Henrik André Johannessen

Agile mechanical joint for oil pipeline inspection tool

Master's thesis in Industrial Design
Supervisor: Jon Herman Rismoen
June 2023

Master's thesis

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Abstract

This thesis utilized the design thinking process to create an improved mechanical joint, with specific design criteria determined by exploring ROSEN Norway and engagement with its employees. Through an iterative design process, various concepts were brought to life using 3D printing technology and underwent practical testing to glean insights for further iterations. This cycle continued until the “Triple Joint” design was realized. The design was further optimized using Generative Design to minimize weight, reduce internal stresses, and uphold safety limits. The study yielded three key findings: the mirrored motion in the “Twin joint” providing agility, stability, and control; the introduction of the “Triple rod” replicating this motion in an extra dimension; and the implementation of the pins, which helped eliminate the catastrophic flaw in such a design. The research process was primarily enabled by rapid 3D prototyping. However, the study acknowledges the lack of testing at a real-world scale as a limitation and recommends future testing of the joint, made from 3D-printed titanium, against the forces it is designed to endure and beyond. Additionally, designing joints for compatibility with diverse modules could improve the applicability of future work.

NTNU
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Master thesis for student Henrik André Johannessen

Agile joints for pipeline inspection devices
Smidige ledd for rørledningsinspeksjonsenheter

ROSEN Norway AS provides solutions for inspecting oil and gas pipelines for fracture or fatigue damage. One of their solutions consists of a device built up from individual modules with unique purposes. This device travels inside the pipeline and does the inspection from there. This solution uses an umbilical cord to supply the device whit power while also carrying data about the inspection back out of the pipeline. The umbilical cord also connects the modules making up the device. This approaches whit the umbilical cord limits the range of the device but whit the tradeoff of being able to maneuver back and forth within a pipe. Additionally, pipelines that terminate at unreachable locations necessitate a device that can exit from the same point it entered.

The Master thesis will center around the mechanical joint connecting the modules of the device. The main goal will be to reduce the radius of the turns the device can maneuver through the design of the mechanical joint. Generative Design will be used to ensure that the mechanical joint can withstand the necessary forces. Generative Design is a prosses where material is removed and added to an object based on a simulation of the forces acting on the object. Furthermore, the mechanical joint must withstand the forces it experiences in multiple scenarios, including moving the modules in both directions (push and pull) and around a turn. While accomplishing this, the mechanical joint must also protect the umbilical cord in the open space between the modules.

Expected approach

- Investigate the current implementation at ROSEN Norway AS
- Find the forces acting on the mechanical joint in different scenarios

Use an iterative process to approach the best design.

- Explore and find solutions that improve the device's turning radius by changing the mechanical joint's design while protecting the umbilical cord.
- Use the force scenarios and generative design to ensure that the strength of the mechanical joint can withstand the necessary forces, including pushing and pulling the modules.
- Test and learn from the conclusion of one iteration and use it to start a new iteration

Expected Result

Multiple 3D models from the different iterations and one final 3D model.
A report documenting the design decisions and showing the insight gained during the processes

The assignment is carried out according to the "Guidelines for master's theses in Industrial Design".

Main supervisor: Jon Herman Rismoen
Business contact: Anders Thomassen

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NTNU, Trondheim, (6. January 2023)

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Contents

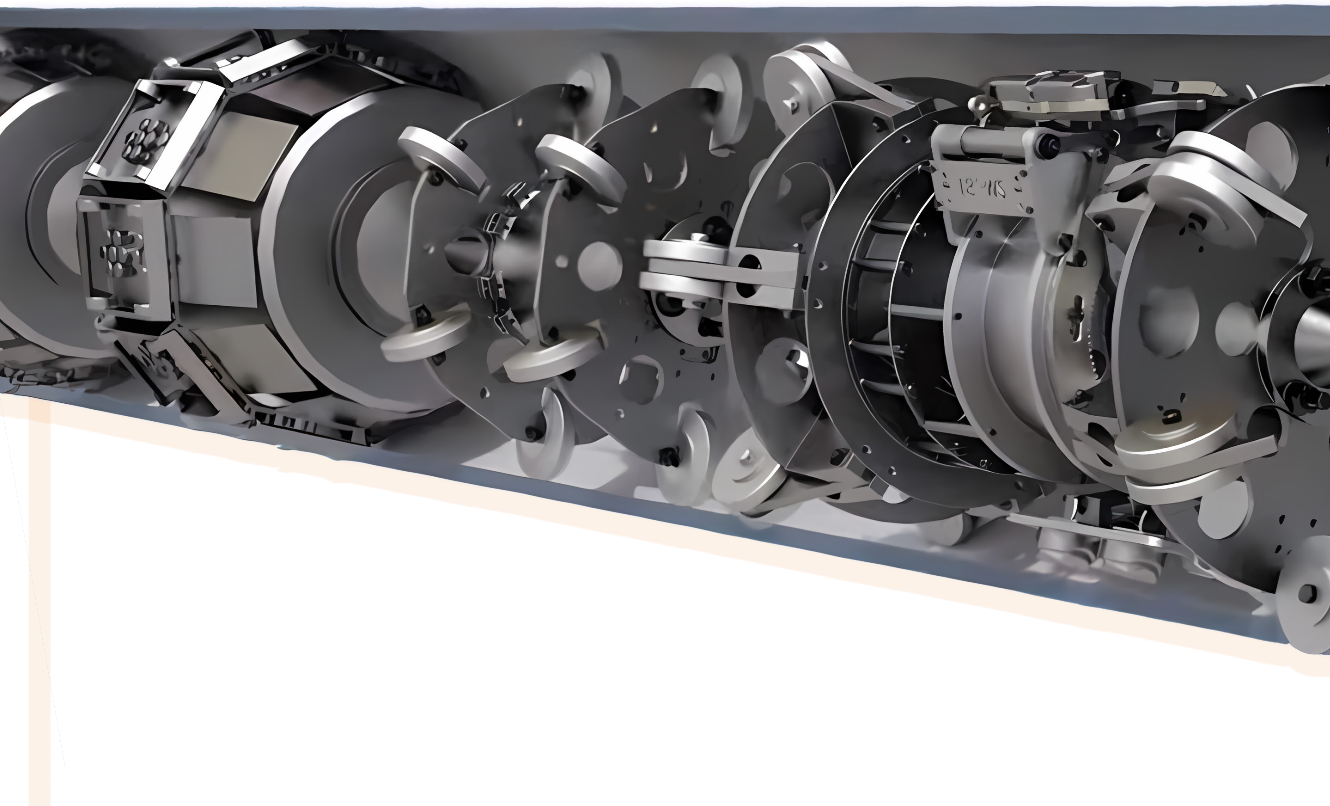
1.0 Introduction

ROSEN Norway, a specialized division of the ROSEN Group, excels in using a tethered and self-propelled tool to inspect oil pipelines for potential damage. Their service centers on providing detailed condition reports for their clients' pipelines. To gather the data for these reports, they employ a tool that crawls through the pipeline's interior, using ultrasound to assess the structural integrity of the pipes.

This tool is composed of interconnected modules joined together by mechanical joints. This structure provides the tool with the necessary flexibility to maneuver around the curves within an oil pipeline. This thesis aims to develop a new mechanical joint to replace the current joint used in ROSEN Norway's inspection tool.

"By leveraging Design Thinking, Rapid Prototyping, and Generative Design, this study aims to develop a new mechanical joint for ROSEN Norway's inspection tool. The anticipated outcome is an agile joint that will enhance the tool's reliability and safety."

2.0 Background



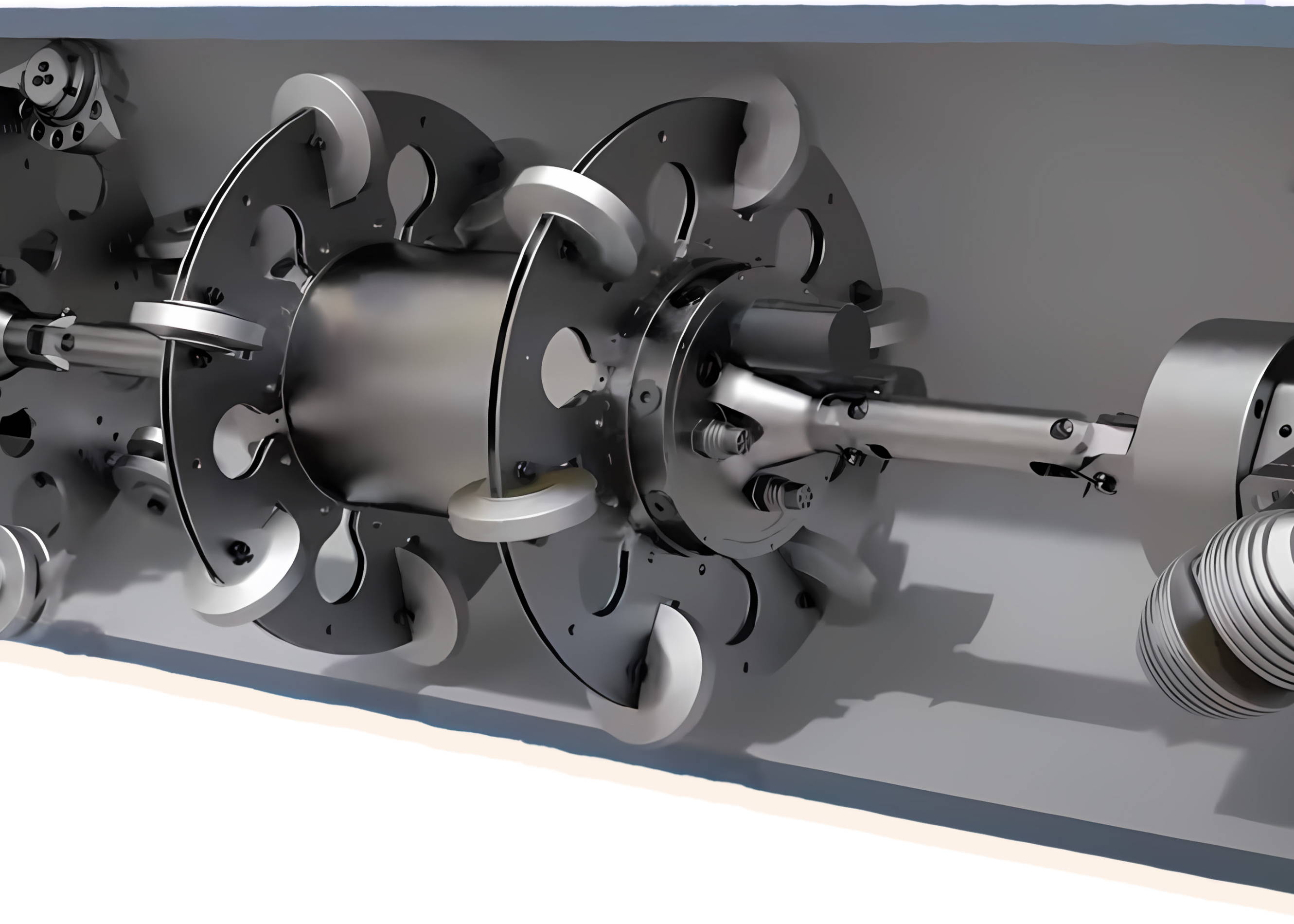
2.1 The Tool

ROSEN Norway's Inspection Tool is a modular design for inspecting oil pipelines. It is constructed of modules reminiscent of a locomotive comprised of train cars. Each module contributes a unique function making up the cohesive system that is the tool. Key components include an engine module for propulsion, an ultrasound sensor module for inspection data acquisition, and various other modules for data transmission and power distribution.

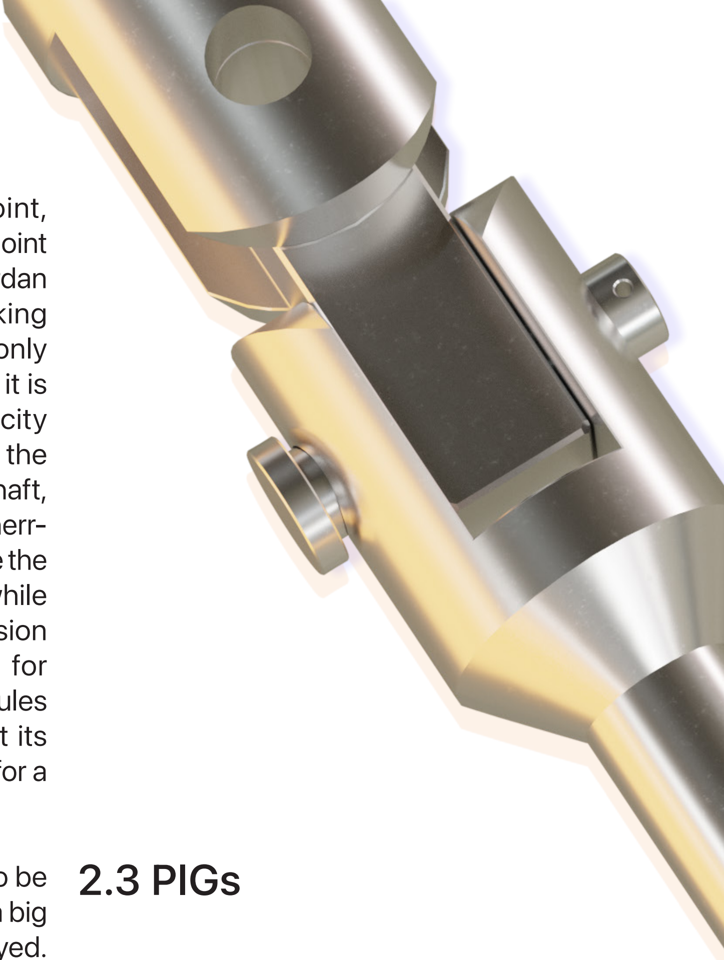
The modules can be reconfigured to optimize the tool functionality across different missions. However, the typical layout is as follows: the engine module leads, followed by the engine controller, which doubles as a buffer isolating the vibrations of the engine module from the sensor module.

The subsequent order from the sensor module is a module for receiving ultrasound emissions, a data relay module, and an electrical supply module. This final component distributes power from the umbilical cord to the other modules and relays data back up the umbilical cord to the surface.
It should be noted that the tool can be augmented with additional modules beyond those listed here, as necessitated by particular missions.

The tool enters into the pipeline either via a purpose-built inspection port or when such a port is unavailable, it necessitates partial disassembly of the pipeline to facilitate entry. In addition, inspections are usually scheduled to coincide with other maintenance activities, as the tool requires the production to cease while investigating the pipeline. As a result, the flow in the pipeline is suspended during the inspection, but they remain filled with oil throughout.



2.2 The Current Joint



This is the existing design for the joint, consisting of a rod mounted to a universal joint on either side. It appears to be a double Cardan joint with an extended center rod, making it a Double Cardan shaft. This is commonly used in drive shafts for vehicles because it is a constant velocity joint. Constant velocity joints ensure that the angular velocity of the output shaft is equal to that of the input shaft, regardless of the angle between them (Seherr-Toss, 2006). This is useful in vehicles where the shafts must transmit torque and power while accommodating changes in the suspension and steering geometry. This is helpful for ROSEN Norway's tool as it stops the modules from rotating relative to one another, but its coincidental benefit, the joint is optimized for a different scenario.

Other already-developed joints could also be used for the tool, but since weight is such a big concern, Generative Design will be deployed. The shapes of the joints will not be preserved. Therefore, the benefits in maintenance and reduced cost from using of-the-self parts will not be realized even with an existing design. Creating a custom design tailored to the needs of the tool is just as expansive or cheap in terms of production and upkeep. Development and design are different concerns.

2.3 PIGs

Conventional Pipeline Inspection Gauges (PIGs) are tools that float through the pipeline, propelled by the flow of the transported material (SLB, 2015). One common issue hindering this approach can be a pipeline layout that necessitates a one-way journey to the sea floor. Another frequent obstacle arose when pipelines were not initially designed with inspection in mind. ROSEN Norway's tool overcomes these problems as it can use the tether or 'umbilical cord' and on-bord propulsion to retrace its path and exit at the point of entry.

2.4 Degrees of Freedom

Degrees of freedom (DOF), Concerning mechanical joints, indicate how many ways a joint can move or be moved (Sheldon, 2022). For example, a hinge joint has one DOF, as it can only rotate around one axis. On the other hand, a ball-and-socket joint has three DOF, as it can rotate around three axes. Therefore, an independent object has at most 3 degrees of freedom in rotation and 3 in translation, giving it 6 degrees of freedom. Using a ship as the independent object, the degrees of freedom are described by (Sheldon, 2022) as:

Translation and rotation in nautical terms:

Surge: Move forward and backward, along the x-axis.
Sway: Move left and right, along the y-axis.
Heave: Move up and down, along the z-axis.

Roll: Rotate around x-axis, pivoting side to side.
Pitch: Rotate around y-axis, tilting forward and backward.
Yaw: Rotate around z-axis, swiveling left and right.

2.5 Weight & The Capstone Equation.

Weight is a considerable concern because of the Capstan equation. Often employed in marine environments, a capstan winds a rope around itself, enabling a smaller force to hold a larger one (Attaway, 1999). This principle becomes significant when considering the umbilical cord as the tool traverses a pipeline. The umbilical cord is tensioned on the twists and turns of the pipeline. Each bend effectively acts as a capstan around which the umbilical cord is partially wound. Despite turns of opposite direction, a left turn followed by a right turn, both turn increases the practical windings around a Capstan.

The Capstan equation, as described by (Attaway, 1999), represented as *T_load = T_hold * e^(uø)*, provides insight into this phenomenon. Here, *T_hold* symbolizes the combined effects of the tool's weight and friction. The variable *u* denotes the frictional coefficient between the pipeline and the umbilical cord, while *ø* stands for the number of turns around the capstan. *T_load*, conversely, signifies the maximum force that can be applied to the rope before it begins to slip. Consequently, the pulling force from the winch, tasked with extracting the tool from the pipeline, must surpass *T_load* for the tool to move.

For example, consider an instance where *e^(uø)* equals 286, derived when the friction coefficient is 0.3, and there are three windings around the capstan. After increasing the windings to four, *e^(uø)* escalates to 1881. As this product can surge rapidly and is multiplied with *T_hold*, the system displays extreme sensitivity toward the tool's weight. The Capstan equation describes the drastic amplification of the tool's weight from the viewpoint of the external winch/engine. Therefore, a seemingly negligible addition to the tool's weight, a 500g joint, results in the winch contending with an additional 143kg load in this example.

It is, therefore, necessary to minimize the weight of the joint, which consequently increases the tool's safety and capability. Safety is paramount; a lighter tool is simpler to extract from the pipeline, enhancing operational safety. Regarding capability, a lighter tool could navigate further into the pipeline while maintaining the same level of risk as the current deployment. Even though it takes several bends in a pipeline to count as a complete rotation around a capstan, the number of windings remains the principal constraint dictating how far the tool can reach, even more so than the length of the umbilical cord.

Number of turns	Coefficient of friction u				
	0.1	0.2	0.3	0.4	0.5
1	1.9	3.5	6.6	12	23
2	3.5	12	43	535	535
3	6.6	43	286	12 392	12 392
4	12	152	1 881	286 751	3 540 026
5	23	535	12 392	6 635 624	153 552 935

Table shows different values for the factor e^(uø)
Source: (Capstan equation, 2023)

2.6 Nominal Pipe Size

Nominal Pipe Size (NPS) is a standardized system used in North America for sizing and identifying pipes used to transport fluids (Wermac, 2023). It is important to note that NPS is not a direct measurement of the actual pipe but rather an approximation that helps standardize pipe sizes. The actual outside diameter of the pipe is found by consulting a reference table corresponding to the NPS values.

The NPS system's wall thickness is described by the schedule number (SCH), which increases with the thickness of the pipe wall (HardHat Engineer, 2023). However, the outside diameter stays the same, so a thicker wall means a smaller inside diameter. Sch80s and SchXS are used for the pipes the tool travels through.

Long Radius return bends have a centerline radius of 1.5 times the outside diameter (Wermac, 2023). This represents the tightest bend the tool must travel through.

3.0 Method

3.1 Preliminary Research

Given the inherent mechanical intricacies of developing a new joint, the adopted approach prioritized empirical testing and iterative design over extensive theoretical research. The methodology was based on the five stages of the Design Thinking and iterative prototyping facilitated by 3D printing technology. A generative design algorithm was later employed to refine the final joint design, ensuring a balance of strength and weight.

A short initial period was allocated for desk research to facilitate a deeper understanding of the subject matter before fieldwork at the facilities. This strategy was designed to lay a solid foundation of knowledge, consequently enriching the investigation and maximizing the potential to gain valuable insights.

3.2 Site Visits and Problem Identification

Site visits to the company's facilities were conducted, enabling a closer examination of the challenges inherent in the existing joint and identifying potential improvements. The information was obtained through informal interviews, observations, and guided tours. These visits were crucial in establishing the design criteria for the new mechanical joint.

3.3 Concept Generation, Iterative Design and Rapid Prototyping

The design process was initiated with a brief sketching phase, during which multiple distinct joint concepts were generated. This approach served to expand the breadth of the subsequent experimentation.

The primary design phase followed an iterative process: models were created in 3D, printed, tested, and evaluated, with each cycle informing the next set of designs. This iterative process was repeated until a design that met the established criteria was achieved. Three iterations were planned within the project's time constraints, and three and a half were executed.

Rapid prototyping was essential, as it enabled testing a large quantity of ideas, not just the good quality ones. These experiments and the insight obtained from them facilitate the ingenuity in the prosses. The number of ideas that could be tested within one iteration was increased by creating a large batch of designs so that the components from multiple designs could share 3D printers.

Through this iterative approach, the functionality and concept of the joint were determined. The dimensions were applied after to ensure that the finer details did not eclipse the larger design objective. This dimensioning was conducted before the generative design and calculated the restrictions the algorithm must work within

3.4 Generative Design

Generative design is a simulation-based approach to creating parts with optimized strength-to-weight ratios. The process involves using simulations to analyze stress distribution in the parts, adding material where stresses are high, and removing material where stresses are low. Generative design algorithms differ from topological optimization methods in that they can generate a whole part without needing existing geometry to modify.

The models from the iterative prosses need to be recreated to be compatible whit the generative design setup. The models were analyzed to evaluate what features were necessary and which could be altered by the algorithm. The model's primary purpose is no longer to describe where material is; it is more important to declare where material should not be. It is like the models from the iterative proses are used to create a mold, which generative design can fill as it pleases.

As Generative Design changes the shape of the design, the task of ensuring the joints assembly procedure was conducted last. The concept for the assembly was already worked out, but the specific dimensions needed to wait for the generative design output.

3.5 Methodology

The design process described here is inspired by the five stages of the Design Thinking process. The stages are Empathize, Define, Ideate, Prototype, and Test (Lozano, 2022). This is an iterative process, so it is common to circle back on earlier stages. It is also non-linear, which means what points are circled back on can change in each iteration, and the order of operation is malleable as well. The process has a reputation for adapting to situations and problems not instantly apparent with our initial level of understanding. Thus, seem fitting for a task that seemed so simple at first viewing.

The five stages of the Design Thinking process are as follows:

1. Empathize: The goal here is to gain an empathetic understanding of the problem at hand. This typically involves interviews, observations, and immersive experiences to understand the users' perspectives and challenges. Empathy allows the designer to set aside assumptions and gain insights into users and their needs. The site visits to the company aimed to acquire this understanding, mainly through an immersive experience, trying to absorb as much of the ordinary as possible, as one is usually only told about the extraordinary.

2. Define: In the Define stage, the information gathered during the Empathize stage is analyzed to define and identify the core problems, creating a list of design criteria. An important thing to note is that this list can be changed as the process progresses, and more is understood about the design and the problems they are trying to solve.

3. Ideate: During the Ideate stage, designers are ready to generate ideas. The goal is to develop as many solution ideas as possible, using free thinking and postponing judgment to create a wide array of ideas from which to select. Therefore, it is essential to avoid being held back by assumptions at this stage.

4. Prototype: This stage involves producing a small-scale, low-cost, simplified product version, like a 3D-printed model. This is to investigate the potential solutions from the previous stage and their feasibility. The two factors getting the most attention under the looking glass in this stage were the assembly of the joint and how it moved. The prototypes are investigated and either improved, used for inspiration in the next iteration, or rejected based on these findings.

5. Testing: The testing stage was mainly consumed with simulations to ensure the designs complied with the design criteria. The motion range of the joints was measured digitally in this stage, and the calculations were verified to align with reality in the previous stage since the stages do not need to be in sequence.

4.0 Results

4.1 Finding the Purpose of the new mechanical joint.

During the visit to ROSEN Norway, it quickly became evident that their primary concern was reliability. The oil industry is a significant economic sector, and any downtime in pipeline operations can result in significant opportunity costs. As a result, inspections are conducted concurrently with other maintenance tasks. The primary concern for the owners of pipelines, ROSENS's clients, is to have as little downtime as possible. This then naturally becomes ROSEN's biggest worry too. If the inspection tool gets stuck in a pipeline, it can extend the period of downtime beyond the schedule, something very costly for the clients. This is why clients fear having inspections done on their pipelines, but they are demanded by law. Therefore, such services' most significant selling point is a high success rate.

The mechanical joint helps with this reliability through its strength. The joint must withstand the force applied in a power loss scenario. The inspection tool is connected to an external winch via an umbilical cord, which allows for retrieval in case of power loss or motor failure. In such situations, the mechanical joint must withstand the same forces as the umbilical cord when the tool is forcefully removed from the pipeline to prevent leaving any modules behind. The umbilical cord can withstand 2 tons. The standard operating limit is 25% below that (1.5 tons), making the safety factor 1.3333 (4/3). The usual way for the tool to exit is to reverse while the umbilical cord is being retracted, but if the motor on the tool cannot assist, it must be forcefully pulled out.

The inspection tool is shipped worldwide to assess pipelines in various countries. When transported, the tool is securely fastened within a pipeline segment, with its upper half removed, and then mounted onto a linearly arranged series of standard shipping pallets. The modules are arrayed in a sequence determined by the specific mission requirements, with auxiliary equipment separately transported in designated crates. Upon reaching the inspection site, modules fetched directly from other missions can be assimilated into the tool if needed.

A distinguishing characteristic of the Norwegian company branch is that it is only assigned missions requiring unconventional approaches. The tool is, therefore, modular to achieve the necessary flexibility and adaptability. The tool's modularity allows for easy rearrangement or replacement of modules according to the mission requirements. Occasionally, individual modules, particularly the motor module, are sent separately to be combined with another tool in the field after completing a mission. This necessitates a mechanical joint that can be quickly and efficiently detached from the modules, even in remote locations.

Furthermore, the assembly process must be user-friendly for the mechanics, minimizing the risk of losing small components or dealing with hard-to-reach areas. Ensuring the joint mechanism's ease of assembly can streamline the inspection process, increasing efficiency and avoiding delays. Important when the work has to be carried out in tandem whit other maintenance.

Regarding the assembly process, it is important to consider the electric wires and data cables that connect the tool's modules. At present, these cables "hang" between the modules. However, an improved joint design should protect these cables without increasing assembly time.

There are also some specific requirements for the capabilities of the joint: It must allow the tool to navigate a turn with a radius 1.5 times the other diameter of the pipe. It must also be mountable on a module suitable for 12-inch pipes. These modules are 161mm in diameter; the part of the joint interfacing whit the module must therefore fit inside this diameter.

ROSEN Norway's team also expressed some more abstract wishes. One was for a joint that would remain stable during reverse operations, enabling the equipment to target specific pipeline segments for detailed scans accurately. The more reliable motion would make it easier to aim at one part of a pipe where damage is suspected. The other was that the joint should center the modules in the pipe, helping to avoid obstacles and hazards. One example is T-junctions in the pipeline, where two pipes meet perpendicularly. The risk is that a module can fall into the other pipe and get stuck.

Design specifications

1. Reliability: The mechanical joint must be highly reliable to minimize downtime and increase the success rate of missions.

2. Strength: The joint must withstand forces equivalent to the umbilical cord during a power loss scenario (1.5 tons with a safety factor of 1.3333).

3. Light Weight: The joint must be as light as possible while fulfilling the presiding criteria, ensuring the new joint does not limit the tool's capabilities.

4. User-friendly assembly: The assembly process must minimize the risk of losing small components and the potential of dealing with hard-to-reach areas.

5. Mobility: The joint must enable the tool to navigate turns with a radius of 1.5 times the outer diameter of the pipe.

6. Stability during reverse operations: The joint must remain stable during reverse operations, so the tool can accurately target specific pipeline segments for detailed scans.

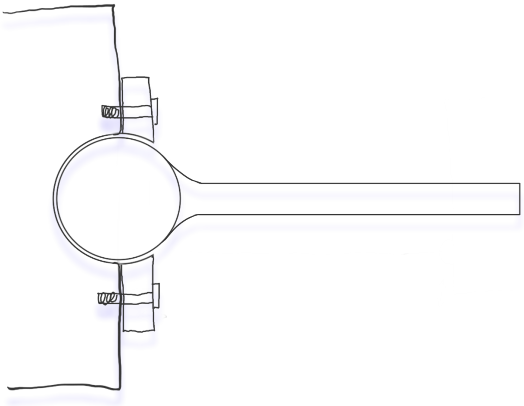
7. Optimal Positioning: The joint must help center the modules in the pipeline, reducing the risk of instances where a module comes into contact with a hazard.

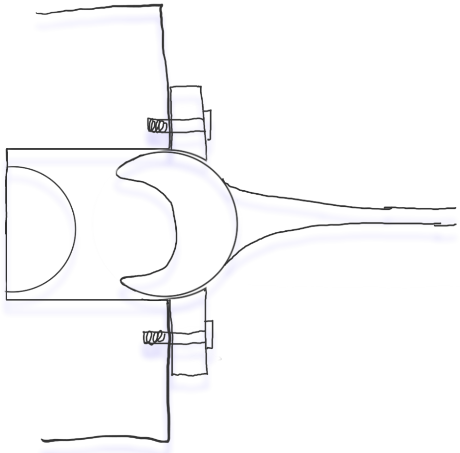
8. Protection of Cables: The joint design must protect electric and data cables without increasing assembly time.

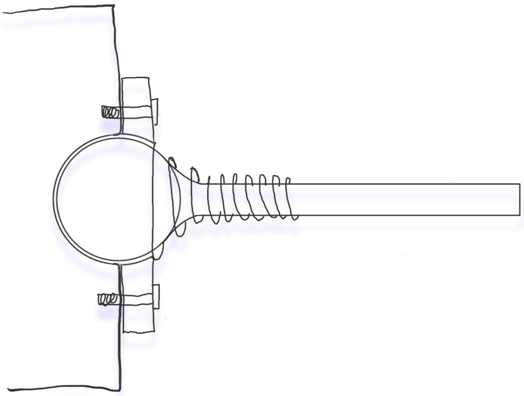
9. Compatibility: The joint must be mountable on a module type, suitable for 12-inch pipes. The diameter must be below 161mm at the extremities of the Joint.

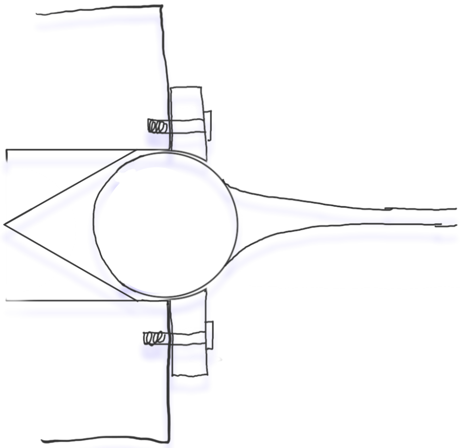
4.2 Sketches

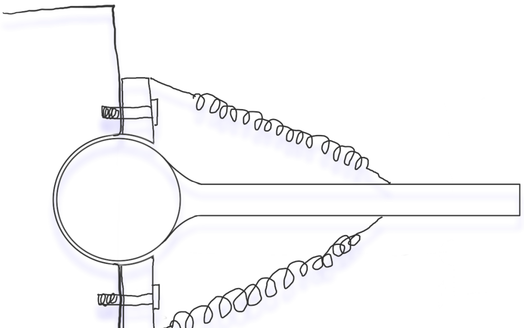
These sketches are made to explore the breadth of possible solutions, so the expectations of what a joint should be are held back. Some designs also get minor variations digging deeper into what they offer, but a diverse selection is more important to achieve in this step.

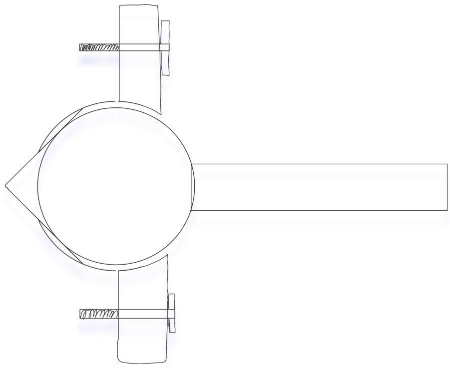


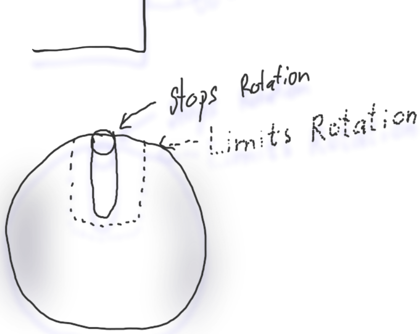








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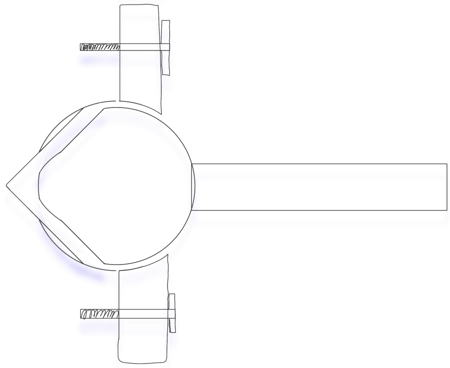

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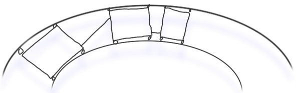

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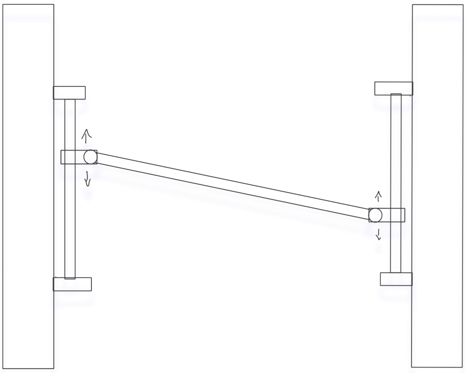

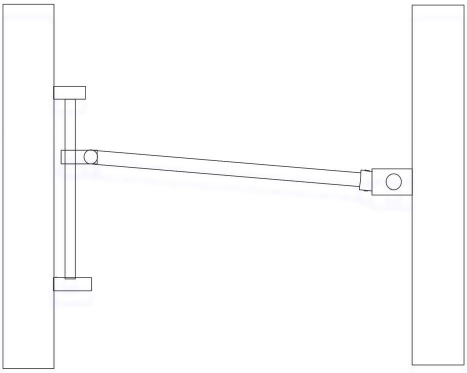

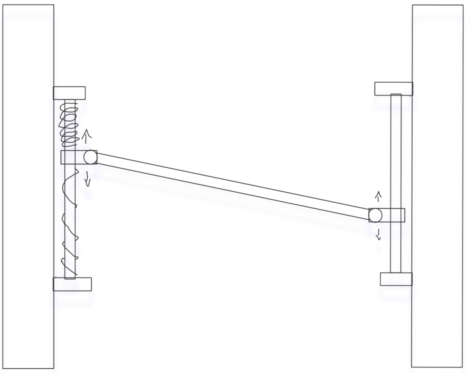

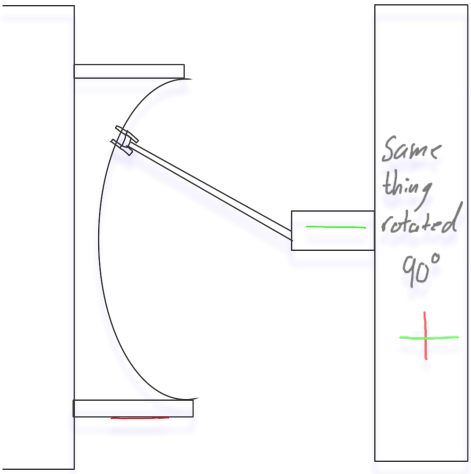

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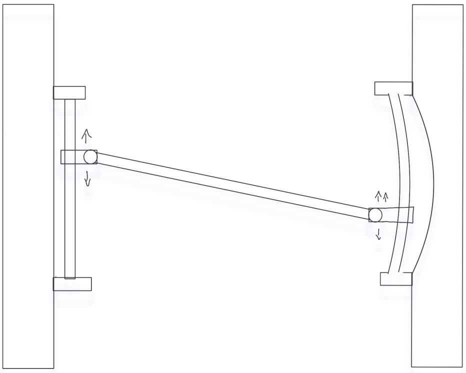

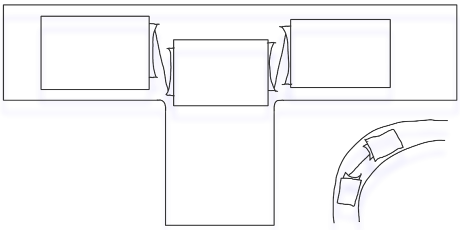

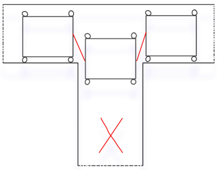

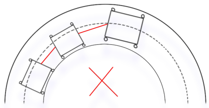

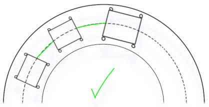

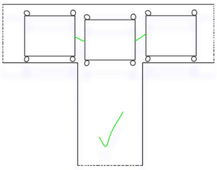

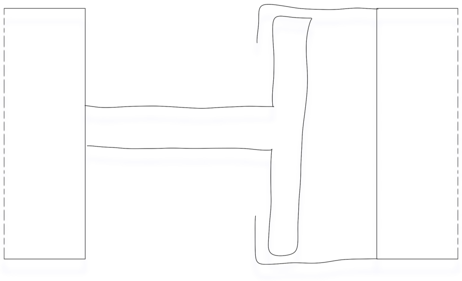

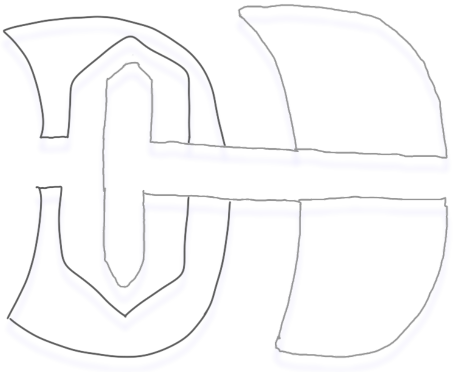

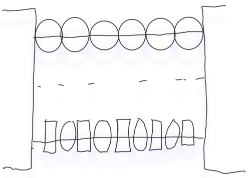

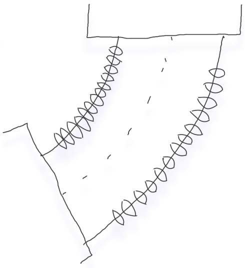

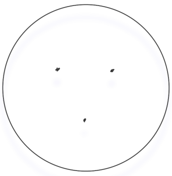

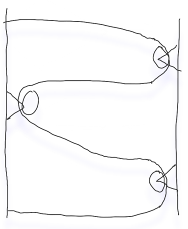

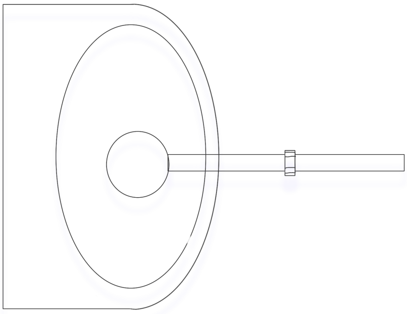

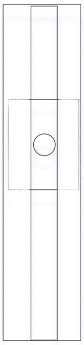

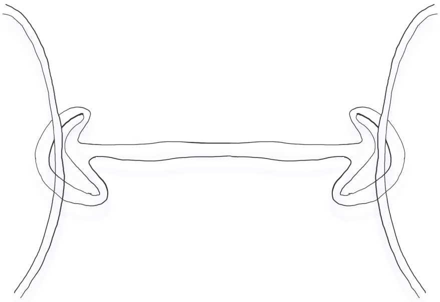

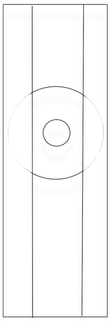

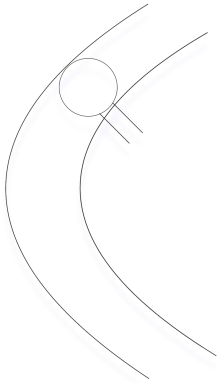

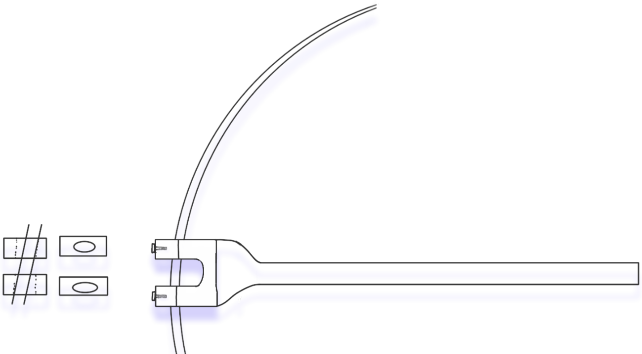

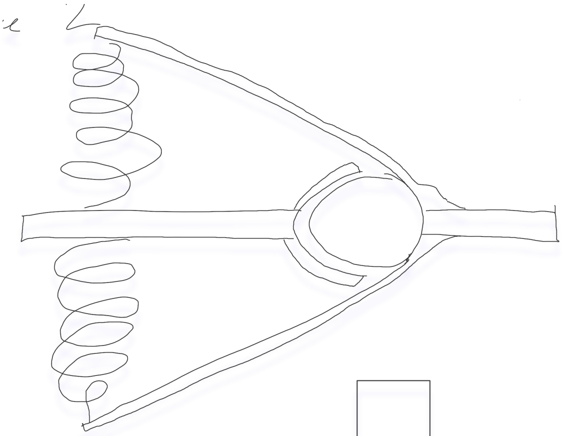

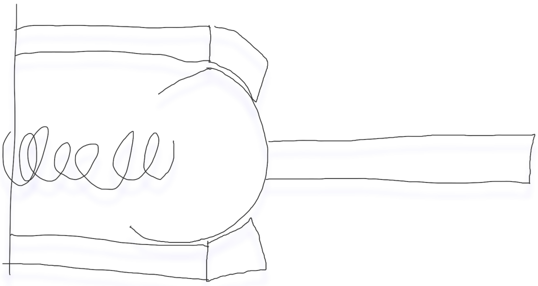

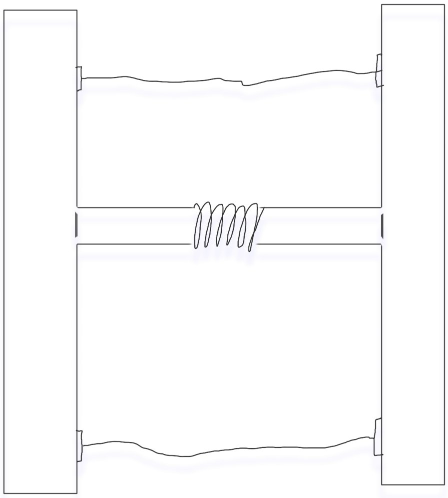

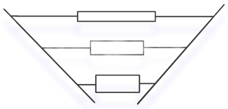

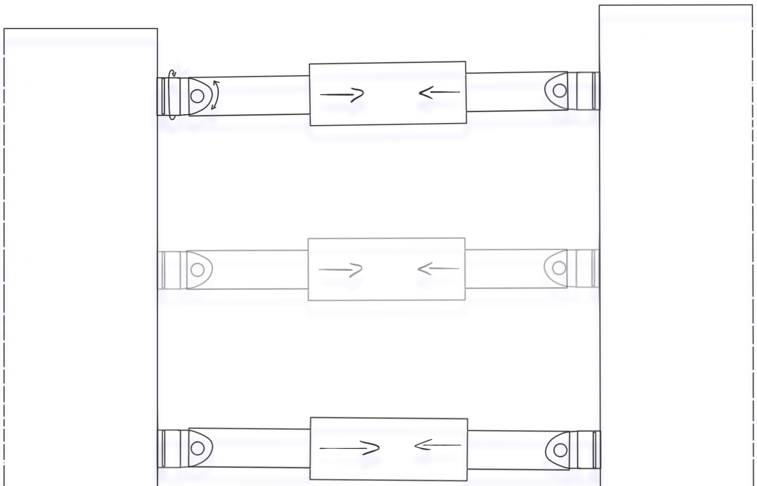

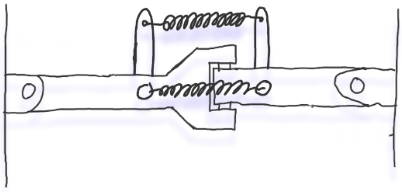

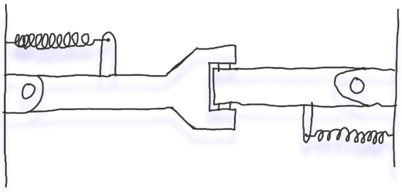

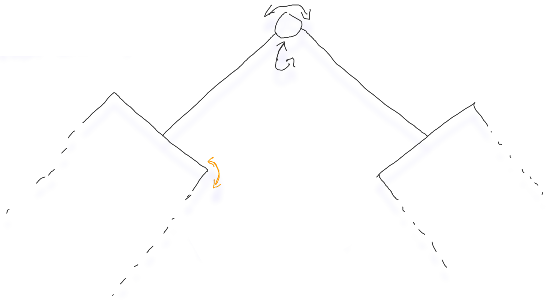

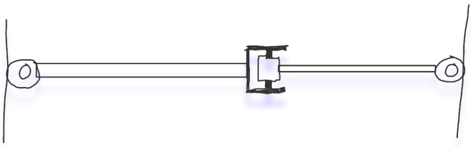

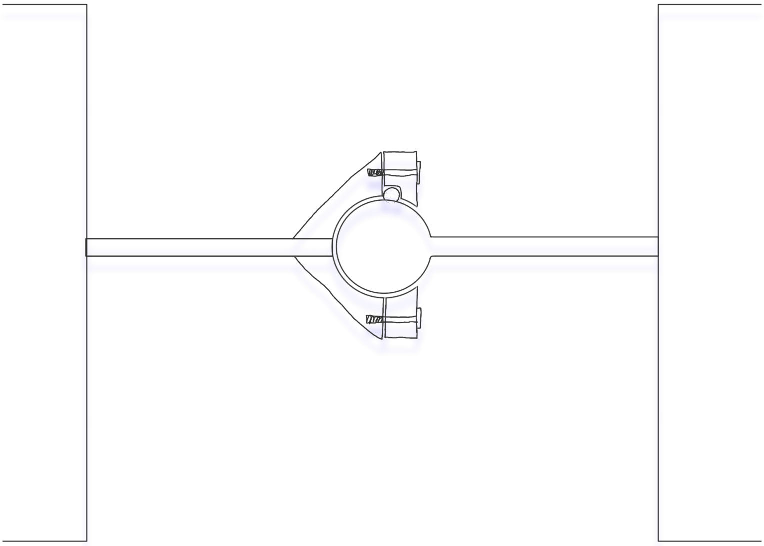

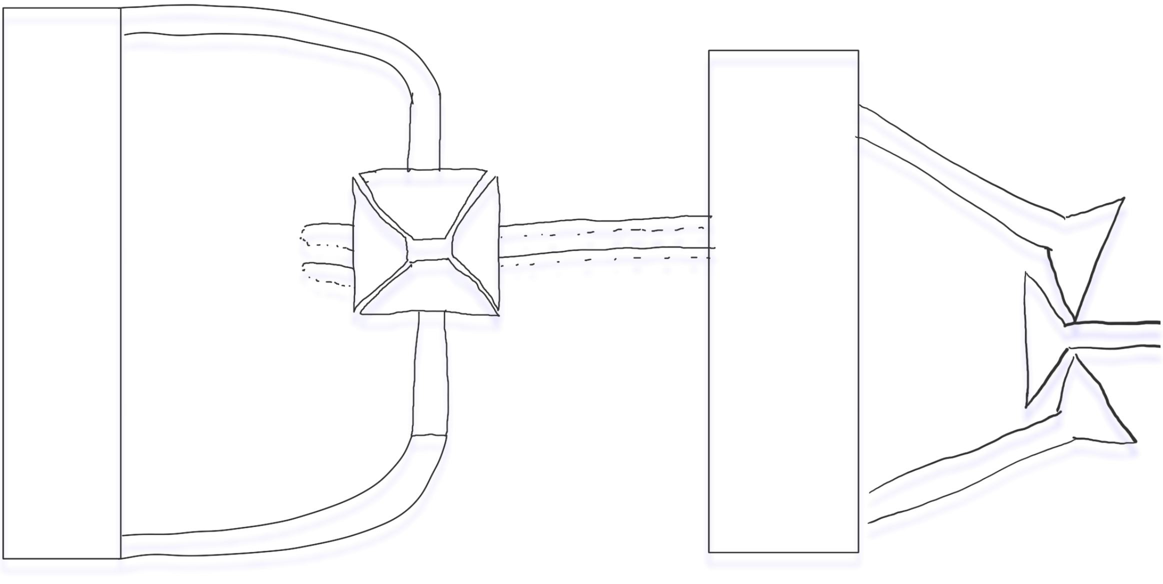

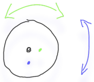

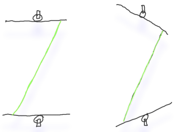

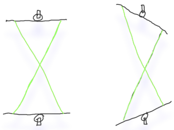

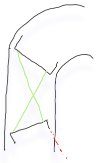

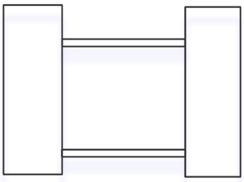

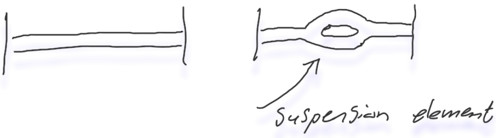
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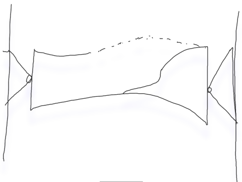

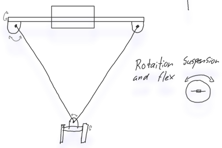
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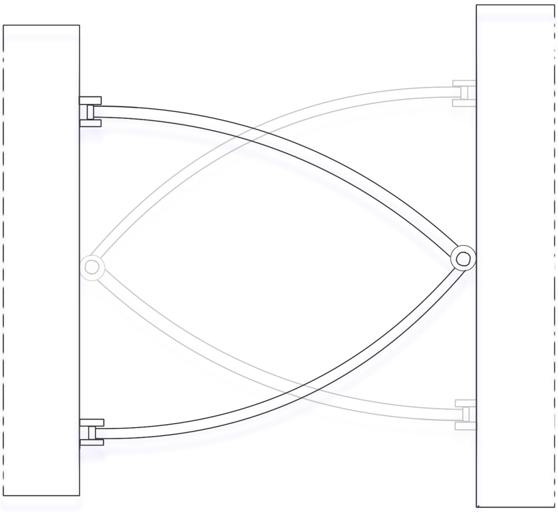
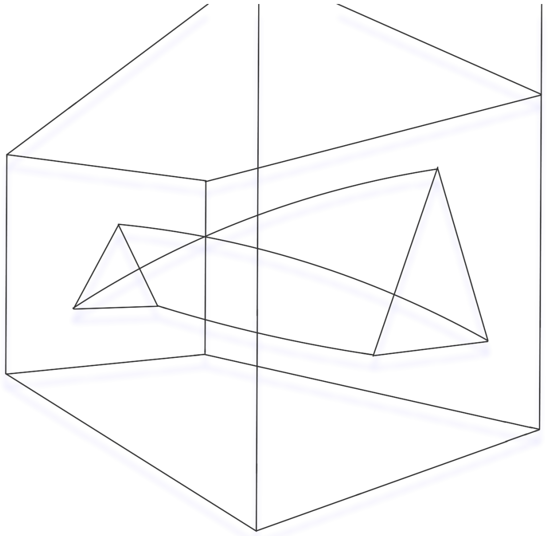
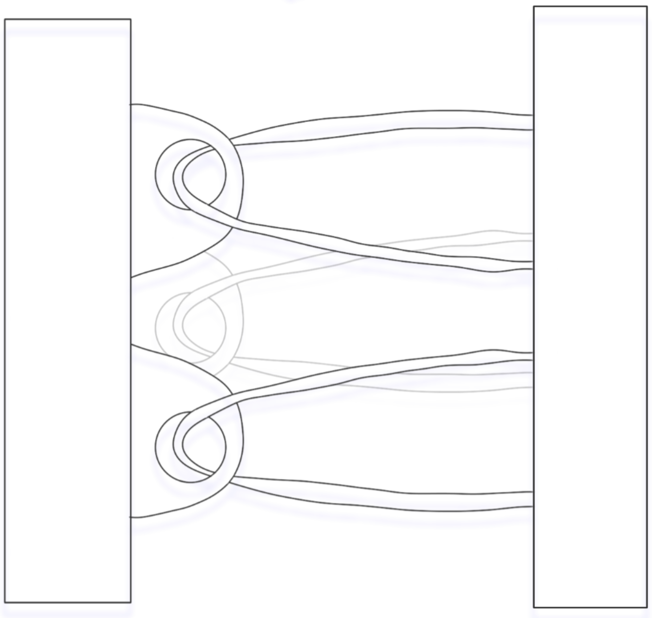
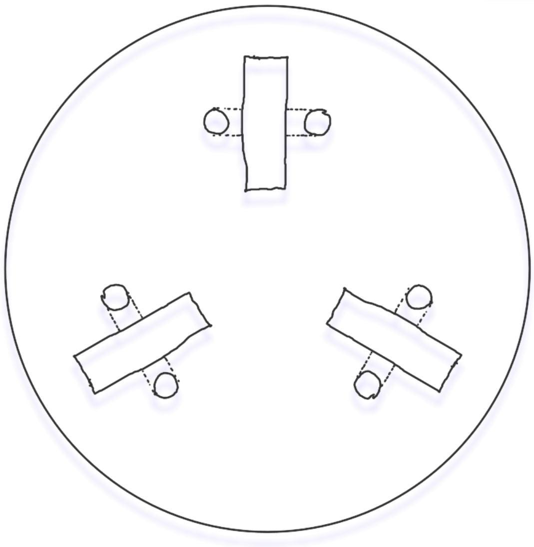








4.3 Design Iterations: 1st Batch

In this phase, the designs were 3d-modeled and printed in batches, meaning that all designs were simultaneously developed. Rather than sequentially finishing one design before moving on to the next, work was conducted circling between each joint, gradually completing them. This approach aimed to expedite the 3D-printing process. However, it also meant that testing one design could not contribute beneficial insights to the other designs within the same batch. These refinements could only be applied in the subsequent batch.

3D-printing

Various components from different designs were printed on the same build plate. These parts were not grouped based on their respective designs but on the necessary settings for their printing requirements. Although this strategy was initially implemented to accelerate the 3D printing procedure, it inadvertently resulted in a slower process. If a single part failed to print correctly, it caused collateral damage to the other parts sharing the same plate. Stopping not one but several designs from being completed. Components were segmented in the subsequent batches to circumvent this issue, isolating failures and preventing them from cascading. As a result, instead of having several designs per build plate, the new approach necessitated several build plates per design.

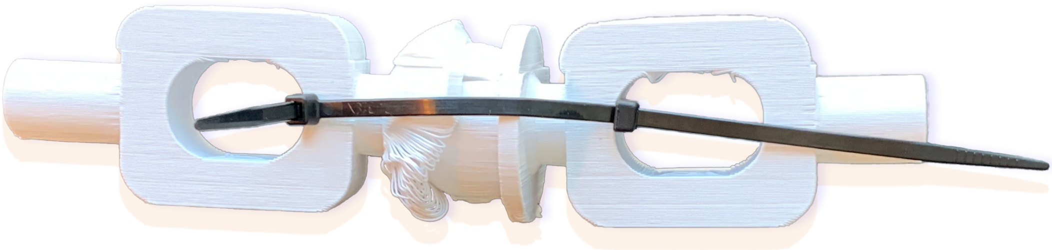
Ball joint

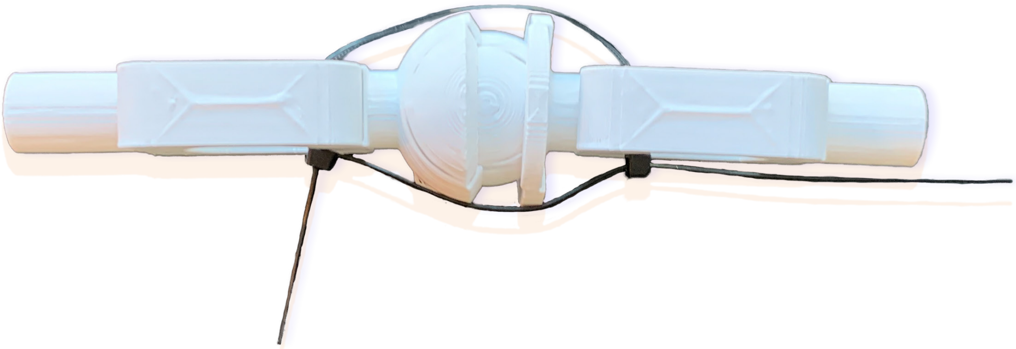
The ball joint concept is simple, allowing for free movement with three degrees of freedom. The main challenge in the design process was to devise a method to facilitate easy disassembly and reassembly of the joint. The angle of pitch and yaw can be limited by the ring holding the ball. The disadvantage of this joint lies in the third degree of freedom, roll, which permits relative rotation between the modules. This allowance for roll could cause wires to break or cause entanglements. Therefore, future designs need to incorporate a mechanism to limit this rotation.

Centered ball joint

The centered ball joint places the connection point in the center between two connected modules. The goal is for the joint to better align with the pipe's centerline, theoretically causing the modules to be pulled less toward the pipe walls than if the rotation center were at the modules.

The experiment with this design tested whether a steel wire could simplify the joint's assembly by holding it together. A zip tie was used with the 3D print for testing. While the zip tie effectively handled rotation in yaw, it slipped when pitching. Thus, more guides would be necessary to secure the steel wire (zip tie).

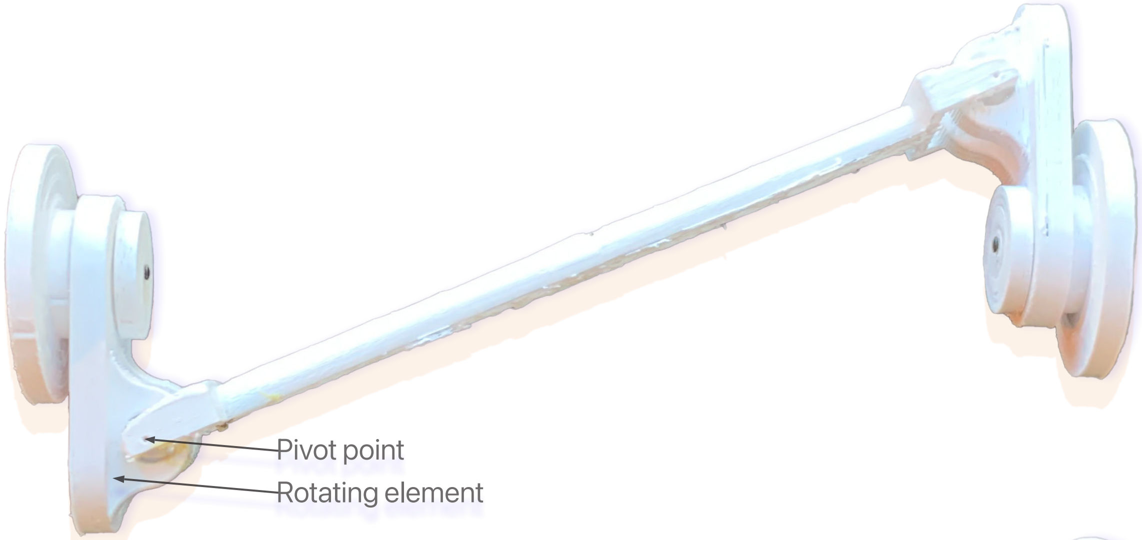


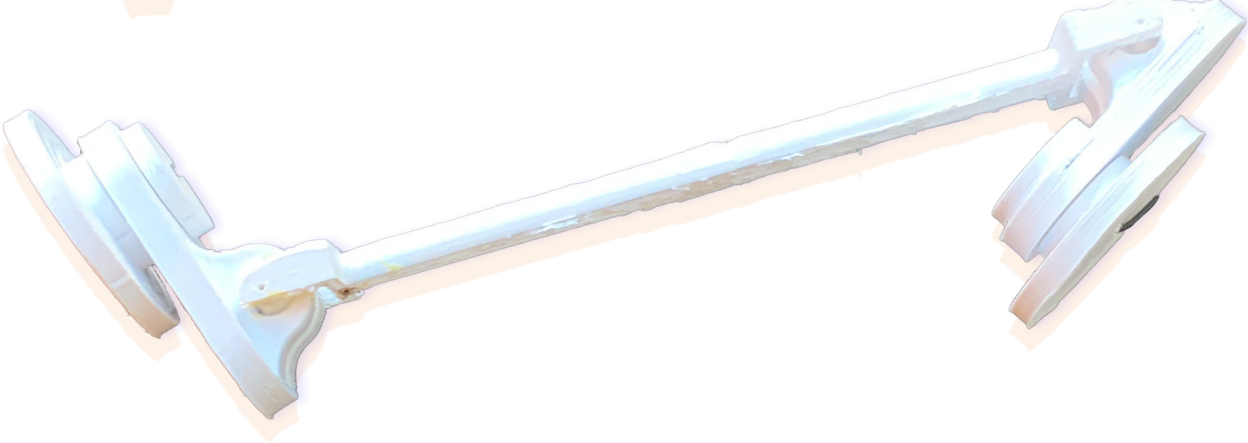


The Z joint.

Named after the joint's shape resembling the letter 'Z,' the Z joint employed rotation and pivot to create a connecting rod that crosses the centerline from one side to the other. The goal was to lift the following module off the inner wall of the pipe corner. However, in practice, if the pivot was too straight, the rotating element failed to turn, making lean turns harder than sharp ones. This design was unsuccessful, with no immediate solution short of a different design. Therefore, this concept will be discarded moving forward.

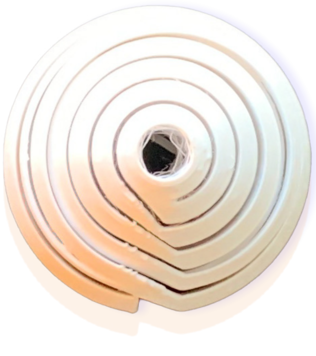
The set of images shows when the rotation element is free to move (left) and when it stops working (right)





The Spring

The spring emerged as a surprisingly effective candidate for the joint. It limits roll while enabling pitch and yaw and also self-recenters. Additionally, the spring bends evenly, offering a smoother path for cables. An intriguing aspect of this spring design is that it restricts pitch and yaw movement when compressed and allows more when extended. This feature provides greater precision when reversing the machine to a specific point of interest on the pipe.

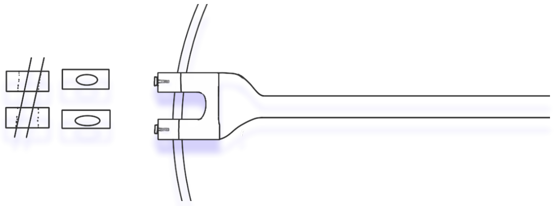


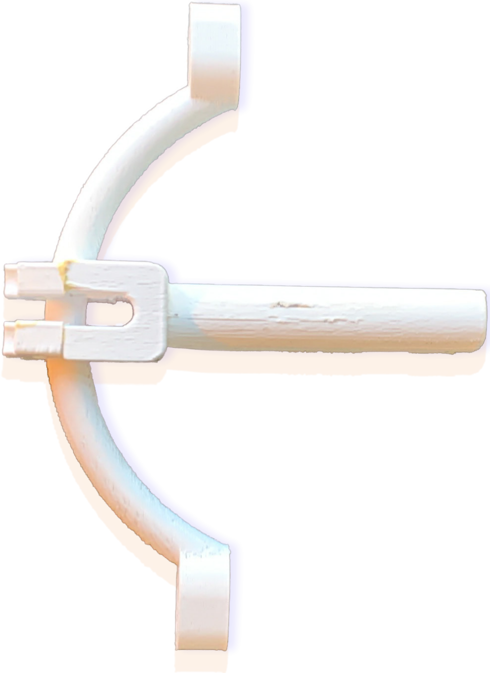
The Arc Joint.

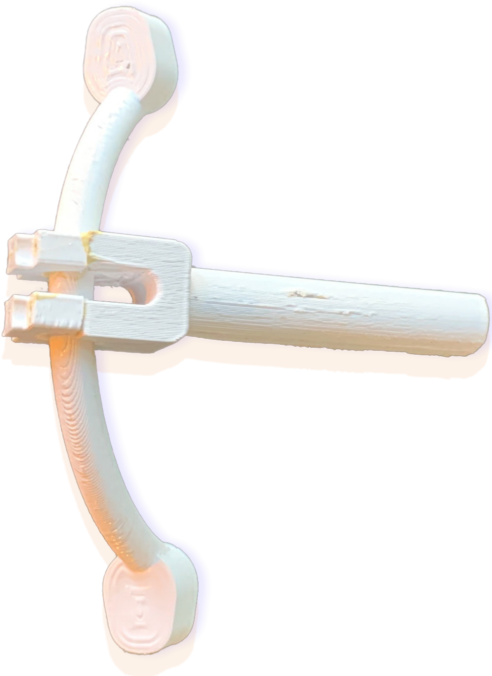
The Arc joint aims to replace rotation around a cylinder with translation along a rail while essentially moving the connecting module similarly. The goal was to guide the emulated rotation of the joint with careful shaping of the rail. Another part of the design aimed to limit how far away the module could fall from the machine when crossing a T-junction in the pipe.

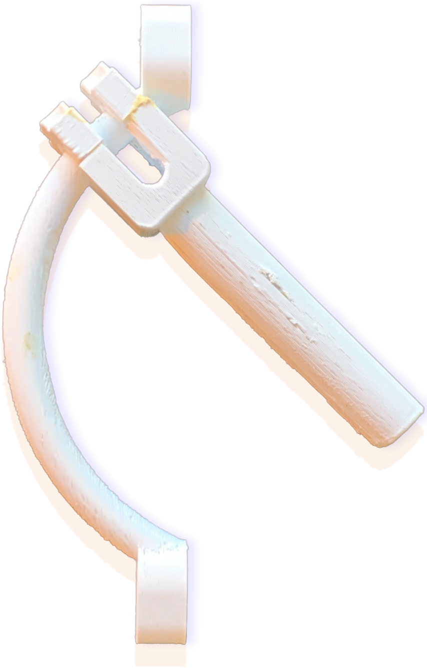
The problem was that the oval holes that held the connecting rod on the rail did not allow for yaw rotation. The oval shape could only handle the changing cross-section of the rail when sliding along it, not rotating around it.

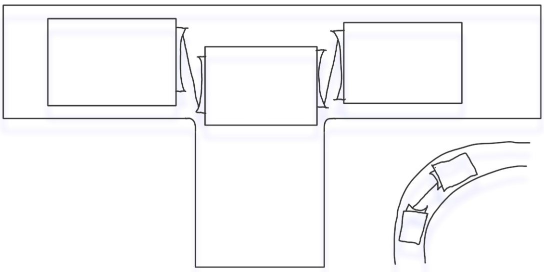
Additionally, the rail occupied a significant amount of space, and the connecting rod needed even more space to pitch and yaw. This would make it challenging to fit electronics and wires between the modules. While this joint could be made to work, the fundamental space and cable management concerns make it an unlikely candidate.









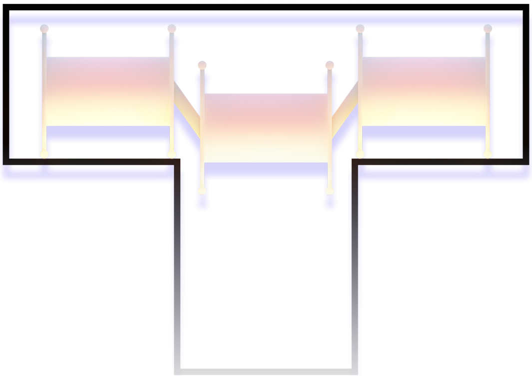


Tripel Rod Joint

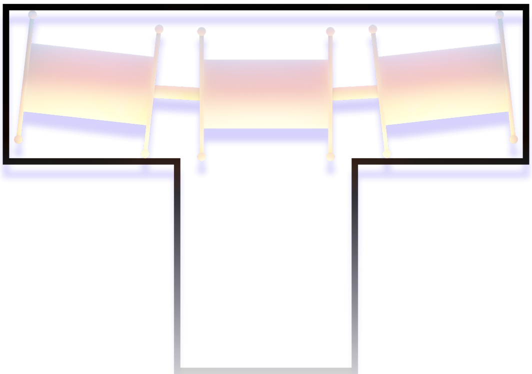
The triple rod design, upon construction, was immediately found to be immobile, acting more like a stick than a joint. However, the design transformed when just two of the three rods were connected.

Twin Rod Joint

With the Twin Rod design, adjusting one side of the joint would result in the other side mirroring the motion and vice versa. Therefore, when going through a bend in the pipeline, both sides of the joint must agree on a sheered pitch, averaging each side's "preferred" pitch into a compromise. This led to a stabilizing effect where both modules were pushed onto the centerline by each other's mechanical force, similar to a coiled spring but less lenient.



Furthermore, a module between two other modules in the machine would not be able to fall into a T-junction in the pipe. The reason being the module's pitch would be locked by the two other modules not being able to participate in any bend because they are in a straight pipe segment. Thereby "stiffening" the joints holding the module out of the hazard.

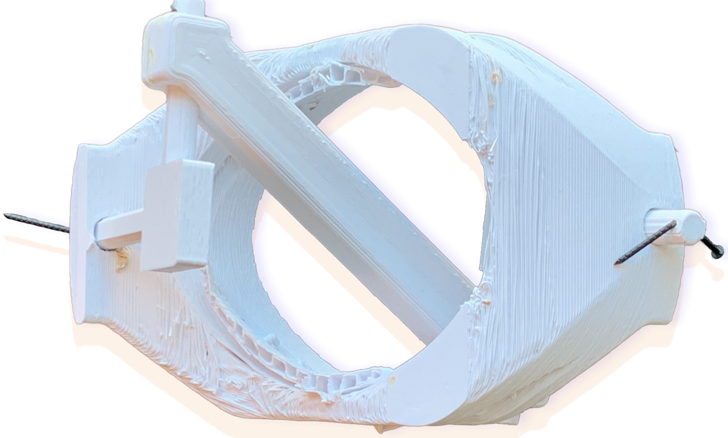


It may be worth noting that this design was included primarily for visual interest and not for anticipated benefits. It was just a curiosity about how it would move with connecting rods poisoned in such a configuration. Therefore, the interesting motion of the joint was discovered, not designed. The next step for this joint is to extend its mirrored pitch functionality to yaw.

4.4 Design Iterations: 2nd Batch

Auto Joint

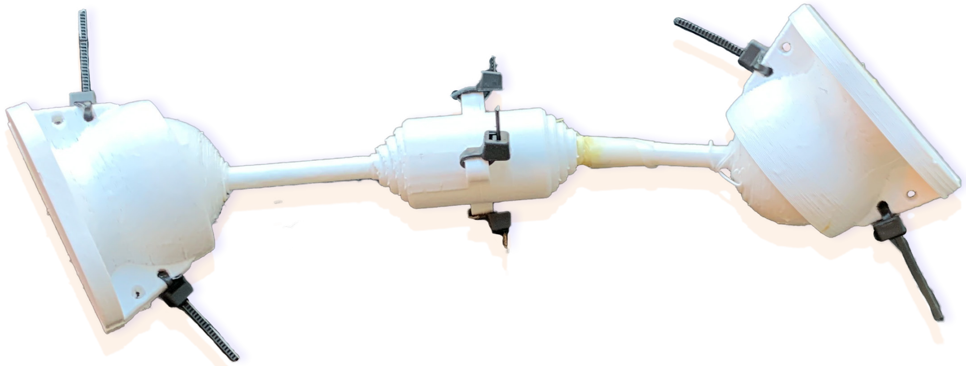
The Auto Joint was the first print of Stage 2, but it encountered a problem. All its sub-joints required an additional joint to achieve the desired motion, rendering it immobile in its current state. Another joint from Stage 2 had the same issue. Considering the similarity the fixed version of these two joints would share, only the other joint will receive the fix as it is closer to the shared solution. The Auto Joint was easier to print successfully, so the other joint received this fix before its first edition could be successfully 3D-printed. This other joint is the first one shown in batch 2.5.

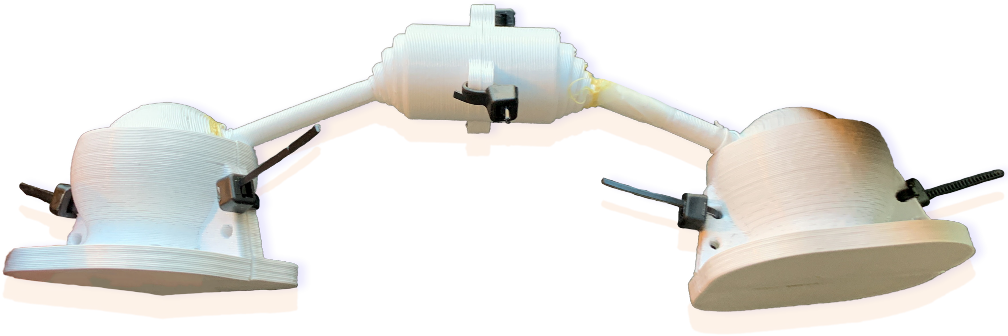


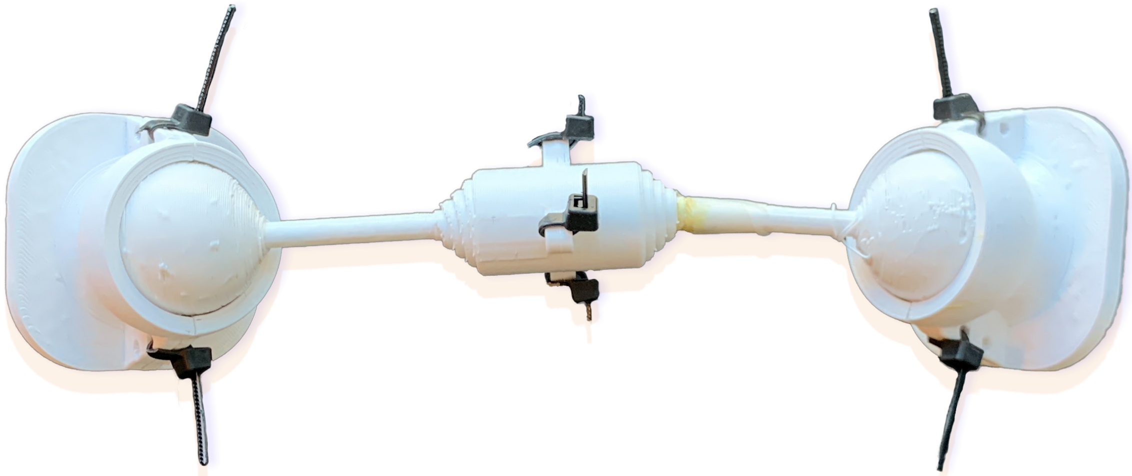
Centered Spring Joint

The advantages are similar to the spring described earlier, but this joint leaves the springs exposed and susceptible to damage. The goal of centering the springs within the connecting rod was that they would bend during a turn, attempting to straighten out afterward, thereby lifting their modules onto the pipe's centerline to avoid hazards.

During this stage, it was discovered that the spring suspension might make it challenging to position the sensor accurately, as the springs can absorb and release tension unpredictably when moved by small amounts.

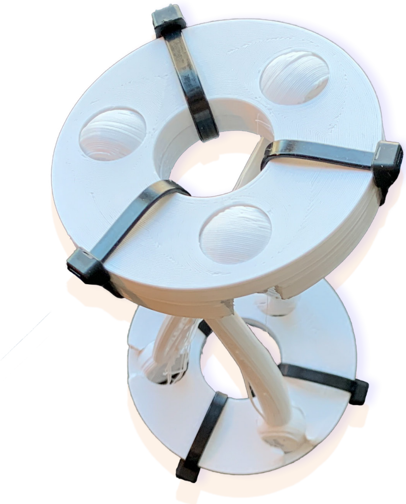


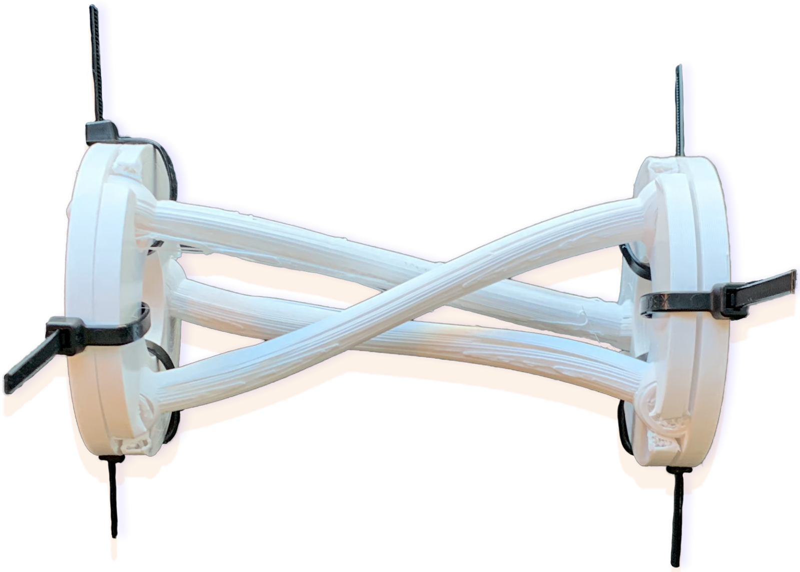


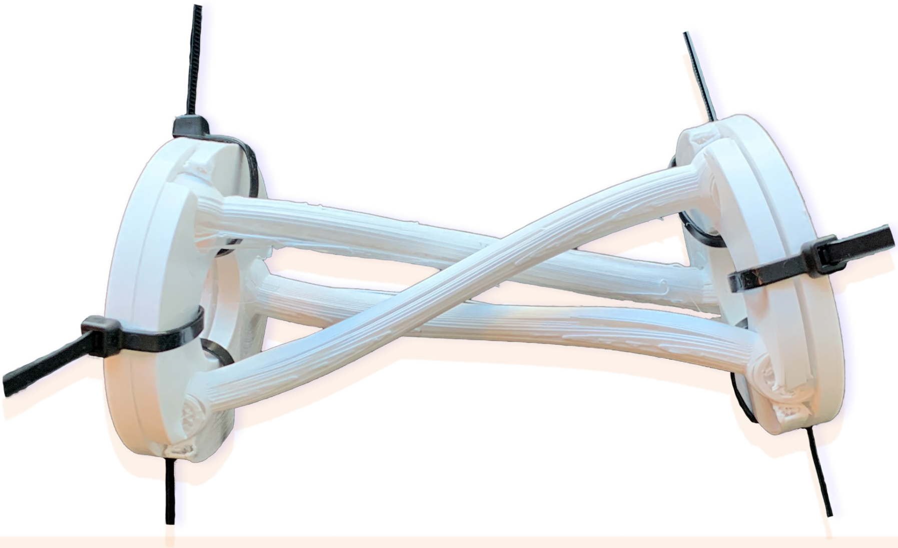


Triple Connecting Rod Joint

Like the Auto Joint, this design is a spiritual successor to the Twin Rod, attempting to add another dimension to its motion. Upon interacting with the 3D printed model, it became apparent that the intended motion occurred when the relative rotation between the two endplates was 180 degrees, not 90. This aspect was not adequately considered, and 90 degrees was only used to prevent the connecting rods from colliding. Therefore, the connecting rods needed a redesign, as shown in batch 2.5.

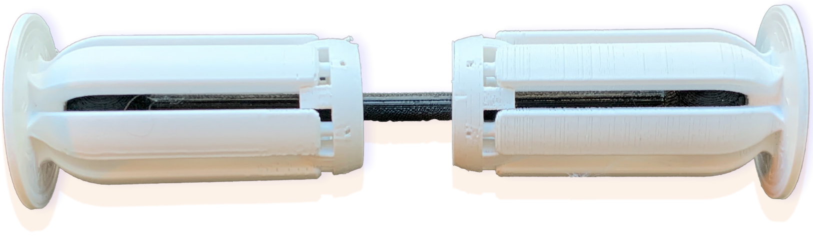






Deep Sockets Joint

Another experiment was also conducted in this batch. It consisted of ball and socket joints where the sockets were deep, allowing the ball to fall far into the sockets. This design limited the movement of the joints in compression. It successfully demonstrated the concept and could be integrated into the ball joints of other designs.



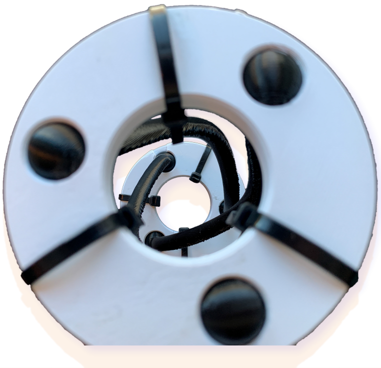
4.5 Design Iterations: 2nd & ½ Batch

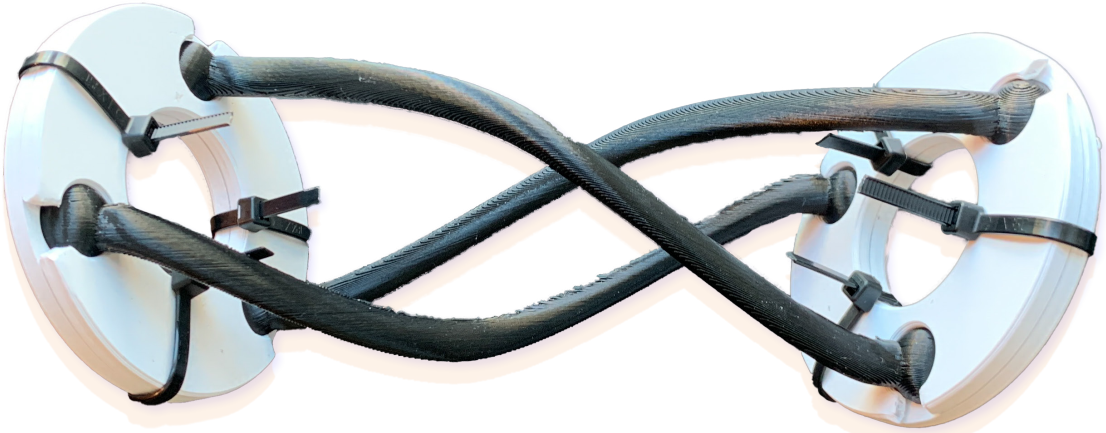
Before proceeding, this partial batch was introduced into the process to address the minor alterations required for some of the designs.

Triple Connecting Rod Joint v.2

This design successfully replicates the controlled mirrored motion of the Twin Rod in both pitch and yaw, as well as any combination of the two. Furthermore, from a tactile feel, it is like having an assist motor when moving the joint. The joint is also ideal for cable management, with ample space at the center between the connecting rods. Another advantage is that the distance between the end planes does not change, at the dead center, as the device moves through a bend.

When this design was printed and assembled, it became clear how sensitive to rotation it was. This iteration had more clearance in the ball joints than the previous iteration, which made movement easier, revealing the issue. The joint only functioned as intended when the two endplates were twisted 180 degrees relative to one another. Any other relative rotation resulted in completely undesirable joint motions. This joint offers the most desired motion and operation when in its ideal state. However, any deviation renders it completely unusable. If this rotation problem can be fixed, this joint will be the ideal choice for the machine. Nevertheless, this joint must be discarded if it cannot be corrected.





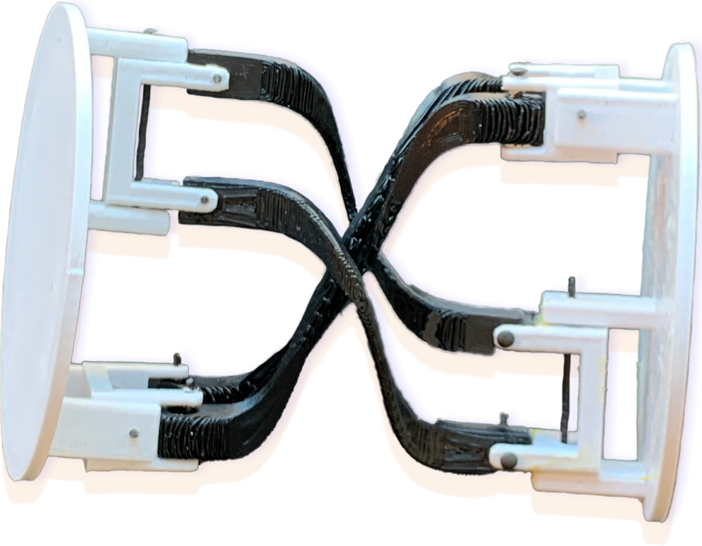
Double Twin Rod

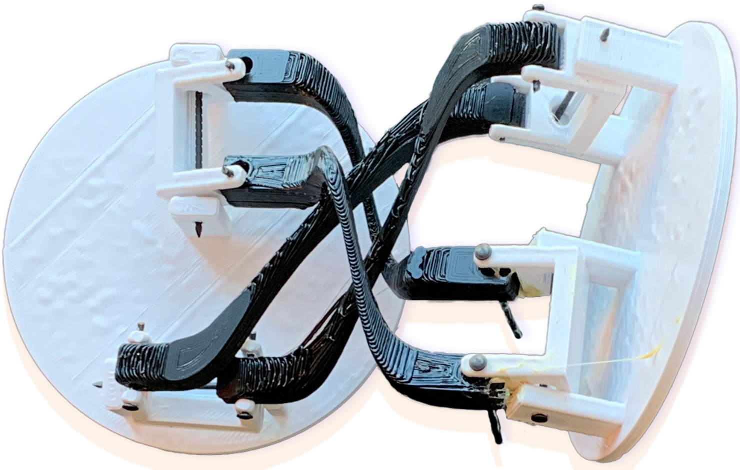
After the changes revealed by the first joint of Stage 2, this joint functions as intended, albeit at the cost of complexity. The idea behind the design was straightforward, replicate the successful mechanism of the Twin Rod joint but for yaw rotation as well. However, the execution was complex. This design comprises a Twin Rod joint within another Twin Rod joint, with the two inception joints rotated 90 degrees relative to one another.

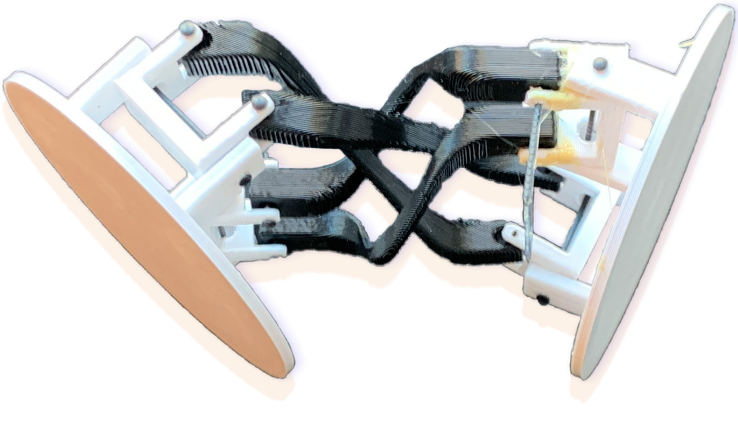
The issue with this joint is that the connecting rods collide with each other, resulting in different maximum angles in pitch and yaw in each direction. While this issue could be resolved, the previous design has a more elegant solution providing the same benefit, if not more..

Summary

The two designs selected to move to batch 3 are the Triple Connecting Rod Joint and the Centered Spring Joint. Two designs were chosen due to the high-risk nature of the Triple Connecting Rod; if it does not pan out, the Centered Spring Joint serves as a more conservative alternative. Additionally, even if a fix is found for the Triple Connecting Rod, the controlled motion at the heart of the design may have unforeseen consequences in specific combinations of pipeline turns. This is why an alternative is brought along. While the Triple Connecting Rod strictly enforces the controlled motion, the Centered Spring Joint only suggests it. In other words, the Centered Spring Joint can be overpowered if necessary. Therefore, the Triple Rod is considered the high-risk, high-reward option, and the spring, is the conservative one.





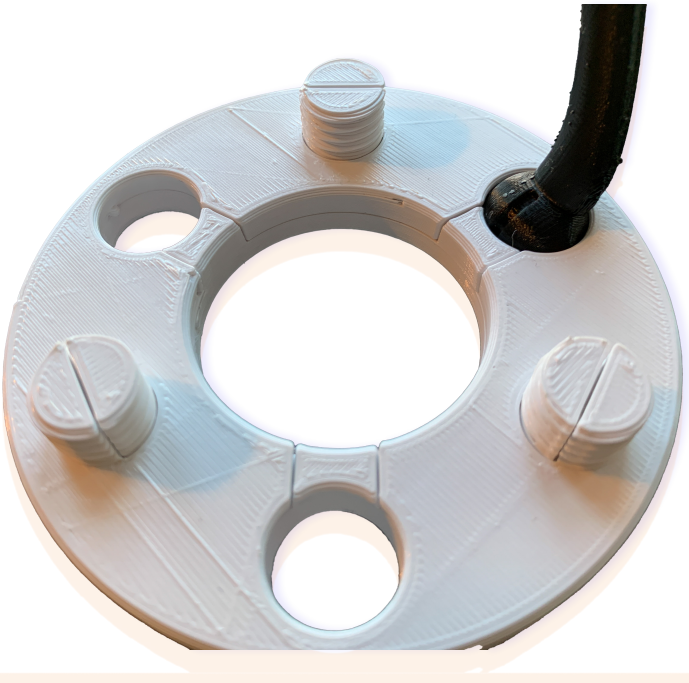


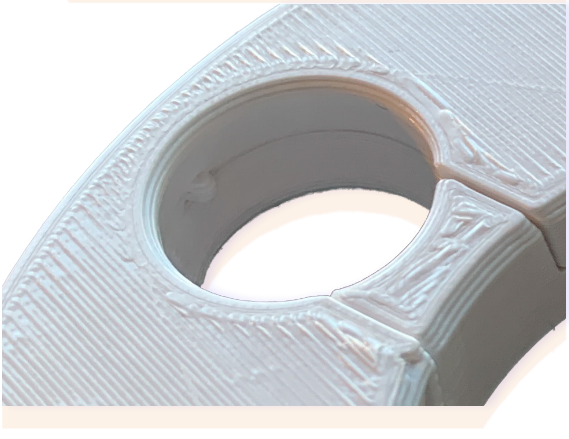
4.5 Design Iterations: 3rd Batch

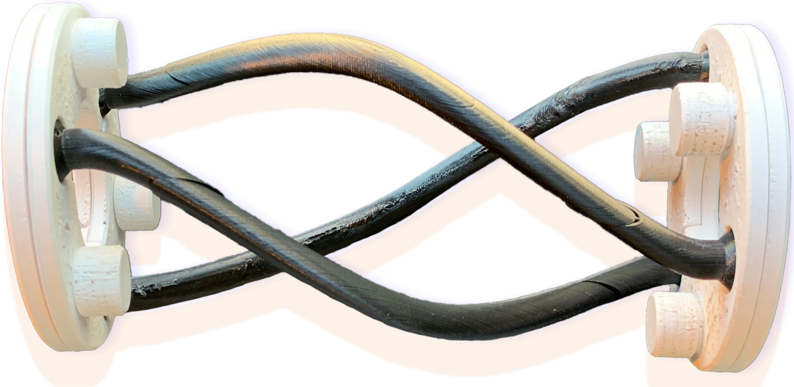
Triple Connecting Rod Joint v.3

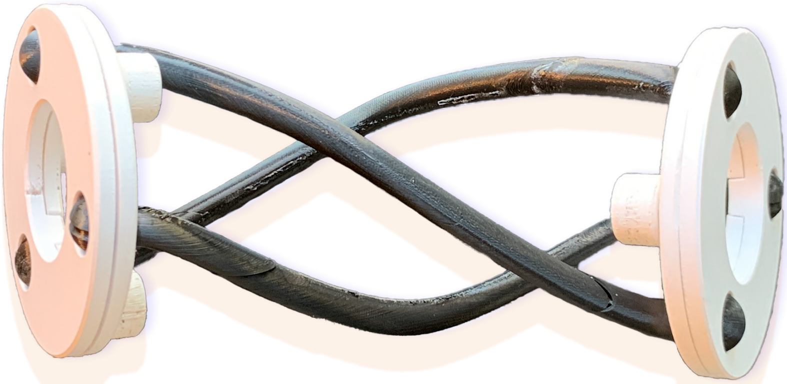
To fix the catastrophic rotation problem, a small ball bearing was inserted into a grow in the ball joint, blocking the joint from rotating in its socket. With all three rods unable to rotate in their socket, the endplate would also cease to rotate. This relationship was observed by fiddling with the 3D model over an extended period of time.

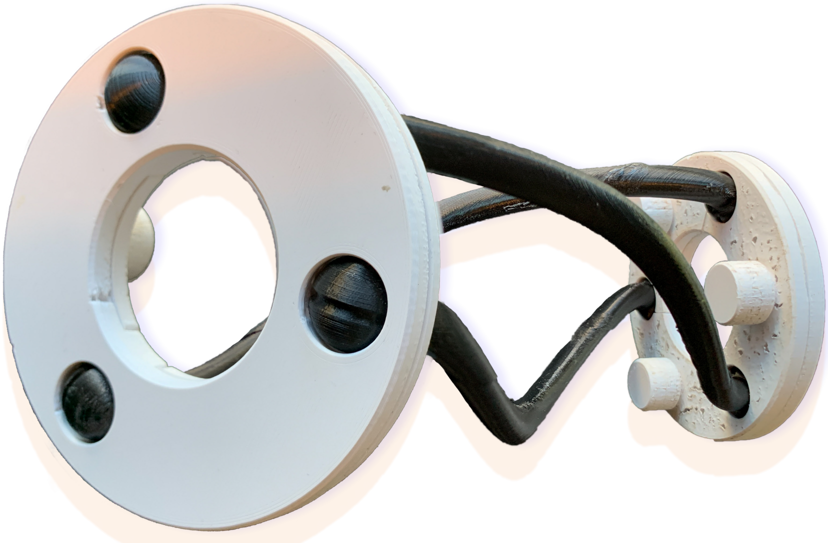
Another problem was discovered when assembling this new solution, as it took hours to complete. Having to balance the joint while inserting the ball bearings with a pair of twicers, careful not to let the two other ball bearings slip out while the last one was inserted. This is not an acceptable method of assembly. There was another discovery, however. The ball bearings were 3D printed and barely round, but the joint still operated flawlessly in the end, which led to the realization that the ball bearings do not have to be free moving to work. They were changed to pins protruding from the socket, no longer their own part, and no longer slowing down the assembly.





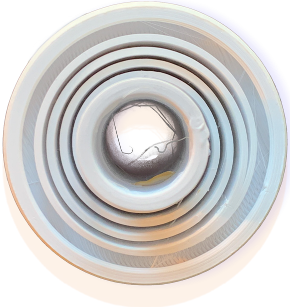


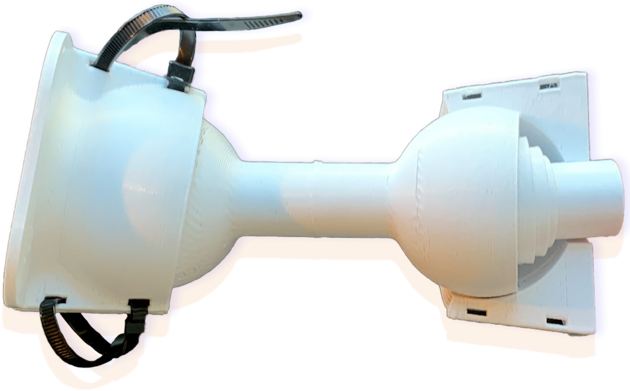


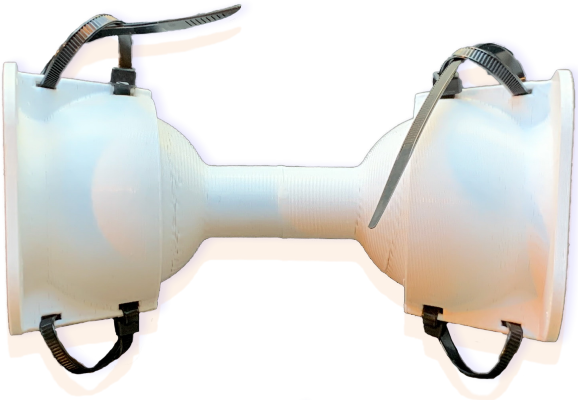


Internal Spring Ball Joint

The springs were moved inside the balls to improve the Centered Spring Joint. This protected them and placed the main load of the joint entirely onto the ball and socket element of the design, helping to remove the biggest problem with the previous iteration — its vulnerability to damage. This adjustment somewhat restricted the movement of the joint since there was no longer a bendable element in the center of the rod. However, this did not become much of an issue, as the previous joint already had more movement than necessary. The insides of the joint were also opened up to allow cables to be carried through it, bringing the cable management capabilities of this joint closer to those of the Triple.







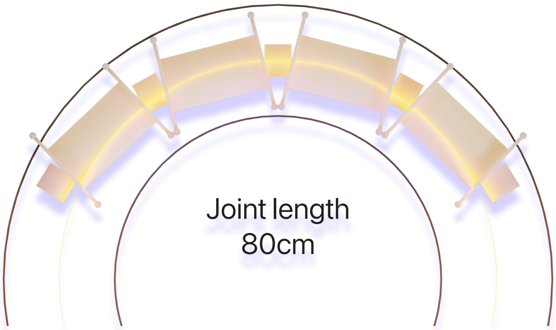
4.6 Dimensioning

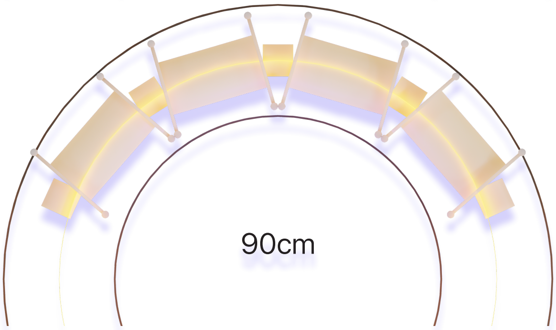
After developing the general concept for the idea, the subsequent step entailed refining the specific dimensions for the mechanical joints. This was achieved through a geometric test utilizing 2D sketches with lines and constraints in Fusion 360 software.

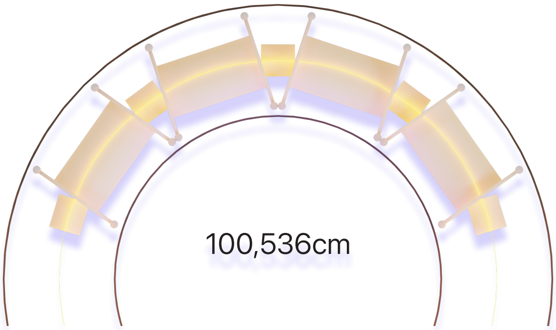
An experiment was performed within Fusion 360's 2D sketches to determine the optimal length of the joint. This investigation harnessed the software's constraint functionality to simulate scenarios revealing the ideal length of the joint. This joint length is crucial in preventing module collision, particularly concerning the module's wheels. These wheels are affixed to a steel plate with a diameter constituting 90% of the pipe it travels through.

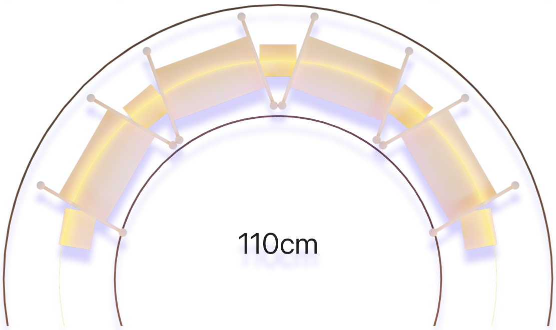
In the illustration, the protrusions on the larger cylinder represent these steel plates, while the circular tips denote the wheels. The smaller cylinders symbolize the joints, with the larger ones representing the modules. If the joint is too short, the wheels of the modules will collide during a bend. This experiment cycles through various joint lengths to evaluate if they allow the tool to conform to the centerline of the pipe.

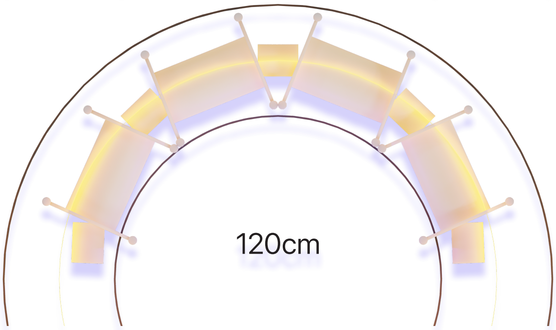
The machine must be capable of navigating a bend with a radius 1.5 times the pipe's other diameter, which was the standard used here. The angle between two adjacent modules was also observed to determine the maximum pitch/yaw the joint could perform before colliding. These angles were set to be equal across all joints and were measured from the joint's center plane to the module. Consequently, the measured angles represent half the angle between two adjacent modules. The sole variable modified in these scenarios was the joint's length.











Findings from the test revealed a linear relationship where longer joints corresponded to larger maximum angles.

The optimal joint length was precisely identified as 100.536mm. This specific length was established by pinning the leftmost and rightmost joints to the centerline and maintaining all other constraints in the Fusion 360 sketch. This dimension represents the minimum length the joint can possess while perpetually aligning with a bend's centerline, a bend with a radius 1.5 times the pipe's other diameter.

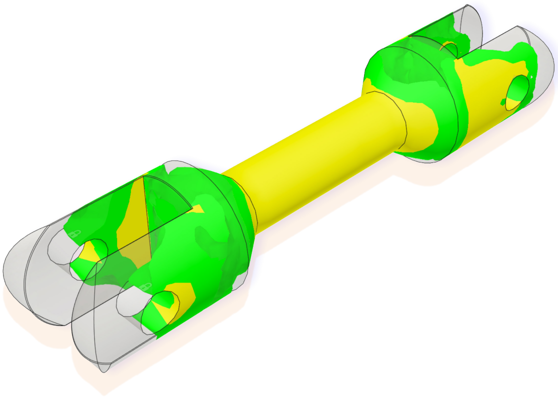
A joint length exceeding this measurement allows unnecessary movement, and a shorter length fails to provide sufficient mobility to accommodate the pipe's bend. A shorter joint is favored as minimizing weight is essential. However, it is also crucial to maintain a safety margin. Following the precedent set by the wheel's design, a 10% mobility safety margin would be suitable, setting the ideal joint length at 110.589 mm.

The joint's corresponding angle at a length of 110mm was found to be 20 degrees.

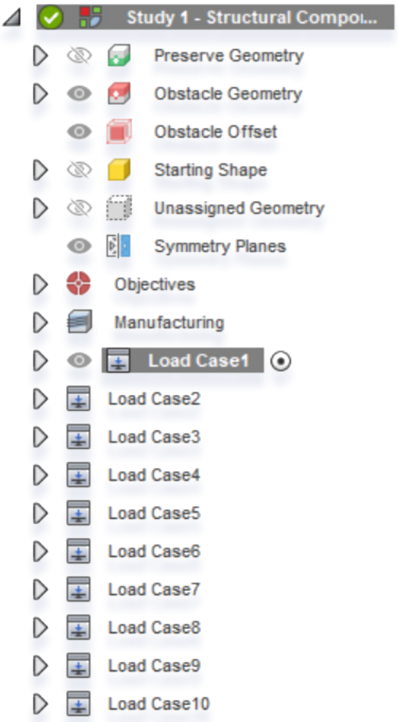
Length	Max Angle
50	9,1
60	10,9
70	12,7
80	14,5
90	16,3
100	18,2
110	20
120	21,9
130	23,8
140	25,8
150	27,8
160	29,8
170	31,8
180	33,9

4.7 Generative Design

To verify the information obtained from ROSEN Norway, a simulation was performed using the joint currently deployed by ROSEN Norway, configured to a load scenario of 1.5 tons with a safety factor of 1.3333. When one side of the joint was constrained in all directions, and the force was pulling from the other side, the minimum safety factor was indeed found to be 1.333. This result confirmed the values and method for adding forces to the simulation. The simulator and generative design share their physics engine, transitively validating the load scenarios.



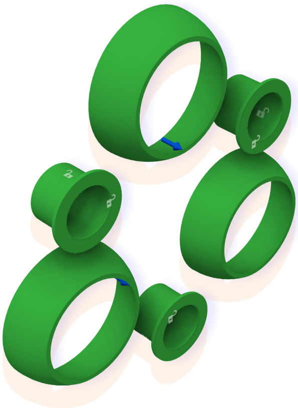
Each joint component was separated and subjected to its own Generative Design study. As some components were identical, only two studies were needed for the triple joint: one for the plate and one for the connecting rod. Likewise, the two parts of the backplate are mirrored, so only one generative design study was needed.

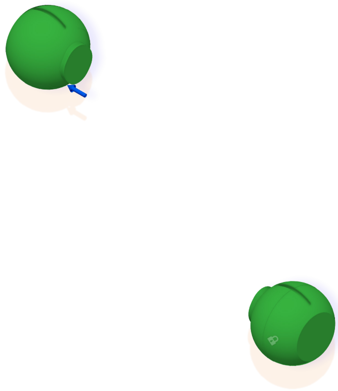


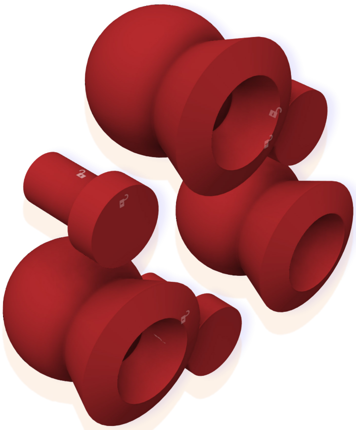
- Study 1 - Structural Compo...
  - Preserve Geometry
  - Obstacle Geometry
  - Obstacle Offset
  - Starting Shape
  - Unassigned Geometry
  - Symmetry Planes
  - Objectives
  - Manufacturing
  - Load Case1 ⦿
  - Load Case2
  - Load Case3
  - Load Case4
  - Load Case5
  - Load Case6
  - Load Case7
  - Load Case8
  - Load Case9
  - Load Case10

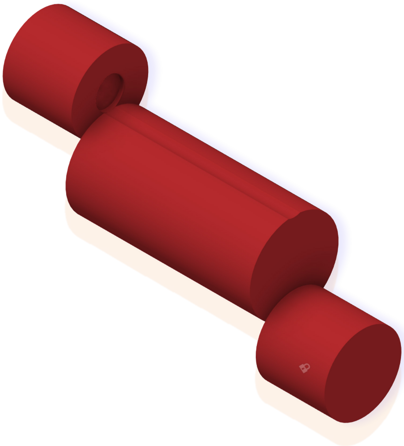
Forces were applied to the simulations based on how they would propagate between components. The interaction points between components were identified as the force and constraint application areas. The main scenario is a 1.5-ton force pulling on one side of the component. Alternative scenarios describe circumstances where the forces come from varying directions, such as through a bend. Each scenario is computed separately. The forces introduced in one scenario do not impact others. Nevertheless, all scenarios in the study collectively affect the shape being generated.

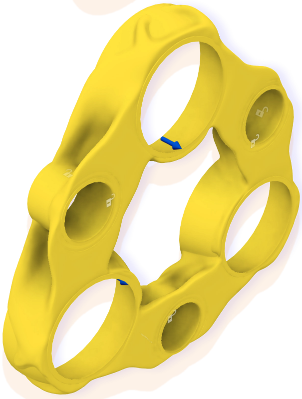
Titanium 6Al-4V was the only valid material offered by Fusion 360 for the Generative Design study. The other materials would balloon out of proportion, as they do not have a good enough strength-to-weight ratio to keep the components slim enough to keep the joint operational.

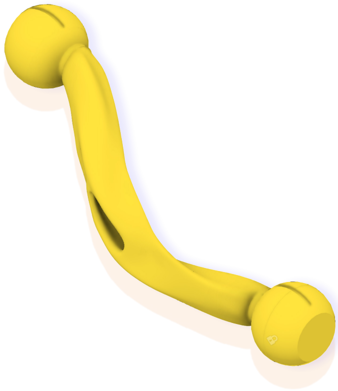


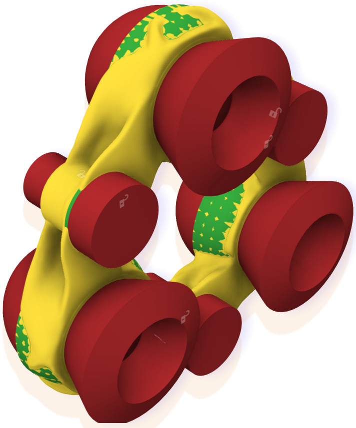


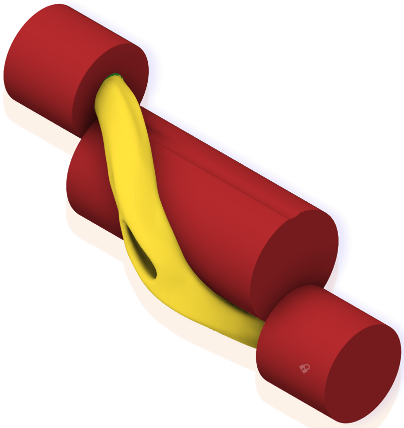








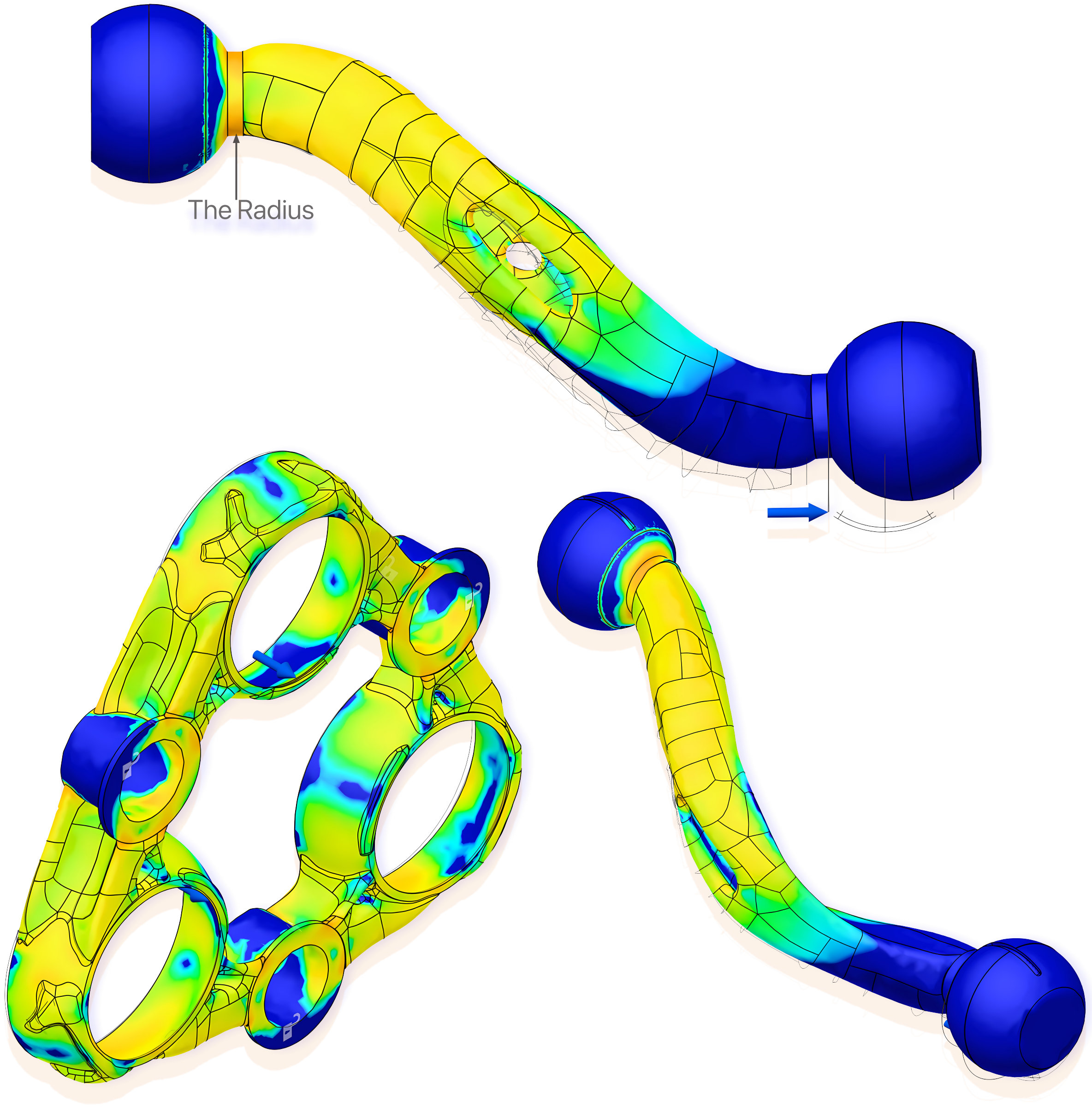




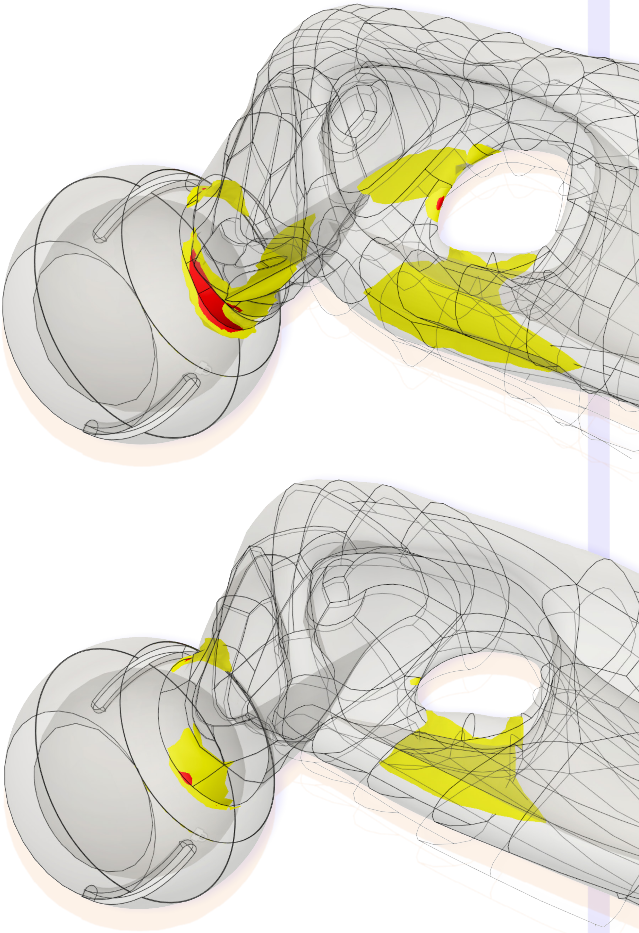
The generative design phase began by crafting a 'negative' of the iterative designs. However, to fully leverage the benefits of generative design, it is crucial to allow maximum freedom in shaping the parts.

The challenge thus involves describing the design with minimal geometry, or more precisely, minimal volume. This applies to the preserve geometry (colored green). In contrast, the obstacle geometry (colored red) can encompass more volume as it does not force the material to be included in the component.

The development process revolved around iterative adaptations of the generative design outputs. Each cycle commenced with a simulation of the output to analyze and better understand the shapes the Generative Design algorithm utilized. Variables and initial geometries were then methodically adjusted to guide the designs toward desired outcomes.



Paramount among these was determining the optimal radius for the rods. The radius needs to be fixed where the rod interacts with the socket opening since this determines the pitch and yaw limits of the joint. Consequently, the socket opening is calculated using the rod's radius to enforce a 20-degree angle limit.

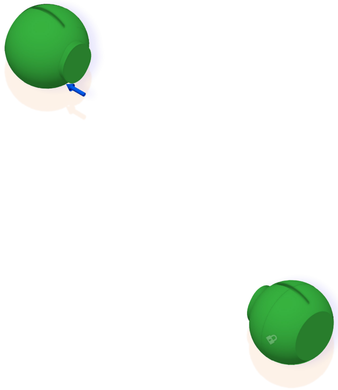


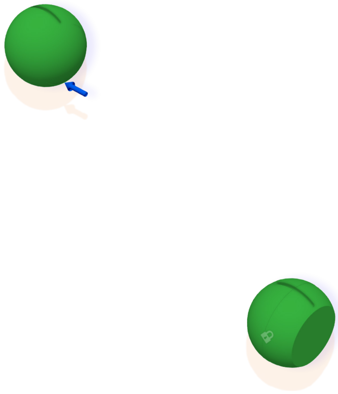
The rod's radius was identified by progressively reducing the preserved geometry radius, allowing the generative design algorithm to fill the available space. When the radius became overly small, leading to algorithm spillover, it was increased again.

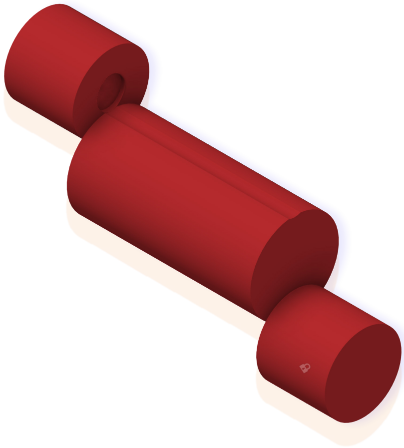
The simulations revealed the accumulation of internal stresses at the sharp transition between the rod and the ball. Thus, a fillet was added to the rod's preserve geometry to smooth the transition. This is essentially similar to what the generative design algorithm does, just done manually, as the algorithm cannot change the preserved geometry. This adjustment necessitated a corresponding modification to the socket opening to ensure the joint's pitch and yaw limit was accurately enforced.

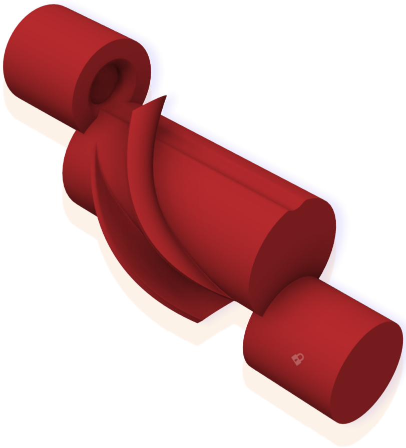
Having established the rod radius and socket opening, the ball size within the sub-joints could be determined. With the other variables fixed, changing the ball diameter was the sole means of increasing the cross-sectional area, withstanding the forces pulling the ball out of the socket. A similar iterative approach was taken on the backplate to pinpoint the optimal ball diameter. A diameter of 36 mm was found to be large enough to accommodate the necessary forces.

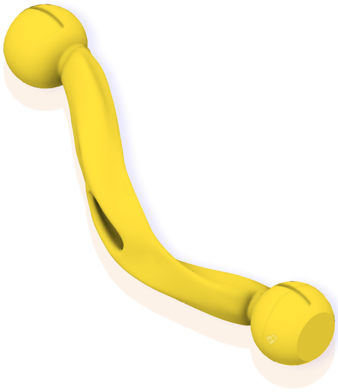
When updating the preserve geometry to include the smooth transitions, more obstacle geometry was introduced to avoid the rods swelling to the point where they would collide when the joint bends.

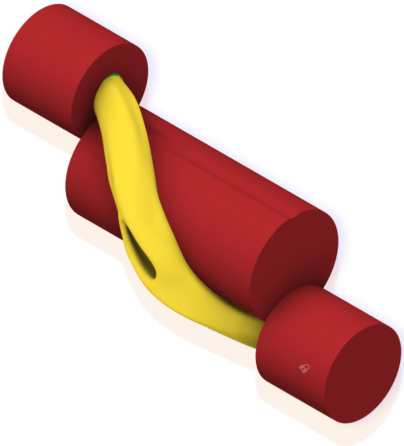


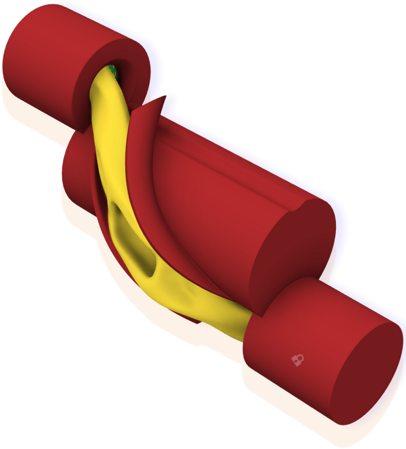




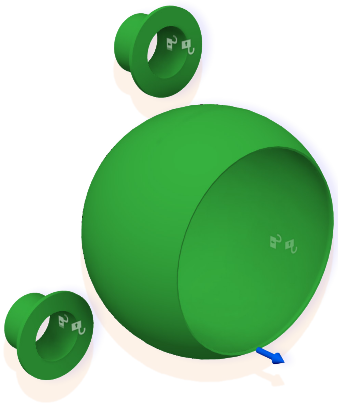


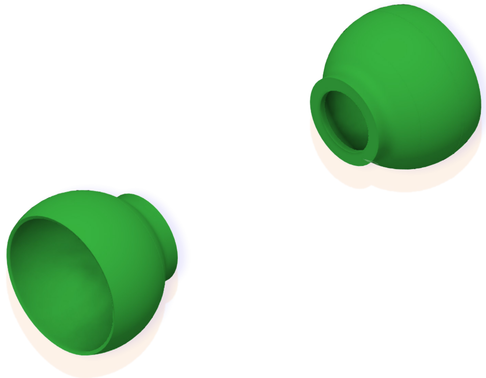


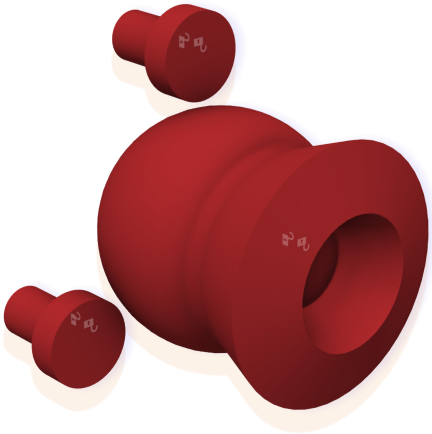


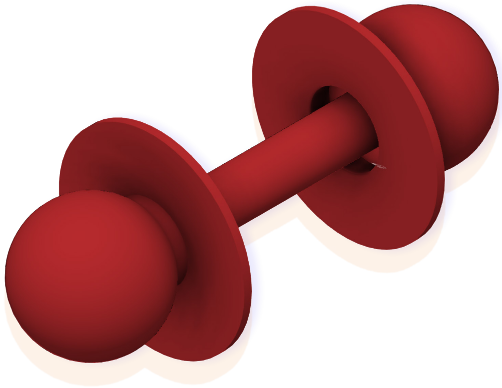


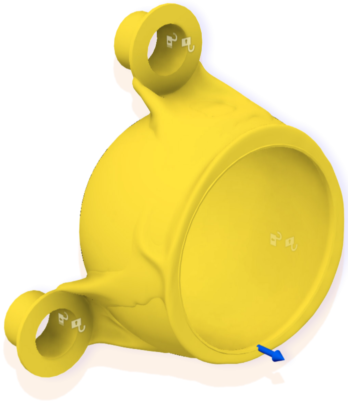
A similar approach was taken for the ball and spring joint. Here, the generative design algorithm was first employed to determine the rod radius, which, in this case, was hollow. The inner radius was specified, leaving the outer radius for the algorithm to establish. The ball and socket dimensions were calculated and integrated into the preserve geometry. Since both design concepts incorporated a ball and socket as the load-bearing element, many calculations could be reapplied, with minor adjustments to reflect size differences. The constraints in Fusion 360's 2D sketches were utilized to calculate these values.

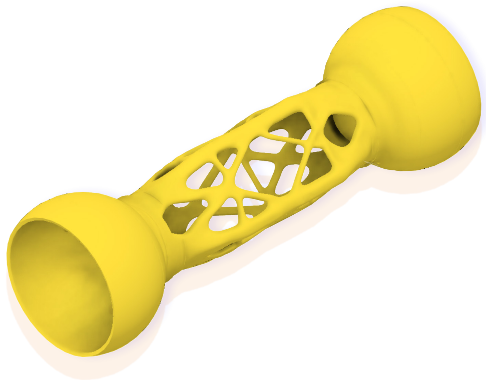


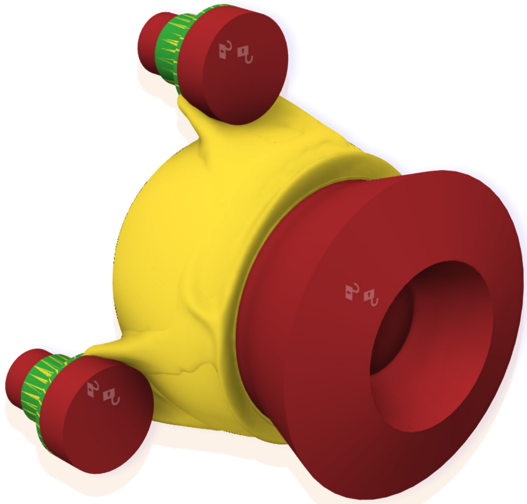


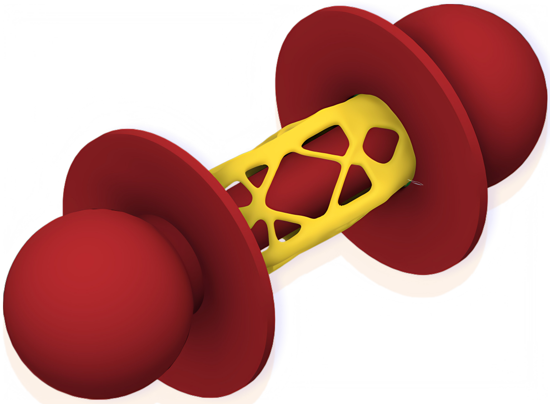


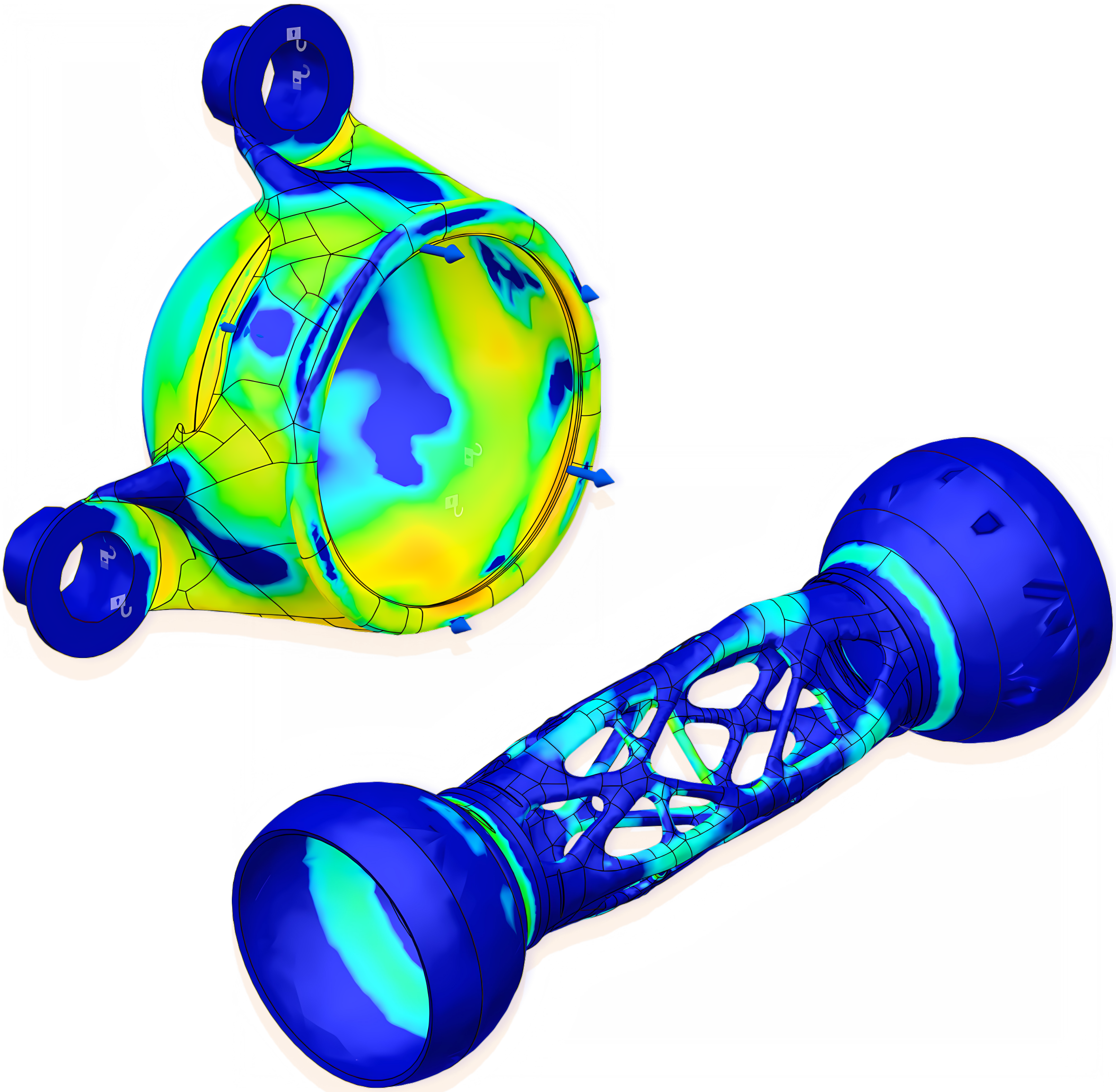


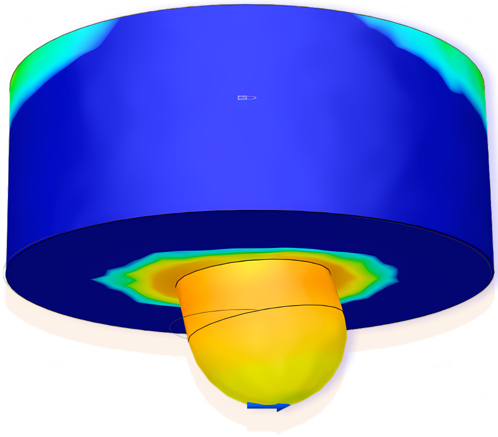








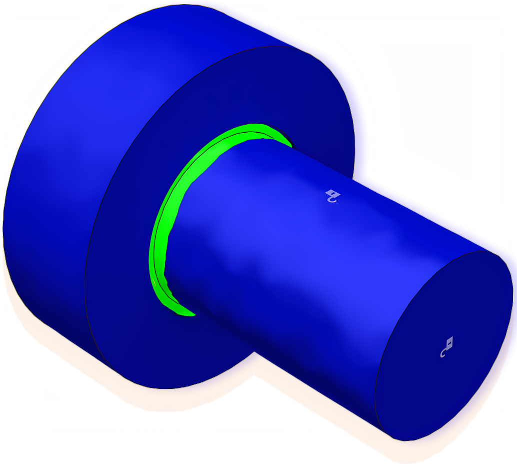


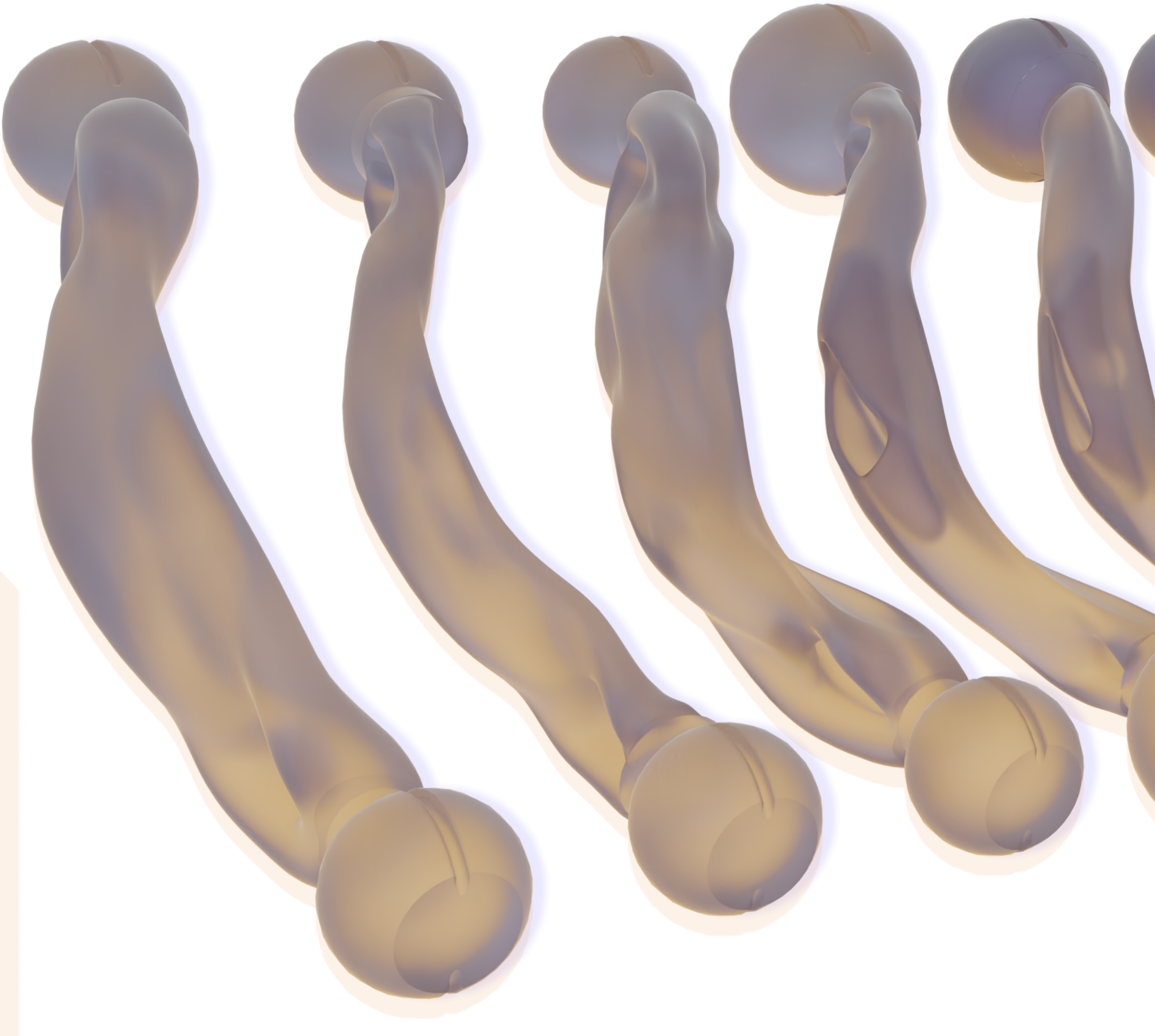


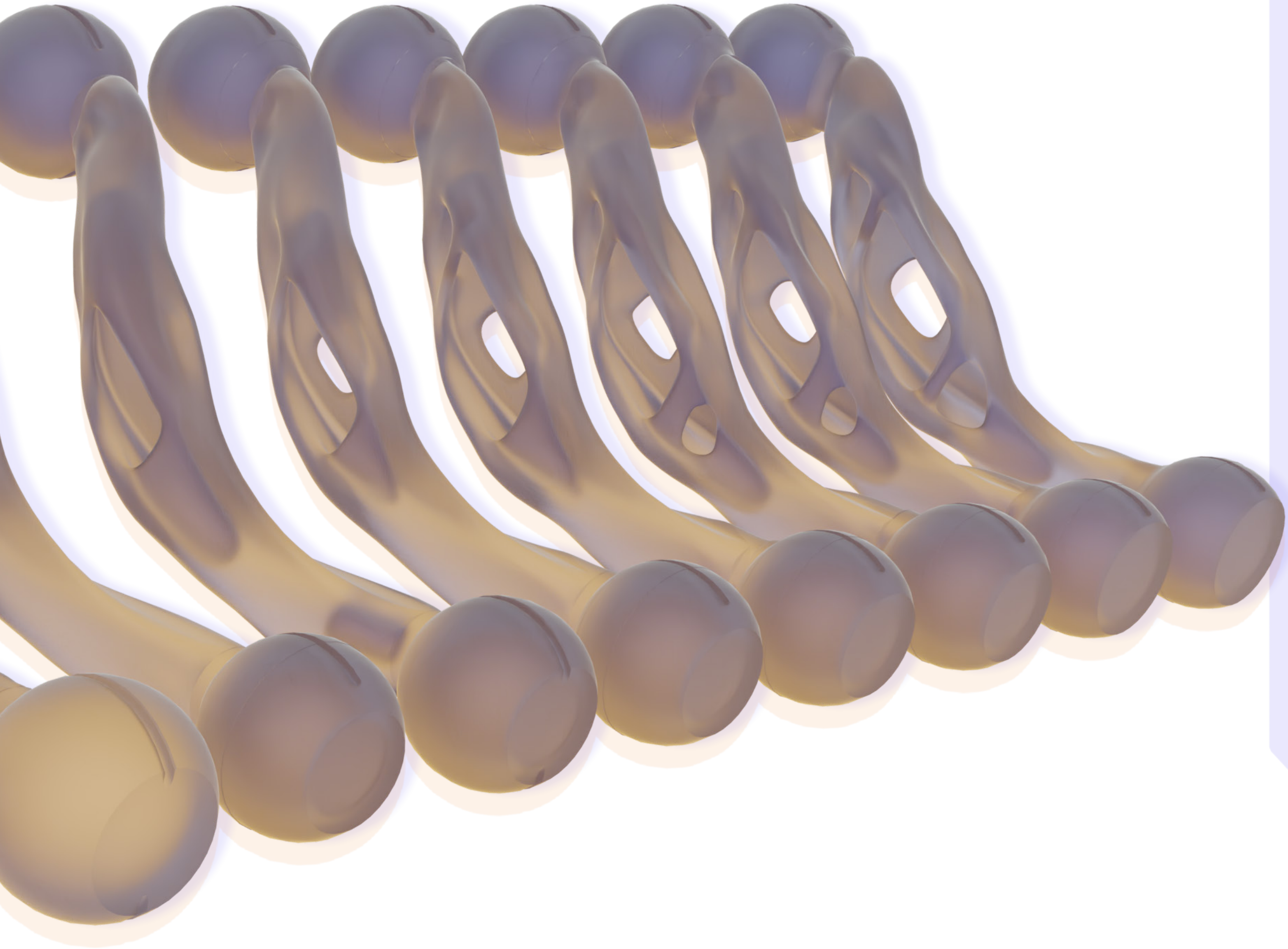
A second pin was added to each sub-joint for safety. Each pin is calculated to hold 80 kg before breaking.

Simulations were also conducted on the bolts to ensure their capacity to withstand the forces. The bolts were M12 and thus slightly over-dimensioned, enabling two out of three bolts to maintain the joint within operating limits. Although all three bolts are ideal for stability, this contingency allows the joint to endure all required forces if one bolt comes loose, ensuring an emergency scenario safety provision.

The joint shapes were further refined using the output from one iteration as the initial shape for subsequent iterations. The resolution of the generative design study was incrementally increased with each iteration, with earlier iterations running at lower resolutions to expedite the process.

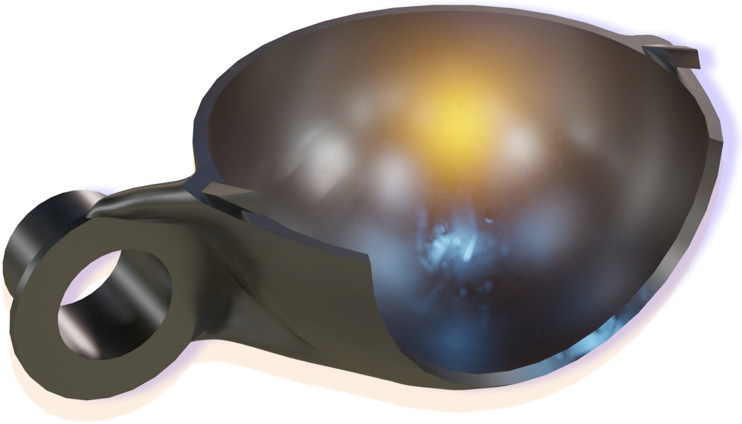


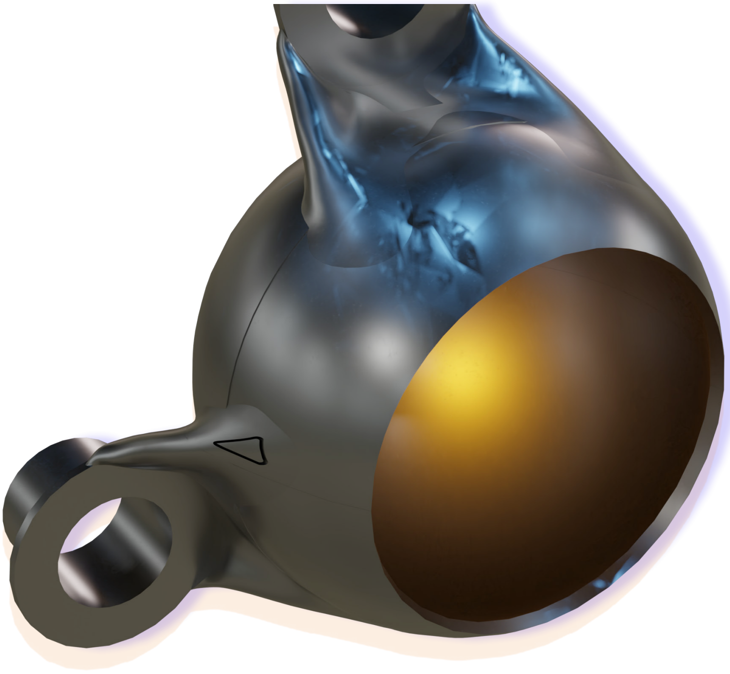


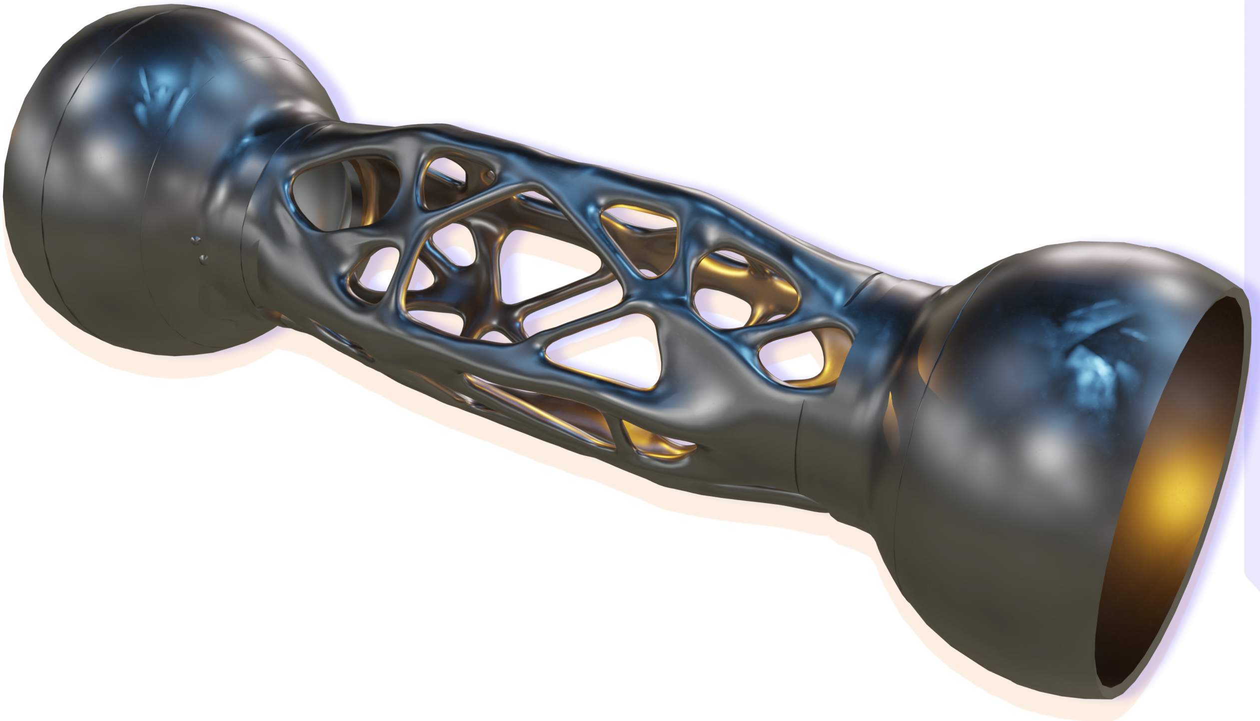


4.8 post-processing

The Spring joint has a hook/sliding element introduced so that the socket can be secured in place, as it needed to be cut in two so the ball could be inserted during assembly.







For the Tripel joint, the rod entry point into the socket was added as tested by previous iterations. The shapes were cut out and moved to preserve the Generative Design shapes.

4.9 Spring Joint Insight

Reliability: The spring joint has safety factors in both strength and mobility to ensure reliability, and attention has been given to relieving areas of high stress observed from the stress simulations. Generative design has options to increase stiffness, not preserve springiness, so the spring could not be verified. However, the spring can also break without causing a problem since it is not load-bearing, making it less of an issue.

Strength: The spring joint provides sufficient strength while the joint's weight is 575g, the minimum local safety factor is 1,333, and the Max Von Mises Stress is 662MPa. Of note is that steel was strong enough to be used in the socket for this joint, which has not been the case for other designs. This is probably a sign that this joint shape demands more material than necessary. It also means it can be made with a cheaper material.

Light Weight: The generative design algorithm has done most of the job. However, it is observed that the spring inside the ball needs the socket to be a complete enclosure. Therefore, material that is not needed from a strength perspective is included in the joint, driving up the weight. Further increasing weight is that the spring is inside the ball, forcing the ball and socket to be larger to fit the spring.

User-friendly assembly: Great care has been given, as mentioned previously. Uniquely for this joint is the spring which is printed in place, simplifying the part count to just 5, not counting the mounting bolts.
Mobility: The Spring joint enables the machine to navigate turns with a radius 1.5 times the diameter of the pipe.

Stability during reverse operations: The triple joint has inherent stability, while the spring joint uses the force of the spring to correct the module back into position. The spring joint is fixing the symptom rather than the illness.

Optimal Positioning: The modules are inclined to be centered by the Spring joints spring, but this centering can be overpowered, which is the feature of the joint. However, real-world testing is needed to see which of the two joints has the right approach.

Protection of cables: The area at the center of the spring joint has been hollowed out to allow cables and wires to be run through. The spring element keeps the cables bending evenly when the tool navigates the pipeline.

Compatibility: The joint fits the modules, the module has a diameter of 161mm, and the joint has a diameter of 110mm.

4.10 Tripel Joint Insight

Reliability: The triple joint has safety factors in both strength and mobility to ensure reliability, and attention has been given to relieving areas of high stress observed from the stress simulations. The risk is that if the pins break, the forces they have to withstand are unknown without a real-world test. As the joint is 3D-printed, more pins can be added to hold the joint without increasing production complexity, as many as can fit along the circumference of the balls.

Strength: The triple joint provides sufficient strength while the joints weight is 661g, the minimum safety factor is 1,333, and the Max Von Mises Stress is 662MPa

Light Weight: The generative design algorithm has done most of the job. However, several manual adjustments have been made to the preserved geometry based on the simulations to reduce their weight.

User-friendly assembly: Great care has been given to assembly, as every joint has been assembled multiple times during the testing. The assembly has naturally seeped into all areas of development. The most considerable benefit has been removing any small components. Through 3D printing, several parts could be condensed into one, simplifying the assembly process.

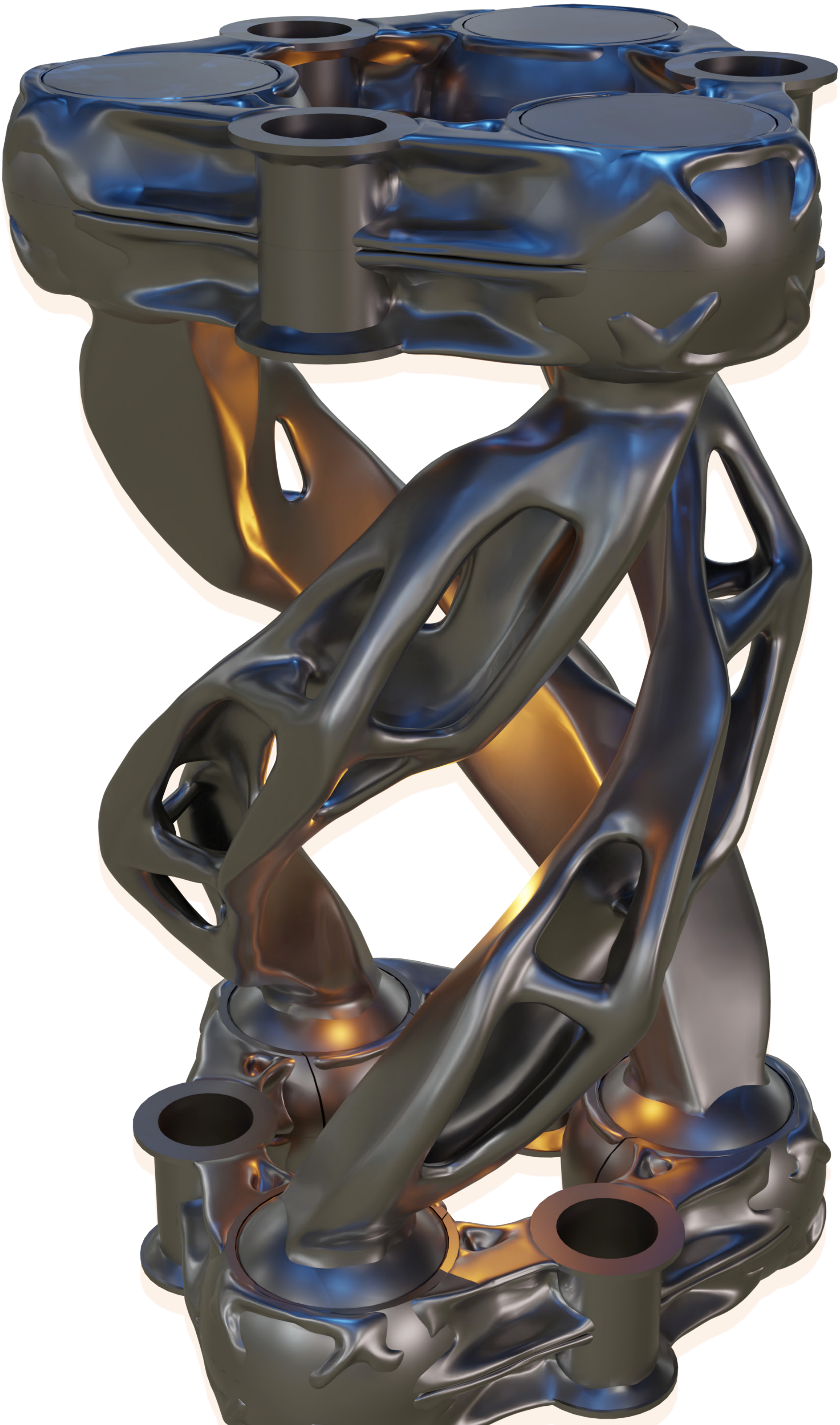
Mobility: The Tripel joint enables the machine to navigate turns with a radius of 1.5 times the other diameter of a pipeline. The mirrored motion of the joint is to align whit the following two design criteria.

Stability during reverse operations: Having the force transferred by three rods spread across a large area gives the joint this stability, like a person taking a wide stance.

Optimal Positioning: The modules are held centered by the Tripel joints “mirrored movements,” helping to avoid hazards like the T-junction.

Protection of cables: The area at the center of the triple joint has been kept open to allow cables and wires to be run through. This part of the joint also has the least length changes through a bend, with the dead center not changing its length.

Compatibility: The joint fits the modules, the module has a diameter of 161mm, and the joint has a diameter of 100mm.



4.11 Final Design

5.0 Conclusion

The design thinking process was utilized to create an improved mechanical joint. First, an emphatic understanding was reached through the exploration of the tool, alongside interviewing and observing employees at ROSEN Norway. This information got condensed and defined into a list of design criteria for the mechanical joint. Ideations generate designs from there, and the most unique were developed into prototypes to learn more from. Testing also involved ensuring that the strength and mobility requirements were met.

The design process was iterative. A variety of designs were conceptualized, realized through 3D printing, and subsequently subjected to practical testing for insights. The insights were then used in the next iteration, and this cyclic process continued until the Triple Joint was found and had its quirks ironed out.

From there, the design was reworked using Generative Design. The algorithm was run multiple times, analyzing the outputs for the best ways of modifying the input to nudge the subsequent output. The goal was to reduce internal stresses while minimizing weight further and ensure the safety limit was upheld throughout the components.

Three key findings punctuated this design journey. First, the mirrored motion discovered in the Twin joint endowed the desired agility into the design. Second, the introduction of the triple rod replicated this agile motion in an additional dimension. Finally, the ball-bearing turned pin was implemented, which proved crucial in preventing self-destruction of the triple joint through rotation. These discoveries were all made because the joints were 3D printed and tested practically. This rapid prototyping was the key method that allowed the joint to be developed.

Nevertheless, the current study does have a notable limitation: the absence of real-world testing. It is recommended that future work should involve subjecting the joint fabricated from 3D-printed titanium to the forces it has been designed to withstand. Additionally, it would be beneficial to develop versions of the joint compatible with all types and sizes of modules to ensure broader applicability.

This study has developed a new mechanical joint for ROSEN Norway's inspection tool by leveraging Design Thinking, Rapid Prototyping, and Generative Design. The outcome is an agile joint that enhances the tool's reliability and safety.

6.0 Discussion

Initially, the problem to solve was enhancing the agility of the joint, particularly its pitch and yaw range, to help the tool navigate tighter bends. However, following the visit to ROSEN Norway, it was discovered that this was unnecessary. The current joint already provides more pitch and yaw than required to navigate the tightest turn according to pipeline standards.

With this understanding, the focus for the new joint shifted from agility to the design criteria. However, agility is still referenced in the title as it resonates with the unique motion of the triple joint. This alteration changes the original intention but is still applicable.

Traditionally, the Design Thinking approach emphasizes crafting a human-centered problem statement. In this case, it was replaced with a list of design criteria, a move that deviates strongly from the standard process. However, knowing when to break the rules is the most important part of learning them. This deviation was justified by the absence of human perspectives in the process, as the primary concerns arose from ROSEN Norway's corporate clients, which prioritize risk management and profit. The corporations stress safety and reliability to avoid profit loss due to extended pipeline closures. Consequently, the problem statement was adapted into design criteria to better align with the client's concerns.

Another reason it is more acceptable to break this rule in this scenario is because it mainly exists to improve teamwork, which is less of a problem when working alone.

The triple joint may appear overly intricate, which could cause apprehension about its production. However, through the use of 3D printing, the complexity of the shape becomes irrelevant. The organic shapes and swirling connecting rods are inconsequential as far as the printer is concerned. The printer can handle simple or complex parts equally, though overhangs pose a challenge. A problem primarily mitigated by the generative design algorithm, filling out the overhangs to make them. The appearance of the joint thus becomes irrelevant as long as it offers an improvement.

3D printing is ideal because the tool is a low-volume product that also demands a high degree of customizability. This scenario rarely comes up in practice outside of prototyping. 3D printing is often perceived as an experimental production technology due to its limited scalability, but it is a mature technology in certain cases like this one.

While practical testing was carried out during the joints' development, testing at a real-world scale remains necessary. The joints have been appropriately sized but not made of titanium nor subjected to a two-ton force. The performance in the environment the joint will be deployed in has yet to be evaluated. While simulations indicate this performance, their abstractions leave much to be desired. Doing a practical, real-world test and then more simulations would also give more context to the numberers of the simulation, aiding further analysis.

It is probable that half of the triple joint's endplate and one-half of the socket from the spring joint will form part of the module itself. However, given the upcoming changes to the modules within the company, this integration stage was omitted. What remains of the integration step is the footprint requirement in the design criteria. The future work is, therefore, to do this integration but whit the benefit of also changing the shape of the modules.

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