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The FRE Gripper with Planar Grasp Stability, using Spatial Form-Closure

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Challenge the future

Preface

This paper ends my college days and I am happy to finish my MSc in Mechanical Engineering at the Delft University of Technology. It is a great relief to finally start my career in mechanical engineering and to conclude my days as a student.

I would like to thank my supervisors Ad Huisjes and Just Herder for the constructive support and supervision throughout my project and for their enthusiasm every meeting. I would like to thank Spiridon van Veldhoven for his help in manufacturing and building an experimental set-up. I would like to thank my fellow students who provided both theoretical and personal feedback every week in our weekly meetings. And finally, I would like to thank my friends and family for always supporting me and believing in me.

Neil Smit

Amsterdam, July 2022

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The FRE Gripper with Planar Grasp Stability, using Spatial Form-Closure

MSc Thesis

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ABSTRACT *Fin Ray Effect (FRE) grippers have proven versatile and effective in pick & place automation applications. However, spherical and lateral round objects are still a challenge for the state-of-the-art, as solutions are unstable when placing those objects off-centre from the longitudinal line. Resulting in large and heavy FRE gripper assemblies. The object often shoots out of the grip, since the gripper cannot counteract the lateral forces from the object with normal forces from the structure, but instead has to rely on friction forces. In this paper, a new spatially designed FRE based gripper is proposed that form-closes around the spherical object, providing a stable grip. The design variables, such as structural variations and different thicknesses of segments, are modelled using LiveLinks between SolidWorks, COMSOL and MATLAB, resulting in an optimal design. The optimal design is then compared to a basic FRE gripper design, using the model, and the stability of both is validated in the real world by an experiment. The new design shows improved performance compared to the Basic FRE grippers, and even shows centering capabilities for frictionless objects.*

1 Introduction

Automation of manufacturing and distribution is in full swing. The food industry however, showed slow adaptation of automation at first, but has shown great increases in process automation [9]. Automation of the food industry is particularly hard due to organic shapes and variety in products. Grippers for this industry are therefore designed for their ability to adapt their grip to the object at hand and come in different forms, sizes and methods [1, 2, 15, 20].

For this paper, focus lies on the Festo DHAS gripper finger [4], since it is a widely applied gripper finger in industry. The gripper uses its compliant structure to deform, consisting of a triangle with a front and back sheet, that is connected at the tip and with ribs along the longitudinal direction of the gripper. The gripper adapts its shape to the the object when pressed against it [12] and thereby form-closes around the object in longitudinal direction. This functionality of the FRE gripper comes from the front and back sheets alternating between tension and pressure, while being flexibly connected by the rigid ribs [8]. It is a mechanically underactuated gripper finger, since it has more Degrees of Freedom (DoF) than it has actuators [6]. This underactuated method of gripping is applied in a variety of gripper methods already like the gripper design bij Doria & Birglen or by Steutel [3, 4, 6, 11, 17].

The FRE grippers are versatile in their application due to their shape adaptation. However, two problems arise with current FRE gripper fingers. The first problem being planar enclosure and the second being a torsional DoF. These two problems together create an unstable situation when gripping lateral round objects. These problems come from the grippers being designed and evaluated in 2D, while these effects arise in the 3D world. The FRE grippers like the Festo DHAS gripper [4] apply form-closure in their longitudinal direction, but solely rely on friction in their lateral direction. This friction dependency is problematic for lateral round objects, due to the friction surface becoming very small and object material experiencing low friction with the gripper material. Since the gripper does not form-close in lateral direction, any slip can result in the object being released by the gripper. Moreover, the gripper also shows a parasitic rotational DoF around its longitudinal axis. Resulting in the gripper opening up due to torsion caused by reaction forces on the object. The assembly becomes unstable, as the object solely relies on friction and any movement inducing a force greater than the friction force, can cause the object to slip, which then causes the gripper to open up and push away the object even more. A simple solution provided by literature and industry [5], is to add fingers and assemble a tripod configuration. However, this adds a lot of extra volume to the gripper, which often is undesirable in the food and agricultural industry due to the dense working environments.

To solve the current problems with the 2D designs that are extruded to the 3D world, a new FRE gripper finger will be designed spatially and evaluated in a 3D environment. The focus thereby on gripping a spherical object, with the FRE structure as a base. It is envisioned in this paper to create a spatially designed FRE gripper that behaves like a mattress. The object thereby sinking into the gripper and the gripper forming itself around the spherical object in both longitudinal and lateral directions. The grip would then solely depend on form-closure, instead of friction, and therefore create a stable assembly. Moreover, to prevent the gripper from opening, the rotational DoF must be constrained.

The goal of this paper is to present the design and performance evaluation of a 3D FRE-gripper grasping convex objects by spatial structural form-closure.

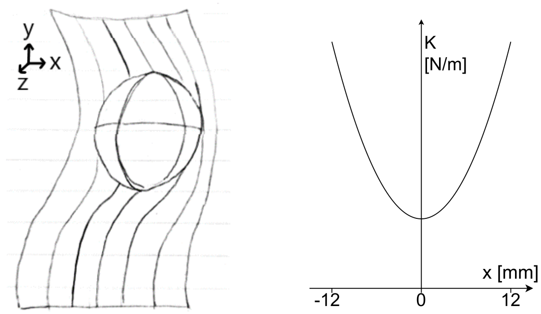
First, a new spatially designed FRE form-closed gripper is presented in section 2.1. Second, the performance criteria are described in section 2.2 and the model used to collect data regarding that performance in section 2.3. Then, the results following from data collected through the model and a validation experiment, are presented in section 3 and discussed in section 4. Finally, the conclusions of this research are presented in section 5.

2 Method

The method of this research was to design a new spatially design form-closed FRE gripper finger, set-up performance criteria for the new design and to then test the performance of different design variations by a newly built FEM model.

2.1 The concept design

The initial idea for the spatially designed FRE gripper is to create a mattress effect, shown in fig. 1. The sphere is pressed into the surface and is enclosed by that surface spatially. The middle of the gripper is most compliant, while the stiffness increases towards the edges of the gripper, as shown in fig. 1b. Thereby pushing the sphere to the center of the gripper. Essential is that the FRE remains included in the design. To establish this effect, the FRE Mattress Gripper was designed, shown in fig. 2.



(a) Sketch (b) Stiffness Profile

Figure 1: The Mattress Effect

The FRE Mattress Gripper (shown in fig. 2) has characteristic changes from the basic FRE grippers. The first important change is the asymmetry. The FRE Mattress Gripper has a clear difference between front and back, while a Basic FRE Gripper does not. The gripper was designed using FACT-method [7], to gain knowledge in the desired degrees of freedom and constraints per part of the gripper. The front is designed with perforations, creating wire flexures and thereby allowing the front sheet to deform in both longitudinal and lateral directions simultaneously. Without the wire flexure configuration, the front sheet is expected to show the carpenter's tape effect [14], where the curvature around the lateral axis of the gripper would prevent the front sheet from deforming around its longitudinal axis. The ribs connecting the front and back are triangle shaped, creating space and compliance for the front sheet to deform into the gripper structure, while simultaneously directing the stiffness to the edges of the front sheet. The back sheet is equipped with triangular torsion reinforcements [16] that constrain the rotational DoF around its longitudinal axis. These aspects altogether establish the desired initial mattress effect.

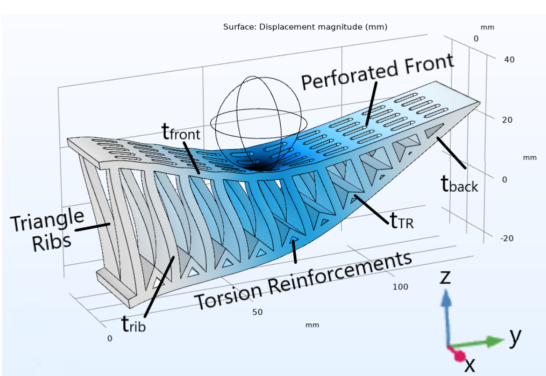


Figure 2: FRE Mattress Gripper Final Design

Design Variations

Between the Basic FRE Gripper and the FRE Mattress Gripper, a number of design variations were evaluated using the model. These consisted of structural and parametric variations. There were 5 structural variations which each apply one or more of the structural elements relative to the basic FRE gripper finger and all have a constant thickness of 2mm. The 5 structural variations:

- **Basic FRE** The base design, a basic FRE gripper. A 2D design extruded to the 3D world.
- **Torsion Reinforcements** Basic FRE gripper with added Torsion Reinforcement, placed to counter the opening movement of the gripper fingers when the object is misaligned from the lateral middle of the gripper.
- **Triangle Ribs** Basic FRE gripper with triangular ribs. The shape is meant to give the front sheet space to deform and to move the stiffness to the outside of the front sheet.
- **Perforated Front & Triangle Ribs** Triangle Ribs with added perforated ribs. The perforation is added to counter the measure tape effect and add the necessary DoF to the front sheet to deform in multiple directions at once.
- **Full Concept** All previous structural concepts together to provide the fully applied concept with a constant thickness.

Besides the structural variations, parameter variations were evaluated using the model to gain insights in the effect of those variations on the performance. The parameter variations consist of thickness variations per segment of the gripper finger (see fig. 2). The different functionalities per segment of the gripper finger led to the hypothesis that segments do not necessarily have the same ideal thicknesses. The standard thickness is set to 2mm and each variation only varies one parameter. At last, the final design is created with parameters that proved best for each segment from the extracted results The different parametric variations (in mm) for this research:

2.2 Performance

The performance criteria consist of the FRE performance, the centering performance and the stiffness. The performance criteria were applied to find tradeoffs and specific differences between the concept variations. Resulting in the final design of the FRE Mattress Gripper.

Variation	tFront	tRib	tTR	tBack
Full Concept	2	2	2	2
1	1.5	2	2	2
2	2.5	2	2	2
3	2	1.5	2	2
4	2	2.5	2	2
5	2	2	1.5	2
6	2	2	2.5	2
7	2	2	2	1.5
8	2	2	2	2.5
Final Design	2	2.5	1.5	2.5

Table 1: Thickness in mm of front sheet (tFront), ribs (tRib,), torsion reinforcements (tTR) and back sheet (tBack) per parameter variation

FRE performance

The Fin Ray Effect is highly important for the performance of the gripper. This characteristic is the essential characteristic that differentiates this gripper from others. It is therefore important to ensure that the FRE is not lost. Conceptual additions to the basic FRE gripper, may have an effect on the degree of FRE the gripper has. The FRE Performance was monitored by the dimensionless number:

$$P_{FRE} = \frac{u_{max} - w}{u_{max}} \tag{1}$$

The FRE performance was measured by dividing the maximum displacement minus the displacement at the tip of the gripper, by the maximum displacement of the gripper. More FRE results in a higher P_{FRE} number. With u_{max} being the maximum displacement of the spherical object into the gripper along the z-axis (0.015m in this research) and w being the displacement of the end of the gripper along the z-axis. Considering the coordinate system applied (see fig. 2), u_{max} is always a negative number, while w can be either positive or negative depending on the degree of FRE.

Centering performance

Centering of the objects was measured to quantify the extent to which the gripper pushes the spherical object towards the middle or away from the middle of the gripper. The minimal requirement for this research was to show no force in this performance metric. This would result in a non existent centering performance number. As the magnitude of centering performance number was defined by the force in x-direction on the spherical object RF_x, devided by the gripping force RF_z (see 2). The x-coordinate was taken into the equation to define the direction of the centering, as direction is of utmost importance in this performance number. If the gripper pushes the spherical object to the outside of the gripper and thereby out of the grip of the gripper, the performance number will come out negative.

$$P_c = \frac{RF_x \cdot x_{co}}{RF_z \cdot |x_{co}|} \tag{2}$$

Centering performance was measured on every coordinate at which the model computes and also differs per displacement of the spherical object, or gripping force exerted on the spherical object. It was therefore important to choose a situation that can be compared, regardless which concept was chosen. Since gripping forces differ greatly between concepts due to great variations in stiffness, a constant force for all concepts could not be chosen. however, a constant displacement could be chosen. The displacement must be significant enough to induce the centering effect, but not enough to induce buckling or go outside of the scope of the study. However, a displacement that is normal for the center of the gripper, might cause the gripper to buckle when applied at the tip of the gripper. While a displacement that is suited for the tip of the gripper, might be insignificant for the center of the gripper.

The method to create an equal situation for all concepts was therefore to choose a displacement at the center (0,60) of the gripper (u_F) and then calculate the corresponding gripping force (F_u) and apply that force for all coordinates. This way, a constant gripping force is applied, based on a displacement at the center of the gripper. The gripping force differs for every concept and also the displacements at other coordinates than (0,60) will differ. However, the situation is always in the correct range on the gripper and comparable for every concept.

Stiffness

Stiffness was taken into account as a measure to which the different concepts and variations change the mechanical behaviour of the gripper. The stiffness was taken as a performance metric to monitor the mechanical changes per concept design. Stiffness was not considered a performance criteria to optimize, as it was used to monitor mechanical changes in behaviour of the design.

$$K = |\frac{RF_z}{u}| \tag{3}$$

Stiffness can be measured in a variety of directions and situations. For this performance analysis, the stiffness was measured as the force exerted by the spherical object in perpendicular direction to the gripper surface in undeformed state, divided over the displacement in that same direction. Since the stiffness may vary for different displacements, the same tactic as for the centering performance, with a chosen u_F and a corresponding constant F_u, was applied.

2.3 The model

The established model consists of a LiveLink between SolidWorks, COMSOL and MATLAB. First, the concept was designed in a 3D CAD model and loaded into the FEM model with a spherical object. Then, the constraints were applied and the object was displaced into the front of the gripper. This results in stresses, deformations and strains which were calculated by applying non-linear contact mechanics. This was done for a chosen set of coordinates on the front of the gripper finger, thereby collecting and storing reaction force data, performance data and plots for every coordinate.

The software functions

In SolidWorks, the concept design was made into a 3D CAD model. This 3D CAD model used parametric dimensions and equations to provide the desired geometry. These parameters in the design are essential for control over variations through MATLAB and COMSOL. For this research, thicknesses were varied, but other dimensions can also be altered to gain mechanical knowledge on the behavioural changes thereof. Besides the parameters, the different conceptual characteristics were build into the 3D CAD model such that they could easily be suppressed. Thereby allowing for those concept characteristics to be either left out or added to the 3D CAD model easily. This altogether made the 3D CAD model designed for variation in parameters and concept designs.

The physics of the FEM model was set-up in COMSOL. The 3D CAD model was imported through the LiveLink between COMSOL and SW, and the desired load was applied in the COMSOL GUI. In this research, the load consisted of a sphere with a radius of 15cm and a set displacement into the gripper. The load can be chosen desirably and can therefore have any form, shape or magnitude by applying the desired physics. The material properties and the meshing were also added in the COMSOL GUI. The chosen meshing is very important for both computational speed and accuracy. Plotted visual results were partially imported through plot groups. These can be chosen and created in the COMSOL GUI for later exportation through MATLAB.

MATLAB was then used to apply computational sweeps and easy data extraction and processing. MATLAB was used to run the COMSOL study on a chosen grid of coordinates on the gripper. Those coordinates being:

x = [-12 -8 -4 0 4 8 12]

y = [40 60 80 100 120]

The MATLAB segment of the model used several functions to apply the input parameters, run the COMSOL study for each coordinate, extract and store the data from COMSOL, process and interpolate the data and to plot the results.

Material

The material chosen for the gripper was Thermoplastic Polyurethane (TPU). This material was also used for the Festo DHAS gripper finger [4], which was an inspiration for this research. This material is widely used for elastic plastic materials and can be injection molded or 3D printed. The Young's modulus was set to 25MPa [10, 18] and Poisson's ratio was set to 0.48 [13, 19].The material properties can be changed in the model for future research or performance evaluations where different materials are used.

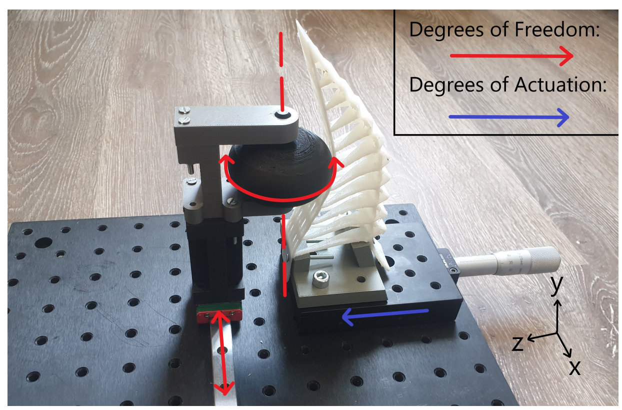
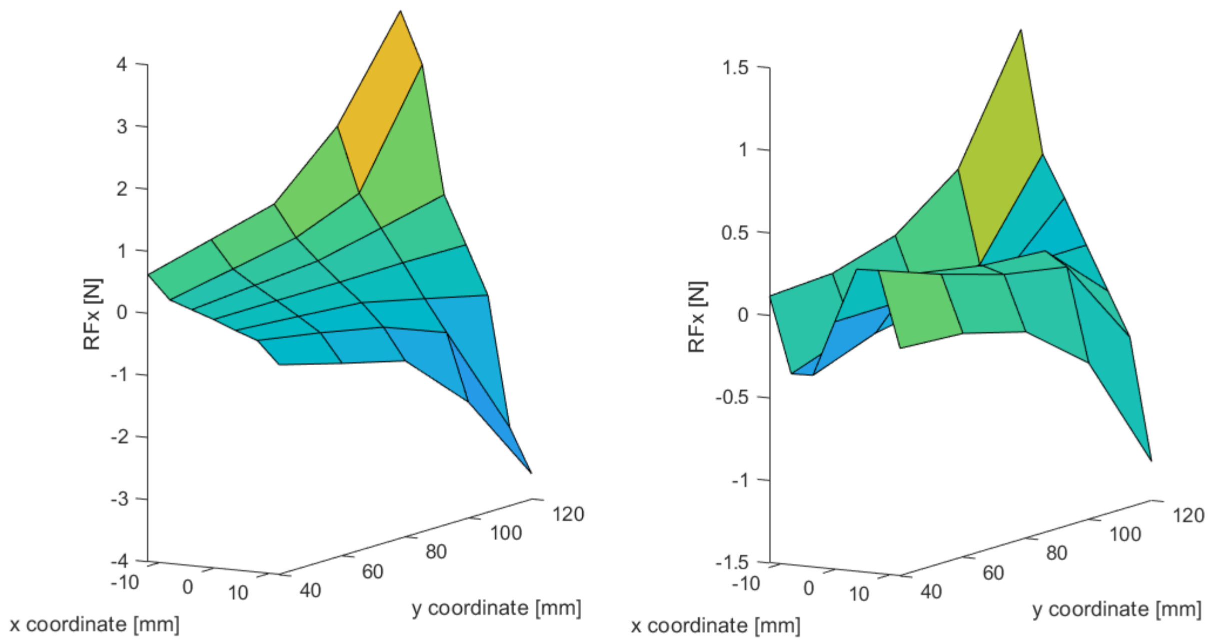


Figure 3: Rotating sphere on linear slider with gripper finger on linear actuator

Validation

The model was validated through an experiment. The experiment concerned the stability of the gripper when gripping a spherical object at different lateral locations on the gripper surface. The experiment pushed the gripper finger into a spherical object, thereby simulating a gripping situation of the object. The spherical object was constraint in the longitudinal direction of the gripper, but unconstrained and frictionless in the lateral direction and free to translate by rolling over the gripper finger's surface.

A grasp is stable when the spherical object does not



(a) Basic FRE Gripper

(b) FRE Mattress Gripper

Figure 4: Reaction Force RF_x surface plots, showing the change in Force directions and magnitudes

move when gripped, or moves to the lateral center of the gripper and then stops moving. In these cases, the gripper did not exert any lateral force to the object, or the gripper showed centering capabilities. If the object moved toward the side of the gripper or even away from the gripper, instability was observed. The spherical object was positioned at y = 60 and lateral locations along the x-axis:
x = [-16 -12 -8 -4 0 4 8 12 16]
The results were formatted as: Out, Still and In. If the sphere was pushed to the outside of the gripper and beyond, 'Out' was noted. If the sphere stayed still in its position, not being pushed to either side, 'Still' was noted. If the sphere moved toward the center of the gripper, 'In' was noted as it moved into the grip.

3 Results

The model from section 2.3 resulted in the reaction forces, performance and displacementes of the FRE Mattress Gripper. This section shows the relevant data and comparison for designing the FRE Mattress Gripper.

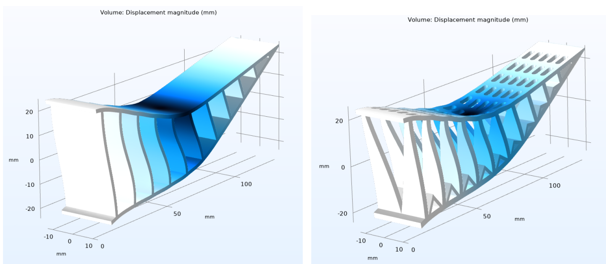
Reaction Force plots

The reaction force plots (shown in fig. 4) show the planar reaction forces RF_x for a constant gripping force F_{grip} in the z-direction. These RF plots give a visual indication of the centering performance.

The difference between the Basic FRE Gripper and the FRE Mattress Gripper is shown in fig. 4. The Basic FRE Gripper shows a slope, always pushing the spherical objects away from the gripper itself. While the FRE Mattress Gripper shows a wave form at the base, but also a slope similar to the Basic FRE Gripper, at the end of the gripper. The slope in the middle (x=0) is inverted compared to the slope on the Basic FRE Gripper, meaning the FRE Mattress Gripper is pushing the spherical object to the center of the gripper. The end of the FRE Mattress Gripper shows a similar slope to the Basic FRE Gripper, meaning no centering is done at the tip of the gripper finger. Also, the sides at x=-12 and x=12 show a force directing the spherical object away from the gripper in both grippers. The FRE Mattress Gripper showed no centering at the edges of its gripping surface. However, the plot already shows a greater area on the gripper surface where centering was occurring and also shows a decreased force with which the object was pushed away at the edges of the gripper.

Deformation plots

Deformation plots show how far each part of the geometry has displaced for a load case at a given coordinate. This differs from the previous plots, as those include the load cases at all coordinates. The deformation was plotted per load case. As shown in the plots provided in fig. 5, the darker the color, the higher the displacement at that location on the geometry. The plots show how the FRE ensured that the tip of the gripper moved towards the load, resulting in a relatively small displacement at the tip of the gripper finger. This happened similarly in both cases.



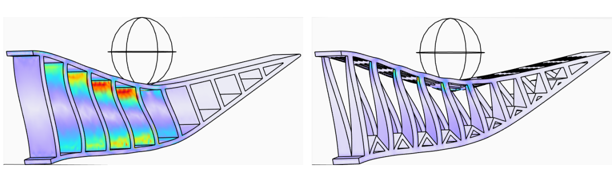
(a) Basic FRE Gripper (b) Final Design Gripper

Figure 5: Deformation plots as result of a u=0.015m displacement of a sphere with 15mm diameter at position (0,60)

It was observed in fig. 5a that the Basic FRE Gripper deformed constantly over its lateral direction, while the sphere only contacted the middle of the gripper. Visually no form-closure along the lateral direction of the gripper was observed. Differently for the FRE Mattress Gripper in fig. 5b, there was visual form-closure observed in both the lateral and longitudinal directions. The large dark area on the Basic FRE Gripper, has changed to a circular and considerably smaller area on the Final Design Gripper.

Stress plots

Stress plots are similar to the deformation plots since they are plotted per load case. The difference is the colouring of the geometry. In the stress plots, the Von Mises stresses (Pa) were plotted over the geometry. This was important to compare peak stresses, and where they occur on the geometry.



(a) Basic FRE Gripper (b) Final Design Gripper

Figure 6: Stress plots as result of a u=0.015m displacement of a sphere with 15mm diameter at position (0,60)

The stress distribution in the FRE Mattress Gripper showed higher peak stresses in the ribs. Where the ribs of the Basic FRE Gripper distributed the stresses along the lateral length of the whole gripper per rib, the FRE Mattress Gripper concentrated the stress at the attachment of the rib to the front sheet of the gripper. Since this connection is relatively small, the peak stresses were found to be about two to three times higher than in the Basic FRE Gripper.

Fin Ray Effect performance

The FRE performance was monitored to provide insight in the loss or gain of FRE. The expectation that conceptual changes in the design might affect the FRE performance was true. However, no loss of FRE performance was found for the FRE Mattress Gripper. The lowest FRE performance was found in the Basic FRE Gripper, at $P_{FRE} = 0.95$. All other structural and parametric variations showed improvement in the FRE performance compared to the Basic FRE Gripper. The FRE Mattress Gripper showed a FRE performance of $P_{FRE} = 1.07$, which is a significant improvement on the Basic FRE Gripper.

Centering performance

The centering performance was determined by the performance number P_C, which is computed for each coordinate. This resulted in a table of performance numbers for each coordinate (see tables 2 and 3). The number describes the amount of centering occurring at the coordinate. At the coordinates with x=0, no performance number was computed as this coordinate is at the center of the gripper. Therefore, no centering is possible at this coordinate. The results per coordinate (shown in tables 2 and 3) show the difference between the Basic FRE Gripper and the FRE Mattress Gripper. The Basic FRE Gripper showed no signs of centering, with a negative P_C at all coordinates. The FRE Mattress Gripper showed improvement with a P_C of 0 or higher for all inner coordinates. All coordinates at the edge of the gripper (x=12, x=-12 or y=120) showed rejection of the sphere, pushing it away from the gripper. Also, a correlation between the distance to the base of the gripper and the centering performance was observed. The closer the object is to the base of the gripper, the better the centering performance (see table 3).
For other design variations, it was observed that the centering only occurs when the perforation of the front sheet and the triangle ribs are combined. And also, that it significantly increased with the addition of torsion reinforcements. The overall combination enables the centering performance to peak.

x\y	40	60	80	100	120
-12	-0.09	-0.13	-0.17	-0.30	-0.53
-8	-0.04	-0.06	-0.09	-0.15	-0.41
-4	-0.02	-0.03	-0.04	-0.08	-0.11
0	NaN	NaN	NaN	NaN	NaN
4	-0.02	-0.03	-0.04	-0.08	-0.11
8	-0.04	-0.06	-0.10	-0.15	-0.42
12	-0.09	-0.13	-0.17	-0.31	-0.52

Table 2: Basic FRE Gripper Centering Performance (P_C) Table

x\y	40	60	80	100	120
-12	-0.02	-0.03	-0.05	-0.11	-0.26
-8	0.07	0.04	0.02	0.00	-0.11
-4	0.07	0.04	0.03	0.02	-0.06
0	NaN	NaN	NaN	NaN	NaN
4	0.07	0.04	0.03	0.02	-0.05
8	0.07	0.04	0.02	0.00	-0.10
12	-0.02	-0.03	-0.05	-0.11	-0.25

Table 3: FRE Mattress Gripper Centering Performance (P_C) Table

Stiffness

The stiffness showed a decrease from the Basic FRE Gripper to the FRE Mattress Gripper. This was already observed when applying the conceptual characteristics to the Basic FRE Gripper and computing the performance. The removal of material at the ribs and front of the gripper, result in stiffness decrease. Thicknesses can be adjusted to counter this loss of stiffness. Overall, stiffness showed an increase when thickening the segments of the FRE Mattress Gripper. However, the torsion reinforcements showed low impact on the stiffness of the gripper.

Structural and Parametric Variations

Each variation showed how a small variation can impact the overall performance of the gripper. Thereby providing insights in the coherence of the Final Gripper Design.

Each of the structural variations showed no centering performance when applied individually. However, the perforated front and triangle ribs did show centering performance when applied simultaneously. The torsion reinforcements showed an increase in the stiffness performance and also showed a doubled centering performance when added to the perforated front and triangle ribs.

The stiffness decreased for both the perforated front and triangle ribs, while the FRE performance was increased compared to the Basic FRE Gripper in all variations.

The thickness variations showed that the front and back variate the stiffness of the gripper finger. However, the front also impacted the centering performance, as the 2.5mm front showed almost no centering performance, while the 1.5mm front showed an increase. The ribs also influenced the centering and stiffness. However, their thicknesses increased both stiffness and centering performance when increased. The torsion reinforcements thickness variations mainly influenced the centering performance, while the stiffness remained in the same range.

Validation

The validation showed no signs of centering for both the Basic FRE Gripper and the FRE Matrress Gripper (see table 4). However, it did show that the outward forces had been reduced to the point where the sphere was not pushed away from the gripper. The FRE Mattress Gripper showed to have a stable grip on the spherical object, while the unstable grip of the Basic FRE Gripper pushed the sphere outward and away from the gripper.

x-coordinate at y = 60	Basic FRE	FRE Mattress
-16	Out	Out
-12	Out	Still
-8	Out	Still
-4	Still	Still
0	Still	Still
4	Still	Still
8	Out	Still
12	Out	Still
16	Out	Out

Table 4: Results of stability experiment: Ball is pushed away (Out), stays stil (Still) or is pushed inward to the grippers' center (In)

4 Discussion

The structural variation results mentioned in section 3, showed the coherence of the structural segments. The perforated front and triangle ribs showed codependent to induce the mattress effect, while the torsion reinforcements showed important to increase the centering performance. The thickness variations then showed how each section has its own function and thereby thickness. A thinner front showed a decrease in stiffness (15% per 0.5mm thickness) with increased centering performance (2 to 3 times higher for inner coordinates at y=60mm, comparing 1.5mm and 2mm thickness). The back however, showed the opposite. Meaning that a thinner front, can be countered with a thicker back. Resulting in a doubled increase in centering, while keeping the stiffness in the same range. The ribs showed a significant impact on stiffness and centering. Thicker ribs, resulted in increased stiffness (40% increase at y=60,80 per 0.5mm thickness) and centering performance(1.2 to 2.3 times higher for inner coordinates at y=60mm, comparing 2mm and 2.5mm thickness). Thickness of the torsion reinforcements showed small impact on both centering performance (1.2 times higher for inner coordinates at y=60mm, for 1mm increased thickness) and stiffness (2% to 7% increase for 1mm thickness increase) and were therefore better kept relatively thin. Their presence did prove a great increase in the mattress effect by countering the rotational DoF of the basic FRE grippers.

The reaction force plots in fig. 4 showed a great increase in centering performance when comparing the FRE Mattress Gripper and the Basic FRE Gripper. The stable gripping area has increased from a line at x=0, to at least 16x100mm. Even at the edges of the FRE Mattress Gripper, where still no centering is occurring, the force pushing the object away has decreased, as the negative P_C has at least halved. The centering performance numbers (shown in tables 2 and 3) confirm the centering in the FRE Mattress Gripper and the decreased force at the edges of the gripper. Although the centering forces seem to remain small, centering is occuring. The improvement of the outward pushing forces to the smaller centering forces is very notable. The centering performance is also confirmed by the deformation plots shown in fig. 5. The deformation plots clearly showed how the spherical object sinks into the FRE Mattress Gripper as if it is pushed into a mattress. The gripper thereby form-closes around the object, while the Basic FRE Gripper clearly shows no such behaviour.

The FRE performance showed no loss, which was confirmed by the deformation (shown in fig. 5) and stress plots (shown in fig. 6). The figures showed no visible sign of FRE performance loss. The stress plots did show a great difference in stress distributions. The stress was mainly in the connection of the ribs to the front and back of the grippers. The Basic FRE Gripper could distribute that over a greater volume, while the FRE Mattress Gripper concentrated the stress in the small attachment of the ribs to the front sheet. The stresses did increase significantly. However, they did not increase enough to cause problems with plastic deformation or even buckling or breaking of the ribs.

The validation did not confirm any centering. This had to do with the friction in the axle of the sphere and in the linear slider. Especially the linear slider seemed to suffer extra friction when loaded with a moment. The centering force of the FRE Mattress Gripper was not high enough to overcome that friction, while the force of the Basic FRE Gripper, pushing the sphere away, was. The validation did confirm that the FRE Mattress Gripper acquired a stable grip on the spherical object, while the Basic FRE Gripper showed to have an unstable grip.

The model showed that spatial and asymmetric design of FRE gripper fingers can have a great impact on their performance. Thereby, the model is of great help at acquiring insights and performance criteria for FRE gripper fingers. Many variations of FRE gripper designs on structural, material or parametric variations, can be tested and compared through the model, showing a great addition to future research in this field. Even the load applied, can be altered to test for different load cases. That way, a design can be tested and optimized for a certain specific load case.

Although the model has proven to be a great addition in FRE gripper design, it is not considered as the real world and has to be used with cause. As incorrect use might lead to faulty or non-converging results. Results and their deviations from the real world will differ per case. It is therefore important to at least check the data for counter-intuitive results and best to build the design in the real world and compare it to the model. Wrong meshing for instance, can lead to high stress concentrations, far beyond realistic results.

5 Conclusion

This paper present a new spatially designed form-closed FRE gripper. The envisioned mechanical behaviour is similar to a mattress, where a spherical objects sinks into the structure and the structure spatially forms around the object. First, the structure is designed using FACT Method to determine the compliant and constraint topologies of the structure. Thereby creating the mattress effect and even centering behaviour. Resulting in 5 structural design variations containing three structural segments: the perforated front, the triangle ribs and the torsion reinforcements. Second, the structural design features were parameterized and a FEM model is build using LiveLinks between SolidWorks, COMSOL Multiphysics and MATLAB, to optimize for the established performance metrics P_C, P_{FRE}

and K.
The model is a nonlinear frictionless contact mechanics FEM model and calculates the deformations, reaction forces and performance of a gripper loaded with a rigid and frictionless sphere at multiple positions. The results from the model provided parametric design guidelines. A medium front, thin TR and thicker ribs and back came out as the best design, resulting in the FRE Mattress Gripper. The FRE Mattress Gripper compared to the Basic FRE Gripper, showed an increase in centering area, from a line at x = 0mm, to an area of at least 16 x 100mm. The P_{FRE} shows an increase of 11% and the stiffness a decrease of at most 35% and an average 23%.
An experiment showed the stability of the Basic FRE Gripper and FRE Mattress gripper, while gripping a spherical object. Tthe Basic FRE Gripper suffered from unstable gripping situations and losing the spherical object from its grip when misaligning the sphere at least 8mm from the center, while the FRE Mattress Gripper showed a stable grip for all positions within its gripping surface.

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Appendices

The appendices contain extra information regarding the overall thesis project.

Important note: The appendix has its own independent bibliography.

A Definitions

DoC	Degree(s) of Constraint
DoF	Degree(s) of Freedom
FACT	Freedom And Constraint Topology
FRE	Fin Ray Effect
PCHIP	Piecewise Cubic Hermite Interpolating Polynomial
RF	Reaction Force(s)
TPU	Thermoplastic PolyUrethane
TR	Torsion Reinforcements
SW	SolidWorks

Table A.1: Abbreviations

Perpendicular Direction	Spanning the depth of the gripper. The depth of the gripper is considered the direction perpendicular to the front sheet.
Form closure	When the gripper encloses the object it is gripping. Form closure helps to constrain an object in the grip of the gripper.
Lateral Direction	Spanning the width of the gripper. The width of the gripper is considered the short side of the front sheet.
Longitudinal Direction	Spanning the length of the gripper. The length of the gripper is considered the long side of the front sheet.
The Fin Ray Effect	The FRE is caused by the triangular shape with ribs and concerns the movement of the structure towards the load instead of along with the direction of the load.
Torsion reinforcements	Structural additions to provide higher torsional stiffness to the structure.

Table A.2: Definitions

Variable	Definition	Value
$model$	COMSOL Model loaded into MATLAB	1x1 ModelClient
$VariantName$	Variant name to run COMSOL-SW model and save data	1x1 string
$CoordName$	Coordinates in string form for data saving purposes	1x1 string
$ThickName$	Name for thickness variation for data saving purposes	1x1 string
x_{co}	Vector with x coordinates to run	$[x_1, x_2, ...]$ 1xx_n double
y_{co}	Vector with y coordinates to run	$[y_1, y_2, ...]$ 1xy_n double
$tFront$	Parameter for thickness of the front sheet	1x1 double
$tFlex$	Parameter for thickness of the wire flexures on front sheet	1x1 double
$tRib$	Parameter for thickness of the ribs	1x1 double
tTR	Parameter for thickness of the torsion reinforcements	1x1 double
$tBack$	Parameter for thickness of the back sheet	1x1 double
n	Amount of iterations per load case in COMSOL	1x1 double
F_{grip}	Constant gripping force to interpolate for	1x1 double
$RFdataRAW$	Raw RF output data extracted from COMSOL $[Nm^3]$	2D Array
$ErrorLog$	List of encountered errors during computation	..x1 string
$ErrorCount$	Amount of encountered errors during computation	1x1 double
$tstudy$	Time passed to run the model in seconds	1x1 double
$coordinates$	List of coordinates in chronological computation order	$(x_n \cdot y_n)$x2 string
$StressPlots$	Plots of stress distributions for every coordinate	$(x_n \cdot y_n)$x2 cell
$DefPlots$	Plots of deformation for every coordinate	$(x_n \cdot y_n)$x2 cell
u	Displacement of spherical object per iteration step	$(n$+1)x1 double
u_{max}	Maximal displacement of the spherical object	1x1 double
u_F	Displacement at (0,60) to interpolate F_{grip} for	1x1 double
u_{cF}	Displacement at every coordinate for F_{grip}	x_n x y_n double
V_{sphere}	Volume of the spherical object	1x1 double
RF_x	Reaction Force in x-direction data	$(n$+1)x$(x_n \cdot y_n)$ double
RF_y	Reaction Force in y-direction data	$(n$+1)x$(x_n \cdot y_n)$ double
RF_z	Reaction Force in z-direction data	$(n$+1)x$(x_n \cdot y_n)$ double
RF_xcF_z	RF_x per coordinate for constant RF_z	x_n x y_n double
RF_ycF_z	RF_y per coordinate for constant RF_z	x_n x y_n double
P_{fre}	Performance number for FRE	1x1 double
P_c	Centering performance per coordinate and iteration	$(n$+1)x$(x_n \cdot y_n)$ double
P_ccF_z	Centering performance with constant RF_z	x_n x y_n double
K	Stiffness per coordinate and iteration	$(n$+1)x$(x_n \cdot y_n)$ double
KcF_z	Stiffness per coordinate for constant RF_z	x_n x y_n double

Table A.3: MATLAB Variables

B Festo FRE Gripper Limitation Analysis

The current Festo FRE Gripper Design has proven to be very versatile already. The gripper is already widely used and common as it has good value for the price. The monolithic and simplistic design keeps manufacturing costs low and the underactuation characteristics and stiffness has proven to be versatile. It is therefore used to grip and reposition many items. However, the current design still has limitations and therefore serves as a starting point for this research. From this widely used and proven design, some limitations are brought to the surface and possible solutions for those limitations are noted. The further research is intented to tackle the spherical object limitation mentioned in appendix B.2.

B.1 Unable to grip soft objects

The current Festo FRE Gripper is unable to grip soft objects like bags of soup or chips. This issue comes from the stiffness of the gripper. The gripper is designed with a certain stiffness that makes it versatile to grip many objects. However, the gripper is too stiff for soft objects. The underactuation requires forces from the object it is gripping to shape the gripper around the object. A soft object does not give sufficient force on the gripper to create the necessary shape to surround the object.
The core of this issue is the low in-plane stiffness required to form the gripper around the object, while also requiring high in-plane stiffness and perpendicular support stiffness when moving the object.

Figure B.1: Festo DHAS grippers grabbing a bag of chips.

Regulating the stiffness

By regulating the stiffness of the gripper in different gripping positions, the gripper would be able to softly shape around soft objects, after which it can lock the object by increasing the stiffness and thereby locking its configuration. To regulate the stiffness, varying methods can be applied.

- **Layer Jamming [5]**
  Layer jamming has been applied already to FRE mechanisms and shows a sudden increase in stiffness when the gripper reaches a certain deformation. The layered ribs in the FRE gripper start making contact if the deformation is sufficient and thereby limit the motion. The FRE gripper starts 'layer jamming' and thereby provides a higher stiffness.
- **Hydraulics and sheets [7](Soft Robotics- Octopus Inspired Gripper)**
  Already performed by Soft Robotics. This method uses a change in pressure to either press sheets on top of each other, creating stiffness characteristics of a beam, or leave the sheets floating in a medium at which the sheets have stiffness characteristics of sheets. The sheets move much more freely and bend easy compared to the pressed sheets that form a beam-like structure.
- **Phase Shift**
  By phase shifting a medium (e.g., water to ice), different stiffnesses can be achieved. The method, simply said, freezes the gripper in a certain configuration and thereby increases the stiffness highly. Phase changes are known to be relatively slow, so this might cause problem in high-speed applications.
- **Bi-Stable Mechanism with 2 states**
  Use a bi-stable switch to increase the stiffness when desired. The idea is quite abstract and the application to the gripper might be complex.

Softening the in-plane gripping stiffness, while maintaining gripping support stiffness

The in-plane gripping stiffness can be low to help the underactuation form around the object. However, it must have high supports stiffness perpendicular to the plane and high in-plane stiffness when formed around the object. This is a challenge as it is one-way stiffness desired in-plane.

- **Pre-tensioning the gripper to form around the object / Design in actuated state [12]**
  By adding pre-tension that pushes the gripper form around the object, while fighting to leave that enclosed form, one-way stiffness can be approached. This can also be done by designing the resting position of the gripper close to the actuated state. The gripper would then have to be opened with an actuator. This can be done by a fixed constraint on the inner ends of the gripper fingers, while rotating the outer ends around that fixed point.

- **Asymmetry to create a preferred bending direction [2, 5]**
  By creating asymmetry and angling the ribs of the FRE in a certain direction, the gripper will have a preferred bending direction which is the direction folding around the object. This increases the ability to easily bend around the soft object.

B.2 Hard to grip onto lateral round or spherical objects

Round objects are hard to grip unless they are perfectly aligned with the grippers. Cone shaped and round object tend to slide off the gripper fingers and even shoot away. This causes problematic and even dangerous situations.
The core of this issue has two components. The first component is the rotational DoF in the FRE gripper finger (shown in fig. B.3). This DoF causes the gripper to open-up when a non-parallel surface is pressed into the gripper. When two are positioned in-line to grab object, this DoF causes the issue at hand. The second component is the fact that the grippers are now force-gripping using friction onto the object in the direction perpendicular to the plane of the two grippers (see fig. B.2). In the longitudinal direction, the object is gripped by form-closing around it. The gripping by friction in lateral direction however, is far less effective. Insufficient friction causes the round objects to slip and shoot out of the gripper.

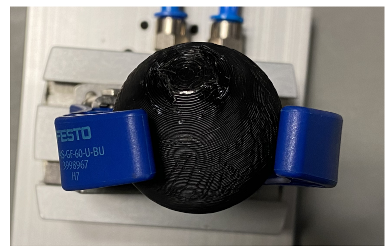


Figure B.2: High Friction Spherical Object

Adding torsional constraint to the gripper

To tackle the first problem, the rotational DoF, a torsional constraint can be added. The FRE Gripper acts as a sheet that rotates around its length. Tackling this problem is therefore sought after in literature concerning the rotational stiffening of sheets.

- **Adding Torsion Reinforcements to the outer sheet [13]**
  The gripper only uses one side to grip the object. The other side remains untouched and can therefore be expanded to add an extra constraint in this case. The symmetrical design of the current Festo Gripper is not mandatory to keep manufacturing costs low.

- **Designing the outside sheet as rigid body-hinge combinations [8]**
  This is an extra step onto the torsion reinforcements. By applying rigid bodies with hinges for the outside of the gripper finger, much higher rotational stiffness can be achieved.

- **Adding multi-material to increase stiffness in certain areas of the gripper [14]**
  A multi-material gripper might pose a great solution to increase the rotational stiffness of the gripper, while ensuring low stiffness to shape the gripper around the object. However, manufacturing does become much more complicated as the materials must be attached to each other.

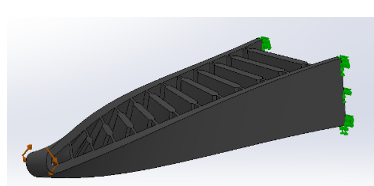


Figure B.3: The rotational DoF

Form-closing around the object in two directions

- **Change the grip-surface shape to be more rounded and cup-shaped**
  Changing the shape of the surface to be more rounded and cup-shaped might help to grip round objects. Cone-shaped objects, however, remain hard to grip.

- **Add underactuation direction to shape the gripper around the object in two directions**
  By using underactuation not only to fold along the length of the gripper, but also around the sides, the object can be form-locked all around. This would tackle the problem with force-gripping by friction.

- **Creating a mattress-like effect**
  By creating a mattress-like effect for the object, the object will sink into the surface of the gripper. The gripper will thereby form-close around the object.

B.3 Hard to grip objects with sharp edges

Object with sharp edges (e.g., a cube) are hard to grip for the Festo FRE gripper. This has to do with the inability of the gripper to enclose around the edge of the object. Objects with more rounded shapes are much easier to grip since the gripper can easily enclose those objects and create a distributed load to carry the object around.
The core of this issue is the inability of the gripper to enclose the sharp edges. The gripper cannot adapt its shape into such a sharp angle. This also has to do with the gripper being compliant. The PRBM version of the gripper has set points of rotation at the hinges and has more options to enclose the sharp edges.

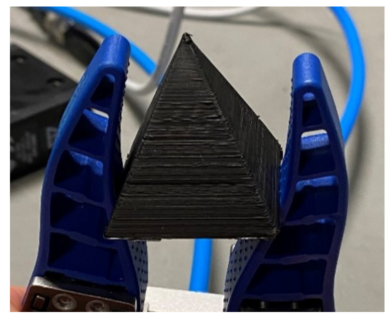


Figure B.4: Sharp edged object

Adding hinge-like rotational pivots on the gripper [4]
By adding hinge-like rotational pivots, the gripper has better adaptability to the sharp edges. Every hinge can shape itself to a corner in which an edge of the object can rest. This solution is based on the PRBM version of FRE grippers in which hinges are applied.

Softer material for the gripping surface
When using soft material for the gripping surface, the object will somewhat submerge into the soft material. This is positive for the gripping surface providing friction to lift the object. Though, as said before, the material stiffness has been designed to fit a large range of applications. Changing the stiffness of the gripper might cause problems for applications where a higher stiffness is desired or even needed. Multi-material designs might be possible, but monolithic design is a highly desired characteristic in current designs.

B.4 The support stiffness decreases when actuated

The support stiffness of the Festo FRE Gripper decreases when the gripper deforms away from its straight resting position. This causes problems for high speed applications in 3D spaces in which the gripper is used to move items with large accelerations. The gripper then tends to lose the objects due to the sideways forces on the gripper, caused by those accelerations. The core of this issue lies with same rotational DoF as mentioned in appendix B.2. This rotation causes a translation when the gripper is actuated. The point of the gripper can move out of the plane when the gripper is actuated because of this rotational DoF (see fig. B.3). This rotation therefore turns into translational movement when the gripper is moving at high accelerations. Since this issue comes from the same core issue as the second issue, the solutions are the same and therefore not duplicated for this subsection.

C Extensive Design

This section of the appendix elaborates on the whole design phase of this research project. This includes alternate discarded designs and ideas. The problem at hand is the spherical object limitation for the current FRE grippers.

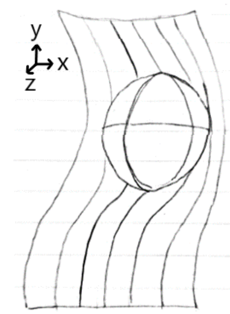


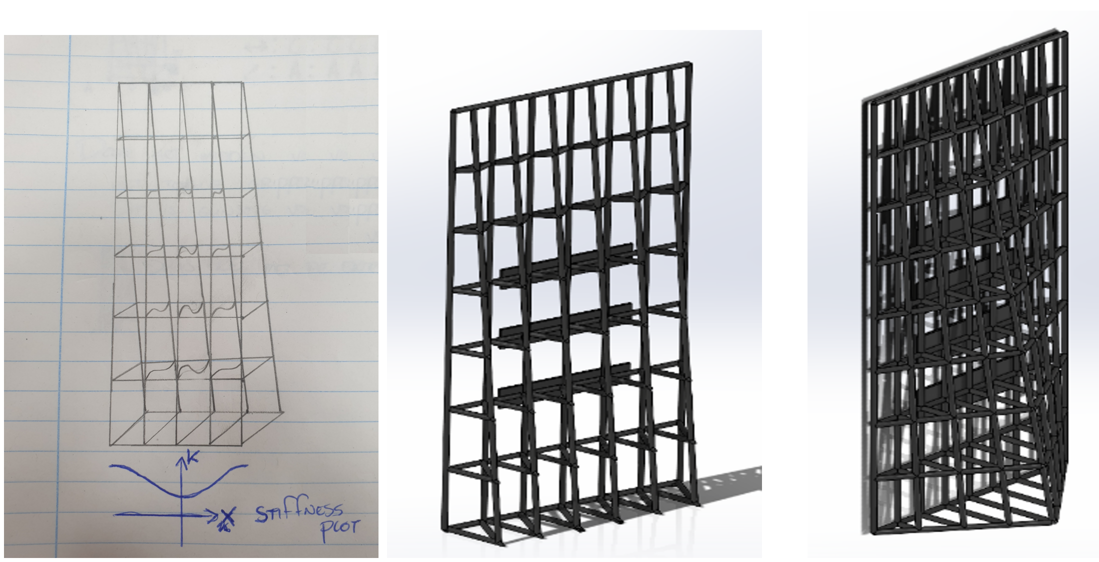
Figure C.1: Mattress effect illustration

C.1 The initial idea

The initial idea with which designs are created, is to form-close both in longitudinal and lateral direction around the object. This can be done by creating a mattress-like surface. Where the objects sinks into the surface and the surface forms around the object. Thereby form-closing around the object at hand. This effect is shown in fig. C.1. The idea is to bring most of the stiffness to the edges of the gripping surface, while the inside surface is more compliant to the displacement of the sphere. This idea helps in form-closing around the object, while also creating a better force distribution on the object and might even create a centering effect. While centering is not necessary for the design to grasp spherical object, it does help for situations with slip as the sphere would only be pushed more towards the middle of the gripper finger. Thereby increasing the grip of the gripper finger onto the object.

C.2 The first designs

The conceptual design first considers the kinematics before applying the mechanical requirements. By first finding kinematically suitable concepts, the design space is kept open for creativity. By later applying and iterating for mechanical properties, the final design is established.
A number of initial designs were considered in the design stage of the research. Although only one design/method was used and further elaborated to use in this research, some discarded design options are shown in fig. C.2.



(a) Spring Ribs FRE gripper (b) Parallel FRE Gripper (c) The two-way FRE Gripper

Figure C.2: Alternate designs from the design phase

The FACT Method [6] was applied for the design that is used in the research. FACT method uses Degrees of Freedom (DoF) and Degrees of Constraint (DoC), to visualize the possible flexure based designs that are possible for the situation at hand.
Before the FACT design is proceeded, the basic FRE gripper is cut into segments in a functionality analysis. Each segment has its own function within the gripper and might have new functions for the new design.

This segmentation creates the possibility to design the new FRE gripper asymmetrically.

Functionality Analysis

For the structural design of the concept, the FRE structure is divided into three parts. Each part has its own function within the FRE structure and is considered separately to provide the new functionalities needed for the new concept.

The front sheet is the side of the FRE gripper that makes contact with the product. This part has to apply pressure to the object, while deforming around the object and maintaining its length. The constant length might seem unimportant at first, but is very essential for the FRE effect to work. The shape adaptation is the most notable functionality of the front sheet. In the basic FRE grippers, it only has to shape in its length. However, for the new design it has to shape around the object in two direction, the lateral and longitudinal directions. However, since the front sheet is a smooth sheet, the tape measure effect becomes a problem(shown in fig. C.3). A smooth sheet cannot curve two ways at ones, as it will start folding one way instead of smoothly curving.

Kinematically, the ribs provide the connection between the front and back sheet. Thereby enabling the FRE. They provide an essential link between the two to enable the FRE. They also provide stiffness to the structure. Thicker ribs ask for more actuation force to deform the gripper and activate the FRE.

The back sheet provides stiffness to the FRE structure and has to maintain its length just like the front sheet. It experiences tension when the gripper is actively gripping an object. The main functionality is to maintain its length and take on the tension. For this functionality, it can be build out of wire flexures and still provide the FRE [10].

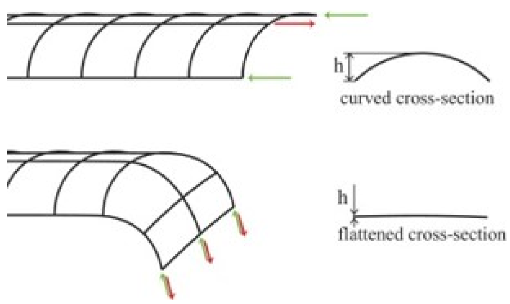


Figure C.3: Measure Tape Fold [11]

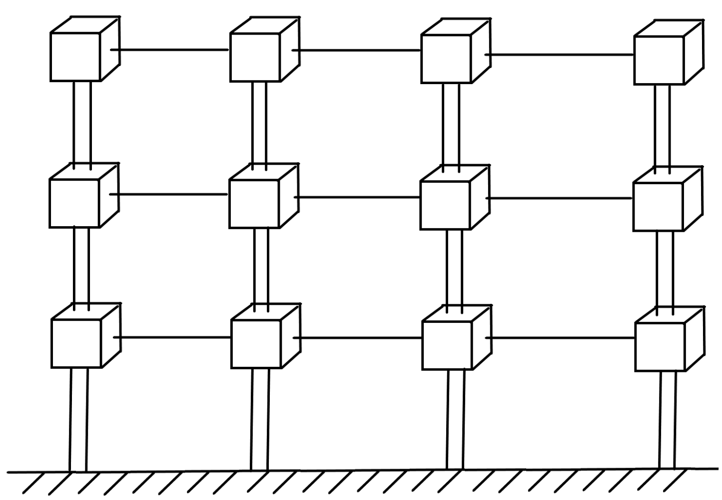


Figure C.4: Front Sheet FACT design

The FACT method design

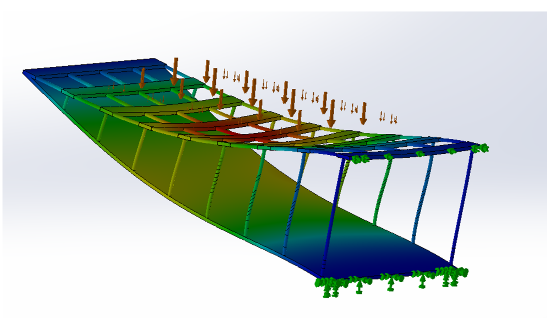
FACT Method [6] is applied to acquire an understanding in the minimal mechanical requirements of the gripper. This method is used to develop a basic design for this research case, and also to develop a greater understanding in the functionality of FRE grippers. Since the most important deformation is at the front sheet, this segment is evaluated by FACT method and redesigned.

First, the front sheet was evaluated by applying the FACT method. Since the front sheet is a sheet without a necessary end-effector. The FACT method would not do much. However, the front sheet is split up into an arbitrary amount of solid blocks (end-effectors) connected by wire flexures (see fig. C.4). This creates an understanding in the kinematic constraint of each block in the front sheet and of the whole front sheet itself. Each block is horizontally connected and coupled with blocks at the same level. Vertically, each block receives its constraints. The desired constraints only contain a rotation and translation, provided by the two wire flexures, the DoC. Each block should be able to rotate around the vertical and horizontal axis and to translate on the out-of-plane and horizontal axis, the DoF. The rotation around the vertical axis and translation on the horizontal axis allow for curvature of the sheet around the longitudinal axis of the gripper, while rotation around the horizontal axis and out-of-plane translation allow for the FRE deformation to occur. These DoF are therefore necessary for the front sheet to enable it to form close around the object in both lateral and longitudinal directions.

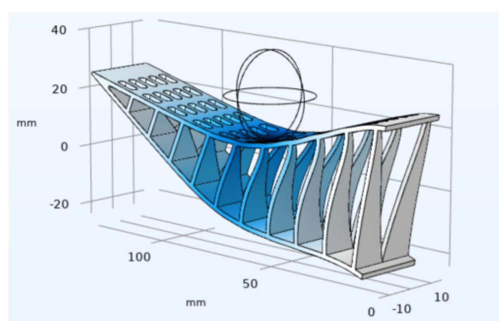
The horizontal blocks are coupled by only one wire flexure. However, this coupling can be expanded to three in-plane wire flexures, which equals a sheet flexure. By applying a sheet flexure, the mass, stiffness and gripping surface is increased, while maintaining the desired DoF. So sheets are chosen.

It was already shown that the ribs and back of a FRE gripper can only exist of wire flexures [10]. Therefore, the first minimal design uses simple wire flexures for the ribs, while maintaining a sheet for the back sheet. Resulting the first FACT method design, shown in fig. C.5a.

This first design was already performing kinematically. However, it is a mechanically weak design. The parasitic rotational DoF of the whole gripper is occuring heavily due to the lack of stiffness and the overall design shows to be very weak. Therefore, the design was redesigned as the design shown in fig. C.5b. The front sheet has perforations, countering the tape measure effect and thereby allowing for the two-way deformation of the sheet. The ribs have triangular cuts, allowing for the deformation of the front sheet, while concentrating stiffness to the edges of the gripping surface and maintaining material and therefore stiffness in the design. The rotational DoF however, is still present.



(a) First FACT Design



(b) Final FACT Design

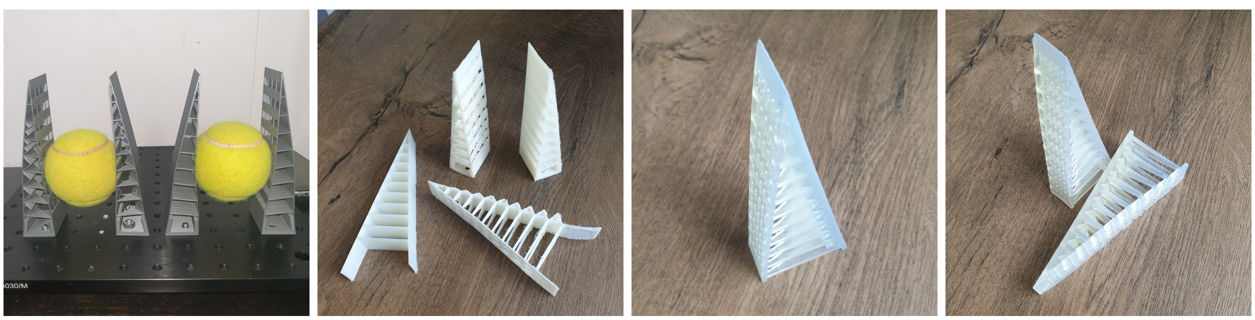
Figure C.5: Structural FACT concept designs

Torsion reinforcements

The basic FRE design opened its grip when grippig a lateral round object. This is due to the rotational DoF along its longitinal axis. In order to counter this DoF, which is unwanted for lateral round objects, torsion reinforcements (TR) are included in the design. Torsion reinforcement have proven to be an effective strategy to counter rotational DoF for sheet flexures in compliant mechanisms [9, 13, 15]. The basic FRE gripper and also the Final FACT concept design, can be considered as two sheets that cross at the tip of the FRE gripper. The ribs in between the sheets do not constrain the rotation, since the ribs are not connected to the fixed world, nor do they cross the same intersection as the front and back of the FRE grippers. The rotational DoF can be constrained by adding extra connections to the fixed world using FACT method [6] again. However, extra connections to the fixed world are considered undesirable as it will probably interfere with the FRE due to the change in structure. Addition of TR on the back sheet however, only influence the rotational DoF of the back sheet en therefore the whole geometry. For this research the triangular design from Rommers 2018 [13] is taken and applied to the back sheet of the FRE gripper finger. This design can be made into a relatively low volume design, to keep the added volume low and to prevent interference of the TR with either the outside world, or other segments of the gripper itself. The back sheet is chosen as the location since it mainly functions for stiffness and FRE. the TR do not interfere with that functionality, but even add to it. The TR are placed on the inside of the gripper, so they do not take any extra space in the outside world where the gripper has to function. And therefore, not compromising the workspace requirements of the gripper.

C.3 Prototypes

During the research, prototypes were built to gain insights in the behaviour of the gripper design at that stage. These prototypes used different materials, thicknesses and design variations. All prototypes were built by 3D printing and the available materials were limited. Other manufacturing methods such as injection moulding or assembly of parts were considered unnecessarily complicated, due to the structure of the FRE Mattress Gripper and the available tools.



(a) PLA (b) Flex45 (c) Flexible 80A (d) Elastic 50A

Figure C.6: Prototypes

Materials used for prototyping from hard to soft: PLA, Flex45, FormLabs Flexible 80A and FormLabs Elastic 50A.

The PLA material was used in the beginning of the project due to the easy accessibility at the university. This way rapid prototyping was achieved to gain quick insights in the structure and its effect. However, the material is considered very stiff for the gripper application and was prone to break. It is therefore not considered a suitable material for the FRE Mattress Gripper.

The Flex45 material was used a lot for prototyping and is also used for the prototypes in the validation experiment. This material is relatively stiff, compared to the TPU intended for the FRE Mattress Gripper. However, it proved to be the best suitable material for the experiment, due to its flexibility and fast spring back properties. The higher stiffness was countered by decreasing the overall thickness of the geometries. This material did use a lot of support material, which had to be removed quite delicately to not damage the gripper in the process. However, with a small design tweak (repositioning the torsion reinforcements) the support material was minimized.

The FormLabs Flexible 80A was a promising material. The material is printed in a resin bath and the gripper could therefore be printed without any support material, keeping the prototype very clean. The flexibility was closest of all materials to the intended flexibility. However, the material had very slow spring back properties. Meaning, that the gripper would deform very slow compared to other materials. This is an undesired property, as gripping an object often happens quite fast. Therefore, this material was discarded for further prototyping.

The FormLabs Elastic 50A is also a resin based material. Resulting in no support material and a clean prototype. However, the material was prone to bad connection at the connection of the ribs and front sheet. Resulting in a lot of disconnected ribs. Also, the material was too elastic, causing the gripper unable to exert any significant force onto an object. The material was almost gum-like and even thickening the geometry did not improve the prototype to a notable extent. The material was therefore discarded as a prototyping material.

D The Model

This appendix extensively describes the model that was built to help design the Spatially Designed Form-Closed FRE Gripper. The model utilises LiveLinks between SolidWorks, COMSOL and MATLAB.

D.1 SolidWorks

SolidWorks is used to create the geometry of the gripper finger. The geometry is built using parameters and equations for the dimensions of the grippers. Those parameters are important, since they are later used to run different parametric variations of the gripper through MATLAB. The parameters used in this research all concern thicknesses of different segments of the gripper finger. However, any parameters can be applied in the model to variate for parametric sweeps.

D.2 COMSOL GUI

The COMSOL GUI is used for the application of the nonlinear FEM contact mechanics. The physics are applied here. The physics in this model consist of nonlinear contact mechanics. To apply the physics, the SolidWorks geometry is loaded into the COMSOL GUI, along with its parameters, through the LiveLink and a sphere is created in the geometry environment. The material properties are chosen, the physics are applied and meshing is done. The meshing is important to check for every new geometry variation. In the model, a sphere is loaded into the gripper finger, causing the gripper to deform and reaction forces and stresses to occur. The results are then computed by COMSOL.

D.3 MATLAB

MATLAB is used to run the COMSOL FEM analysis in a loop for different coordinates, creating a grid of locations at which data is computed. The MATLAB part of the model consists of 2 scripts and 3 functions. When using the model, the scripts are run by the user with the desired input data. The scripts then use the functions to compute the data, progress and interpolate the data and to plot an overview of the resulting data.

The Scripts

The model can be run by using one of the two available script, which are the Data Collection Script and the Data Processing Script. The Data Collection Script (found in appendix D.5) is used to run the model and collect the data. This script applies the Study Run Function and saves the data found while running that function. The Data Processing script (found in appendix D.5) does not run the Study Run Function and instead, loads previously saved data that was computed with the Data Collection Script. It then interpolates and evaluates that data, opening the data for later evaluation and processing.

The Study Run Function

Inputs: *tFront, tFlex, tRib, tBack, tTR, x_co, y_co, model, n*
Outputs: *RFdataRAW, ErrorLog, ErrorCount, tstudy, coordinates, StressPlots, DefPlots, Pfre*

The Study Run Function (found in appendix D.5) runs the study multiple times for each coordinate that is given as an input. Inputs therefore consist of the coordinates to run, but also the parameters, the COMSOL model (*model*) and the amount of steps for the displacement (n).
The function runs the COMSOL study in a for loop with each loop containing a new set of coordinates until all coordinates are done. The data comes out of the COMSOL Model as Reaction Forces [Nm^3] in x-,y- and z-directions. These RF are saved in the 'RFdataRAW' array. If the COMSOL computation does not converge for a coordinate, the function saves that in the ErrorLog and also displays a message, informing the user of the non-converging computation. The non-converged iteration is then removed from the data and the remaining data is stored in the 'RFdataRAW' array. Besides the RF data, the function also saves stress- and deformation plots for every coordinate. The plots saved are the plots of furthest displacement of the spherical object. For non converging coordinates these plots can therefore show a smaller displacement of the spherical object. Also, the P_{FRE} is saved at the (0,60) coordinate. If this coordinate is not included

in the computation, the function will show a warning that the P_{FRE} is not found.

The Interpolation Function
Inputs: *Fgrip, u, RFdataRAW, Vsphere, x_co, y_co, coordinates, ErrorLog*
Outputs: *u_cF, RFx_cFz, RFy_cFz, RFx, RFy, RFz, Pc, Pc_cFz, K, K_cFz, ErrorLog*

The interpolation function (found in appendix D.5) is used to interpolate all values for a constant gripping force (RF_z). The constant gripping force is applied to effectively compare the characteristic changes in performance for different design choices. These choices can vary in structural design iterations, but also in parametric changes. The function starts with isolating the RF_x, RF_y and RF_z data in $[N]$. Since the raw data comes out of COMSOL as the reaction forces on the spherical object in $[Nm^3]$, the data is divided by the volume of the sphere (V_{sphere}) to find the RF in $[N]$.
The interpolation first interpolates to find the displacement u at every coordinate for a constant gripping force RF_z. This gives a single value for the displacement in every coordinate combination, stored in u_{cF}). Then, RF_x and RF_y are interpolated to find their values for the constant RF_z. At last the Interpolation Function also computes the Centering Performance (P_c) and Stiffness (K). These are also computed for the interpolated values at every coordinate to find $P_c cF_z$ and KcF_z.
For the interpolation method, several MATLAB supported methods [1] were considered. Most importantly spline, makima and Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) Interpolation. The spline method shows great behaviour for undulating data. However, the data in this research does not show undulations and therefore the spline method is disregarded. The PCHIP method of interpolation is well known for being shape preserving [3], but bad for undulating data. PCHIP is great at preventing overshoot and aggressively reduces undulations. Makima is similar to PCHIP, but not as aggressive. Not unimportant is the computation times. Spline is the most expensive in computation time with makima coming in second [1]. PCHIP is the fastest in computation time and memory requirements. Overall PCHIP interpolation is considered the best option for this research, as data shows almost no undulations and shape preservation is desired. Also, considering the computation time and the amount of interpolations executed in this research, PCHIP interpolation is best suited.

The Plot Function
Inputs: *x_co, y_co, u_cF, RFx_cFz, RFy_cFz, model*
Outputs: *RFfigure*
The plot function (found in appendix D.5) is applied to plot a quick overview of 4 subplots after running the model. This overview plots the displacement, RF_x and RF_y for every coordinate. Also, the displacement, projected onto the undeformed geometry is plotted, to give a visual indication of the displacement at every computed coordinate compared to the geometry.

D.4 Short user's manual

This section explains how to use the model in the same way it was used for this research. Knowledge of SolidWorks, COMSOL Multiphysics and MATLAB is expected.

Files needed:
V5-Full-Concept.SLDPRT
V5-Full-Concept.mph
Data_Collection_Script.m
Data_Processing_Script.m
Study_Run.m
InterpolateFgrip.m
RFplot.m

This user's manual assumes that the provided files are available, so the model does not have to be built from scratch. This manual therefore only provides a user's guide for the existing model.

Modifying the 3D CAD model
In SolidWorks:
1. Build FRE Gripper
2. Use of Parameters for dimensions to be variated
3. Ensure Front Sheet is Vertical.
4. Set-up Parameters to be shared through the LiveLink

In SolidWorks, the geometry of the FRE Gripper is built and the parameters are set-up for the parametric variations. During the build of the FRE Gripper, each structural segment is build in a manner that allows the user to later suppress any of the structural segments individually. This way, the same SolidWorks file can be used to easily create a Basic FRE Gripper, the FRE Mattress Gripper and all variations in between. The parameters can be changed in the equation management menu. Other parameters can also be added in the sketches and then changed from that menu. The parameters have to be set-up for the LiveLink with the COMSOL GUI. This is done in the "Parameter Selection" menu, under the COMSOL Multiphysics tab in SolidWorks. For this research, only the thicknesses were variated and therefore necessary to export to COMSOL.

Setting up the COMSOL GUI
For this part open both the *V5-Full-Concept.mph* file in COMSOL GUI and the *V5-Full-Concept.SLDPRT* in SW. The LiveLink is established by linking COMSOL to the active SW CAD Model.

In COMSOL:
1. Import the geometry including parameters and add the sphere with parameters.
2. Create explicit selections for MATLAB
3. Set-up the Solid Mechanics
4. Mesh the assembly
5. Set-up the result plot groups for extraction to MATLAB

1. The SolidWorks geometry, including parameters, is imported in the *Geometry* section of COMSOL via the LiveLink with SolidWorks. The parameters of the gripper are noted in COMSOL with the prefix 'LL_'. Then, other parameters concerning the sphere and the load case (*u_max*, *n* and *par*), are defined in the *parameters* section and the sphere is created in the *geometry* section. Important is to ensure that the geometry forms an assembly and not an union, since the objects cannot merge together.
2. In *Definitions* there are 2 explicit selections. *Explicit 1* containing the sphere, and *Explicit 2* containing the edge at the tip of the gripper finger. This is done, since MATLAB needs a constant name for the domains, planes edges or points, while COMSOL changes the names/numbers of those for different

situations. The explicit selections therefore prevent MATLAb from extracting wrong data.
3. Next in *Definitions*, the *Contact Pair 1* is defined. Thereby, defining the 4 boundaries of the sphere at the gripper side as the *Source Boundaries* and the front plane of the gripper as the *Destination Boundary*. In the *Solid Mechanics* tab, the *Fixed Constraint 1* is added at the base of the gripper finger. Next, we add a *Contact* node and select *Contact Pair 1*. The gripper is a linear elastic material, which is selected automatically. However, the sphere is assumed a rigid domain. Therefore, the *Rigid Domain* node is used and the sphere is selected. In the *Rigid Domain* node, a *Prescribed Displacement/Rotation* is added to define the displacement of the sphere into the gripper. The displacement is defined using the *par* parameter for the auxilary sweep at the computation.
4. After setting up the physics. The mesh is added. The mesh has great influence on both computation time and accuracy. In this research, sheets were chosen to mesh relatively coarse, while the mesh was refined at edges. Especially inside edges. It is most important to monitor any errors or warnings from COMSOL concerning the meshing.
5. After running the study in the COMSOL GUI once, the results node is visible. By default, *Stress (solid)* and *Contact Forces (solid)* are given. However, *Deformation (solid)* is also desired and therefore added. This is done by adding a *3D Plot Group*, selection *Volume* and then *Deformation*. Each plot group can be given different design features until satisfactory for the user. Make sure that the *Stress (solid)* plot group is "pg1" and the *Deformation (solid)* is "pg3" in the COMSOL GUI. This is important for the MATLAB code, which imports those plot groups.

Running the MATLAB Scripts

If no data is collected yet concerning the desired case, the 'Data_Collection_Script.m' file is used. If data has already been collected and you just want to analyze that data, the 'Data_Processing_Script.m' file is used.
Make sure the relevant SolidWorks file is opened in SolidWorks when running the MATLAB scripts, otherwise the model cannot change the parameters of the geometry.

In the Data Collection Script:
1. Addpath for the important storage locations
2. Fill in the variables, coordinates, name variations, amount of steps and (0,60) sphere displacement
3. Run the script to collect the data and plot results

In the Data Processing Script:
1. Addpath for the important storage locations
2. Choose data set by variant names
3. Fill in (0,60) sphere displacement
4. Plot Deformation or Stress by Plotnum in *Coordinates* Array

D.5 MATLAB code

MATLAB variable definitions can be found in table A.3.

The Data Collection Script

```
%% Startup
clear all
close all
clc

addpath('N:\TU Delft\MSc Thesis\Model\Functions')
addpath('Data')
addpath('Models')
format shortE

import com.comsol.model.*
import com.comsol.model.util.*
ModelUtil.showProgress(true);

%% Set up the variables to run:
% Set the geometry parameters in mm
tFront  = 2;       % Default 2mm - Front Sheet Thickness
tFlex   = 2;       % Default 2mm - Front Sheet Flexure Width
tRib    = 2.5;       % Default 2mm - Thickness of Ribs
tBack   = 2.5;       % Default 2mm - Back Sheet Thickness
tTR     = 1.5;       % Default 2mm - Torsion Reinforcements Thickness

% Set the desired XY coordinates
x_co    = [-12: 4: 12];
y_co    = [40:20:120];

% Set up the name of the data-file
VariantName = 'V5-Full-Concept';                  % Structural Variant
CoordName = 'x -12 4 12 - y 40 20 120';           % Coordinates
ThickName = 'tFront 2mm';                                 % Thickness Variation

% Set amount of steps for the Auxilary sweep
n       = 8;        % Default n = 8

% Sphere displacement at (0,60) to interpolate for
u_F = 0.0125;

%% Run the Study Function

model = mphload(VariantName);
[RFdataRAW,ErrorLog,ErrorCount,tstudy,coordinates,StressPlots,DefPlots,Pfre] =
    Study_Run(tFront,tFlex,tRib,tBack,tTR,x_co,y_co,model,n);

%% Save Data from Study
save(strcat('Data\',VariantName," - ",CoordName," - ",ThickName,'.mat'),'RFdataRAW',
    'x_co','y_co','tFront','tFlex','tRib','tBack','tTR','StressPlots','DefPlots','n'
    ,'ErrorLog','coordinates','tstudy','Pfre')

%% Interpolate the data for Fgrip = Constant
% Extract parameters from model:
u(:,1) = 0:1/n:1;
u_max = mphevaluate(model,'u_max');
u = u*u_max;    % u is the distance of the sphere moving into the gripper.
Vsphere = mphevaluate(model,'Vsphere');

% Call Interpolation Function for constant Fgrip:
[Fu,u_cF,RFx_cFz,RFy_cFz,RFx,RFy,RFz,Pc,Pc_cFz,K,K_cFz,ErrorLog] = InterpolateFu(u_F
    ,u,Vsphere,RFdataRAW,x_co,y_co,coordinates,ErrorLog);
Fgrip = Fu;

%% Plot the data:
[RFfigure] = RFplot(x_co,y_co,u_cF,RFx_cFz,RFy_cFz,model);
```

```
        set(gca,'Color',[.98 .98 .98])
        sgtitle(strcat(VariantName," - ",ThickName," ",'Data'," for Fgrip = ",num2str(Fgrip)
            ,'[N]'),'Interpreter','none');
```

The Data Processing Script

```matlab
%% Startup
clear all
% close all
clc

addpath('N:\TU Delft\MSc Thesis\Model\Functions')
addpath('Data')
addpath('Models')
format shortE

import com.comsol.model.*
import com.comsol.model.util.*
ModelUtil.showProgress(false);

%% Choose data set by name
VariantName = 'V5-Full-Concept';
CoordName = 'x -12 4 12 - y 40 20 120';
ThickName = 'tFront 1_2';

% Sphere displacement at (0,60) to interpolate for
u_F = 0.0125;

%% Import Data and COMSOL Model and modify dimensions

load(strcat(VariantName," - ",CoordName," - ",ThickName,'.mat'));
model = mphload('V5-Full-Concept');
model.param.set('LL_t_front',strcat(num2str(tFront),'[mm]'));
model.param.set('LL_t_flex',strcat(num2str(tFlex),'[mm]'));
model.param.set('LL_t_rib',strcat(num2str(tRib),'[mm]'));
model.param.set('LL_t_back',strcat(num2str(tBack),'[mm]'));
model.param.set('LL_t_TR',strcat(num2str(tTR),'[mm]'));

%% Interpolate the data for Fgrip = Constant

% Extract parameters from model:
u(:,1) = 0:1/n:1;
u_max = mphevaluate(model,'u_max');
u = u*u_max;    % u is the distance of the ball moving into the gripper [m]
Vsphere = mphevaluate(model,'Vsphere');

% Call Interpolation Function for u_F at (0,60) %
[Fu,u_cF,RFx_cFz,RFy_cFz,RFx,RFy,RFz,Pc,Pc_cFz,K,K_cFz,ErrorLog] = InterpolateFu(u_F,u,Vsphere,RFdataRAW,x_co,y_co,coordinates,ErrorLog);
Fgrip = Fu;

%% Surface plot the data.

[RFfigure] = RFplot(x_co,y_co,u_cF,RFx_cFz,RFy_cFz,model);
sgtitle(strcat(VariantName," - ",ThickName," ",'Data'," for Fgrip = ",num2str(Fgrip),'[N]'),'Interpreter','none');

%% Plot any point (See Coordinates array for PlotNum corresponding to Coordinates)
PlotNum = 17;    % Default set to 17

figure
mphplot(StressPlots(PlotNum,:));        % Choose StressPlots or DefPlots to plots
set(gca,'Color',[.98 .98 .98])
title(strcat(VariantName," - ",ThickName," ",coordinates(PlotNum,2)),'Interpreter','none')
```

Study Run Function

```
function [RFdataRAW,ErrorLog,ErrorCount,tstudy,coordinates,StressPlots,DefPlots,Pfre
    ] = Study_Run(tFront,tFlex,tRib,tBack,tTR,x_co,y_co,model,n)

% Create Coordinates String Array
coordinates = strings(length(x_co)*length(y_co),2);
for i = 0:length(x_co)-1
for j = 1:length(y_co)
coordinates(i*length(y_co)+j,:) = [num2str(i*length(y_co)+j) strcat("(",int2str(x_co
    (i+1)),",",int2str(y_co(j)),")")];
end
end


tstart = tic;
RFdataRAW = zeros(n+1,1);

ErrorLog = ["ErrorLog"];
ErrorCount = 0;
StudyCount = 0;
StressPlots = cell(length(x_co)*length(y_co),2);
DefPlots = cell(length(x_co)*length(y_co),2);

xyz= ['x' 'y' 'z'];
count = 0;

% Set all parameters to their chosen value
model.param.set('n',strcat(int2str(n),''));
model.param.set('LL_t_front',strcat(num2str(tFront),'[mm]'));
model.param.set('LL_t_flex',strcat(num2str(tFlex),'[mm]'));
model.param.set('LL_t_rib',strcat(num2str(tRib),'[mm]'));
model.param.set('LL_t_back',strcat(num2str(tBack),'[mm]'));
model.param.set('LL_t_TR',strcat(num2str(tTR),'[mm]'));

for i = 1 : length(x_co)
model.param.set('x_sphere',strcat(num2str(x_co(i)),'[mm]'));       %Set x coordinate
for j = 1 : length(y_co)
model.param.set('y_sphere',strcat(num2str(y_co(j)),'[mm]'));   %Set y coordinate
try
model.study('std1').run                                     %Run the study
% If study succesfull, data is stored
for k = 1:3
DataToWrite = mphint2(model,{strcat('solid.rd1.RF',xyz(k))},'volume','selection','
    sel1');
RFdataRAW(:,count+k) = DataToWrite;
end

catch % Unsuccesfull study (not converged) gives warning, ErrorLog and stores only
    the usefull data
warning(strcat('COMSOL study did not converge for coordinate (',num2str(x_co(i)),','
    ,num2str(y_co(j)),')'))
ErrorLog(end+1,1) = strcat("COMSOL study did not converge for coordinate (",num2str(
    x_co(i)),",",num2str(y_co(j)),")");
ErrorCount = ErrorCount + 1;

% Only store usefull data:
for k = 1:3
DataToWrite = mphint2(model,{strcat('solid.rd1.RF',xyz(k))},'volume','selection','
    sel1');
DataToWrite(end) = NaN;         % Eliminate last faulty value in data column
if size(RFdataRAW,1)==length(DataToWrite)
RFdataRAW(:,count+k) = DataToWrite;
else
RFdataRAW(:,count+k) = nan(1,size(RFdataRAW,1));
RFdataRAW(1:length(DataToWrite),count+k) = DataToWrite;
end
end
```

```
        % Plot if not converged to show the situation
        figure
        mphplot(model,'pg1')
        title(strcat('Coordinates: (',num2str(x_co(i)),',',num2str(y_co(j)),')'))
        end
        count = count+3;
        StudyCount = StudyCount+1;
        StressPlots((i-1)*length(y_co)+j,:) = mphplot(model,'pg1','rangenum',1,'createplot','off');
        DefPlots((i-1)*length(y_co)+j,:) = mphplot(model,'pg3','rangenum',1,'createplot','off');
        disp(strcat('Finished study for coordinates: (',num2str(x_co(i)),',',num2str(y_co(j)),')'));
        if ErrorCount > 2 && ErrorCount == StudyCount
        error('Study not computing, check if SolidWorks LiveLink is connected');
        end
        if x_co(i) == 0 && y_co(j) == 60
        probe = mpheval(model,'w','unit','m','selection','sel2');
        probemean = mean(probe.d1,2);
        end
        end
        end

        tstudy = toc(tstart);

        % Performance Criterium: FRE Ratio
        try
        u_max = -mphevaluate(model,'u_max');
        Pfre = (u_max - probemean(end))/u_max;
        catch
        warning('Pfre not found, no (0,60) coordinate selected')
        end
```

Interpolation Function

```
function [Fu,u_cF,RFx_cFz,RFy_cFz,RFx,RFy,RFz,Pc,Pc_cFz,K,K_cFz,ErrorLog] = InterpolateFu(u_F,u,Vsphere,RFdataRAW,x_co,y_co,coordinates,ErrorLog)

% Set up Array sizes for faster computation:
RFx = nan(length(u),length(coordinates));RFy=RFx;RFz=RFx;Pc=RFx;
u_cF = zeros(length(x_co),length(y_co)); RFx_cFz=u_cF; RFy_cFz=u_cF;Pc_cFz = u_cF;

% Isolate Force Data from COMSOL
for i = 1:length(x_co)*length(y_co)
RFx(:,i) = RFdataRAW(:,3*i-2)/Vsphere;
RFy(:,i) = RFdataRAW(:,3*i-1)/Vsphere;
RFz(:,i) = RFdataRAW(:,3*i)/Vsphere;
end

% Eliminate any Gripping Force (RFz) Data after buckling by not allowing decrease in RFz
for i = 1:size(RFz,1)-1
for j = 1:size(RFz,2)
if abs(RFz(i,j)) < abs(RFz(i+1,j))
else
RFz(i+1,j) = NaN;
end
end
end

[midrow,~] = find(coordinates=='(0,60)');
if isempty(midrow) == 1
Error('No (0,60) coordinate in data');
else
Fu = interp1(u(1:length(rmmissing(RFz(:,midrow)))),rmmissing(RFz(:,midrow)),u_F,'pchip');
end

% Interpolate for the given Gripping Forces
for i = 0:length(x_co)-1
for j = 1:length(y_co)
try
u_cF(i+1,j) = interp1(rmmissing(RFz(:,i*length(y_co)+j)),u(1:length(rmmissing(RFz(:,i*length(y_co)+j)))),Fu,'pchip')';
catch
warning(strcat('Force of RFz=',{' '},num2str(Fu),{' '},'cannot be interpolated at position',{' '},coordinates(i*length(y_co)+j,2)))
ErrorLog(end+1,1) = strcat("Force of RFz=",{' '},num2str(Fu),{' '},"cannot be interpolated at position",{' '},coordinates(i*length(x_co)+j,2));
end
end
end

% Interpolate RFx for the ConstantForce displacements found in u_cF
for i = 0:length(x_co)-1
for j = 1:length(y_co)
try
RFx_cFz(i+1,j) = interp1(u(1:length(rmmissing(RFx(:,i*length(y_co)+j)))),rmmissing(RFx(:,i*length(y_co)+j)),u_cF(i+1,j),'pchip');
catch
warning(strcat('Displacement of',{' '},num2str(u_cF(i+1,j)),{' '},'for RFx cannot be interpolated at position',{' '},coordinates(i*length(y_co)+j,2)))
ErrorLog(end+1,1) = strcat("Displacement of",{' '},num2str(u_cF(i+1,j)),{' '},"for RFx cannot be interpolated at position",{' '},coordinates(i*length(x_co)+j,2));
end
end
end

% Interpolate RFy for the ConstantForce displacements found in u_cF
for i = 0:length(x_co)-1
for j = 1:length(y_co)
```

```
try
RFy_cFz(i+1,j) = interp1(u(1:length(rmmissing(RFy(:,i*length(y_co)+j)))),rmmissing(RFy(:,i*length(y_co)+j)),u_cF(i+1,j),'pchip');
catch
warning(strcat('Displacement of',{' '},num2str(u_cF(i+1,j)),{' '},'for RFy cannot be interpolated at position',{' '},coordinates(i*length(y_co)+j,2)))
ErrorLog(end+1,1) = strcat("Displacement of",{' '},num2str(u_cF(i+1,j)),{' '},"for RFy cannot be interpolated at position",{' '},coordinates(i*length(x_co)+j,2));
end
end
end

%%%%% Compute Performance Criteria
% Centering PerformanceRF
for i = 1:length(x_co)
for j = 1:length(y_co)
Pc(:,j+(i-1)*length(y_co)) = (-RFx(:,j+(i-1)*length(y_co))*x_co(i))./(RFz(:,j+(i-1)*length(y_co))*abs(x_co(i)));
end
end
% Compute the Centering Performance for constant Fu (Pc_cFz)
for i = 1:length(x_co)
for j = 1:length(y_co)
Pc_cFz(i,j) = (-RFx_cFz(i,j)*x_co(i))./(Fu*abs(x_co(i)));
end
end
% Stiffness K
K = abs(RFz./u);
K_cFz = abs(Fu./u_cF);
```

Plot Function

```
function [RFfigure] = RFplot(x_co,y_co,u_cF,RFx_cFz,RFy_cFz,model)

RFfigure=figure('units','pixels','outerposition',[0 0 1500 800]);

% Surface plot the displacement of the gripper per position.
subplot(2,2,1)
view(45,20)
hold on
surf(x_co,y_co,u_cF'*1000)
colorbar
axis equal
title('Displacement per location of the sphere for constant Force')
xlabel('x coordinate [mm]')
ylabel('y coordinate [mm]')
zlabel('Displacement [mm]')

% Surface plot the RFx for Constant Gripping Force of the gripper per position.
subplot(2,2,2)
view(30,10)
hold on
surf(x_co,y_co,RFx_cFz')
colorbar
set(gca, 'DataAspectRatio', [repmat(max(diff(get(gca, 'XLim')), diff(get(gca, 'YLim')
    ))), [1 2]) diff(get(gca, 'ZLim'))])
title('RFx for constant RFz per position')
xlabel('x coordinate [mm]')
ylabel('y coordinate [mm]')
zlabel('RFx [N]')

% Surface plot the RFy for Constant Gripping Force of the gripper per position.
subplot(2,2,3)
view(45,10)
hold on
surf(x_co,y_co,RFy_cFz')
colorbar
set(gca, 'DataAspectRatio', [repmat(max(diff(get(gca, 'XLim')), diff(get(gca, 'YLim')
    ))), [1 2]) diff(get(gca, 'ZLim'))])
title('RFy for constant RFz per position')
xlabel('x coordinate [mm]')
ylabel('y coordinate [mm]')
zlabel('RFy [N]')

% Plot Displacement over the model
subplot(2,2,4)
mphgeom(model)
hold on
surf(x_co,y_co,25-u_cF'*1000)
axis equal
title('Displacement per (x,y) plotted over the model')
xlabel('x coordinate [mm]')
ylabel('y coordinate [mm]')
zlabel('Displacement [mm]')
```

E Data and Performance

This section of the appendix provides extra information on the data output from the model. with a more in-depth review of the performance data concerning the structural variations.
The model outputs a lot of data in the form of numbers, tables and graphs. The first visual data is plotted by the RFPlot function (see appendix D.5). This function plots 4 graphs containing the displacements of the sphere, the reaction force in x-direction(RF_x), the reaction force in y-direction (RF_y) and the displacements projected onto the undeformed model (see fig. E.1). Other data, such as deformation and stress plots or performance numbers are obtainable by providing commands through the MATLAB Command Window.

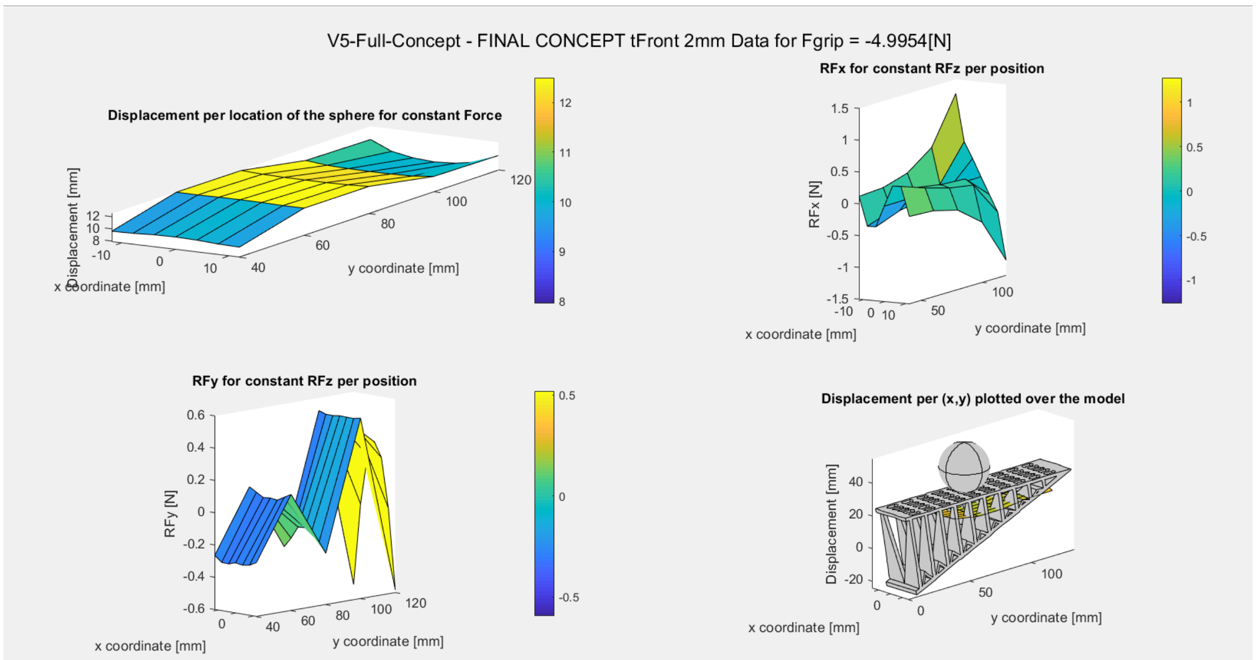


Figure E.1: RFPlot Output

E.1 Performance Data of Structural Variations

The performance data concerns the performance criteria described in section 2.2. The centering performance (P_C) and stiffness (K) are compared through coloured tables, to visualize the result and easily observation of the differences. This method was chosen because it gives fast insights in the performance differences, without having to compare each number per coordinate.

The FRE Performance P_{FRE}

Each structural segment of the new concept shows improvement of the FRE performance, when compared to the Basic FRE Gripper (see table E.1). The Full Concept even shows the greatest FRE Performance number, with the Final Design coming in a very close second. The FRE Performance was monitored to ensure that the FRE effect would not decrease too much. However, the FRE performance only improved with the new gripper design.

	Basic FRE	Torsion Reinf.	Tri-Ribs	Perf. Front & Tri-Ribs	Full Concept	Final Design
P_{FRE}	0.95	0.97	1.03	1.05	1.07	1.06

Table E.1: FRE Performance P_{FRE} of Structural Variatons

The Centering Performance P_C

The structural variations give distinct differences in the performance of the gripper, except for the Torsion Reinforcement compared to the Basic FRE Gripper (see table E.2 and table E.3). The Torsion Reinforcement should counter the rotational DoF of the gripper and thereby prevent the gripper from opening its grip and thereby pushing the sphere away. However, the results do not show any decrease of this effect by the Torsion Reinforcement.

The centering performance of the structural variations clearly shows the coherence of the segments. The Perforated Front & Triangle Ribs only provide centering when combined (see table E.4 and table E.5), while the Torsion Reinforcement provide great improvement of that centering performance (see table E.6). The Final Design Gripper also has improved parameters instead of constant thickness over the whole geometry, thereby increasing the P_C even more and gaining the highest P_C of all variations (see table E.7).

Centering Performance P_C of Structural Variations

x\y	40	60	80	100	120
-12	-0.09	-0.13	-0.17	-0.30	-0.53
-8	-0.04	-0.06	-0.09	-0.15	-0.41
-4	-0.02	-0.03	-0.04	-0.08	-0.11
0	NaN	NaN	NaN	NaN	NaN
4	-0.02	-0.03	-0.04	-0.08	-0.11
8	-0.04	-0.06	-0.10	-0.15	-0.42
12	-0.09	-0.13	-0.17	-0.31	-0.52

Table E.2: Basic FRE Gripper

x\y	40	60	80	100	120
-12	-0.09	-0.12	-0.17	-0.31	-0.57
-8	-0.05	-0.07	-0.10	-0.15	-0.44
-4	-0.01	-0.03	-0.05	-0.07	-0.11
0	NaN	NaN	NaN	NaN	NaN
4	-0.01	-0.03	-0.05	-0.07	-0.12
8	-0.05	-0.07	-0.09	-0.15	-0.33
12	-0.09	-0.12	-0.17	-0.31	-0.54

Table E.3: Torsion Reinforcements

x\y	40	60	80	100	120
-12	-0.09	-0.11	-0.12	-0.13	-0.25
-8	-0.02	-0.03	-0.04	-0.06	-0.10
-4	-0.01	-0.01	-0.01	-0.02	-0.05
0	NaN	NaN	NaN	NaN	NaN
4	-0.01	-0.01	-0.01	-0.03	-0.05
8	-0.02	-0.03	-0.04	-0.06	-0.11
12	-0.09	-0.11	-0.12	-0.13	-0.24

Table E.4: Triangle Ribs

x\y	40	60	80	100	120
-12	-0.05	-0.05	-0.07	-0.11	-0.19
-8	0.02	0.00	-0.01	-0.04	-0.11
-4	0.02	0.02	0.01	-0.01	-0.05
0	NaN	NaN	NaN	NaN	NaN
4	0.02	0.02	0.01	-0.01	-0.05
8	0.02	0.00	-0.01	-0.04	-0.11
12	-0.05	-0.05	-0.07	-0.11	-0.19

Table E.5: Perforated Front & Triangle Ribs

x\y	40	60	80	100	120
-12	-0.05	-0.05	-0.07	-0.11	-0.19
-8	0.03	0.02	0.00	-0.02	-0.09
-4	0.04	0.03	0.02	0.00	-0.05
0	NaN	NaN	NaN	NaN	NaN
4	0.04	0.03	0.02	0.00	-0.05
8	0.03	0.02	0.00	-0.02	-0.09
12	-0.05	-0.05	-0.07	-0.11	-0.18

Table E.6: Full Concept

x\y	40	60	80	100	120
-12	-0.02	-0.03	-0.05	-0.11	-0.26
-8	0.07	0.04	0.02	0.00	-0.11
-4	0.07	0.04	0.03	0.02	-0.06
0	NaN	NaN	NaN	NaN	NaN
4	0.07	0.04	0.03	0.02	-0.05
8	0.07	0.04	0.02	0.00	-0.10
12	-0.02	-0.03	-0.05	-0.11	-0.25

Table E.7: Final Design

The Stiffness

The stiffness K of each variation is also monitored. As mentioned in section 2.2, the stiffness is a performance metric for monitoring and not for optimizing. The stiffness clearly decreases for every variation except for the addition of the Torsion Reinforcements (see table E.9). Which is logical, since the Torsion Reinforcements add volume, while all other variations decrease the volume of the gripper. The largest stiffness decrease is observed for the Perforated Front & Triangle Ribs (see table E.11), which is more than halved compared to the Basic FRE Gripper (see table E.8) in most positions of the gripper. The Final Design (see table E.13) has a stiffness that comes closer to the Basic FRE gripper than the Full Concept Gripper (see table E.12). The parametric variations have caused the Final Design to increase both in stiffness and centering performance simultaneously. Which implies that the asymmetric parameter distribution can be beneficial to a FRE gripper design.

Stiffness Tables K of Structural Variations

x\y	40	60	80	100	120
-12	623	511	534	567	493
-8	652	534	576	685	574
-4	670	549	602	757	857
0	674	553	610	784	924
4	670	549	601	756	854
8	654	535	576	685	570
12	625	512	533	566	498

Table E.8: Basic FRE Gripper

x\y	40	60	80	100	120
-12	718	585	600	643	542
-8	756	610	645	779	644
-4	775	626	673	859	946
0	780	631	682	888	1017
4	775	626	674	858	945
8	757	611	646	779	721
12	718	584	600	642	537

Table E.9: Torsion Reinforcements

x\y	40	60	80	100	120
-12	319	249	264	348	454
-8	334	257	276	373	572
-4	341	261	282	389	644
0	343	262	284	393	670
4	341	261	283	389	644
8	334	257	277	375	572
12	318	249	264	348	455

Table E.10: Triangle Ribs

x\y	40	60	80	100	120
-12	286	225	232	301	373
-8	292	228	237	318	439
-4	292	229	240	326	488
0	292	229	241	328	506
4	293	229	240	326	488
8	293	229	237	318	439
12	286	225	232	301	373

Table E.11: Perforated Front & Triangle Ribs

x\y	40	60	80	100	120
-12	338	258	263	339	407
-8	344	261	268	355	472
-4	340	260	270	360	517
0	339	260	271	361	533
4	341	260	270	360	517
8	344	261	268	355	472
12	338	258	263	339	408

Table E.12: Full Concept

x\y	40	60	80	100	120
-12	520	402	403	477	484
-8	515	403	408	495	567
-4	505	400	411	500	611
0	501	400	411	502	628
4	505	400	411	500	611
8	516	403	409	495	568
12	520	402	403	478	485

Table E.13: Final Design

F Experimental Validation Set-Up

An experimental validation was set up to validate the new Spatially Designed Form-Closed FRE Gripper. Since the model cannot be considered real world. A quick validation was necessary to prove that the new design can acquire a stable grip on a lateral round or spherical object, since the state-of-the-art FRE grippers show an unstable grip on those objects.

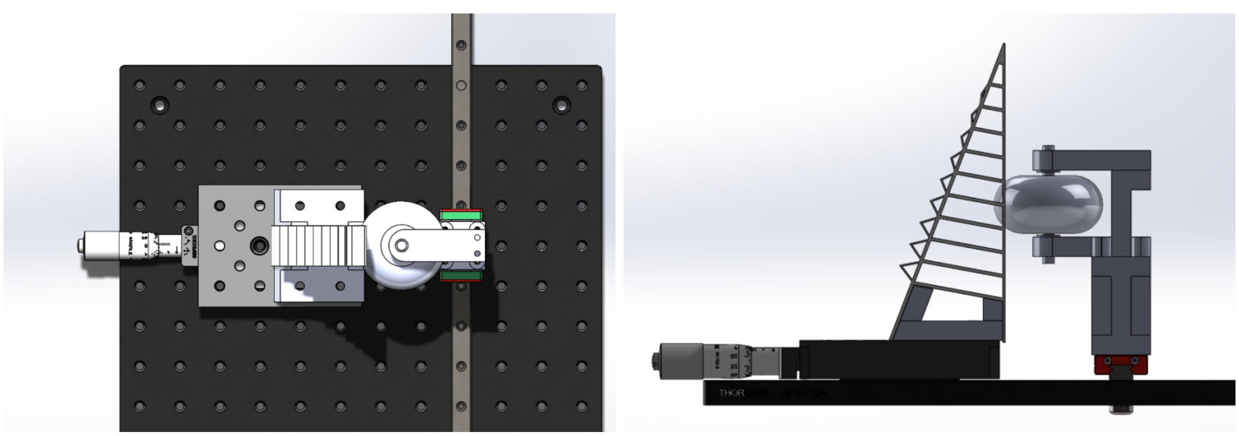
F.1 The Prototype

The prototype used in the experimental validation are 3D Printed Flex45 versions of the Final Design Gripper. The material is different from the material in the research, since this was the available material for 3D printing fabrication of the prototype. Other materials were also printed, but the Flex45 material seemed best suited for the prototype. 3D printing was chosen due to the geometry of the Final Design Gripper, for which 3D printing is a fast and suitable manufacturing method. Other methods such as injection moulding, or assembling by parts (e.g. from wood or metal) take up a lot more time and can make the manufacturing unnecessarily complex.

The thickness dimensions of the gripper were altered for prototype, since the mechanical properties of the Flex45 prototype material differ from the TPU material applied in the research. The Flex45 material is a lot stiffer than the TPU material. Therefore, the prototype is made thinner than the original Final Design Gripper. Also, the ends of the design are extended for easier attachement in the experimental set-up.

F.2 The Experimental Set-up

The experimental set-up (shown in fig. F.1 and fig. F.2) tests for stability of the grip in lateral direction, when gripping a spherical object. The idea is to create a lateral frictionless sphere that is pressed into the gripper. This is done by putting a sphere on an axle, so it can rotate along the lateral direction of the gripper. The sphere is connected to a linear slider, so it can freely move in the lateral direction. The gripper is assembled on a linear slider perpendicular to the linear slider of the sphere. The gripper pushes onto the sphere, to which the sphere can move perpendicular to the gripper's movement. If the gripper pushes the sphere outward from its grip, the sphere would simply roll away from the gripper. If the gripper shows centering capabilities, the sphere would roll to the middle of the gripper's face. If no centering or rejecting of the sphere happens, it would stay in the same place.



(a) Top View (b) Side View

Figure F.1: The Experimental Validation Set-Up

All parts, except for the linear sliders, bolts and nuts, are 3D printed for the experimental set-up. The grippers are printed in flexible Flex45 material, while the rest of the parts are printed in PLA. The PLA material is considered to be rigid. The gripper is screwed into its mount, while the mount is screwed into the linear slider. The sphere on the axle sits in two sliding bearings, one on each side. The bearings are press-fitted into the sphere-mount which sits atop a vertical spacer that is screwed to the linear slider below. The spacer and sphere-mount can also be produced as a single part. However, keeping the spacer apart gives the ability to easily adjust the height of the sphere by applying a different spacer.

The experiment tests for a multitude of misalignment positions of the sphere compared to the gripper. If the sphere is not exactly in the middle of the gripper's face, it is expected that the gripper will exert a horizontal force either pushing the sphere away or to its center. The height of the sphere is set at approximately 70mm from the tip of the gripper, which in the model corresponds to: y = 60mm. The horizontal positions relative to the middle of the gripper are:
x = [-16 -12 -8 -4 0 4 8 12 16]
Both the Final Design Gripper and the Basic FRE Gripper are applied in the experiment to validate their stability on those positions. The results are formatted as: Out, Still and In. If the sphere is pushed to the outside of the gripper and beyond, 'Out' is noted. If the sphere stays still in its position, not being pushed to either side, 'Still' is noted. If the sphere moves toward the center of the gripper, 'In' is noted as it moves into the grip.

F.3 The Experimental Results

The experiment shows no signs of centering (see table 4), but does show that the new Spatially Designed Form-Closed FRE Gripper Finger performs a stable grip on the sphere for most of the tested positions, while the Basic FRE Gripper does not. The Basic FRE Gripper only shows a stable grip when the sphere is exactly at the center of the gripper. The lack of centering is probably due to the friction forces in the linear slider of the sphere and the friction between the axle of the sphere and the sliding bearing. The centering forces were relatively low compared to the original force with which the Basic FRE Gripper pushes the sphere out of its grip. Therefore, those centering forces probably do not outweigh the friction forces in the set-up. The linear slider also seemed inconsistent in its friction, also seeming to gain friction when applying a moment to it.
Both the stability of the new gripper and the instability of the Basic FRE Gripper are validated by the experiment.

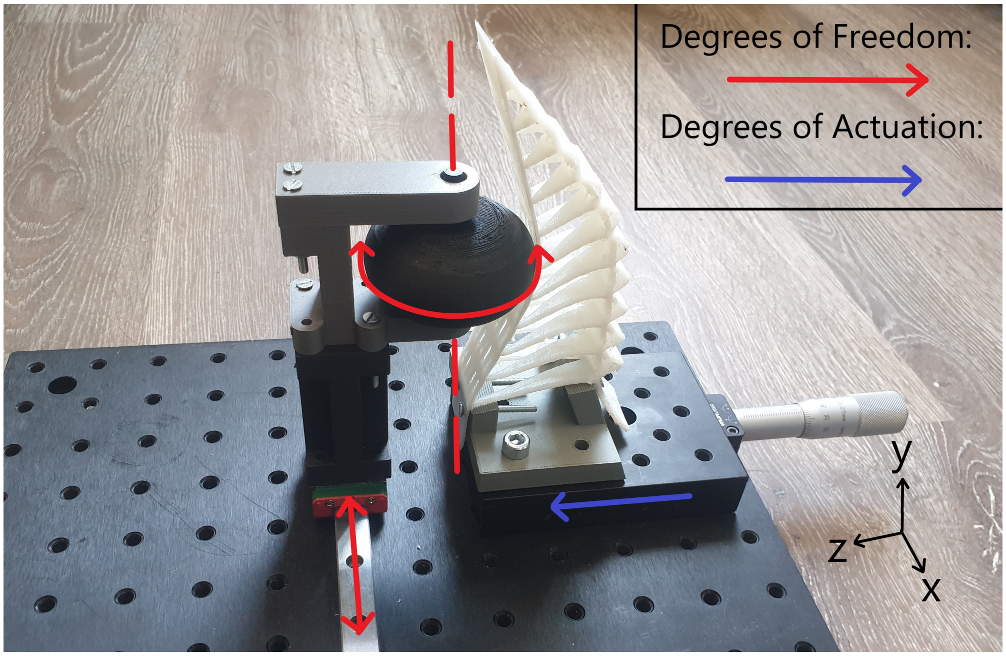


Figure F.2: Real World Experimental Validation Set-Up

G Recommendations

For future research there are several recommendations. First, I would recommend to do more experimental research to verify the model more extensively. I would recommend pull-out force experiments and also dynamic experiments, since it is important for the gripper to maintain its grip in high speed situation and on heavy object. Also, wear and fatigue related experiments and analysis might pose a great knowledge addition. Especially fatigue can be important since the new design does concentrate its peak stresses in the small attachments of the ribs to the front sheet of the gripper.

Second, I would recommend to iterate the design further for a more practical purpose. Thereby, keeping manufacturing and maintenance in mind. For instance, the Torsion Reinforcements can be redesigned to suit better for injection moulding, while the Triangle Ribs can be redesigned to be more arc shaped to prevent sharp edges and to hold more material. The ribs can also be designed to have more width in the middle and notch hinges at their attachments.

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