exact details of manufacturing it we will leave to Vidir, but we expect it to be within their capabilities to either make or acquire, based on some of the components that were in the original carousel's CAD model that they gave us. If we assume it will be milled out of 1" steel rod stock, we can estimate its material cost for Table XV.

TABLE XV. OTHER COMPONENT USAGE AND COST

Part	Quantity	Price per Unit	Cost	Ref.
Rubber Wheel	20	$6.20	$124.00	[4]
Connection Sleeve	20	$1.93	$38.67	[18]
TOTAL COST			$162.67	

The last of our wholly new components contribute $162.67 to our design's total material cost.

5.4 Cost Estimate

In estimating the cost of our design, we are excluding machining and labour as being beyond the scope of our project. We are also excluding any cost savings from parts that were replaced, such as the original shelf-chain connection assembly. Finally, we are excluding any cost increases or savings from parts that were only modified (shown in Section 4.5.5 next), because the changes in material cost will be relatively small.

The total material cost of our design is $687.19, as shown in Table XVI below.

TABLE XVI. TOTAL MATERIAL COST

Section	Contribution
Fasteners	$209.92
Sheet Metal	$314.60
Other Parts	$162.67
TOTAL COST	$687.19

5.5 Visual Identification of Modified Components

In addition to the components that we added as part of our design, we modified some of the existing parts that were already in the CAD model. These changes were relatively minor and would not incur a meaningful amount of material cost, and so were disregarded in our cost estimate.

We do not need to formally list the parts we modified, since Vidir intends on building based on the CAD model deliverable, and we are not estimating the cost of these modified parts. However, it is valuable to visually identify the parts that we modified, as we save Vidir from checking the entirety of the CAD model for differences. The parts we changed are shown in Figure 51 and Figure 52, below.

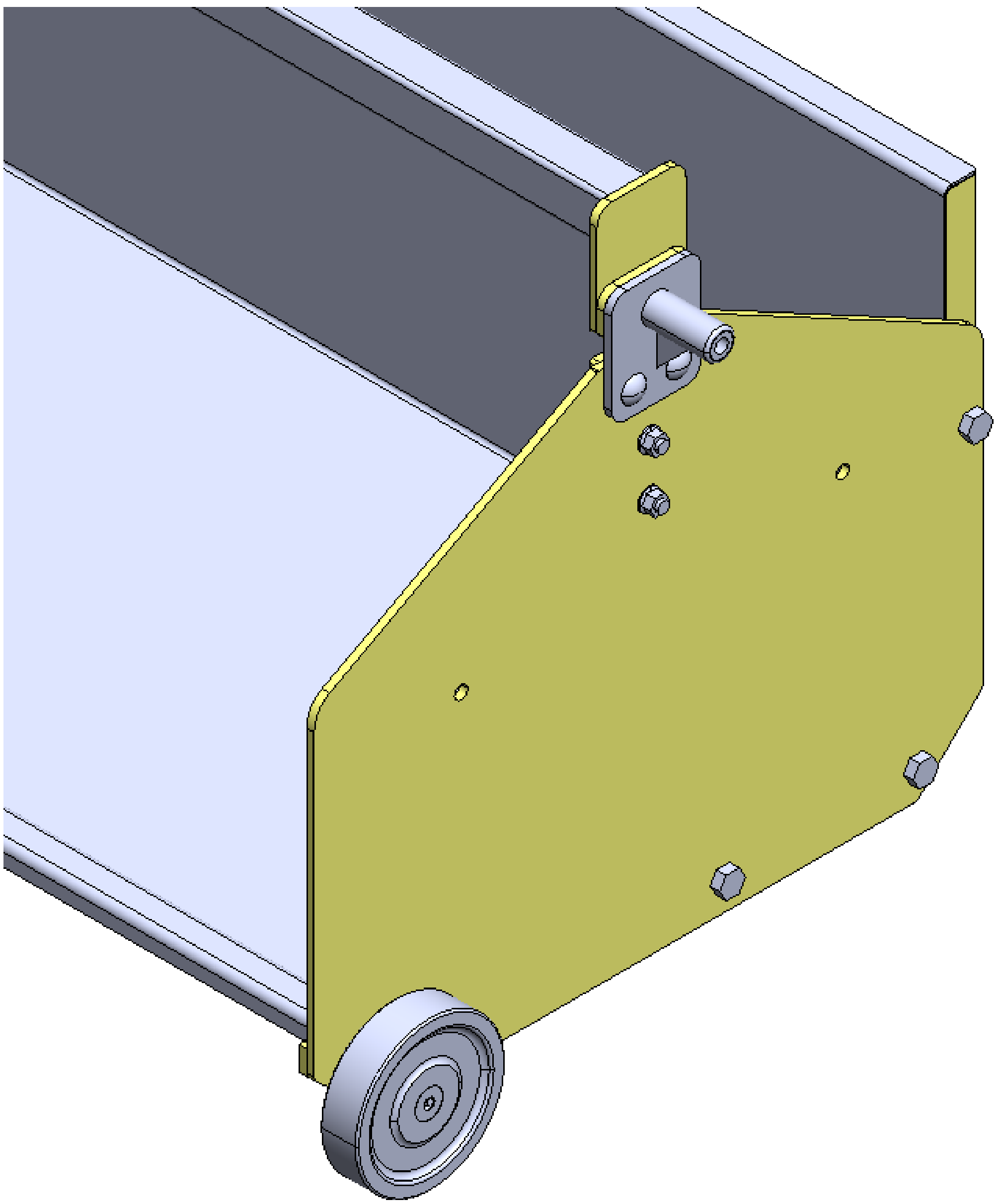


Figure 51. Isometric view of components modifed on shelf, highlighted in yellow.

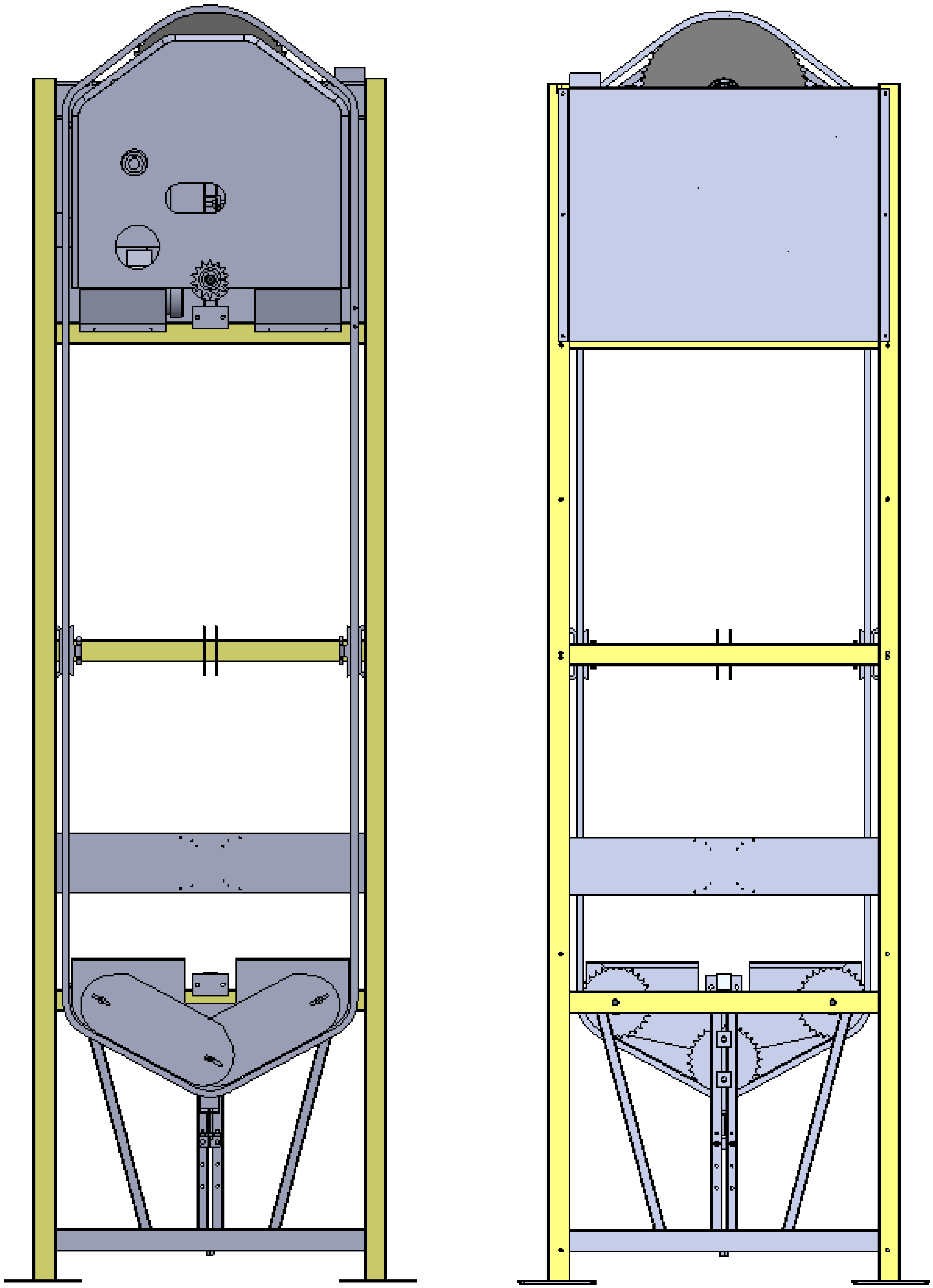


Figure 52. Side views of components modified on carousel tower, highlighted in yellow. Both towers have the same components modified.

6 Carousel Motion Study

Vidir asked for a full rotation simulation as one of the deliverables for the project. We used SolidWorks to perform a motion study to generate analyzable simulations and videos of both our design and the base design in clockwise and counterclockwise motion.

6.1 Motion Study Setup

We used a SolidWorks motion study to simulate the shelves moving around the carousel. This includes the way in which the shelf attachment points traverse around the chain path, the way the shelves pivot about their attachment points, as well as the physical interaction between the wheels and the tracks. For ease of calculation, we use only one shelf on the carousel. None of the shelves collide with any other shelves, so the movement of one shelf on a carousel functions identically to how each shelf moves in a carousel with all its shelves.

6.1.1 Assembly Mates

To set up this motion study properly and consistently, we start by fixing in space all parts other than the shelf. All parts that lie between the two towers are hidden to improve the sight lines, while keeping them fixed. We break down the moving shelf into two subassemblies. The first of these moving subassemblies consists of the two bolts and two nuts that fasten the shelf to the chain. The second subassembly consists of every other part that makes the shelf.

The first subassembly is constrained laterally such that the bolt heads lie along the outside of the chains, as well as being constrained such that the whole subassembly keeps a constant orientation as it progresses around the chain path. Lastly, the bolt is constrained with a Path Mate such that it intersects travels around the chain path. After these constraints, the bolt subassembly can freely translate around the chain path but will never rotate.

The second subassembly, consisting of the entire shelf, is laterally constrained so that it lies directly centered between the towers, which is achieved by mating one face of the nut to the inside face of the shelf wall. Then, the mounting hole is constrained concentrically to a bolt in the first subassembly. Then, holding the bolt subassembly fixed, the shelf subassembly can only rotate about its pivot axis, with no translation.

In total, the bolt assembly handles the translation around the chain path and the shelf assembly handles the shelf rotation. These mates are the basis to allow for the proper motion of the system. After these steps, the shelf is able to move around the carousel similarly to real life.

Lastly, we create a small semicircle extrusion that is as long as the width of the shelf, 152”. We set the mass to 1000 lb and place it at any depth on the floor of the shelf in order to simulate the extreme loading case Vidir gave us.

6.1.2 Motion Study Features

We must add the required features of the motion study which set up the proper behaviour of the study. The movement itself is provided by a Path Mate Motor feature, which uses the Path Mate from section 6.1.1 to propel the bolt assembly along the chain path. This is set to a constant path speed of 4 in/s, as Vidir gave us 20 ft/min as the steady state speed of the shelves along the chain path. Alternatively, we could ramp up the speed from zero to the steady state value, then ramp it down. This would more closely reflect reality. However, the discrepancies in the motion by using a constant speed are only present at the beginning of motion and can be disregarded after a second or two. Therefore, we are using a constant path speed value of 4 in/s for the Path Mate Motor.

We set the mass of the shelf subassembly to 265 lb, as Vidir mentioned that the unloaded shelf has a mass of approximately 120 kg. Then, we add a Gravity feature to the motion study in the Y direction. Back in the model view of the shelf subassembly, we sketch two horizontal lines on the floor of the shelf, at 5" from the front and 5" from the back, respectively. These lines are overlaid on the model in Figure 53 below. The long semicircle extrusion is placed on one of these two lines for the loading cases. These loading locations and values are specified in the introduction, Section 1.2. For this motion study, we apply the force on the line further towards the back wall of the shelf, since the shelf has a back wall and the load near the back would add to the moment about the pivot point instead of subtracting from it. It is therefore a worst-case scenario, meaning that validating the motion when the load is near the back of the shelf encompasses the case where the force is near the front.

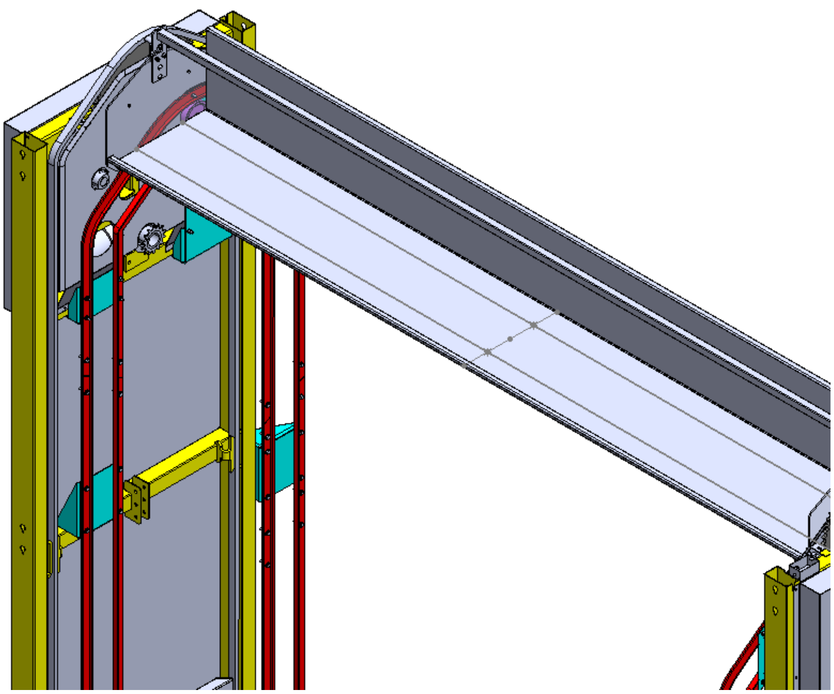


Figure 53. Lines sketched on the shelf floor in order to constrain the load as required.

To simulate the contact between the wheels and the track, we add a Contact feature between the wheel bodies and the track bodies, using the built-in materials of "rubber (dry)" and "steel (dry)", respectively. This motion study setup has the wheels fixed to the shelf, unable to rotate on their respective axes. This means that the wheels drag along the track instead of rotating, which increases frictional forces and likely changes the simulation in ways that we cannot predict. This approximates the real-life case, but it is not completely accurate.

Lastly, we applied a Torsional Damper feature on the shelf about its pivot axis. We use this feature to emulate the way that all real-life systems have inherent damping. In SolidWorks, an undamped shelf will swing perpetually and never lose energy. In real life, even if there is no discrete damper on the shelf, the small amount of air resistance, the small amount of friction forces in the pin, and the other miniscule quantities of damping all add up to visibly damp the shelf. In real life, the amplitude of swinging will lower over time until the shelf comes to a complete stop. After some visual approximations, we found that the value of $30\ \frac{lbf \cdot in \cdot s}{deg}$ gives a settling time around 5 seconds. There is no need to be more specific and rigorous for this value, since the rest of the simulation is not nearly accurate enough to real life to warrant the accuracy in the damping constant. Therefore, we use $30\ \frac{lbf \cdot in \cdot s}{deg}$ as the damping constant in this motion study.

6.1.3 Study Methodology

We ran each study for 90 seconds, and then output relevant plots from the simulation. At a path speed of 4 in/s, the shelf travels around the entire chain path once, plus a bit more distance to account for the transition to steady state conditions at the beginning of the movement. While we expect both directions of motions to be equivalent, we will perform studies for both directions to be thorough. Then we output the plot of angular displacement, which ties into the main goal of this project of limiting the shelf from rotating more than 5 degrees in either direction.

We also run a similar study, set up identically, of the base design of the carousel that was supplied by Vidir. We will compare the plots of angular displacement to judge the efficacy of our final design. This is a gauge, albeit not entirely accurate, of the conditions the system will experience, so we can gather approximate virtual data on how well our design functions.

Here, when we say that the shelf is traveling backwards, this is from the perspective of the operator at the floor level of the carousel. Viewed from the top, this shelf travels towards the front. Likewise, a shelf traveling forwards in total from the perspective of the operator is actually traveling towards the back at the top of the carousel.

6.2 Motion Study Results

6.2.1 Motion Study Plots

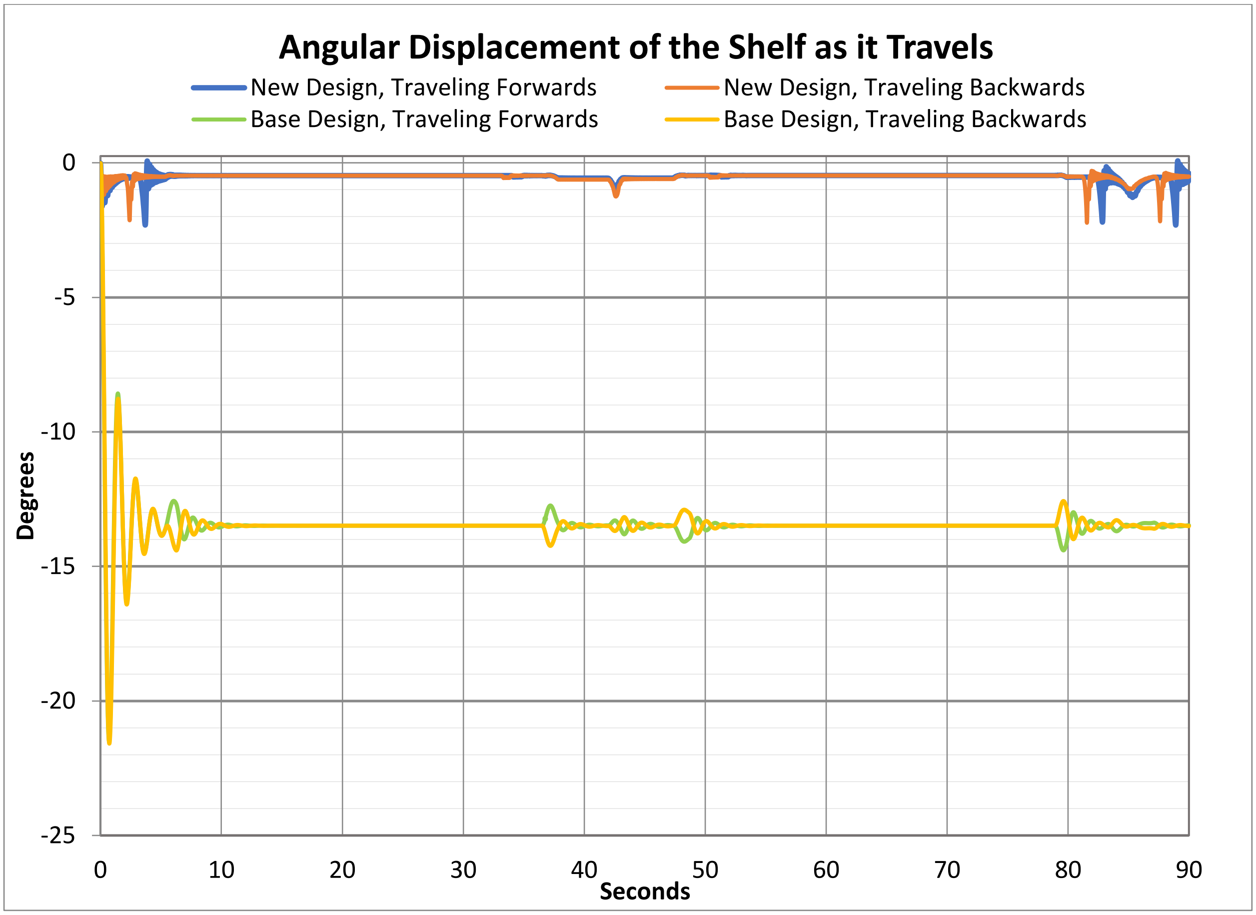


FIGURE 54. COMPARISON OF ANGULAR DISPLACEMENT BETWEEN NEW AND BASE DESIGNS AS THEY TRAVEL.

The plot in Figure 54 shows very similar angular displacements between the forward and backward travel of the shelf. This is to be expected, and this was our intention for the design, as expressed in specification 10 in Section 1.5.1.

With the applied load at the back of the shelf, the base design rests more than 13 degrees off of upright, which is unacceptable. In our new design, the shelf rests less than 1 degree off of upright. However, there are a few locations where the angle spikes. In the blue and orange plots, the leftmost spike is at the same location around the chain path and the rightmost spike, since this plot extends for longer than one full revolution in order to account for settling time. This means that the plot has only two spikes that extend slightly past 2 degrees. These both happen when the wheel is at the gap in the track near the top, as highlighted in Figure 55. One spike happens at this gap in the right-side track, and the other spike happens at this gap in the left side track.

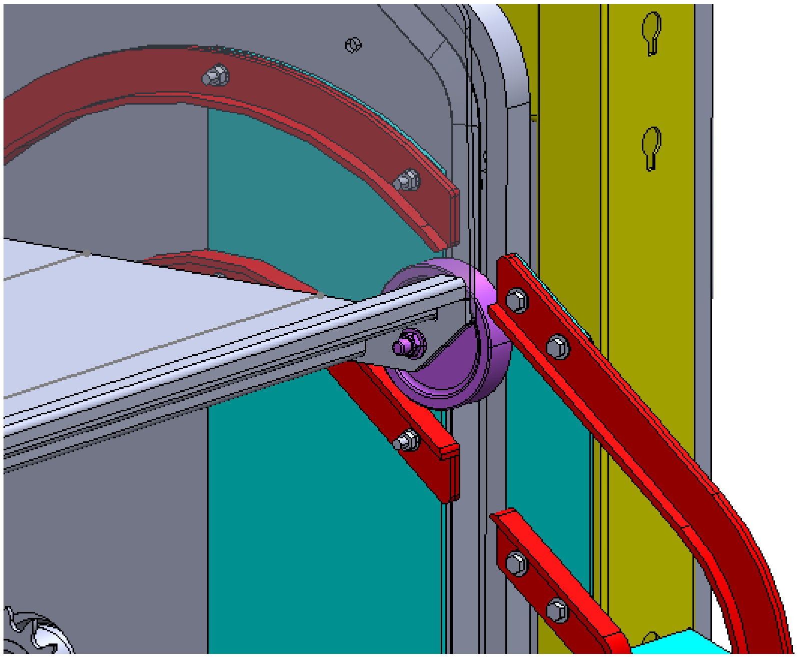


FIGURE 55. LOCATION OF THE WHEEL WHEN THE ANGULAR DISPLACEMENT SPIKES.

This spike represents approximately 1.5 degrees of unconstrained pivoting of the shelf until it impacts the track on the other side of the gap. This is a small amount of movement, but there are still impact forces at play. The angular displacement plot for our design has greater detail in Figure 56 below.

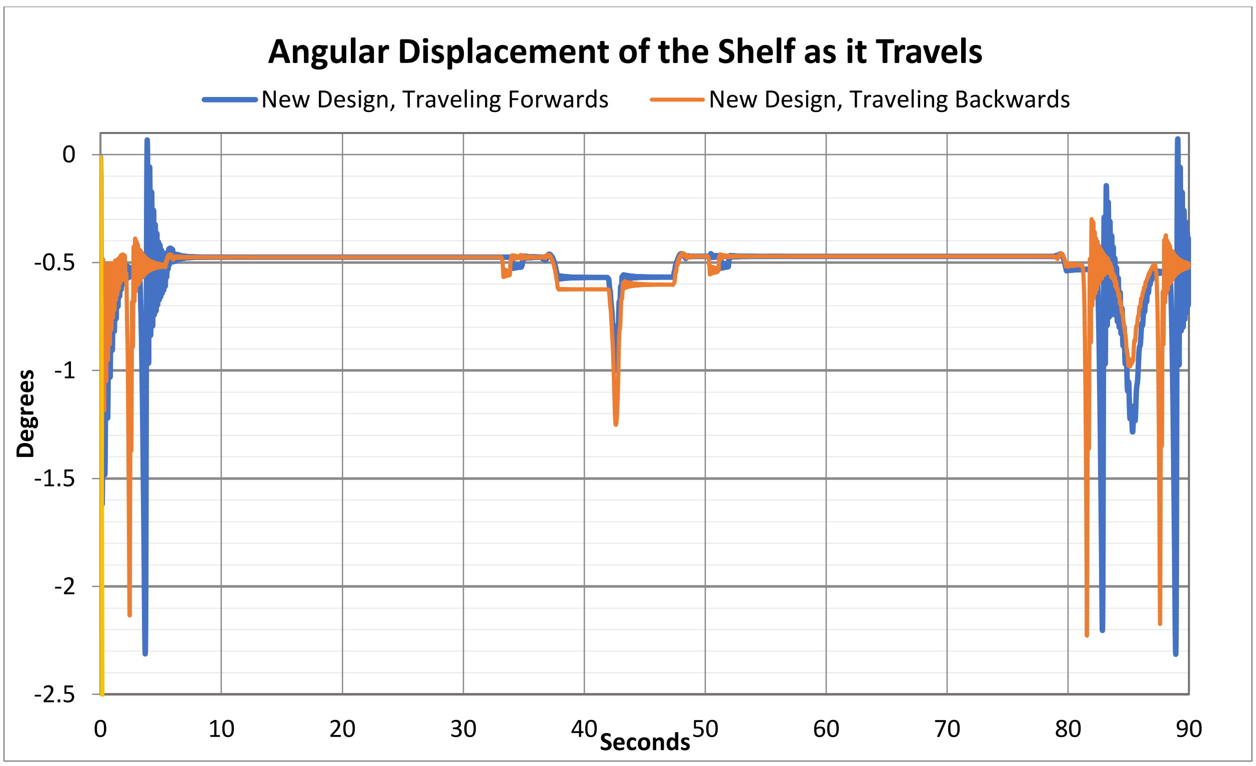


FIGURE 56. ANGULAR DISPLACEMENT OF THE NEW DESIGNS AS IT TRAVELS

6.2.2 Motion Study Results Analysis

Interestingly, the gaps in the track near the bottom barely cause noticeable movement. The wheel crosses this gap at approximately 33 seconds and 51 seconds in Figure 56, for the left and right tracks respectively.

The spike at 42 seconds and the spike at 85 seconds in Figure 56 happen when the shelf is at the bottom and top of its path, respectively. This is where the loads are transferring between surfaces, and there is a small amount of movement. These spikes do not extend as far or have as steep of a slope as the largest spikes. Therefore, if the shelf can handle the other spikes in angular displacement, then it is certainly able to handle these ones.

Although the spikes in angular displacement at the upper track gaps look drastic, they are likely not as drastic in real life. First, the span of the track is 5-¼” to account for misalignment between the towers, which leads to ⅛” of movement for the wheel within the track on either side. In real life, this tolerance will be used up by a certain amount, meaning that the shelf will not be able to swing as far as it does before the wheel collides with the other piece of track across the gap. Secondly, because the wheel cannot rotate in this model, the force transfer from the shelf, through the wheel, and into the track is not accurate.

Thirdly, this model has the track fixed in space, where it is defined to be unmoving. This means that a collision between the wheel and the track simulates a perfectly elastic collision between a moving body and an unmovable body, where the unmovable body will not absorb any energy. In real life, any collision will have a dampening effect on the forces, as the track elastically deforms in response. The spikes in displacement in real life will not be as drastic as shown in Figure 56.

Lastly, in order to reduce the severity of these spikes if needed, Vidir can narrow the gap in the track that accounts for the chain path. Currently, this gap measures 2” across, as shown in section 4.1.2, but this distance may be excessive in real life. The gap may suffice with a width of only 1-½”, which would reduce the clearance of the shelf-chain connection pin to ¼” on either side. Narrowing this gap would have a large effect on reducing the severity of the spikes in angular displacement, reducing the impact forces, ultimately giving this design a longer lifecycle. However, care must be taken to ensure that the clearance that remains is sufficient for the system to operate safely.

7 Numerical Analysis

To validate our calculated chosen part sizes in our design, we performed a preliminary Finite Element Analysis (FEA) to predict stress and resulting factor of safety based on assumed loading conditions. This also gives us the deflection, which can help predict misalignment issues. This analysis is preliminary because we analyzed many parts that transmit stress between each other, but the exact amount of stress that transmits from the track to the brackets is difficult to predict. The track analysis shown in this section does not account for a variety of load locations, but loads will be applied to all parts of the track at some point in operation. We expect to see stress concentrations where the parts are fixed, and where the loads are applied. This depends on how well we set up our FEA SolidWorks study.

7.1 Setup

The complexity of our design warranted examining some parts, and their internal stresses and deflection. To perform FEA, each case was assigned a Loading Condition, which specifies a force amount and direction. To counteract the load, Fixtures are added by specifying certain geometry be completely fixed, which serve to counteract forces and moments. Fixtures are shown below in green, while loads are applied with a pink colour. The brackets also needed to represent the bolt interference, so pin connections were added in place of fixtures at specific locations. All the components analyzed in this section are expected to be made of mild steel. Vidir recommended that we use the properties of A36 steel for our calculations, so we used the SolidWorks built-in material called ‘ASTM A36 Steel’.

We also consider mesh accuracy. Denser meshes generally give better results. To have more confidence in our FEA results, we show the convergence of values as the mesh size decreases. The mesh convergence was performed with the goal of minimizing the error, specifically below 2%. The mesh convergence is performed up to 5 times, but only if the error is still above 2%. Therefore, any errors below 2% will show completely converged solutions for less than 5 iterations.

7.2 Connection

Each load shown represents a total of 1,108N or 250lbs. The fixture location was chosen as shown because the chain is flexible and will bend with the shelf, so that it stays perpendicular at the fixture location. The load was applied to the connection at the point of contact, between the bolts that connect this piece to the side of the shelf. We expect to see stress concentrations at the fixture location.

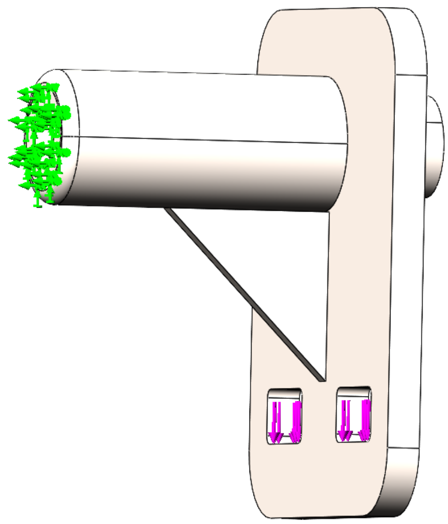


Figure 57. Connection Load and Fixture Conditions.

The fixture of the connection will show the deflection in the opposite direction as intended. The shelf wall stays vertical and the connection bends upwards realistically. However, the amount of deflection is the same for each case. To validate our results, we used FEA for varying mesh densities. A mesh convergence plot for the connection is shown below.

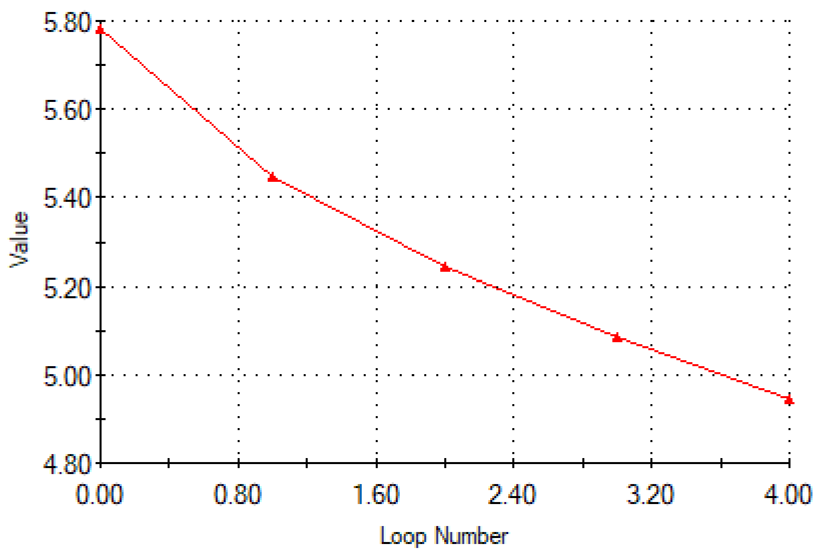


Figure 58. Connection Mesh Convergence, showing error vs iteration number

Since the error decreases, the plot shows convergence, but the accuracy of our results is still limited. This convergence plot shows a minimum error of 4.94%. The deflection and Factor of Safety (FOS) results from performing FEA are shown below.

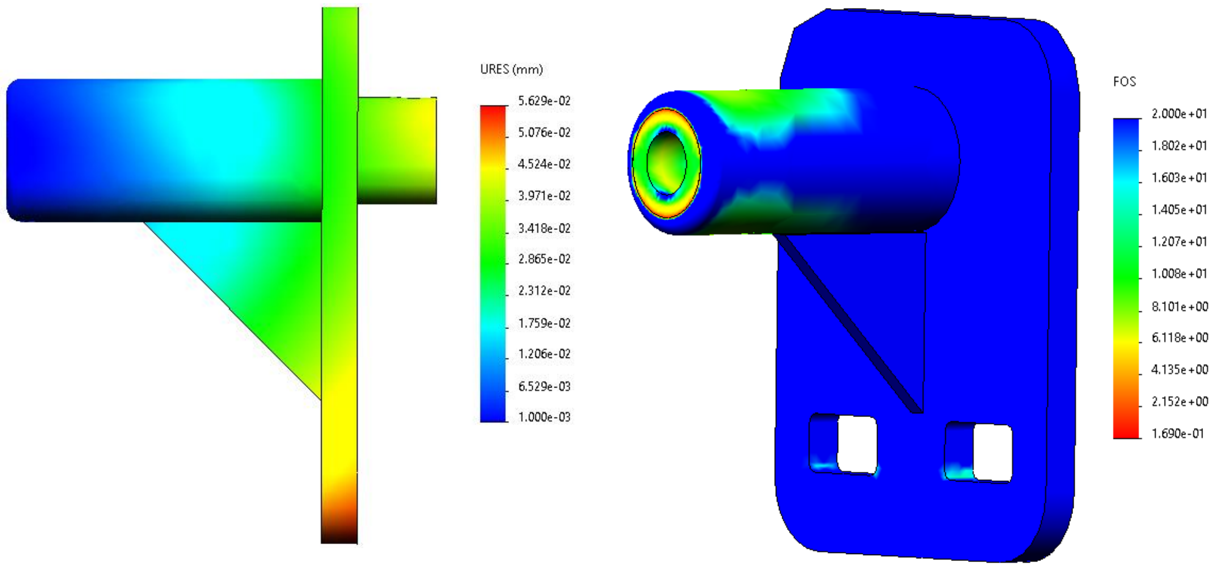


Figure 59. Connection Deflection & FOS Distribution

The deflection plot shows that the total deflection is 0.05629mm. The re-design of the connection is successful in minimizing deflection here. The minimum FOS is 0.169 but increases rapidly away from the fixture location. This suggests the part experiences less stress than that, and also shows the rest of the connection is strong enough to support the load.

7.3 Track

To determine how well the track will support the expected loads, we considered a single configuration of a fully loaded carousel. The track is fixed at every bolt hole that connects to a supporting bracket. The forces are applied by the wheels at 10 locations on the track. The loading and fixture conditions for the track are shown below.

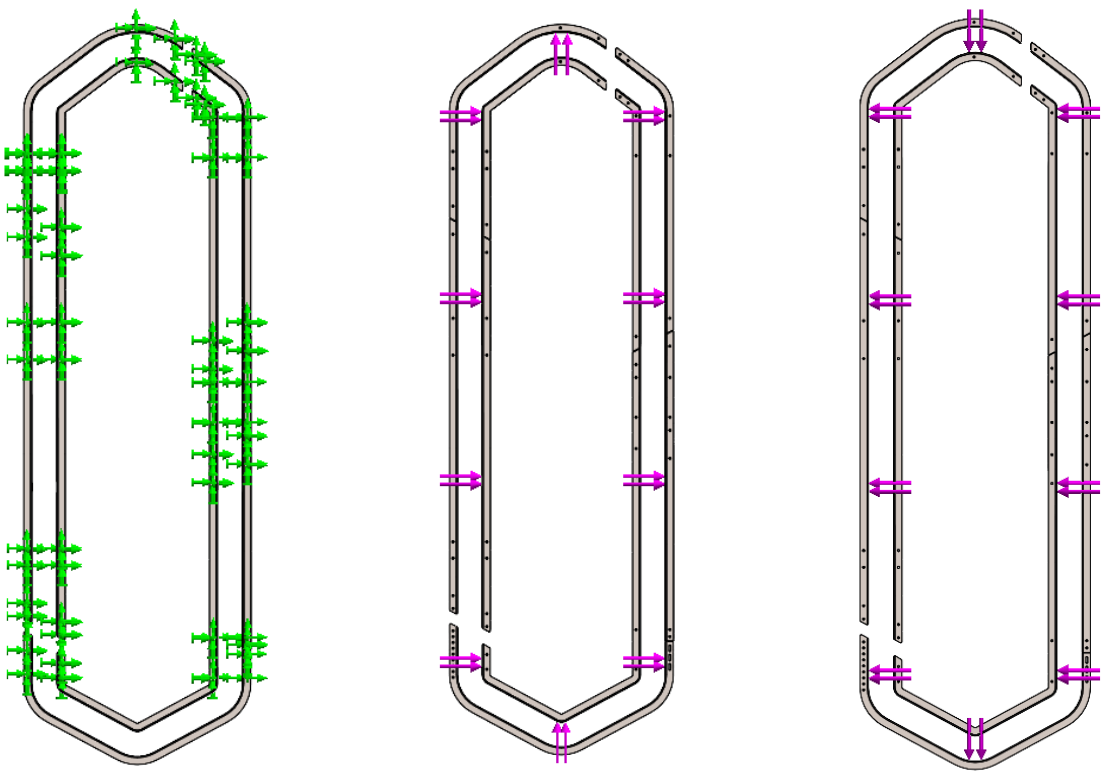


FIGURE 60. TRACK FIXTURES (LEFT) & LOADING CONDITIONS FOR FORWARD (MIDDLE) AND REARWARD (RIGHT)

The fixture diagram looks messy, but the green arrows simply indicate the direction in which the surface is fixed. Circular and square holes were fixed on the interior surface. The loads experienced by the track are always in the direction that counteracts the moment of the shelf, which explains why the track experiences upwards loading in the forward case at the top and bottom. Similarly, the rearward loading condition causes forces left and down on the track. A convergence plot is shown for the forward and rearward loading cases in the figure below.

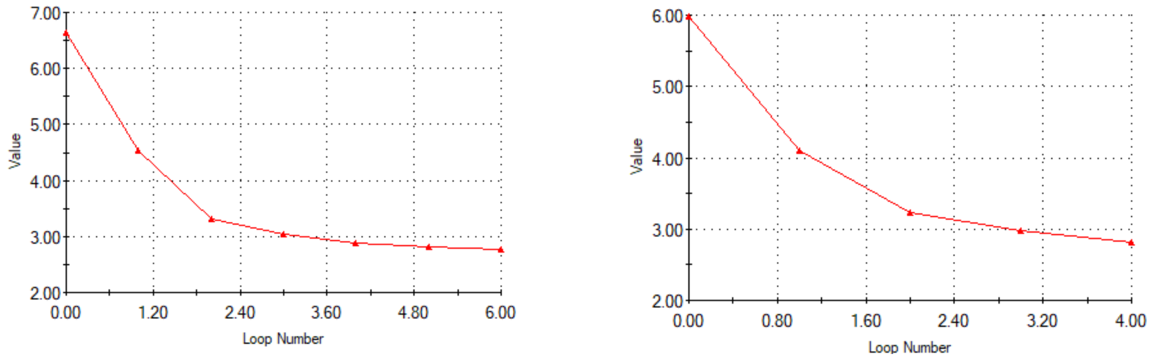


Figure 61. Mesh convergence Plots for Forward and Rearward Track

The convergence plots show that we can accept the results for deflection and approximately for FOS. The error for these plots is below 3%, which is excellent. Deflection and FOS plots for the forward and rearward cases are shown below:

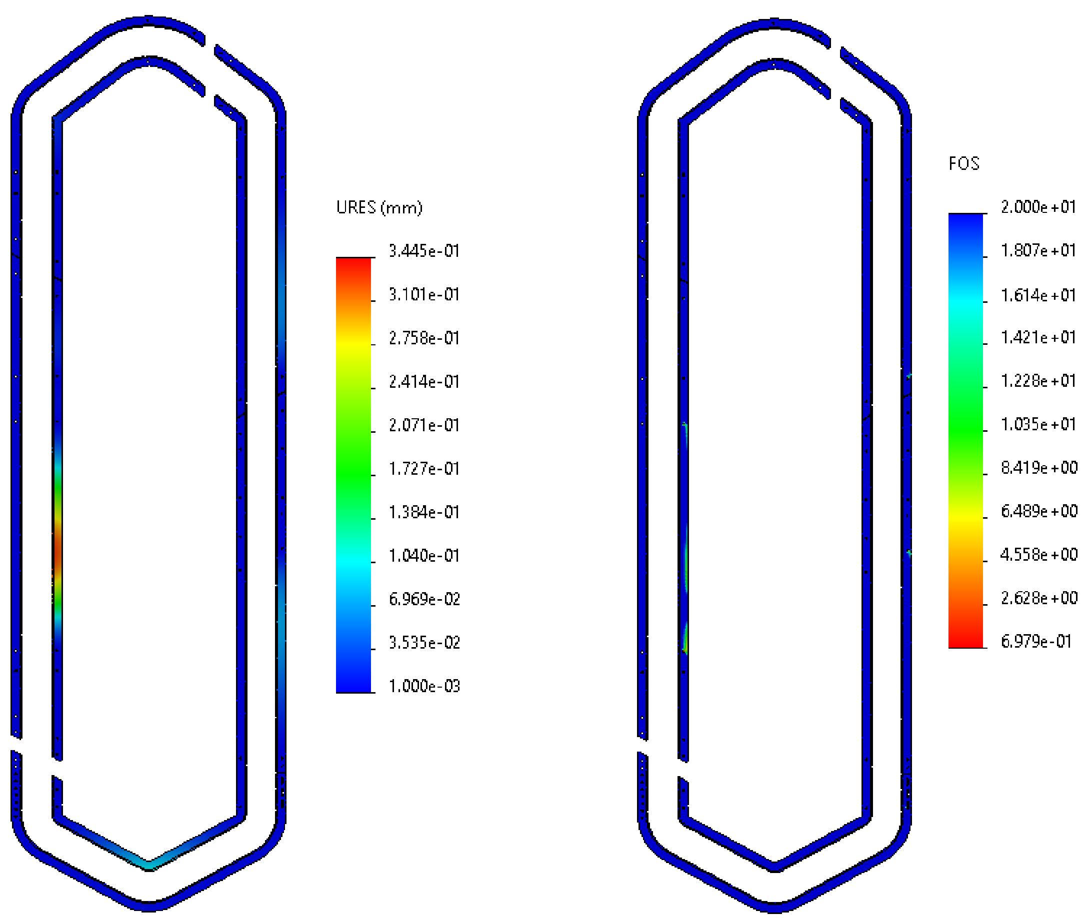


Figure 62. Track Deflection & FOS Distribution for Forward Offset

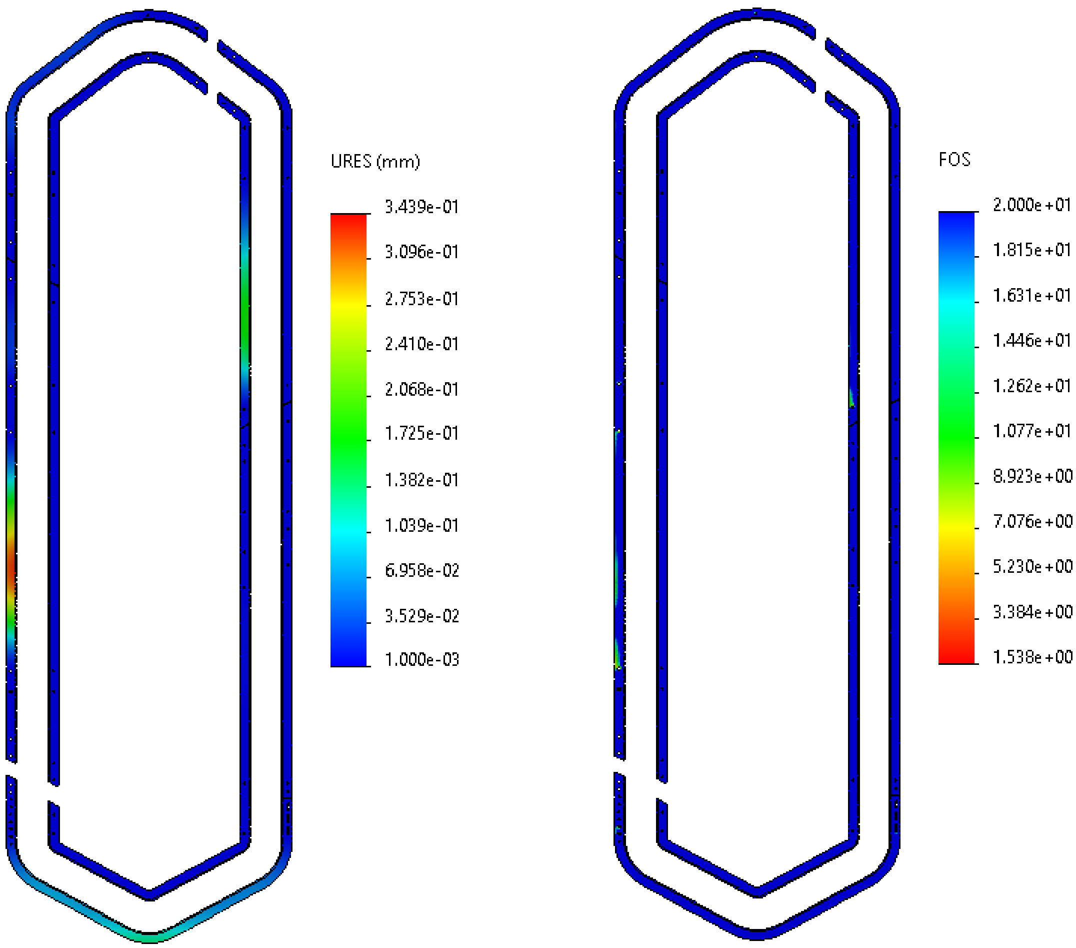


Figure 63. Track Deflection & FOS Distribution for Rearward Offset

Although it is difficult to see in the plots, as the tracks are very large, the FOS is lowest at the fixture points due to stress concentrations. A close-up of a fixture point is shown below to highlight these stress concentrations:

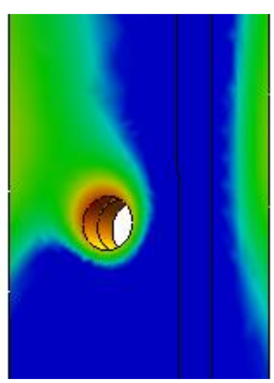
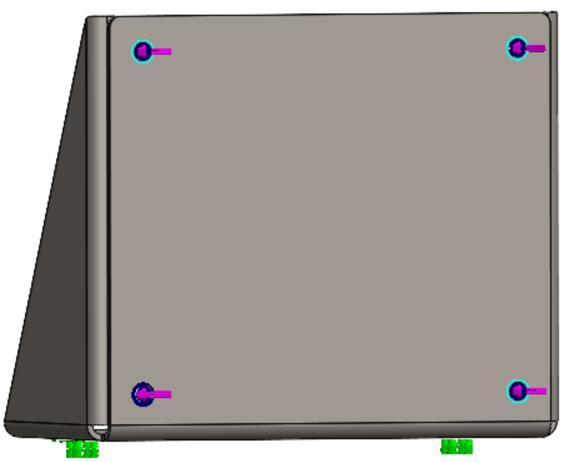


Figure 64. Stress Concentrations from the rearward track offset, visible in green above

7.4 Brackets

To sustain the loads experienced by the track, brackets were designed, which transmit forces from the track to the carousel towers at each end. A total of ten brackets were needed to safely mount the track to the carousel. The FEA for all brackets can be found in Appendix B. Bracket 2 is not as complex as some of the other brackets, so it serves as a good example to look at in detail here.

The loading conditions for this bracket are in the horizontal direction. The load can be applied in either direction, so for consistency, the direction that corresponds to the forward track loading condition was chosen. As most of our brackets are symmetric, the results for reverse loading will be approximately the same. The load is applied to the part of the circle where deflection realistically occurs. A 1/20” planar offset from the centre of each hole allows the load to be applied only to the part that realistically maintains contact.



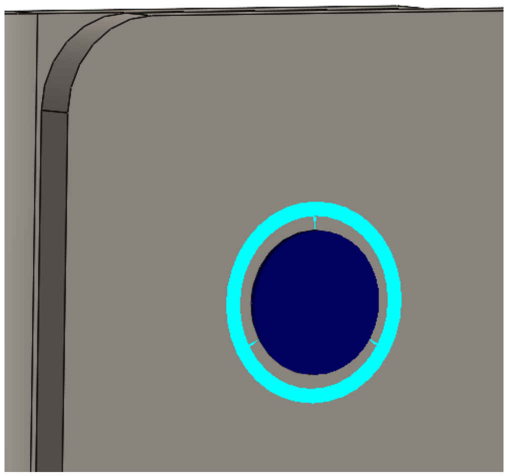


Figure 65. Bracket 2 Fixtures & Loading Conditions (left) & Pin Connection (right)

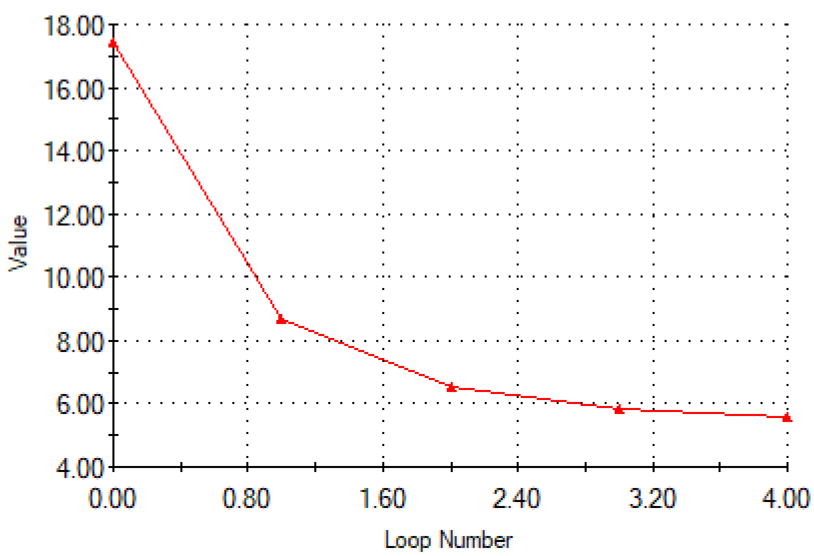


Figure 66. Bracket 2 Mesh Convergence

The connection shown in the detail allows the hole to maintain its concentricity, as if there were a pin in the model to prevent misalignment through interference. The bracket plate is assumed to carry the load, and the stress from this load is transferred to the tabs through the pin connection.

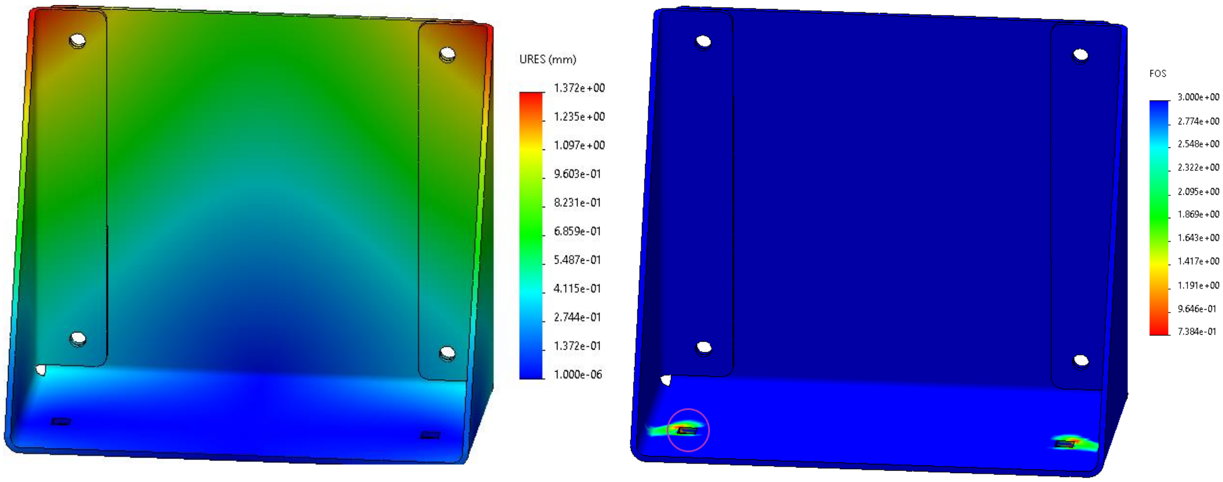


FIGURE 67. DEFLECTION AND FOS DISTRIBUTION FOR BRACKET 2

The bracket shown above primarily undergoes bending stress, which is indicated by the deflection pattern. The stress concentration is highest at the bend points and around the holes. The hole is shown in detail below, corresponding to the left hole encircled in the figure above in the FOS plot.

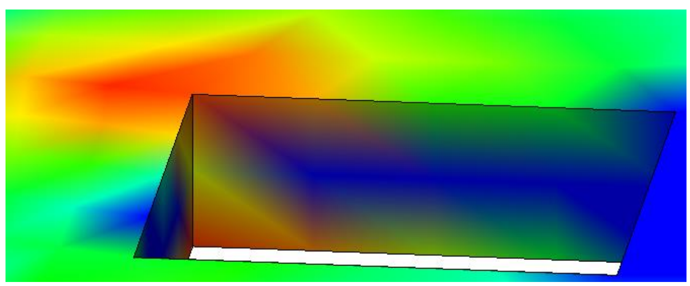


FIGURE 68. BRACKET 2 DETAIL

The bracket shows stress concentrations at the corners of the square hole. The fixtures were applied to the 4 faces that comprise the inner region of the square hole, but a more realistic fixture could be applied to a small vertical area in the centre of each face for increased accuracy. However, to avoid arbitration in our results and for simplicity, we just fixed the faces. This is a recognized limitation of preliminary FEA.

7.5 FEA Summary

After performing FEA on the connection, track and brackets, we examined the plots and iterated through design until we had parts that we were confident in. Appendix B summarizes the results of the rest of the brackets. The deflection plots provide intuition over the validity of the results and compliment the mesh convergences. For specific parts, we also wanted to know the deflection to ensure the loaded carousel would not deform significantly enough to affect the movement of the wheel along the track. The summary of minimum FOS, maximum deflection and convergence error are shown in the table below.

TABLE XVII. FEA SUMMARY

Component	Minimum Factor of Safety	Maximum Deflection [mm]	Approximate Error [%]
Connection	0.169*	0.056	5.84
Track Forward Offset	0.698*	0.345	2.76
Track Rearward Offset	1.538*	0.344	2.81
Bracket 1	4.097	0.001	<2%
Bracket 2	0.738*	1.372	5.58
Bracket 3	0.114*	2.061	5.72
Bracket 4	0.598*	5.516	5.16
Bracket 5	4.033	0.043	<2%
Bracket 6	0.948*	0.941	5.65
Bracket 7	0.128*	2.464	6.77
Bracket 8L	1.692*	0.019	5.21
Bracket 8R	1.022*	2.012	4.23
Bracket 9	0.666*	3.556	5.37

*Local minimum FOS is low due to singularity, not stress concentration.

The most surprising results of our preliminary FEA was how much the stress concentrations affected our results. Despite most of the components shown having a FOS less than 2, which is our general design goal for safety, the stress outside of the fixture region quickly went to above 20. Therefore, our team recommends that more in-depth FEA be done in the development of this design, and in advance of manufacturing.

The approximate error trends show that more complicated parts had larger error, but the biggest factor was in the simplicity of the problem. Bracket 1 and 5 are the simplest brackets, and the stress concentrations can be easily predicted using analytical methods. Both mesh convergence studies only required 2 iterations to reach greater than 98% accuracy.

The maximum deflection of these parts is in millimeters or less, and the scale of our design is over a 20-foot-tall carousel. The preliminary FEA shows that the wheel and track should operate within their design space despite a variety of loads.

8 Design Summary

The final design pictured in **Error! Reference source not found.** meets the needs and s pecifications set out in Sections 1.4 and 1.5. The design utilizes a guide track and wheel system that allows the shelf to self balance and decreases angular displacement to a maximum of approximately 2 degrees. The shelf-chain connection was redesigned to be compatible with the track and in total, 10 different brackets were designed to mount the track to the tower supports. The materials cost estimate for the design is $687.19.

FIGURE 69. RENDER OF THE FULL FINAL DESIGN.

This section compares our needs and specifications to the final design and summarizes how they are met. We recommend areas of additional study not covered within the scope of this report. This includes manufacturing considerations and impact forces between the track and wheel.

8.1 Comparison to Target Specifications

We compare our design to the target specifications we set out in section 1.5 to show how our design successfully meets the needs of the project. This is summarized in Table XVIII below and explained in the sections following.

TABLE XVIII. TARGET AND DESIGN SPECIFICATIONS SUMMARY

		Description	Target	Design
Required	1.	The design allows shelves to rotate smoothly on their pivoting axis.	Yes	Unsure
	2.	The design causes shelves to have a vibrational settling time of no more than 5 seconds after excitation.	5 s	<3 s
	3.	The design causes shelves to stay within 5 degrees of rotation, forwards or backwards, from the upright position.	≤5°	≤2.5°
	4.	The design stays within the bounded volume (design space) with our additions, including shelf movement.	Yes	Yes
	5.	The design does not increase the weight of a shelf by more than 50 pounds.	50 lbs	<5 lbs
	6.	The design allows for safe management of hazardous energy.	Yes	Yes
	7.	The design minimizes and then identifies all pinch points, abrasive surfaces, sharp points, and other physical hazards.	Yes	Yes
Ideal	8.	The design stays within a budget of $5,000.	$5000 (ideal) $20000 (max)	$687.19 (materials only)
	9.	The design's powered sections (if any) are separate from the carousel's shelves and thus stationary.	Yes	Yes
	10.	The design meets all primary needs during both clockwise and counterclockwise operation of the carousel.	Yes	Yes
	11.	The design can be assembled separately and then attached to a pre-existing carousel.	Yes	No
	12.	The design can be assembled and attached to a carousel: by no more than 2 people;	2 people	2 people
	13.	and in 8 working hours per person.	8 hours	Unknown
	14.	The design meets all primary needs when installed on other carousel models.	Yes	Partly

Our design meets our set out requirements and most of our ideal specifications.

8.1.1 Design Requirements

In Table XIX below, the design requirements are listed alongside explanations on how the design does or does not meet each requirement.

TABLE XIX. DESIGN REQUIREMENT FULFILLMENT

	Requirement	Met	Explanation
1.	Rotates smoothly	Unsure	We know that there are impacts, but we cannot conclude on their actual magnitude and effects. We were not confident in our ability to accurately interpret the acceleration data from our motion study. We recommend that Vidir makes a prototype to assess the impact behaviour.
2.	Settles vibrationally	Yes	Since our design is passive, we do not have to worry about the system not reaching a settling point. Making conservative assumptions about the natural damping of the shelf system, we are certain that our design reaches its vibrational settling point quickly. Our motion study settles within 3 seconds.
3.	Stays vertical	Yes	In our motion study, we found that our design limited the shelf's angle to within 2.5° of vertical over the entire rotation, more than meeting the requirement of ≤5° tilt.
4.	In design space	Yes	As can be seen in the CAD model of the full design, our additions are all within the available space of the carousel.
5.	Low shelf weight	Yes	Extremely little of the design's weight rests on the shelves. The tracks are mounted on brackets to the carousel's frame. The design adds about 1 lb of steel per shelf, plus wheels.
6.	Can be locked out	Yes	There are no added components that store energy, even mechanical (gravitational) energy. All components are securely attached to the carousel frame or each shelf.
7.	Hazards identified	Yes	The hazards imposed by the design are obvious and nothing new to the carousel: do not touch the wheels or the insides of the rails while the carousel is moving.

The only design requirement we are lacking in is that of "Smooth rotation". We know that by limiting allowable shelf angles, the inertia of the shelf's contents will cause an impact when the shelf abruptly changes direction from horizontal to vertical movement. The magnitude and significance of this impact is highly implementation-dependent and was beyond our ability to accurately model. We believe that our design will meet Vidir's needs, but we strongly recommend that Vidir makes a prototype to test this specification.

8.1.2 Ideal Specifications

In Table XX below, the ideal specifications are listed beside explanations on how the design does or does not meet each one.

TABLE XX. IDEAL SPECIFICATION FULFILLMENT

	Specification	Met	Explanation
8.	In budget	Yes	We estimate the material cost of the design at $687.19. Manufacturing and assembly costs are beyond the scope of our analysis but are unlikely to be bank-breaking. Most of our design is off-the-shelf parts and laser-cut sheet metal.
9.	Available power	Yes	Our design is completely passive.
10.	Two-directional	Yes	As shown in the motion study we performed, our design works equally well in clockwise and counterclockwise motion.
11.	Retrofittable	No	To retrofit a carousel, it would need bracket-mounting holes somehow added to its frame, in addition to a full refit of shelves.
12.	Assembled by 2 people	Yes	The heaviest single piece is a track section, which weighs about 45 lbs before being installed into place. The awkwardness of getting it into place may necessitate two people, even if pure weight is not a direct limiting factor.
13.	Assembled in 8 hours	Probably	We see no reason why our design would take an excessively long time to install. Parts were designed to be bolted into place as easily as possible. However, we have performed no formal assessment to estimate how long it would take to assemble our design, so we cannot say for sure.
14.	Transferrable	Partly	The design that we made is made specifically for the model of carousel that Vidir gave us a STEP file for. The general idea is transferrable between models of carousels, but the specifics of implementation, especially mounting, are not.

Our design meets most of our ideal specifications. We primarily lacked in transferability, onto pre-existing carousels and other models. The design relies on being mounted to the carousel's frame, which makes retrofitting infeasible and transfer between models somewhat more difficult. Our design can be transferred to other models of carousel with additional design effort for each.

8.2 Areas for Further Study

We recommend that Vidir investigates the shelf wheels, connection sleeve, and impact areas of our design, which were beyond the scope of our project analysis.

8.2.1 Modified Wheel Manufacturing

As was described in Section 4.2.2, our design modifies an off-the-shelf wheel to better fit our needs. However, detailed manufacturing considerations were outside the scope of our project. As a result, it may be beneficial for Vidir to consider adjusting our design for easier or cheaper manufacture. We recommend looking at the operation of milling down the shelf-facing hub of the wheel, and the operation of expanding the wheel axle to fit ½”.

In our design, we milled the shelf-facing hub of the wheel to make room for an additional locknut. Alternatively, Vidir could leave that hub as-is (thus only milling the away-from-shelf hub of the wheel), remove one locknut, and fill the resulting gap on the screw with washers. This would decrease the vibration-resistance of the wheel subassembly, but that may be acceptable.

We expect it will be most prudent to drill out the sleeve of the selected wheel and replace it to fit on the ½” axle. However, other viable alternatives exist. One alternative is to downsize the axle from ½” to ⅜” and reinforce the shelf to make up for the reduced shear strength. The other option is to purchase a wheel sized for a ½” axle, but those wheels are wider and increase the risk of the wheel colliding with things beyond the track. Exploring these options is left to Vidir if our proposed method turns out to be undesirable.

8.2.2 Connection Sleeve Manufacturing

Section 4.3.3 described ways in which the connection sleeve could be modified to be more easily manufactured by Vidir, since we did not make detailed manufacturing instructions for this part. We suggest perhaps milling it from 1” steel rod stock, but frankly this is entirely up to Vidir. Whatever Vidir decides to do, we recommend that they test the resulting fit between the sleeve and the 7/16” bolt it is to rotate on.

8.2.3 Impact Analysis

We were not confident in our ability to accurately interpret the acceleration results from our motion study in terms of impact on the shelf. This was in part because we could not verify the accuracy of our impact results, as our simulation was based on simplified mechanics. The assumptions made discount important factors in impact effects, like the elasticity of the track and wheel. We recommend that Vidir prototypes our design to assess the effects of the impacts, to ensure that they are within acceptable levels for the life cycle of the carousel.

If impacts are found to be unacceptably serious, they can be mitigated in a couple of ways. First, the wheels could be replaced with more impact-absorbent soft rubber wheels (instead of hard rubber), though this would likely reduce the durability of the wheels. Alternatively, a limiter could be placed on the chain feed speed, which would exchange retrieval speed for impact reduction.

9 References

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Appendix A Calculations

Contents

List of Figures

List of Tables

A.1 Introduction

In our design of the self-balancing shelving carousel for Vidir, we performed analytical calculations to determine acceptable dimensions for several components. These are detailed in this appendix.

A.2 Track Bending Resistance

We decided on dimensions for the cross-section of the guide track with a guess-and-check method, using an Excel spreadsheet to calculate the resulting resistance to bending. The tables below summarize the spreadsheet inputs and outputs.

TABLE I. TRACK BENDING RESISTANCE INPUTS

Input	Amount	Units	Source
Face width	1.00	[in]	Input dimension
Face thickness	0.25	[in]	Input dimension
Spine width	1.50	[in]	Input dimension
Spine thickness	0.50	[in]	Input dimension
Applied force	500	[lbs]	Expected applied force from two shelves
Distance	47.50	[in]	From model, see Figure 1 on next page.
Yield Strength	$36x10^3$	[psi]	A36 Steel from [1]
Young's Modulus	$29x10^6$	[psi]	A36 Steel from [1]

TABLE II. TRACK BENDING RESISTANCE OUTPUTS

Output	Amount	Units	Calculation
Centroid, measured from face	0.78125	[in]	$=\frac{\sum(xA)}{\sum A}$
Second moment of area	0.28548	[in^4]	$=\sum\left(\frac{1}{12}x^3y+A(x-\overline{x})^2\right)$
Maximum deflection	0.0674	[in]	$=\frac{PL^3}{48EI}$
Maximum moment	5937.5	[lb-in]	$=\frac{PL}{4}$
Maximum stress	16249	[psi]	$=\frac{Mc}{I}$
Factor of safety	2.22	[---]	$=\frac{\sigma_{max}}{\sigma_{yield}}$

The equation for maximum deflection was calculated from the standard equations for a cantilever beam with one fixed end and either a force or a moment applied at the other. By combining the equations for half the length of the beam, we construct the appropriate formula for our desired boundary conditions of two fixed ends with a force applied in the middle.

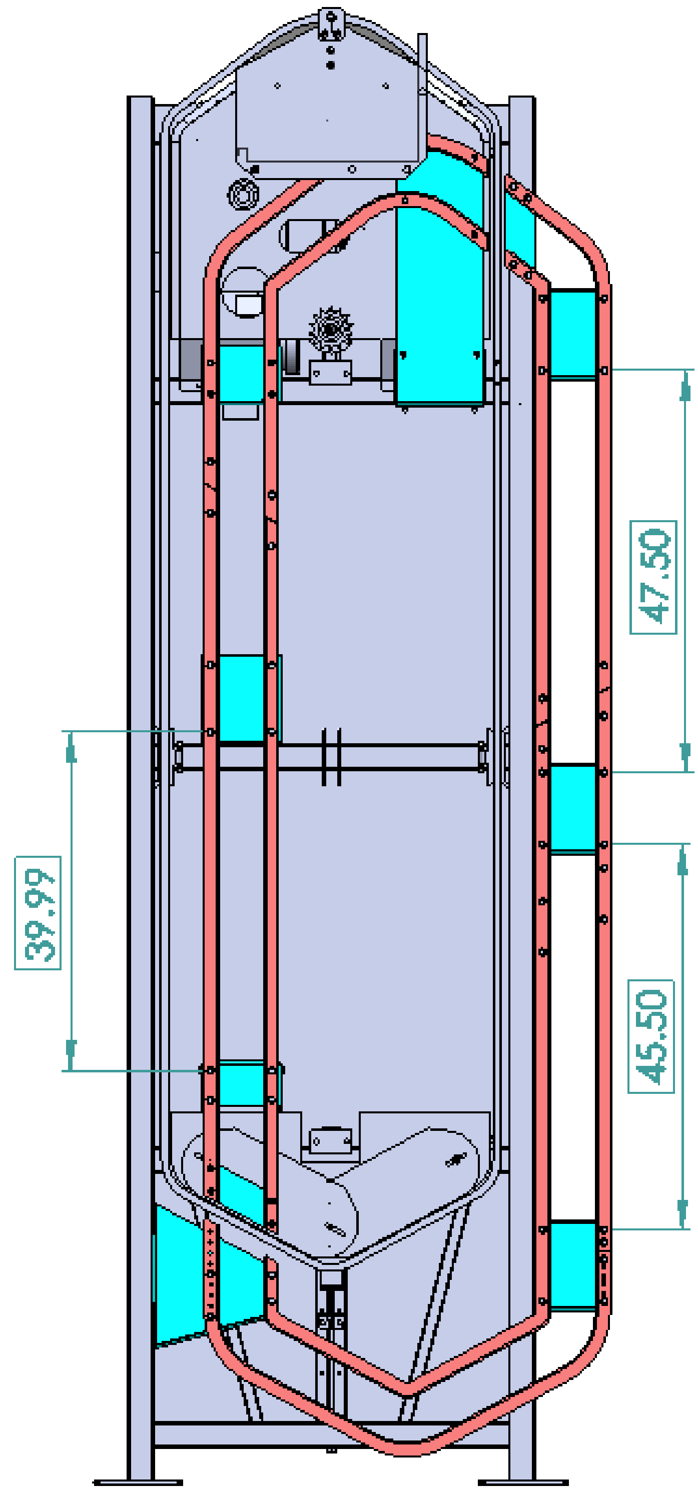

FIGURE 1. LARGEST TRACK SECTIONS BETWEEN BRACKETS, DIMENSIONED.

As seen in Figure 1 above, the largest span between bolted connections for the track is 47.50”.

A.3 In-House Wheel Design

The material selected for the manufacturing of the wheel is based on what Vidir had available to them. We were given ultra high molecular weight polyethylene which is a thermoplastic with the material properties outlined in Table III.

TABLE III. WHEEL MATERIAL PROPERTIES.

Material	Ultra High Molecular Weight Polyethylene (UHMW) - Wheel [2]	Grade 8 Carbon Steel Alloy [3]- Bolt
Ultimate Tensile Strength [kPa]	38,600	630,000
Yield Strength [kPa]	21,000	390,000

Table IV outlines the material properties for a grade 8 carbon steel alloy used for common bolts and fasteners in this analysis.

TABLE IV. GRADE 8 CARBON STEEL MATERIAL PROPERTIES.

Material	Ultra High Molecular Weight Polyethylene (UHMW) - Wheel [2]	Grade 8 Carbon Steel Alloy [3]- Bolt
Ultimate Tensile Strength [kPa]	38,600	630,000
Yield Strength [kPa]	21,000	390,000

Figure 2 shows the critical loading condition which corresponds to 1000 lb being equally distributed along the 12 ft shelf at a 5” offset from the centerline. The b dimension in the photo is the length of the shelf, c is the offset from the centerline, d is the distance from the chain connection to the wheel and D is the diameter of the wheel.

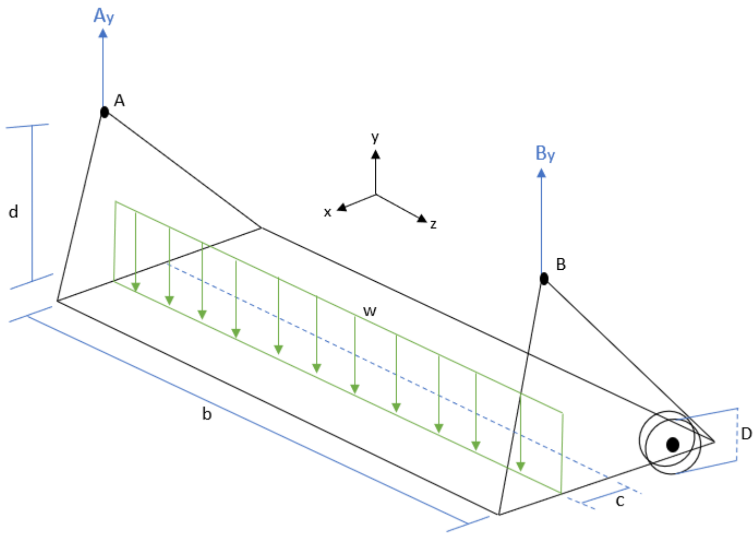

FIGURE 2. CRITICAL LOADING CONDITION.

First, we calculated the moments in the plane parallel to the side of the shelf. This is the moment exerted about the centerline by the offset of the distributed load. The force exerted on the wheel was found based on d, the vertical distance between the wheel and the shelf connection.

$$F_{wheel} = \frac{m * g * c}{d}$$

Next, we introduce the shear stress equation, which allows us to relate the strength of the material to its ability to carry the force. The area depends on the design of the wheel. We assumed a simple design with an outer diameter D_O, inner diameter of D_i and a t corresponding to the thickness of a wheel with non-uniform cross-section. If we want to find the minimum wheel diameter:

$$\tau = \frac{F_{wheel}}{A_{wheel}} = \frac{\tau_{yld}}{FOS}$$

$$D_{O,1} = \sqrt{\frac{4 * F_{wheel} * FOS}{\pi * \tau_{yld}}}$$

If we want to use a larger size wheel than the minimum, we can change the size of the wheel and use a wheel rim thickness, instead of having unnecessary material by keeping a constant cross-section. Also, the centre of a wheel consists of a bearing and shaft and is not just one material. If we want to find the minimum wheel thickness for a given $D_{O,2}$:

$$t = D_{O,2} + \sqrt{D_{O,2}{}^2 - \frac{4 * F_{wheel} * FOS}{\pi * \tau_{yld}}}$$

The inner diameter can be found and sized to fit a bearing, given the thickness and outer diameter. The calculation results that determine the minimum allowed dimensions for a wheel made of UHMW and a bolt made from grade 8 steel are presented in Table V below.

TABLE V. MINIMUM DIMENSIONS CALCULATION RESULTS

Part	BIU	Rounded
Wheel		
Min. diameter	14.45”	15”
Min. thickness	1.18”	1.25”
Bolt		
Min. diameter	0.28”	0.5”

The wheel calculation shows that a wheel made of pure plastic would need to be quite large. Our goal is to use a wheel closer to the 3”-5” range, given the size of the design space. These calculations show that in-house, custom wheels are difficult to properly size without introducing more strength, which is difficult to attain given the manufacturing equipment available to Vidir.

A.4 Shelf Connection Bending Resistance

We estimated the shelf connection's bending resistance analytically, sans the gusset plate. Excluding the gusset plate greatly simplifies calculations and understates the bending resistance of the connection, so we can be sure that the actual part is stronger than calculated.

TABLE VI. SHELF CONNECTION BENDING RESISTANCE INPUTS

Input	Amount	Units	Source
Applied force at shelf	750	[lbs]	3/5ths of expected maximum shelf load of 1000 lbs + shelf weight of 250 lbs.
Applied moment at chain	412.5	[lb-in]	Assumed reaction moment from chain -- half that required to keep bolt horizontal at chain.
Cantilever diameter	1.00	[in]	Specified input dimension.
Cantilever length	2.20	[in]	From model, see Figure 3 below.
Straight bolt mid-length	0.625	[in]	From model, see Figure 3 below.
Yield strength	$36x10^3$	[psi]	A36 Steel from [1]
Young's modulus	$29x10^6$	[psi]	A36 Steel from [1]

The sleeve length and straight bolt mid-length can be found based on Figure 3 below:

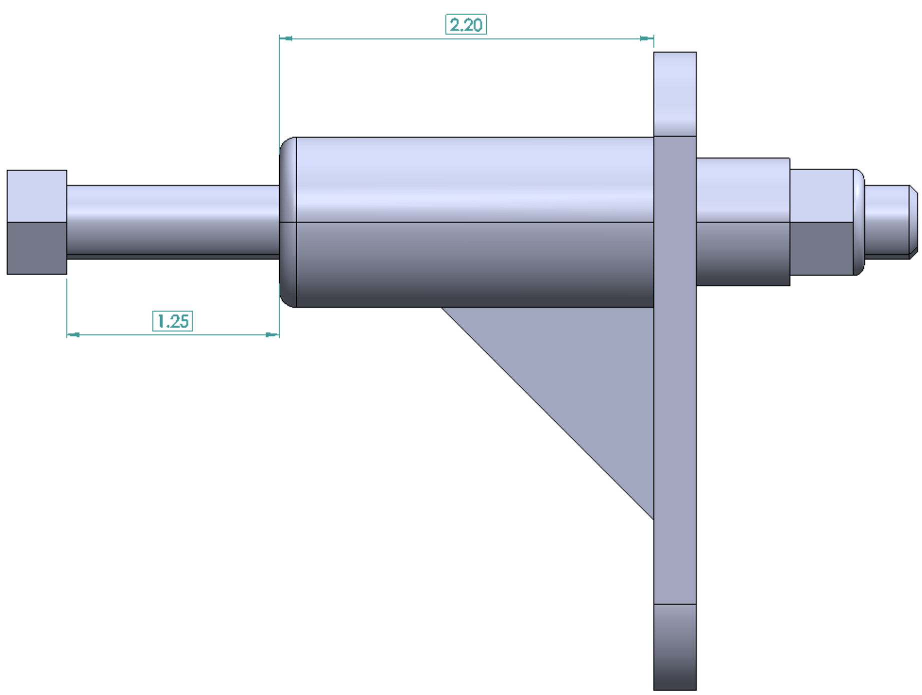

FIGURE 3. SIDE VIEW OF SLEEVE CONNECTION WITH RELEVANT DIMENSIONS MARKED.

The force was applied downwards at the right end of Figure 3, which was allowed to translate but was fixed in angle. The bolt mid-length, located in the center of the 1.25" marked length, was not allowed to translate but was allowed to change angle. The entire length of the 1.25" would be inside a chain segment, and would not be under cantilever conditions, but we are considering its length to estimate effective vertical displacement caused by the angle at the end of the shelf sleeve. The chain applies a counter-moment back to the cantilever, assumed to be half the magnitude that would keep the bolt horizontal (and act as a fixed connection).

The results of this loading condition were calculated in Excel, as shown in Table VII below.

TABLE VII. SHELF CONNECTION BENDING RESISTANCE OUTPUTS

Output	Amount	Units	Calculation
Second moment of area	0.04909	[in^4]	$=\frac{\pi}{4}\left(\frac{D}{2}\right)^4$
Shelf deflection due to force	0.0019	[in]	$=\frac{PL_{2.2}^3}{3EI}$
Shelf deflection due to moment	-0.0007	[in]	$=\frac{ML_{2.2}^2}{2EI}$
Shelf deflection due to slope	0.0228	[in]	$=\sin(\theta_{combined})\,L_{0.625}$
Maximum moment	1237.5	[lb-in]	$=\frac{PL_{2.2}}{4}$
Maximum stress	12605.07	[psi]	$=\frac{M_{max}D}{2I}$
Factor of safety	2.856	[---]	$=\frac{\sigma_{max}}{\sigma_{yield}}$

A.5 References

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Appendix B Mounting Brackets Finite Element Analysis

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List of Figures

B.1 Introduction

This appendix contains the full Finite Element Analysis (FEA) that we performed on the track mounting brackets of the self-balanced carousel we designed for Vidir. The mesh convergence plots are summarized last.

B.2 Methodology

All the brackets are expected to be made of mild sheet steel. Vidir recommended that we use the properties of A36 steel for our calculations, so we used the SolidWorks built-in material called “ASTM A36 Steel”.

For each bracket, we apply a total loading of 250 lbs, the expected amount of force from a full capacity and off-balance shelf. We split the load evenly over all fasteners between the bracket and the track. The direction of loading for each is chosen based on the bracket’s location and orientation to the track. In the plots in Section B.3, the applied loads are coloured pink.

The brackets were fixtured using fixed connections, which prevent all translation and rotation, where they would be bolted onto the carousel frame. Calculated stresses will not be accurate in the immediate proximity to a fixed connection but become much more accurate even a short distance away. In the plots in Section B.3, fixtures are coloured green.

Where the brackets would have bolts going through multiple holes, we applied pin connections to the model. These simulate the shear effect of the bolt shafts, if not the compressive stress and resulting friction forces keeping the two connected plates together. In the plots in Section B.3, pin connections are coloured blue with cyan outlines.

For each bracket, we show the applied loading and fixtures, the resulting displacement, and the resulting factor of safety. For many of the brackets, the minimum factor of safety found by FEA is incorrectly small because of stress singularities at sharp corners. When present, these are expanded on in a separate figure to highlight the nature of the irregularity. A low factor of safety caused by a stress singularity can be safely ignored through more detailed FEA analysis.

We also consider mesh accuracy. Denser meshes generally give better results. To have more confidence in our FEA results, we show the convergence of values as the mesh size decreases. The mesh convergence was performed with the goal of minimizing the error, specifically below 2%. The mesh convergence is performed up to 5 times, but only if the error is still above 2%. Therefore, any errors below 2% will show completely converged solutions for less than 5 iterations.

B.3 Bracket Plots

B.3.1 Bracket 1

Bracket 1 holds the track together at the ends. The fixtures, loading conditions, deflection and Factor of Safety (FOS) is shown in the plots below.

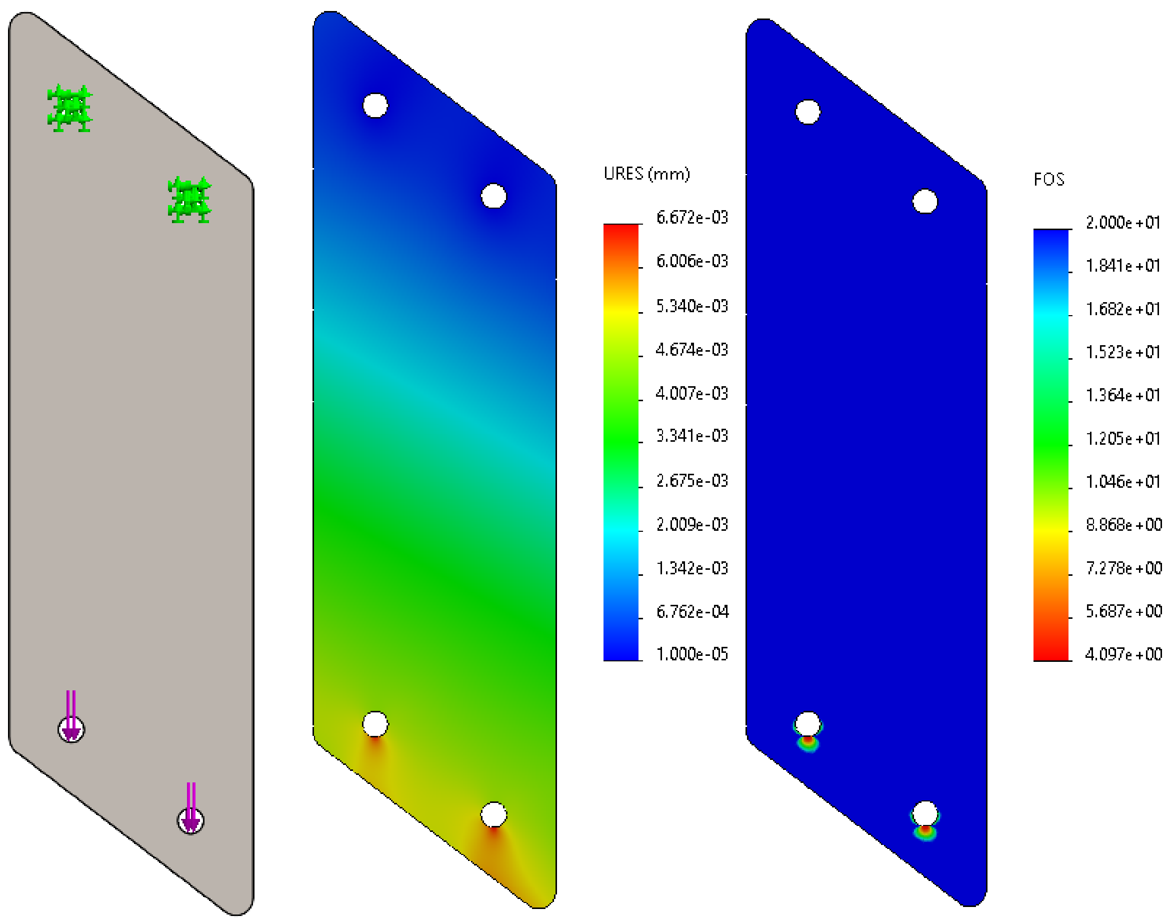

Figure 1. Bracket 1 fixtures and loads (left). Deflection (center), Factor of safety (right).

B.3.2 Bracket 2

This bracket was summarized in the main report but has been provided again here for easy reference. The loading conditions for this bracket are in the horizontal direction. The load can be applied in either direction, so for consistency, the direction that corresponds to the forward track loading condition was chosen. As most of our brackets are symmetric, the results for reverse loading will be approximately the same. The load is applied to the part of the circle where deflection realistically occurs. A 1/20" planar offset from the centre of each hole allows the load to be applied only to the part that realistically maintains contact.

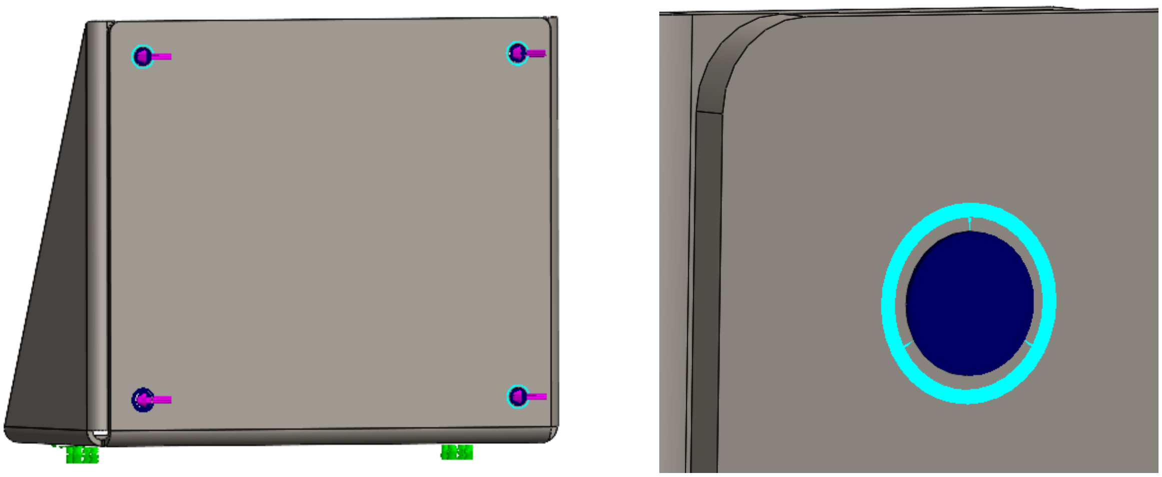

FIGURE 2. BRACKET 2 FIXTURES AND LOADING CONDITIONS (LEFT), PIN CONNECTION DETAIL (RIGHT).

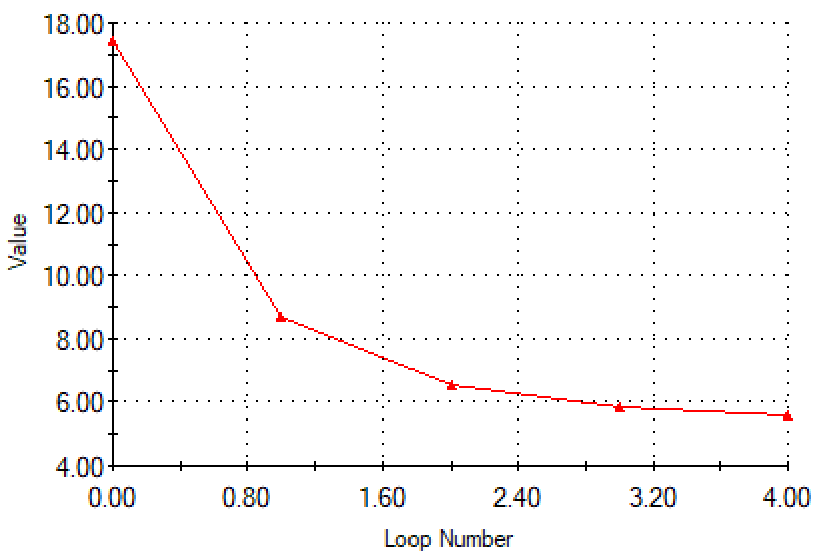

FIGURE 3. BRACKET 2 MESH CONVERGENCE.

The connection shown in the detail allows the hole to maintain its concentricity, as if there were a pin in the model to prevent misalignment through interference. The bracket plate is assumed to carry the load, and the stress from this load is transferred to the tabs through the pin connection.

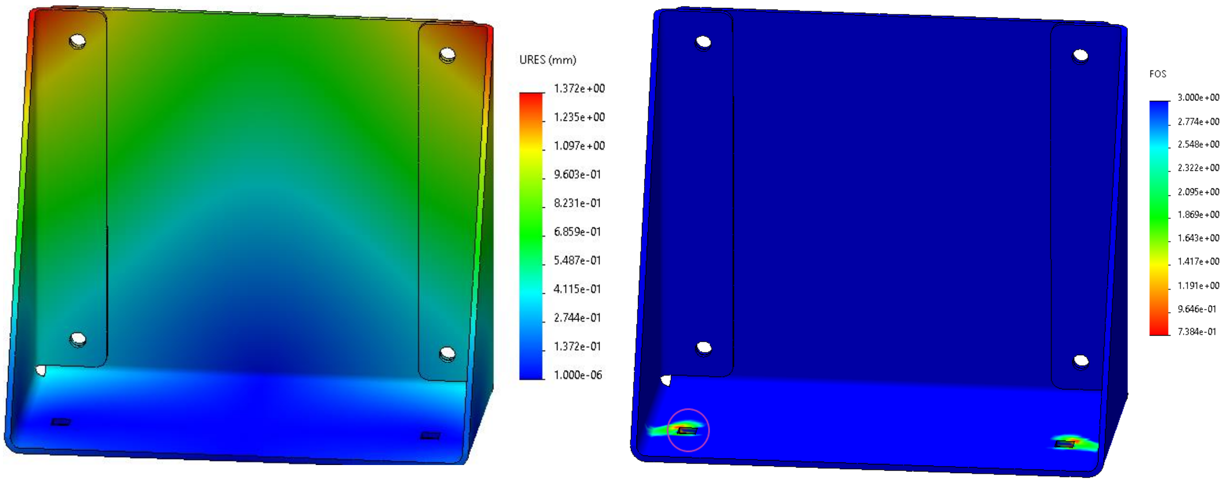

FIGURE 4. DEFLECTION AND FOS DISTRIBUTION FOR BRACKET 2.

The bracket shown above primarily undergoes bending stress, which is indicated by the deflection pattern. The stress concentration is highest at the bend points and around the holes. The hole is shown in detail below, corresponding to the left hole encircled in the figure above in the FOS plot.

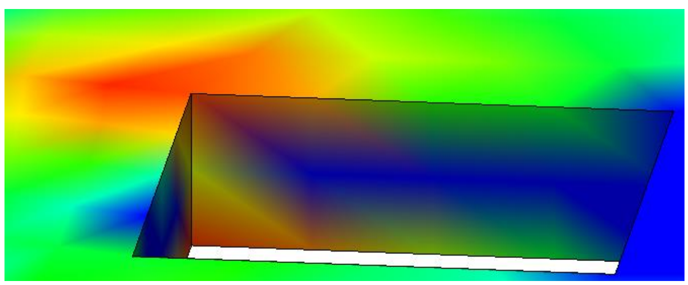

FIGURE 5. BRACKET 2 DETAIL.

The bracket shows stress concentrations at the corners of the square hole. The fixtures were applied to the 4 faces that comprise the inner region of the square hole, but a more realistic fixture could be applied to a small vertical area in the centre of each face for increased accuracy. However, to avoid arbitration in our results and for simplicity, we just fixed the faces. This is a recognized limitation of preliminary FEA.

B.3.3 Bracket 3

Bracket 3 has 6 bolts that transfer load to this bracket. The results are shown below.

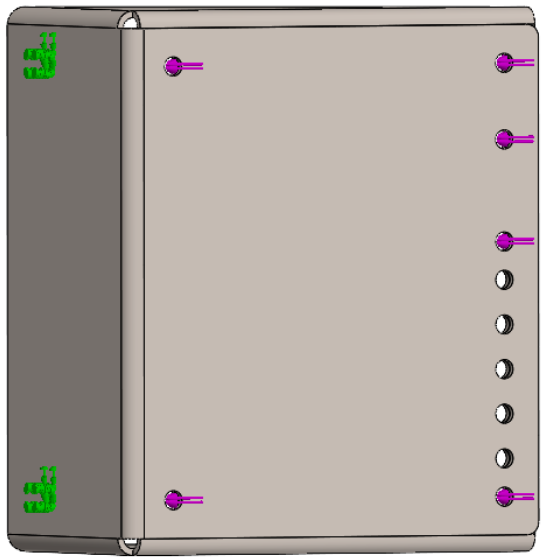

Figure 6. Bracket 3 fixtures and loading conditions.

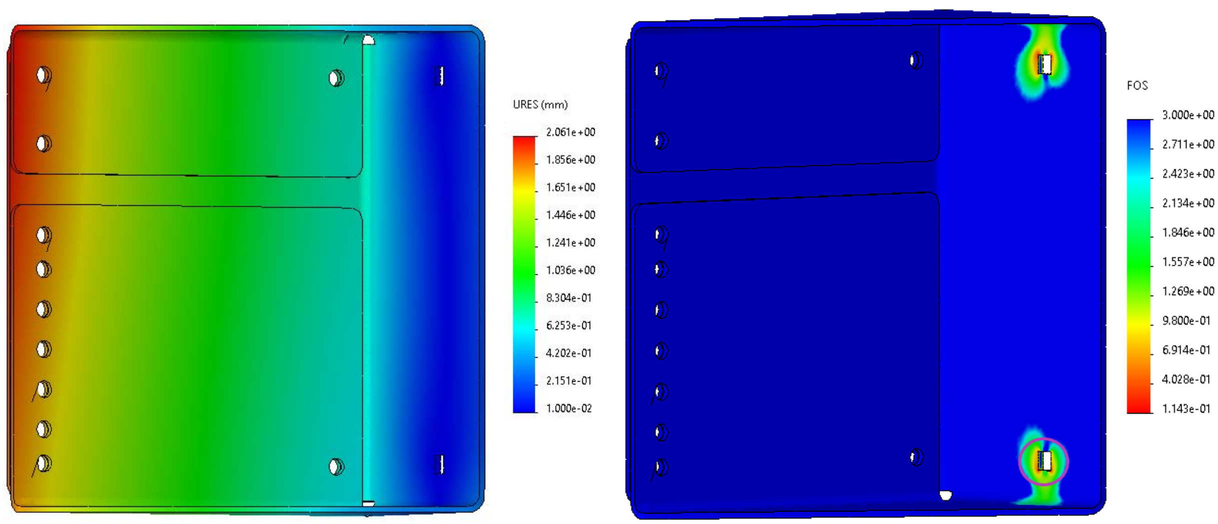

Figure 7. Bracket 3 deflection (Left) and factor of safety (right) plots. Detail location circled.

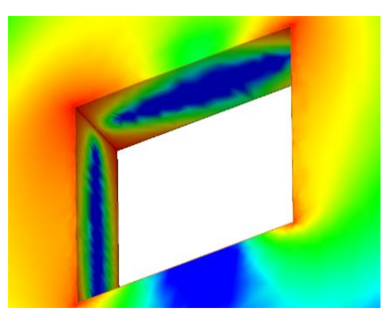

Figure 8. Bracket 3 FOS detail

B.3.4 Bracket 4

Bracket 4 has many holes to allow the track to adjust to multiple heights, which was a result of considering the tensioner in our design. Only one height was modeled. The results are shown below.

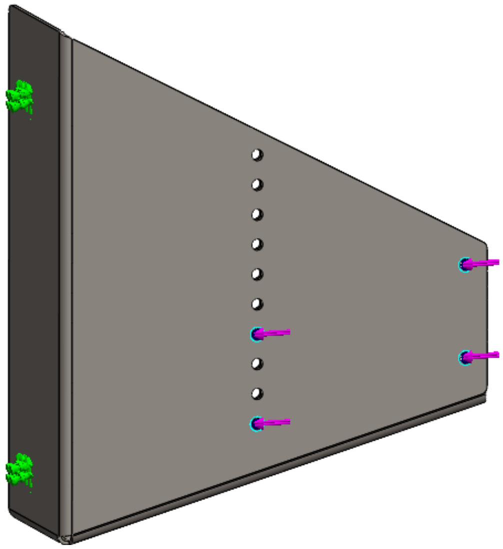

Figure 9. Bracket 4 fixtures and loading conditions.

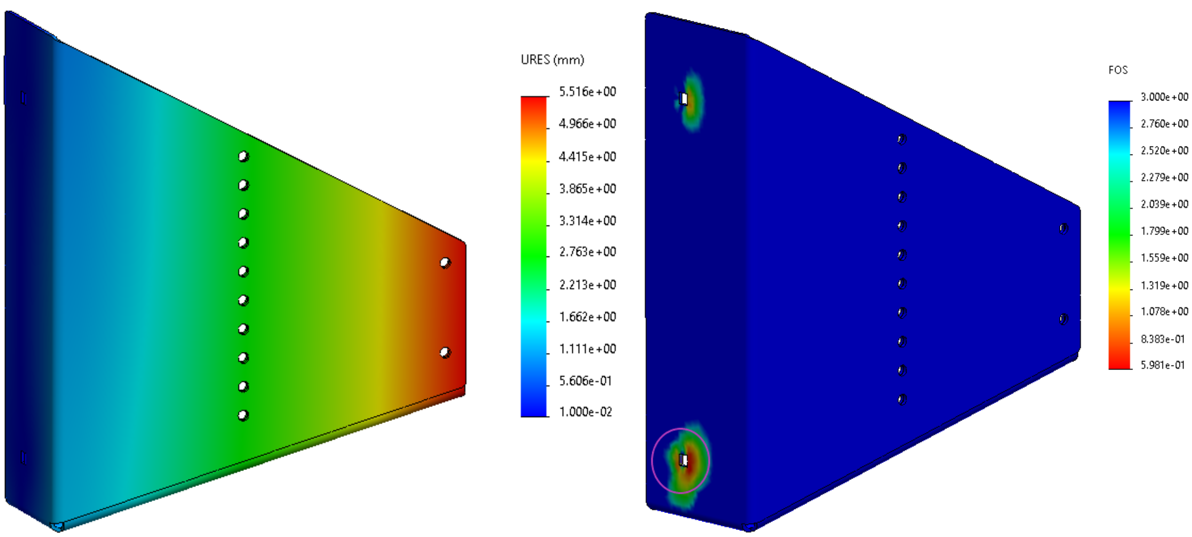

Figure 10. Bracket 4 deflection (Left) and factor of safety (right) plots

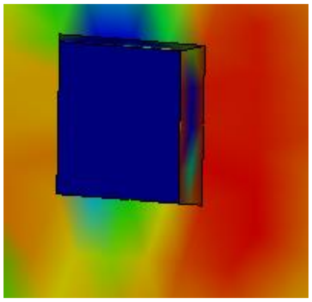

Figure 11. Bracket 4 FOS detail.

B.3.5 Bracket 5

Bracket 5 is very similar to Bracket 1. It is identical in design but differs in length. The results of performing FEA on this bracket is shown below.

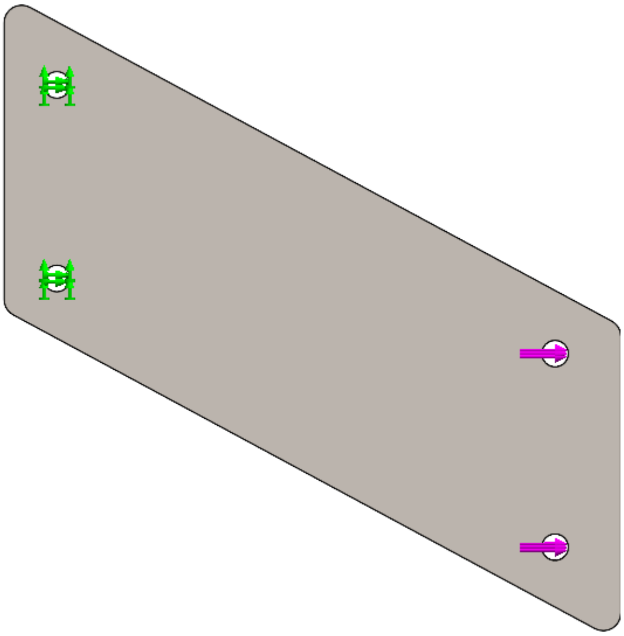

Figure 12. Bracket 5 fixtures and loading conditions.

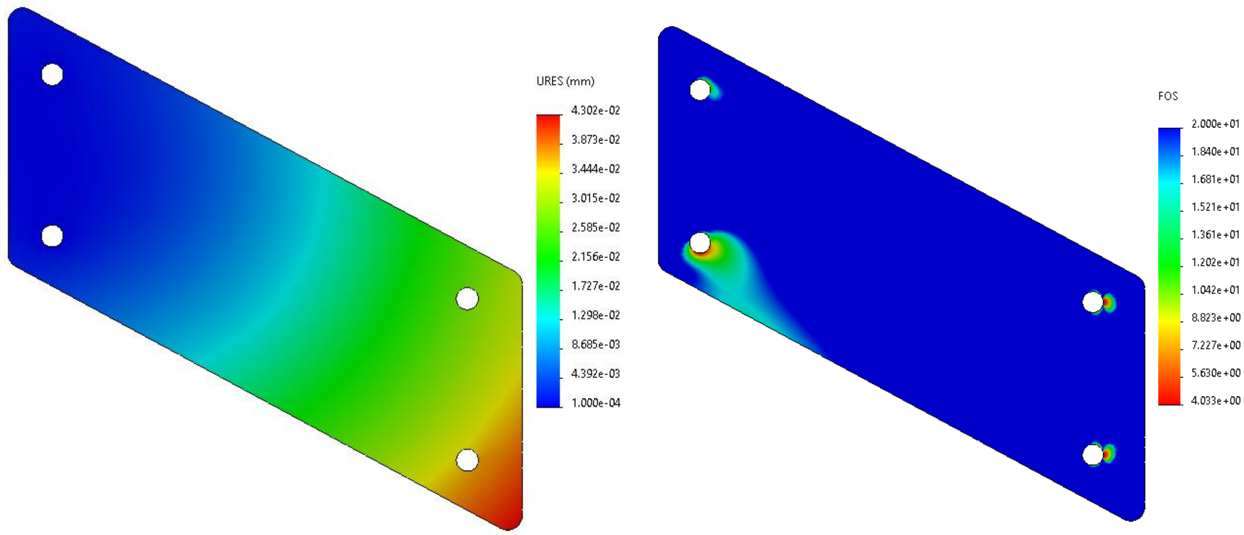

Figure 13. Bracket 5 deflection (Left) and factor of safety (right) plots

The stress shown on bracket 5 peaks around the holes. This is where we see stress concentrations.

B.3.6 Bracket 6

Bracket 6 was predicted to be the weakest of the brackets due to the complexity of a successful design in the minimal space given for this bracket. The results of FEA are shown below.

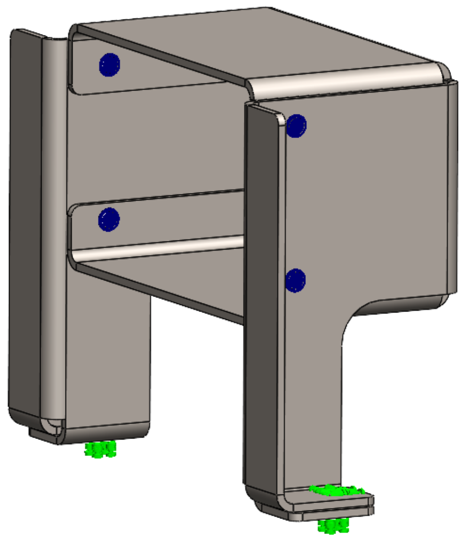

FIGURE 14. BRACKET 6 FIXTURES AND LOADING CONDITIONS.

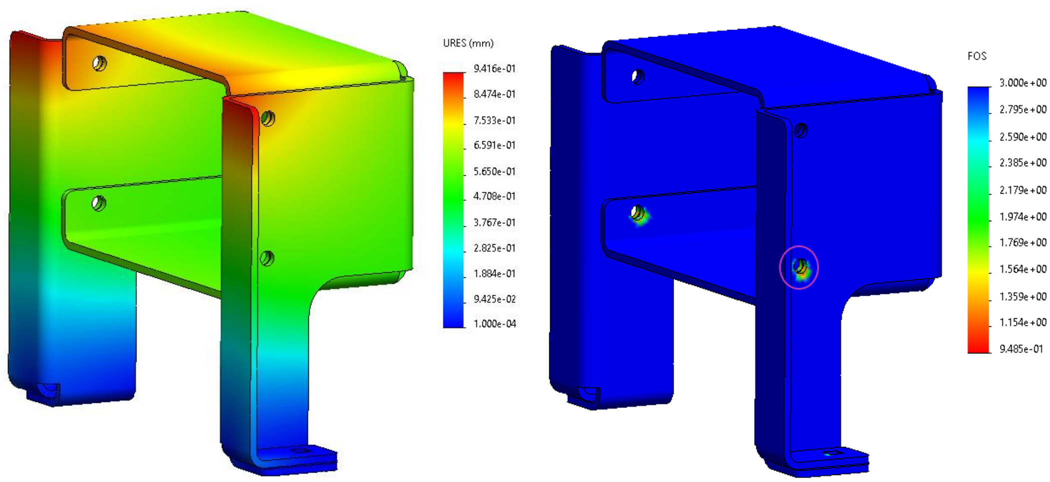

FIGURE 15. BRACKET 6 DEFLECTION (LEFT) AND FACTOR OF SAFETY (RIGHT) PLOTS

The FOS plot shows in red where it is predicted to be less than 1, which would result in failure. This bracket may require some re-design or the use of thicker steel to properly withstand the load.

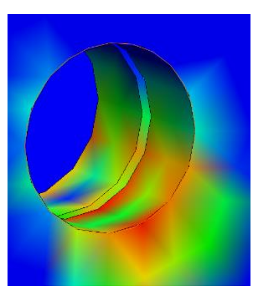

FIGURE 16. BRACKET 6 DETAIL.

B.3.7 Bracket 7

Bracket 7 is similar in appearance to Bracket 2 but is not exactly the same. The results are shown below.

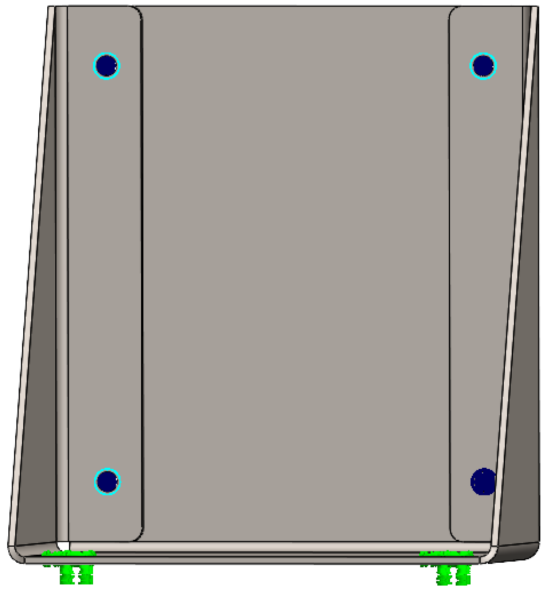

Figure 17. Bracket 7 fixtures and loading conditions.

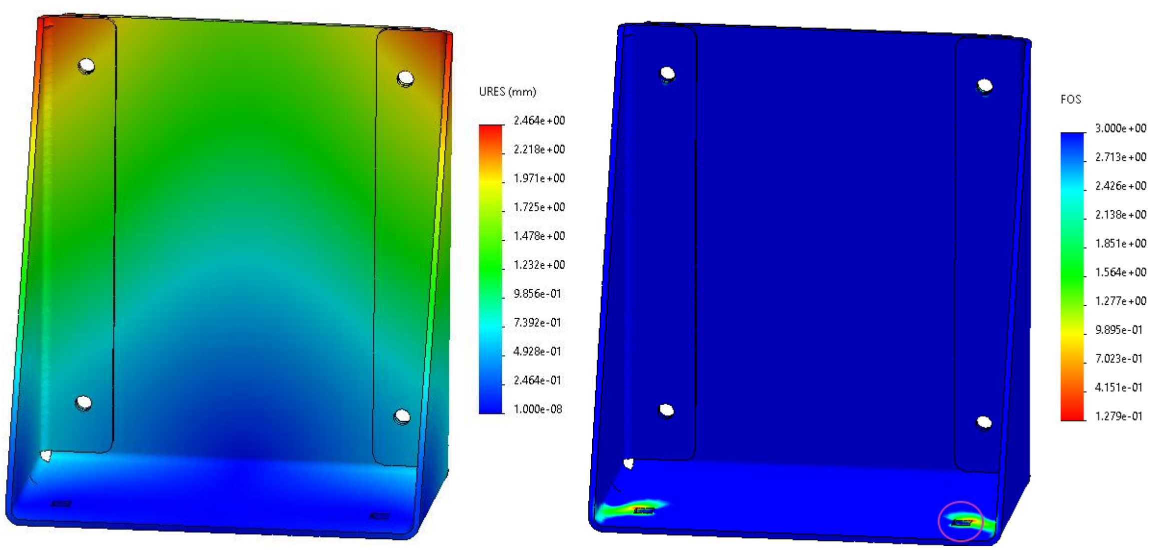

Figure 18. Bracket 7 deflection (Left) and factor of safety (right) plots.

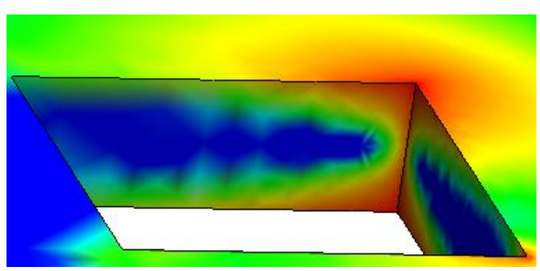

Figure 19. Bracket 7 FOS detail.

B.3.8 Bracket 8L

Bracket 8L is one of two “Bracket 8’s”. Interestingly, the results for each bracket is not the same. For both cases, pin connections were used to accurately reflect the interference of the bolt with the bracket. These results are shown below.

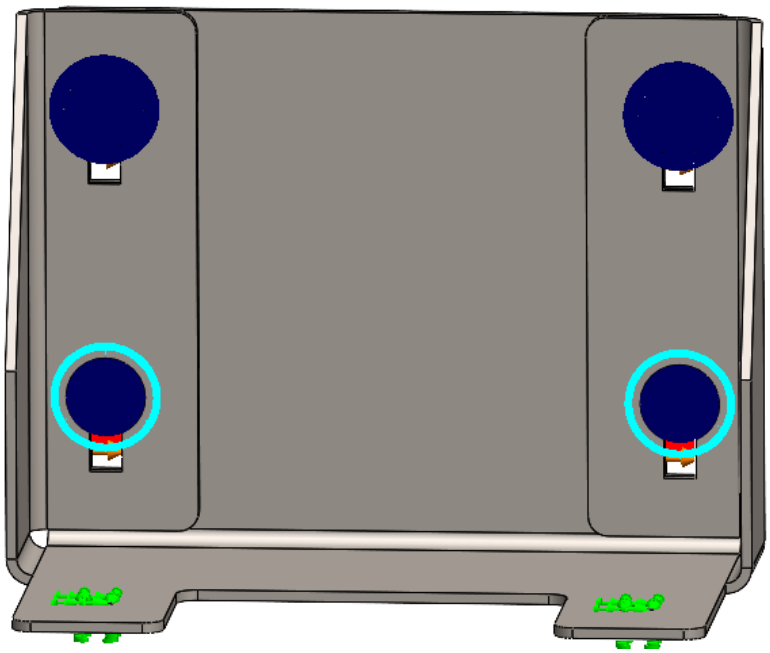

Figure 20. Bracket 8L fixtures and loading conditions.

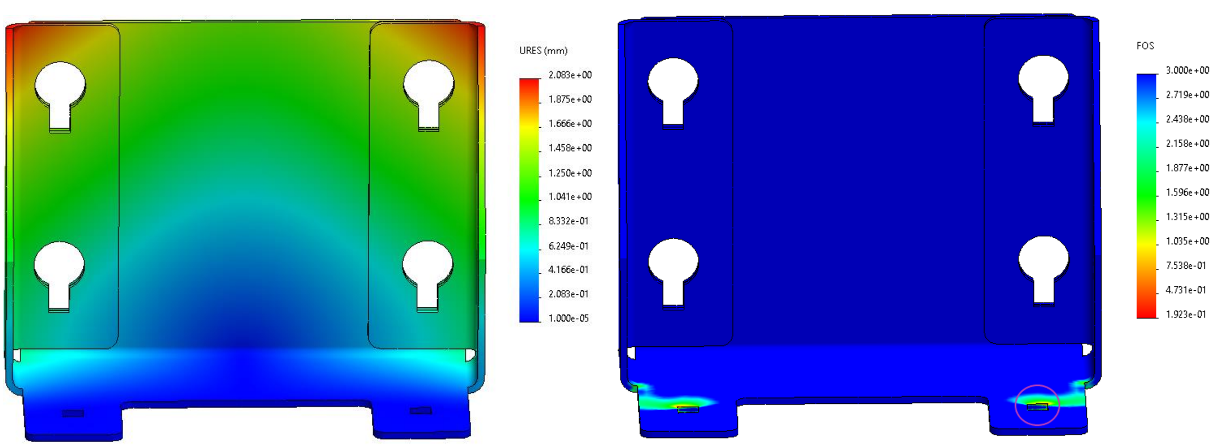

Figure 21. Bracket 8L deflection (left) and factor of safety (right) plots

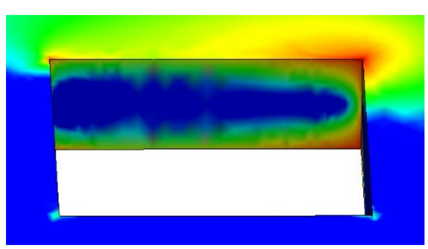

Figure 22. Bracket 8L FOS detail.

B.3.9 Bracket 8R

This is the second Bracket 8. The results of FEA on this bracket are shown below.

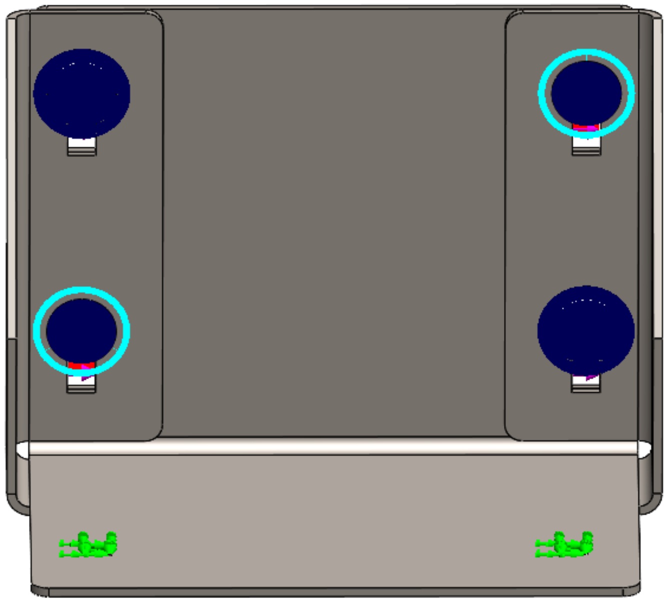

Figure 23. Bracket 8R fixtures and loading conditions.

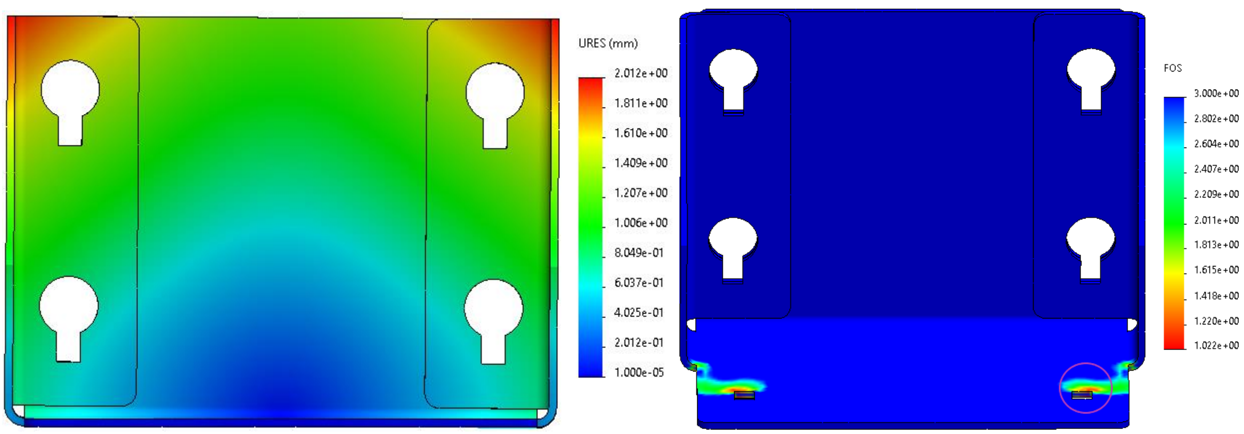

Figure 24. Bracket 8R deflection (Left) and factor of safety (right) plots

Interestingly, Bracket 8L has a FOS 3 times lower than Bracket 8R. This shows how reducing the area around fixtures can increase the FOS by reducing stress concentrations.

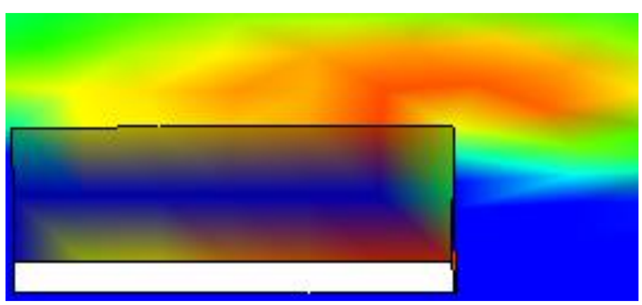

Figure 25. Bracket 8R FOS detail.

B.3.10 Bracket 9

Bracket 9 is the tallest bracket and is used to mount the track at the top. The results are shown below.

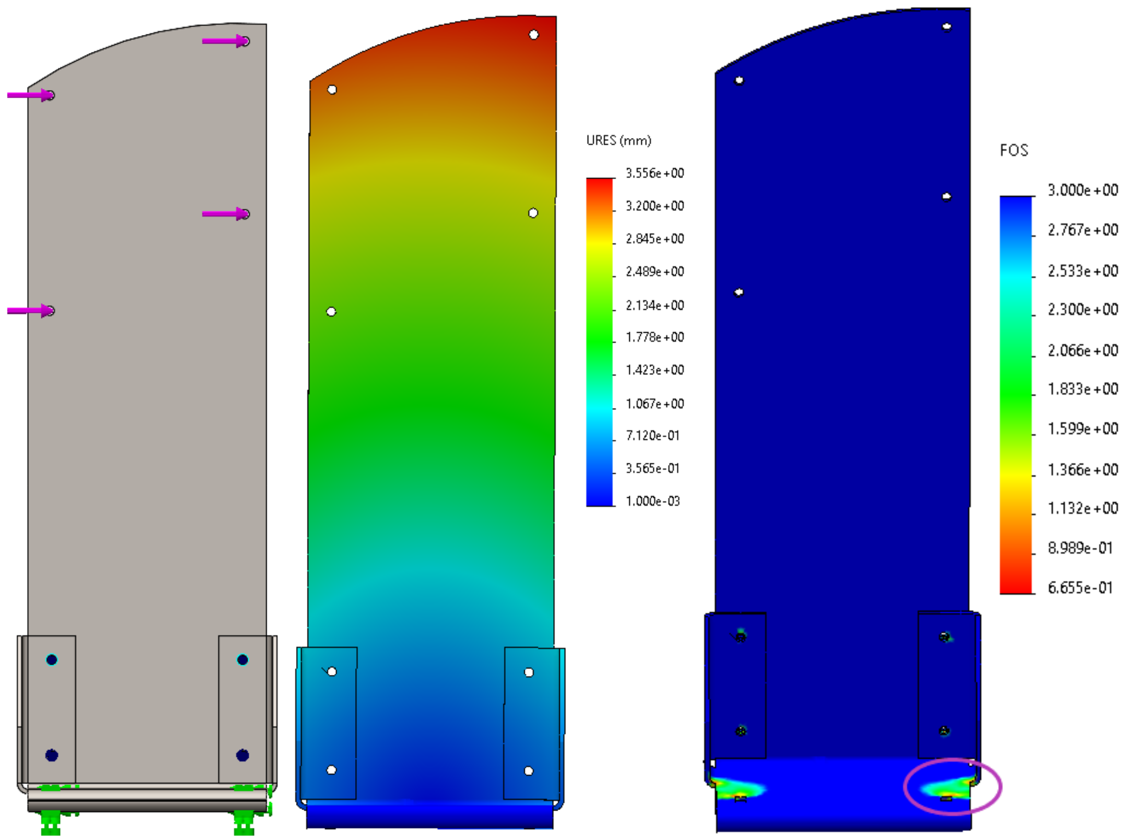

Figure 26. Bracket 9 fixtures and loads (left). Deflection (center), Factor of safety (right)

This bracket, despite being quite tall, maintains excellent strength.

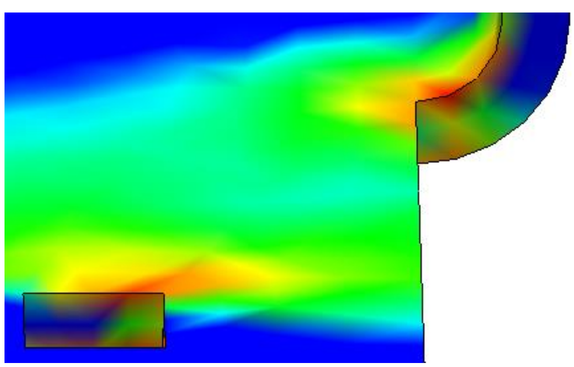

Figure 27. Bracket 9 detail, seen from below.

B.4 Mesh Convergence Plots

For each bracket, mesh convergence was performed to validate our results. The mesh convergence was performed with the goal of minimizing the error, specifically below 2%. The mesh convergence is performed up to 5 times, but only if the error is still above 2%. Therefore, any errors below 2% will show completely converged solutions for less than 5 iterations. The results of these mesh convergence studies are shown below.

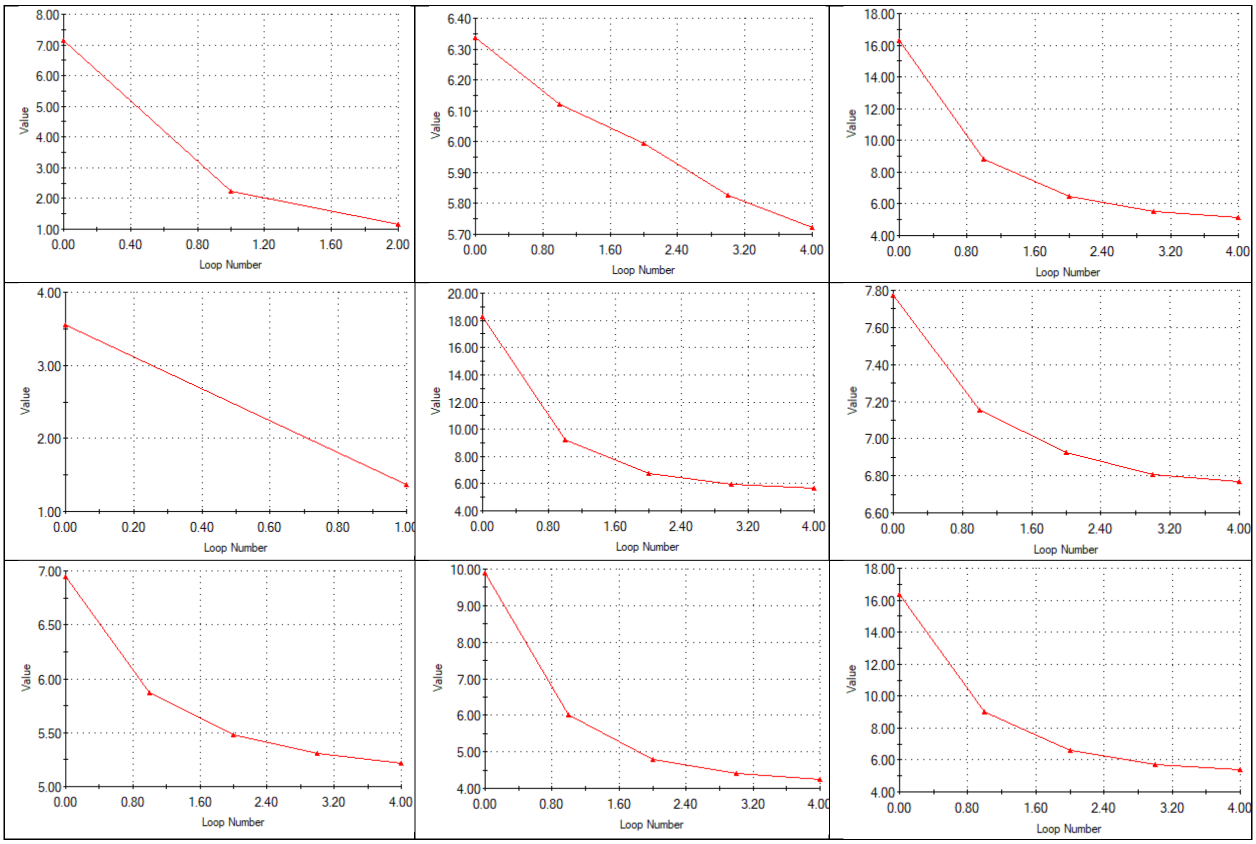

Figure 28. Mesh convergence plots for Brackets 1 and 3-9

From this figure, we can see that the plots converged after multiple iterations. Some plots, such as Brackets 1 and 5, had simple geometry that facilitated fast convergences, thus needing fewer loops to converge.