UNIVERSITEIT TWENTE

Redesign of the Shoulder Elbow Perturbator

Report about internship at Hankamp Rehab

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11/28/2016

Abstract

The Shoulder Elbow Perturbator (SEP) is an apparatus used to measure the force resistance against sudden stretching of the elbow by stroke patients, while simultaneously modulating shoulder abduction and adduction effort. The SEP is in development by the company Hankamp Rehab. A first prototype was produced but it contains a number of problems.

During execution of the internship solution are proposed for the several problems and a redesign of the SEP was performed. The stiffness of the construction and especially the arm holder in the design was a problem. By making a third Sarrus linkage in the design the stiffness improved theoretically with 53.7% in the most unfavorable orientation of the arm holder.

A gravity compensation system enhanced in the design was improved by reducing the number of pulleys and changing the selection of bearings used for the rotation of those pulleys. The number of pulleys was reduced by 1 by rotating the entire setup of this gravity compensation system, including the Sarrus linkages, toward the axis of ration of the arm holder.

Safety end stops in the design of the SEP were difficult to change in position. A new setup for those end stops was designed where the position of those end stops could be fixed with a pin-hole connection present at the edge of the frame supporting the SEP.

Besides this, a housing was designed to protect user from the moving parts. Also some minor issue in the design which could relative easily be resolved were addressed.

As a result the proposed improvements to the design were incorporated in a new SolidWorks file, which makes it possible to view the features of the improvements/new design in a 3D-environment.

Keywords: Shoulder Elbow Perturbator, SEP, Hankamp Rehab, stroke patients, SolidWorks

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Introduction

This is the report about the internship of Robin Braakman at Hankamp Rehab. Hankamp Rehab is a subsidiary of the company Hankamp Gears, which main activity is the manufacturing of high quality gears. Hankamp Rehab however is focused on the development of products for medical and rehabilitation purposes. One of the products they are currently developing is named the Shoulder Elbow Perturbator. A first prototype of this product is made, but during the testing of this prototype a number of flaws in the design was encountered. Purpose of the internship is to come up with a redesign of the Shoulder Elbow Perturbator wherein solutions are proposed which resolves the flaws in the current design.

The Shoulder Elbow Perturbator (SEP) is a device which can measure the force resistance against sudden stretching of the elbow by stroke patients, while simultaneously modulating shoulder abduction and adduction effort. Patients who had suffered from a stroke often are debilitated by abnormal joint movement. This makes daily life activities such as reaching difficult. Abnormal joint movement is, inter altia, ascribed to the abnormal muscle synergies occurring because of the stroke. A detailed description what muscle synergies are is out of the scope of this research, but the hypothesis is that the synergies change the amount of resistance a person exerts when a stretch reflex is initiated compared to what a healthy person would exert. The SEP should function as a tool to determine the extent of interplay between synergies and stretch reflexes in stroke patients.

The first prototype of the SEP was developed during execution of the master thesis of M. van Hirtum. He designed the SEP with the use of CAD/CAM software SolidWorks. A picture of this model made in SolidWorks is shown in Figure 1. This SolidWorks model will be assumed as the current model of the SEP and will be the basis to apply improvements on.

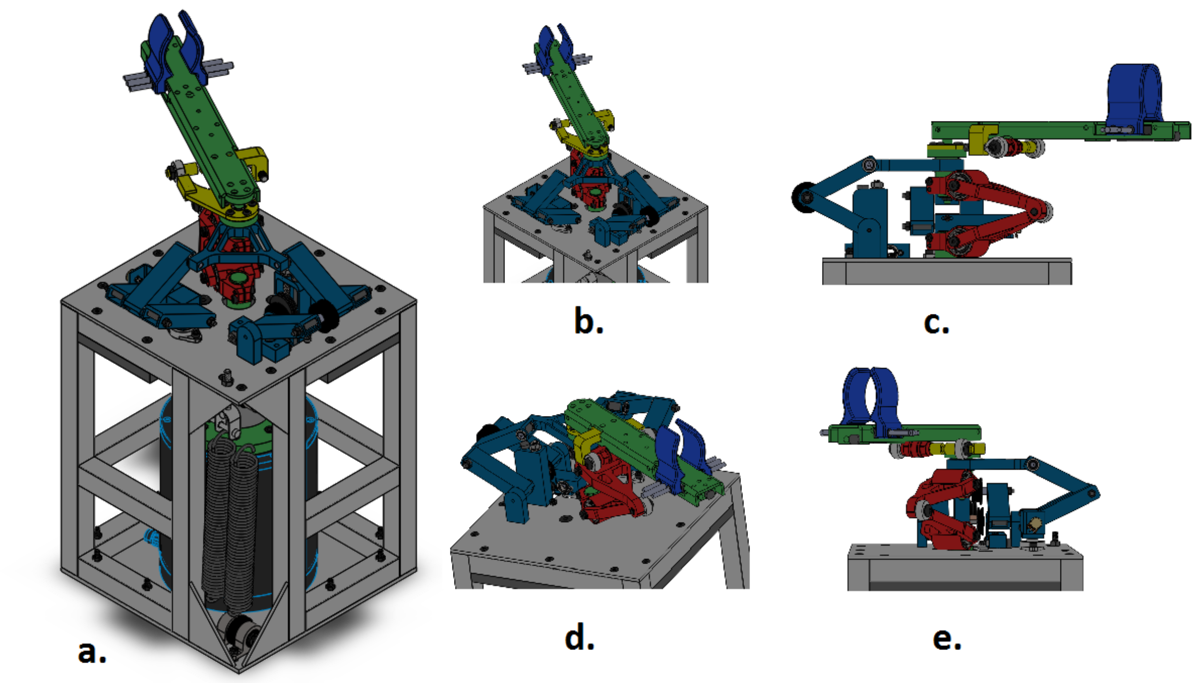


Figure 1: Several views of current design of SEP

The main parts of the current model of the SEP consist of a rotatable arm holder, a torque link, a Sarrus linkage mechanism, a gravity compensation system and a motor. The rotatable arm holder is shown by the green colored part in Figure 1. During operation of the SEP, a stroke patient should put his arm onto the arm holder. By then rotating this arm holder, the elbow will be stretched and an elbow reflex will be initiated. The amount of resistance of this reflex can be measured with the equipment visible as the yellow parts in Figure 1 near the axis of rotation of the arm holder. The arm holder will be rotated by the use of an AC-motor. The AC-motor is visible in Figure 1a in between the frame. The torque created by the AC-motor will be translated to rotation of the arm holder via the torque link. The torque link is shown by the red part in Figure 1. The torque link is designed in such a way that it can translate rotation to the arm holder but makes it also possible that the position of the arm holder is adjustable in height. The arm holder has to be adjustable in height so that a gravity compensation system, enhanced in the design, can compensate for the weight of the arm of the patient and possible shoulder abduction and adduction effort. The gravity compensation system is shown in Figure 1 by the blue parts. It is a cable-spring system able to exert a reaction force to the force exerted on the device when an arm is placed in the arm holder. A more detailed explanation of the gravity compensation system is given in the chapter *Problem 2: Gravity Compensation System*. The gravity compensation system also contains 2 Sarrus linkages. The Sarrus linkage are the combined blue bars and is a mechanical linkage to convert a limited circular motion to a linear motion without reference guideways. They are named after their inventor, Pierre Frederic Sarrus.

The current design of the SEP contains a number of flaws. The most important flaws in the design are the following:

- Current design does not have sufficient stiffness

- Current design does not have sufficient gravity compensation system

- Current design does not have sufficient safety end stops

- Current design does not enhance a housing

All of those 4 problems will be detailed described and be analyzed to find cause of the problem. Concepts to solve and improve the problem will be proposed and those concepts will be evaluated to come up with a final concept to be enhanced into a new design of the SEP. The production of the final concept will be described in comparison to the production of the current model. Finally some minor problems will be discussed and a solution for this will be proposed.

Characteristics of the current model which are of good quality will be kept the same as most as possible and will not or only briefly be discussed. For an elaborate motivation for choices made to those parts of the design consult the report of M. van Hirtum. [1-2]

Problem 1: Stiffness

In the current design of the SEP the stiffness of the arm holder and the supporting system is an issue. If a force is applied on the arm holder the displacement at the end of this arm holder is too high and beyond the specifications. The arm holder is allowed to have a maximum displacement of 10 mm when a force equivalent to 7 kg in applied halfway the length of the arm holder. During operation of the SEP an application of force occurs by the weight of the arm placed onto the arm holder. The current design of the SEP has to be analyzed to map the stiffness of this design. Next possible improvements have to be adapted in the design and reanalyzing have to be determine if this is actual an improvement of the stiffness.

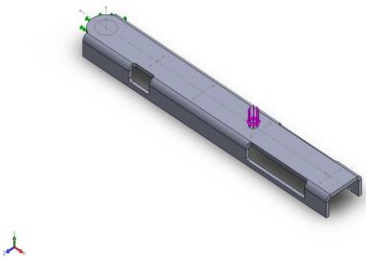
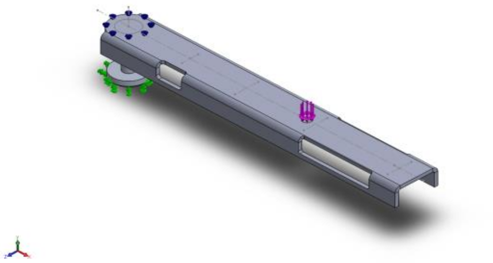
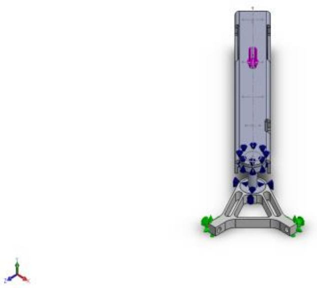
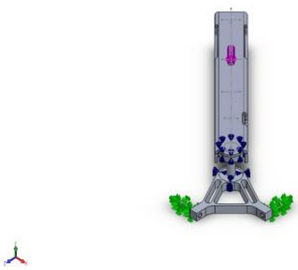
Analysis of current model

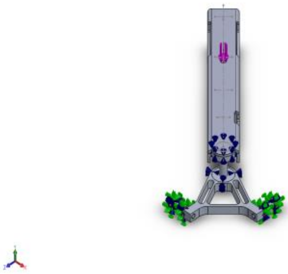
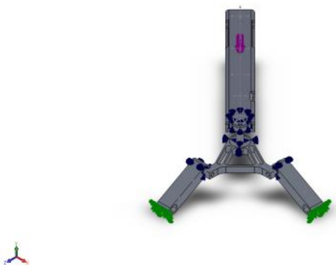
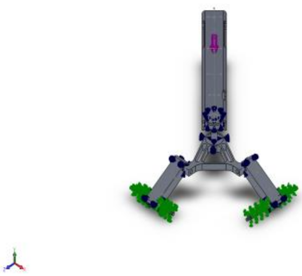
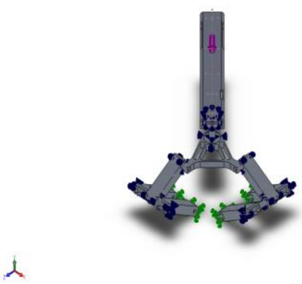
The current model of the SEP will be analyzed with the use of SolidWorks software. SolidWorks is useful software to design parts and assemblies in 3D but also offers you to simulate your designs regarding their stiffness and strength. The software uses the principles of the Finite Element Method (FEM) to determine stress, strain and displacement when a body is exposed to certain loads and (boundary) constraints.

A file in SolidWorks is available of the current model. However, this file is to extensive to simulate with FEM regarding computation time, therefore the model will be rebuilt from top to bottom and simulated during the preliminary steps of rebuilding. The model will be rebuilt until the point that the model is sufficient enough to represent the reality but that the simulation time stays reasonable (max 30-45 minutes). The building of the model in SolidWorks will be started at the arm shaft. A simplified version of the current arm shaft will be used instead of the current arm shaft to reduce simulation time. A simplified version of the parts connection the arm shaft to the frame will be used as well to reduce simulation time. For both parts main geometry, material properties and weight are tried to keep mostly the same. Pictures of those parts are shown in Table 1.

Some of the parameters during the several simulation studies are held the same. In all studies the point where a force will be applied and the size of this will be kept the same, namely a force of 100 N applied at a 10 mm diameter circular area which has its midpoint 130 mm from the outer edge of the arm shaft at the centerline. This enhances a sufficient factor of safety with respect to the specifications. Also, in all simulation studies the outer edge line of the arm shaft will be placed parallel to the edge line of the frame between the two connector points. The Sarrus linkages will be placed at an angle of 30° towards the ground. The mesh density used will be the average setting. Connections between bearing housing and shaft will be specified with the available feature for bearings in SolidWorks. Pin connections will be specified with the available feature for pins in SolidWorks. Connections between screws and bolts will be made rigid to each other during simulation and therefore this connection is specified with the *Rigid* connection in SolidWorks. Unspecified contact between parts and global contact will be defined by the setting *No Penetration*. In the (preliminary) simulation models at least one of the bottom planes is defined fixed to assume that the dismissed parts are infinite stiff. The material properties for every part are the same except for the arm holder, which is Aluminum 6082 instead of Aluminum 6063-T5.

Results of the simulation studies are shown in the Table 1. In the left column the preliminary models are shown and a brief description of that assembly is given. The middle column shown the maximum displacement in the corresponding assembly and is a measure of the stiffness of that model. The right column shows the computation time, which is the time passed from the beginning to the end of the simulation study.

Assembly	**Max displacement (mm)**	**Computation time**
 Arm holder	0.816516	< 5 min
 Arm holder and support	3.81883	< 5 min
 Arm holder, support and frame	0.914966	< 5 min
 Arm holder, support, frame and pins	6.63925	5 – 10 min

 Arm holder, support, frame, pins and bearings	6.38448	5 – 10 min
 Arm holder, support, frame, upper part Sarrus, connection bearings at upper side Sarrus, connections at pins	8.52307	15 – 30 min
 Arm holder, support, frame, upper part Sarrus, connection bearings at both sides Sarrus, connections at pins	13.4159	15 – 30 min
 Arm holder, support, frame, upper part Sarrus, bottom part Sarrus, connections at bearings, connections at pins and connections at the screws	16.1504	30 – 45 min

 Arm holder, support, frame, upper part Sarrus, bottom part Sarrus, connection blocks for mounting plate, connections at bearings, connections at pins and connections at screws	19.2895	> 45 min

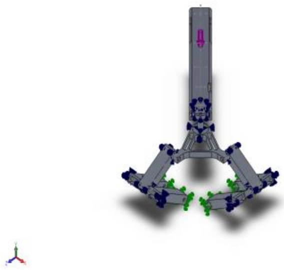
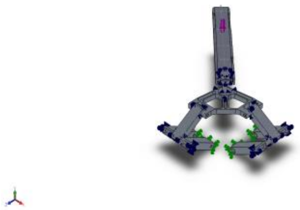
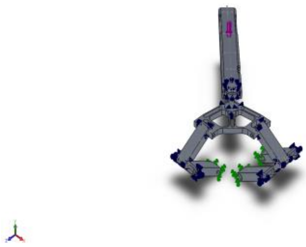
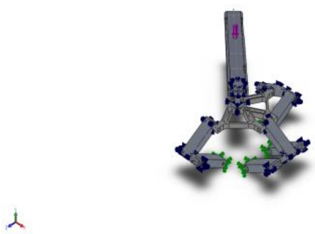
Table 1: Results of simulation studies

The proposed limit regarding computation time is reached during the last simulation study shown in the Table 1, when the computation time exceeds 45 minutes. The second last model represents the prototype also in a sufficient way, only the connection blocks which connects the bottom part of the Sarrus to the mounting plate is not present in this model. Because this model also incorporates a reasonable computation time, this last model will initially be used as a reference model and the maximum displacement in this simulation study will be used as a target value to be improved. Therefore the last model will be used as a reference model and the maximum displacement in this simulation study will be used as a target value to be improved. Possible improvements will be enhanced in this model and the best option will be finally assimilated in the last model to measure improvement in the whole model.

Concept

A number of possible improvements will be proposed regarding the geometry of the construction. Concept 1 regards a change of the frame in such a way that the frame is connected at both sides of the bottom parts of each Sarrus linkage. Concept 2 regards a change of the frame as well but also incorporates an extra Sarrus linkage. Concept 3 concerns the use of different beams in the Sarrus linkages. The idea of those changes is that the extra connections of the Sarrus linkages with the frame will provide a more evenly spread of the stress in the frame and partly cancels out some of the torque, and improve the stiffness.

Pictures of the concepts are shown in the Table 2, as well as the maximum displacement found with the corresponding simulation studies. The main properties are the same as the previous simulations of the current model, as is described in the third paragraph of *Analysis of current model*. A description of each concept is given in this table as well.

Concept number	Assembly	Max displacement (mm)	Absolute change (mm)	Relative change (%)
0	 Current model	16.1504	0	0
1	 Adjusted frame; connection at both sides Sarrus linkage	12.0742	- 4.0762	- 25.2
1	 Adjusted frame; connection at both sides Sarrus linkage, 1 arm less in bottom part one of the Sarrus linkages	12.7254	- 3.425	- 21.2
2	 Extra Sarrus linkage, 2 out of 3 Sarrus linkages contain 1 arm in bottom part, other Sarrus linkage has 2 arms in bottom part; frame is adjusted, but is a simplified version which is difficult to produce	8.28969	- 7.861	- 48.7

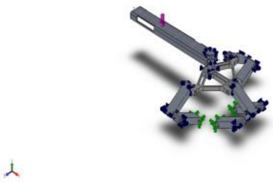
3	 Adjustment of arms of the Sarrus linkages; arms are made thinner and solid [note: model is not fully constrained; bearing connections are dismissed in the adjusted Sarrus linkage]	23.7157	+ 7.565	+ 46.8
2	 Extra Sarrus linkage, 2 out of 3 Sarrus linkages contain 1 arm in bottom part, other Sarrus linkage has 2 arms in bottom part; frame is adjusted, version seems able to produce compared to simplified version, arm holder is put into different angle	6.27413	- 9.876	- 61.2

Table 2: Results of simulation studies

Simulation studies have shown that concept 2 is the best option regarding the improvement of the displacement. The simulation studies have also shown that disobeying one arm in the bottom part of the left Sarrus linkage under this angle of the arm holder in concept 1 does not really deteriorate the displacement (12.0742 mm versus 12.7254, increase of 5.4%). Therefore no simulation study of concept 2 is done when 2 arms in the bottom part of all 3 Sarrus linkages are obeyed. The improvement of displacement will not weigh up against the increase in weight and the decrease of maximum angle of rotation. Despite the fact that the constraints in the simulation of concept 3 are not fully defined, the simulation has shown that this concept will not be the best option to improve the stiffness. Concept 2 will be chosen to evaluate in a more elaborate manor.

Concept Evaluation

The model of concept 2 will be more elaborated with enhancing the connection blocks which connects the Sarrus linkages to the mounting plate. Again the main properties are held the same, but simulations are also done with different angles of the Sarrus linkages and different angles of the arm holder. Results of the simulation are shown in the Table 3.

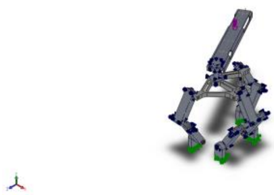
Concept number	Assembly	Max displacement (mm)	Absolute change (mm)	Relative change (%)
0		19.2895	0	0
2		8.93365	- 10.356	- 53.7
2		8.8184	N/A	N/A
2		8.3332	N/A	N/A
2		4.73885	N/A	N/A

Table 3: Results of simulation studies

There are 4 simulation studies done where the angle of the Sarrus linkages and/or the angle of the arm holder are changed. Some simulations are not directly comparable to the old model due to that difference in angles. The simulations show that for every construction setting the maximum displacement is below the specifications.

Besides the improvement regarding the stiffness, an extra Sarrus linkage decreases the maximum deflection of the arm holder because parts of the torque link otherwise will hit the Sarrus linkage. A limited decrease of the maximum deflection should not be a problem, because in the current design the maximum deflection is even more than 180 degrees, while a possible deflection of 120 degrees is desired. The maximum deflection while having a third Sarrus linkage will be calculated. The edge of the upper parts of the Sarrus linkages which consists of 2 arms is at least 90 mm apart from the rotation point of the arm holder. The arms of the Sarrus linkages are 30 mm in width and positioned in the center therefore the arm reaches 15 mm in the direction of the rotation of the torque link. The end of the torque link, which can hit the Sarrus, is 13 mm thick, also positioned in the center and therefore reaches 6.5 mm in the direction of the rotation. With the laws of trigonometry one can determine that maximum deflection the torque link can have is 170 degrees. This still exceeds the desired 120 degrees significantly so the decrease of the maximum deflection is not an issue.

Concept 2 will be chosen as the final concept and will be evaluated regarding producibility and costs.

Production

The subassembly consists of several parts. A number of parts can directly be ordered at a manufacturer. Those are the arms of the Sarrus linkages, the bearings, the connection blocks to the frame, the screws and bolts. The frame and the arm holder have to be produced customized. The arm holder will be considered in another part of this report.

The appropriate manufacturing process of the frame will be determined based on the design factors shown below as is described by Gideon Halevi in chapter 5 of *Principles of Process Planning: A logical approach* [3].

1) Quantity
2) Complexity of form
3) Nature of material
4) Size of part
5) Section thickness
6) Dimensional accuracy
7) Cost of raw material, possibility of defects and scrape rate
8) Subsequent processes

The basic forming technique will be selected as a function of the quantity and the complexity of form. The quantity is low. It will be assumed that the quantity is 1. The shape complexity can be categorized as *Open*, as described by G. Halevi. From Table 4 the basic forming technique can be selected. The capital letters in this table represents a specific forming technique.

Shape complexity							
Mono		*Open*		*Complex*		*Very complex*	
Quantity		*Quantity*		*Quantity*		*Quantity*	
< 180	> 1000	< 150	> 2000	< 50	> 1500	< 100	> 1000
D	B	C	B	C	A	E	B
E	E	D	A	D	B	D	D
B	D	B	D	B	C	C	E
C	C	E	C	E	D	A	C
A	A	F	E	F	E	B	A
—	—	A	—	A	—	F	F

Capital letter	Forming technique
A	Forming from Liquid (casting, molding)
B	Forming from Solid by deformation
C	Forming from Solid by material removal
D	Forming by joining parts
E	Forming by assembly
F	Forming by material increase

Table 4: Forming technique as function of shape complexity and quantity

The shape complexity is *Open* and the quantity is 1, so less than 150 and therefore there have to be looked into the third column. The most economical basic forming technique is forming from solid by material removal. If this basic forming technique is not available then forming by joining parts have to be selected as basic forming technique etcetera.

There will be assumed that the forming technique of forming from solid by material removal is available. The ascending production processes depends on the geometrical and dimensional tolerances, surface roughness required and the nature of the shape that has to be created by a material removal process. Table 5a and Table 5b will be used to determine the production processes.

Process	Surface roughness R_a (in µm) (min)	(max)	Machine type
Round symmetrical shapes			
Turning	0.8	25.0	Lathe
Grinding	0.1	1.6	Grinding
Honing	0.1	0.8	Honing
Polishing	0.1	0.5	Polishing
Lapping	0.05	0.5	Lapping
Prismatic shapes			
Milling	0.8	25.0	Milling
Grinding	0.1	1.6	Grinding
Honing	0.1	0.8	Honing
Polishing	0.1	0.5	Polishing
Lapping	0.05	0.5	Lapping
Holes, Threads, Misc.			
Drilling	1.6	25.0	Lathe, milling Drill press
Reaming	0.8	6.3	Lathe, milling Drill press
Boring	0.8	10.0	Lathe
Peripheral milling	0.8	15.0	Milling
Grinding	0.1	1.6	Grinding
Burnishing	0.2	0.4	Burnishing
Broaching	0.8	6.3	Broaching
Milling	0.8	25.0	Milling

Table 5a: Surface roughness limits as function of process

Tolerance ± (mm)	Surface roughness R_a (µm)
< 0.005	> 0.20
0.010	0.32
0.015	0.45
0.020	0.80
0.030	1.0
0.040	1.32
0.050	1.60
0.060	1.80
0.080	2.12
0.100	2.50
0.150	3.75
0.200	5.00
0.250	6.25
0.350	9.12
0.600	12.50
1.000	25.00

Table 5b: Relation between tolerance and surface roughness

Two views to the frame are shown in Figure 2. The holes that need to be created by material removal are labeled by number 1 to 10. The holes that are labeled from 1 to 6 can be assumed as *Holes, Thread, Misc*. The tolerance that will be used is the same as is used as the tolerance for the old design of the frame, namely ±0.1. Surface roughness is not specified so the maximum surface roughness that is possible with this tolerance will be used, so this is a roughness of 2.50 µm. The first process used for creating this is drilling. Drilling can have a minimum surface roughness of 1.6 µm and a maximum of 25 µm. The drilling process is therefore sufficient to creating holes number 1 till 6.

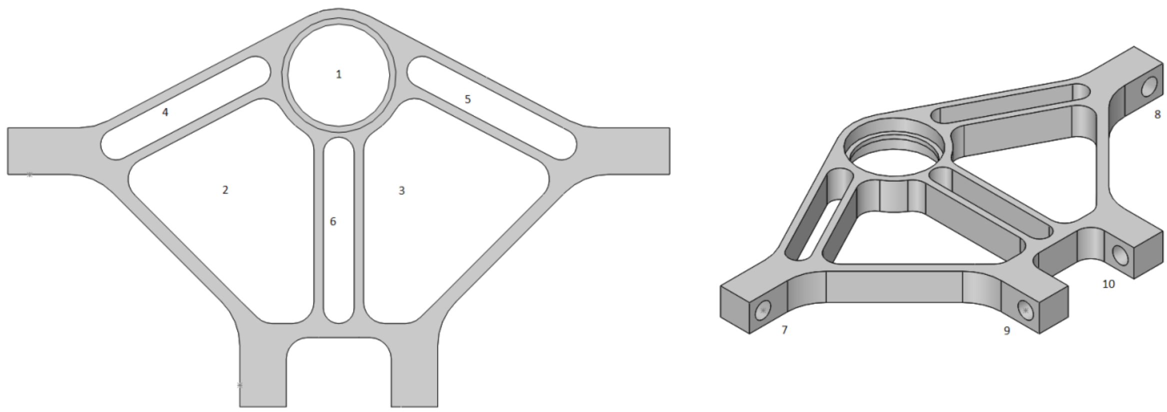


Figure 2: Views on newly designed frame

The holes with numbers 7 to 10 can be categorized as *Holes, Threads, Misc.* The holes are M6 x 1.0 with a tolerance 6H. A tolerance level of 6H corresponds to an ISO2 class and with the use of auxiliary tables it can be found that this can be seen as a tolerance of ±0.0015 mm. This tolerance requires a surface roughness lower than 0.2 µm. The first process used for creating holes in this category is drilling. Drilling cannot provide a sufficient surface roughness so an extra process is needed. Grinding can provide a sufficient surface roughness so this could be used as a finishing process to create the holes. Besides the 6H tolerance, the holes 9 and 10 need a tolerance regarding concentricity. Therefore Table 6 can be used. As can be seen in this table, grinding can provide a tolerance of 0.002 mm, which is sufficient enough.

	Geometric tolerance type (mm)			
Basic process	*Parallelism*	*Perpendicularity*	*Concentricity*	*Angularity*
Turning	0.01–0.02	0.02	0.005–0.01	0.01
Milling	0.01–0.02	0.02	—	0.01
Drilling	0.2	0.1	0.1	0.1
Boring	0.005	0.01	0.01	0.01
Grinding	0.001	0.001	0.002	0.002
Honing	0.0005	0.001	0.002	0.002
Superfinish	0.0005	0.001	0.005	0.002

Table 6: Relation between tolerance limits and basic process

Due to the extra Sarrus linkage and the change in the frame there will be an increasing in weight and therefore and increase in material costs. Instead of 6 arms in the Sarrus linkages, 7 arms will be used in total. This will increase the weight of the Sarrus linkages with about 72 g. The weight of the old frame is 92.58 g and the new frame is 153.83 g so this will increase the weight with 61.3 g. This will increase the weight in total with 133.3 g, so say about 135 g. The costs increasing is in ordering the extra Sarrus arm and the increase is in producing the new frame, which is somewhat more comprehensive to make than the old frame, but this only will be a few percent.

Problem 2: Gravity compensation system

In the design of the SEP a gravity compensation system (GCS) is enhanced to compensate for the weight of the arm placed in the arm holder. A schematic overview of the principle where the GCS is based on is shown in Figure 3. The GCS consists of a Sarrus linkage where a number of pulleys are attached to, which guides a rod which is connected to a spring. The pulleys are arranged in such a way that if a force acts in downward direction to the Sarrus linkage (represented by F in the Figure 3), a reaction force acting in opposite direction is opposed. The force F namely compresses the spring, which then pulls the rod and creates tension, hereby also provoking a force in the upward direction, $F_{sp,y}$, and so compensating the force F. The size of the force $F_{sp,y}$ can be varied by changing the distance A. An extra sensation of the gravity can be created by moving the top pulley below the middle bottom pulley. This is shown in the right hand-side of Figure 3. [4]

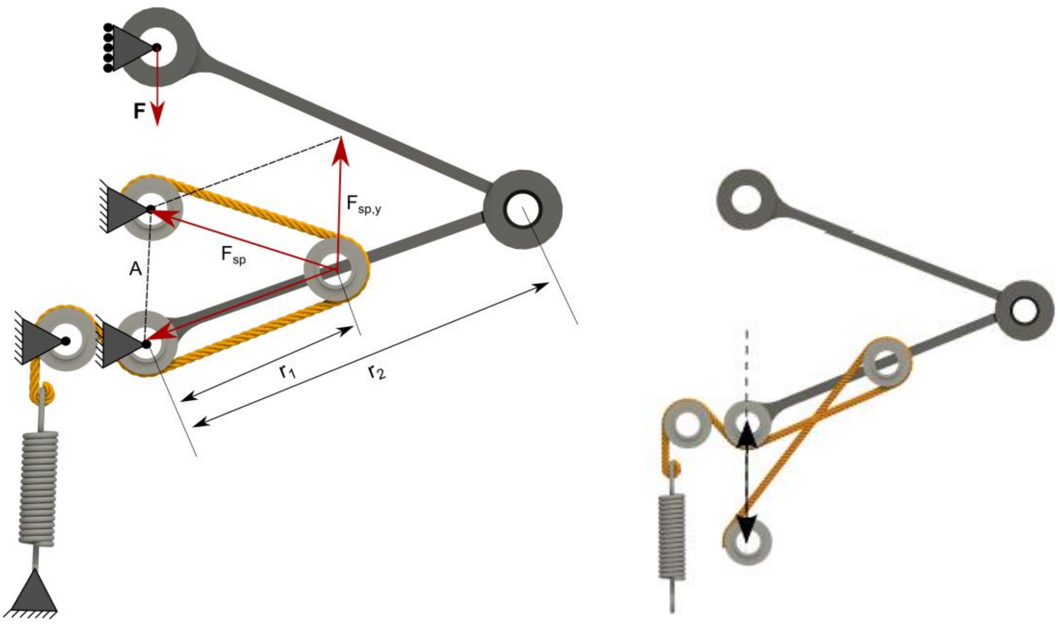


Figure 3: Schematic view of gravity compensation system

This design of the gravity compensation system can be a good solution, especially compared with the other options available to implement into the SEP, as is argued by M. van Hirtum []. However, a number of choices are made in the final design of the GCS, regarding bearing selection and pulley arrangement, which cause for some problems. A number of the pulleys encounter too much friction and do not rotate easily. Also the design could be more simplified with possibly less pulleys.

Analysis of current model

A picture of how the gravity compensation system is comprehended into the SEP is shown in Figure 4. The system consists of 5 pulleys and 1 half pulley (plus a pulley below in the final assembly near the spring, not shown in the picture). A string is guided over the pulleys and is fixed at the end of the half pulley. The half pulley is movable in vertical direction by turning the screw on which it is attached, so the amount of compensation is adjustable. The half pulley is therefore alongside the pulley underneath it, so it can also move below that one to enhance the gravity. The top right-most pulley is mounted with a ball bearing of the type EZO 688 ZZ with an inner diameter of 8 mm and an outer diameter of 16 mm. The bearing is housed inside the center of that pulley. The pulley in the middle of Figure 4 is mounted with a self-aligning plain bearing of the type SKF GE 8C (with d=8 mm, D=16 mm, B=8 mm, C=5 mm, α=15°). The reason that is named for using the self-aligning bearing is that the half pulley alongside it makes that the string is not orientated in one plane so the self-aligning bearing can overcome the tilted angle of the string but maintaining low thickness of the pulley. The left most bearing in Figure 4 is not mounted with bearings by itself, but the bolt where it is screwed on is mounted with bearings, so that both bolt and pulley can rotate together. The bearing used here is a ball bearing of the type PRC 6800 ZZ with inner diameter of 10 mm and an outer diameter of 19 mm. The same holds for the other two lower pulleys, visible in the bottom of Figure 4. They are present to guide the end of the string towards the spring which is below the pulleys, not visible in Figure 4.

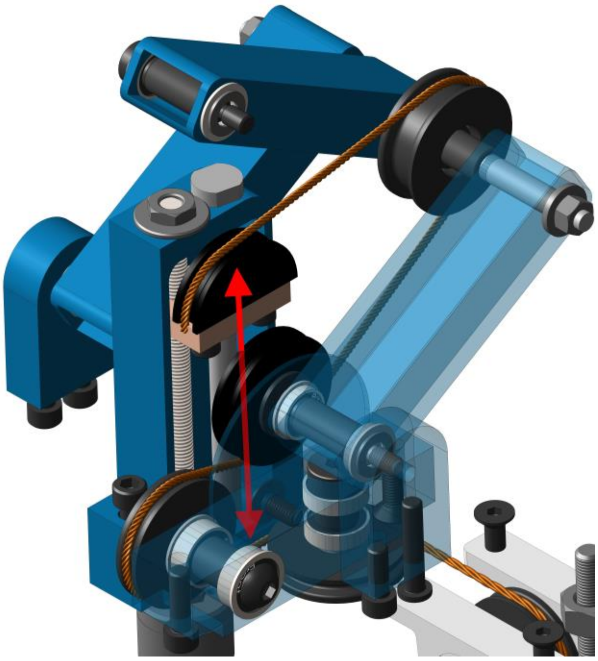


Figure 4: Gravity compensation system

Due to the many pulleys it is difficult to place the string over the pulleys. There can be thought of an arrangement of pulleys where this can be done more easily. The selection of the rotation shafts and bearings of the several pulleys is not clear. Those are selected so that they can meet the requirements but no extra attention is paid to minimize friction for example. One can argue for an alternative selection of rotation shaft and bearings which can rotate with less friction.

The pulleys do not have to rotate with high speeds or even have to make many turns at all. The service life of the bearings used with the pulleys should therefore not be an issue. If prescribed tolerance levels are used for shaft and housing of bearings backlash is not an issue. The top right-most pulley can rotate with the least friction compared to the other pulleys in the current setup. A similar ease of rotation can be seen as an aim for the other pulleys. The size of the pulleys limits the bearing selection to plain or rolling element bearings.

Concepts

Concepts are proposed to reduce the friction in the rotation of the pulleys and make a more simple arrangement of pulleys.

A decrease of the number of pulleys by at least 1 can be established by rotating the entire setup of the GCS and the Sarrus linkages toward the axis of rotation of the arm holder. In the current model of the SEP, the edges of the GCS and the Sarrus linkages including of the GCS are parallel to 2 of the edges of the mounting plate. By rotating the GCS and the Sarrus linkages 45 degrees clockwise, the pulley underneath the GCS guiding the string to the pulley at the corner near the spring is not necessary. One of the consequences of rotating the entire setup is that the mounting plate also has to be adjusted. The holes in the mounting plate require a repositioning.

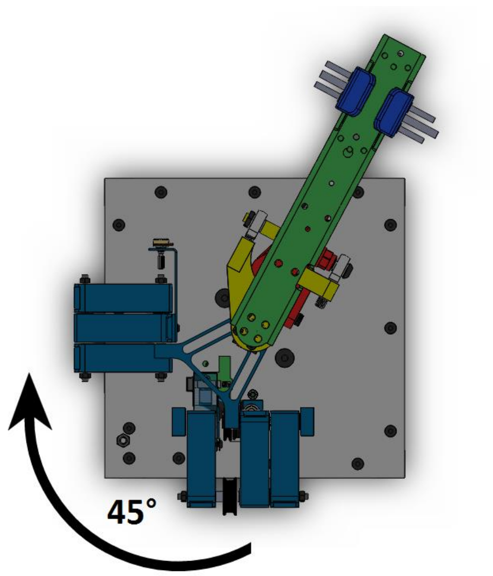


Figure 5: Rotation of GCS

Friction in the rotation of the pulleys should decrease if a same bearing setup as in the top right-most pulley is applied for all other pulleys. Testing of the prototype of the ability to rotate of the top right-most pulley have shown satisfying results so copying the bearing setup of this pulley to the other pulleys should give those pulleys similar ability to rotate. This means that for all other pulleys a bearing should house into the pulley itself. Therefore some of the pulleys have to be replaced with pulleys which also contain a cavity where a bearing can be housed. Also the blocks mounting the pulleys to the mounting plate need redesign. [5]

The pulley now mounted with a self-aligning plain bearing is an issue. The self-aligning plain bearing cannot simply be replaced by a ball bearing because in some way the out of plane orientation of the pulleys has to be overcome, as was stated in the previous paragraph. By elongating the width of the top right-most pulley and turning the string a couple of times around this pulley the misalignment of the pulleys can be overcome. By then creating screw thread onto the pulley and applying a certain pitch the number of turns can easily be guided so less friction is present.

Concept Evaluation

The proposed concepts do not rule each other out so all can be assimilated into a new design for the gravity compensation system.

Comprehending the rotation of the entire setup of the GCS and the Sarrus linkages with 45° clockwise will change in the first place the mounting plate. A picture of the new setup when including this rotation is shown in Figure 6 and the change to the mounting plate are depicted in Figure 7.

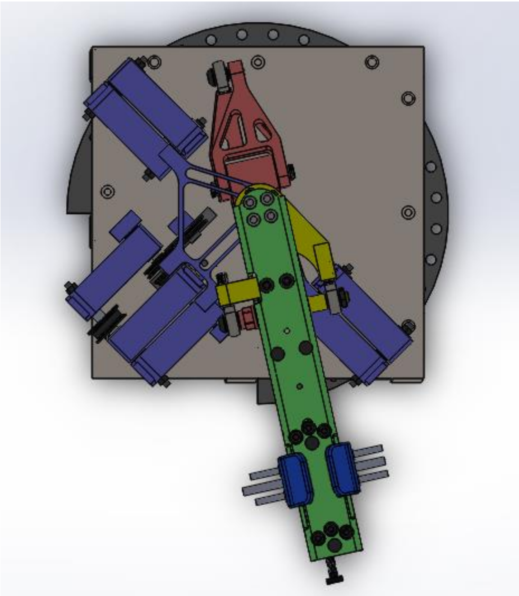


Figure 6: Topview of new setup GCS

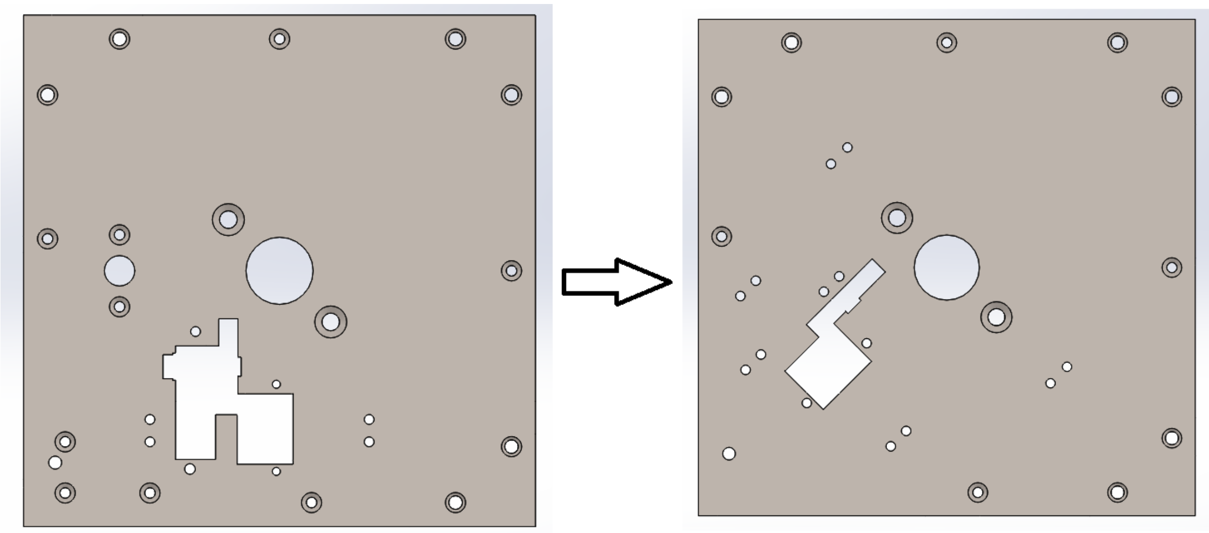


Figure 7: Changes to mounting plate

The new selection of bearings will mean that in total 4 ball bearings of type EZO 688 ZZ with an inner diameter of 8 mm, an outer diameter of 16 mm and a bore of 5 mm are needed. The pulley in the right bottom corner of Figure 4 will also be replaced by a pulley where a ball bearing is housed in a cavity in the pulley. The pulley now containing a self-aligning plain bearing already contains a cavity which is also suitable to house a bearing of the type EZO 688 ZZ. Therefore having 3 such pulleys is suitable. The forth pulley, top right-most pulley, will require an increase in width of 3 mm. Also a thread has to be created on this pulley. In the design of this feature in the SolidWorks-model, a M36x4.0 metric tap is used for the thread. This means that the diameter of the pulley does not need adjustment and that the string can be turned 3 times around the pulley and therefore is able to come in line with the successive pulleys.

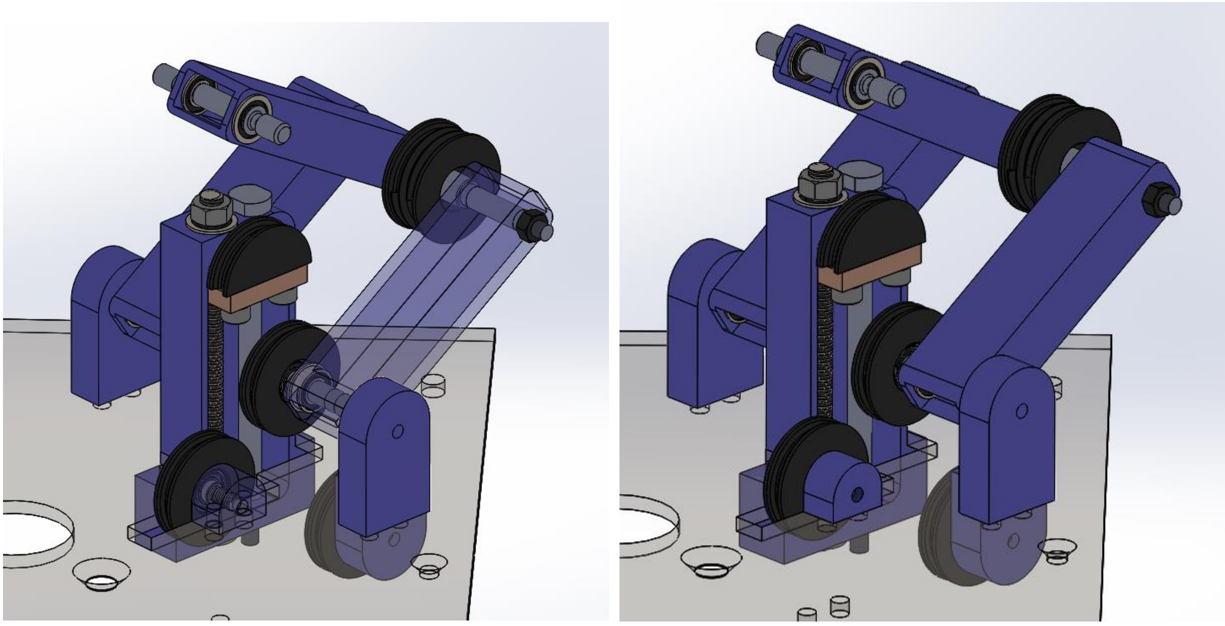


Figure 8: New design of GCS including partly transparent view

Pictures of the final design of the GCS are shown in Figure 8. As can be seen in those pictures, also some connection blocks are enhanced in the design. These need to be designed and are similar to the connection blocks already used to mount the Sarrus linkages. Difference is that they have different length. Dimensions are specified in the SolidWork files.

Production

Briefly the production of the several (new) parts of the gravity compensation system is discussed. There is focussed on how the parts need to be manufactured compared to the current parts of the GCS.

For comprehending the improvement regarding the rotation, a new mounting plate has to be produced. The features of the newly to produce plate are similar; material properties and thickness are kept the same as the current mounting plate. Only the features of the holes are different. The costs for producing the mounting plate is therefore similar as the costs were for producing the current plate. The position of the holes is different but the number of holes is more or less the same so number the number of drillling operations are kept also more or less the same so the costs will not increase much.

The adapting of the other improvements into the final design of the GCS require one less pulley, so costs of ordering/producing is decreased with the costs of one pulley. The top right-most pulley need to be replaced by a pulley which has larger witdh and which contains screw-thread. Production of the screw-thread will increase the costs, but it will not deteriorate the costs with more than € 10 if this would be outsourced, and can be less if done by Hankamp itself.

The current GCS contains a total of 8 bearings. All those bearings where ordered at the company Neita. For the new design of the GCS, only 4 ball bearing are specifically needed for the GCS. All those 4 bearings need to be of the type EZO 688 ZZ. This type of bearing has an inner diameter of 8 mm, an outer of 16 mm and a bore of 5 mm. They are sold by Neita with a retail price of € 2.62 per item. This requires a total of € 10.48 for the costs of the bearings needed for the GCS, which is a decrease in costs compared to the costs of bearings for the current GCS.

Finally 2 additional blocks are needed to mount two of the pulleys to the mounting plate. This are the bottom left-most and the bottom right-most pulley in Figure 8. The feature of those blocks will mostly be the same as the blocks used to mount the Sarrus linkages to the mounting plate, only the dimensions are different. Production of those new blocks will therefore be the same as the production was done of the blocks currently used to mount the Sarrus linkages.

Problem 3: End stops

Safety is an important issue. When using the SEP, too large rotation of the arm holder can injure the person which is examined. Therefore safety end stops are enhanced in the design to ensure that rotation stays within the predefined limits. The current setup for the end stops is save enough; the stops can withstand a force with a sufficient factor of safety such that failure is ruled out. However, in the current design of the end stops, the end stops are very difficult to move into another position to vary the boundaries of rotation. A new setup for the end stops have to be designed, which is easy to move from position, but also has a large enough factor of safety.

Analysis of current model

A screenshot of the current setup of the end stop designed in SolidWorks is shown in Figure 9. The setup consists of two blocks which are mounted with bolts in a circular slot. A rotatable hinge will collide with the end stop if a certain rotation is reached, therefore preventing the arm holder to rotate beyond the end stops. By unscrewing and screwing the bolts, the end stops are moveable over the circular slots, and so the maximum rotation is variable. However, the unscrewing and screwing of the bolts is very difficult. The housing of the end product has to be removed in the first place to make it even possible to reach the bolts with a wrench for example. And due to the orientation of the bolts it is difficult to make the necessary rotation to screw the bolts. Also it is difficult to exactly position the end stops in the slot. There is not an indicator of how much the end stops are rotated or whatsoever. There can be stated that the setup with the bolt and screw mechanism is not ideal in the sense of adjustability.

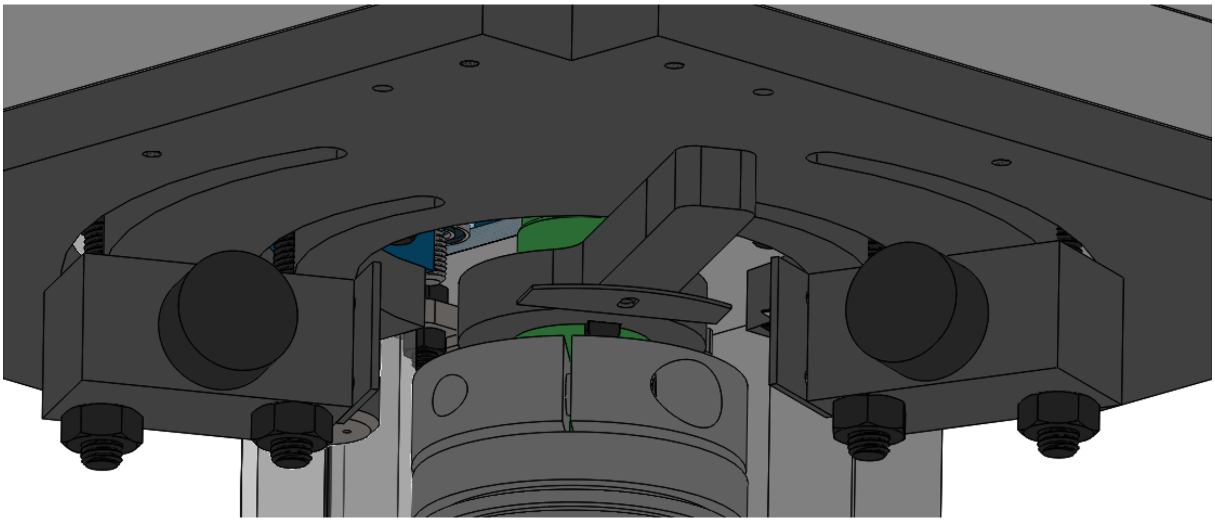
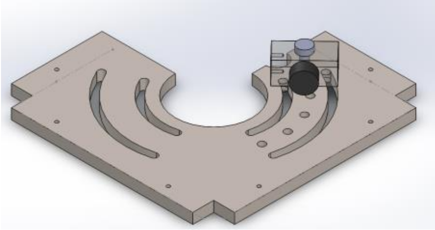
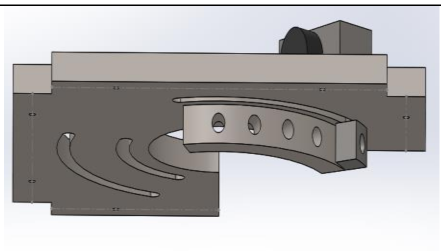
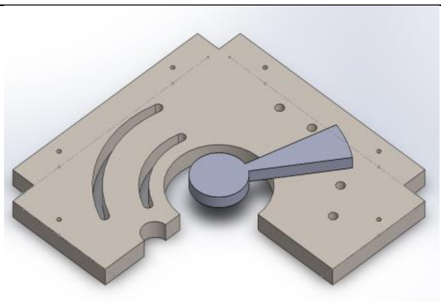


Figure 9: Current design of end stops

Concept

Concept improvements will be proposed where the bolt connections are dismissed and replaced by other types of connections. There will be tried at first hand to keep the features of the blocks the same, because tests have shown that this will enhance the desired factor of safety. The concepts are summed up in Table 7. The table contains a picture of the design and a description of the design. The orientation of every picture is somewhat different to show the specific features of each concept more clearly. The pictures only contain the features displayed in one half of the assembly.

Concept number	Concept design	Concept description
1		In this concept the bolt connections are replaced by a pin connection. The blocks can freely move over the slot, but can be locked with a pin at certain position. Consequence of this connection is that the blocks only can be locked in the position where a hole is drilled. Another consequence of this setup is that the end stop plate cannot be mounted with direct contact to the frame bottom plate. The pin can be taken out and placed back to move and lock the block.
2		This concept makes also, just as concept 1, use of a pin connection to lock the blocks. But instead of locking it with the pin from above, in this setup the block will be locked from the side. This will have the same consequences regarding the fixed position and the mounting of the end stop plate as concept 1. This setup requires the addition of a circular track with holes to the end stop plate and an addition of an extra block with one hole to the stop block so that a pin can lock the stop block.
3		This concept relies also partly on a pin connection but will maintain this connection due to the elastic features of a flexible hinge. By bending the hinge you can rotate the hinge and replace it into another hole, so changing the position of the end stop. This requires the hinge to be flexible enough in the perpendicular direction but have large enough stiffness in the rotational direction. This setup requires also a connection of the hinges to the axis of rotation.

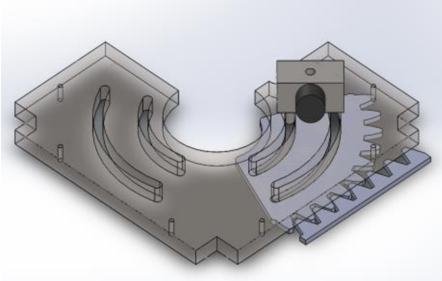
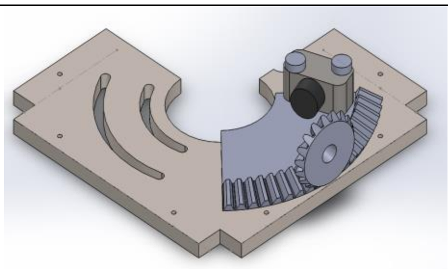
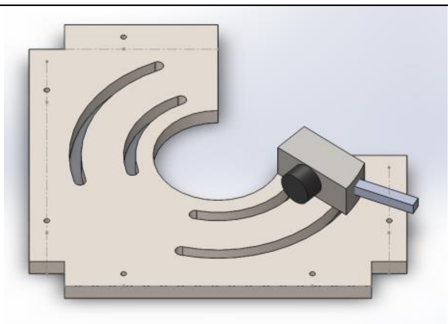
4		In this concept the stop blocks can be repositioned by moving a rack in a rack and pinion system. A pinion, which is a partly gear, is connected to the stop block and can rotate when linear motion of the pinion is translated to it. The pinion can be locked to also lock the position of the stop block. This setup has more freedom in locking the position of the block; the number of teeth of the rack and pinion determines this. With the use of this setup the repositioning of the stop blocks can be done at the edge of the frame.
5		This concept is similar to the previous concept, but this concept uses a different type of gear system. Here a system with bevel gears is used. So instead actuating the repositioning of the stop blocks with a linear sliding motion, a handle have to be rotated. This again has the advantage of the freedom of locking the end stops and adjusting it outside the frame.
6		This concept features the mounting of an arm to the stop block to reposition the stop block outside the housing by pulling the arm. At the end of the arm, the position of the end stop can be locked by locking the arm there with for example a pin connection in a locking rail at the edge of the housing. This requires an adjustment of the position of the circular slot in such a way that the rotation of the arm will not be limited by the presence of the supporting beams for the frame.

Table 7: Concepts for end stops

Concept Evaluation

In this paragraph the concepts for the improvement of the end stops will be evaluated. Each concept will be judged regarding the ease of use, costs and weight. With ease of use will be meant how easy it is to reposition and lock the end stops. The costs involve the total of the costs of manufacturing and the material costs. The judgement of the criteria is done with a plus/minus-sign ranking. Levels consists of --,-,+ and ++ where -- is the worst regarding improvement and ++ is best regarding improvement. The evaluation of the concepts is shown in the Table 8.

Concept number	Ease of Use	Costs	Weight
1	--	++	++
2	-	+	+
3	+	-	+
4	+	-	--
5	++	--	--
6	+	+	+

Table 8: Evaluation of concepts

Concept 1 is the best regarding costs and weight but lack an ease of use compared to the other concepts. Concept 2 is also good regarding costs and weight but still does not have great specs regarding ease of use. Concept 3 is good in terms of ease of use and weight, but lack level in terms of costs. Concepts 4 and 5 concern designs with a gear construction. This really improves the ease of use, but the weight will not improve and regarding the costs, especially concept 5 will have very high manufacturing costs compared to the other concepts. Concept 6 is good in terms of ease of use, costs and weight in comparison to the other concepts.

The principles of concept 6 will form the basis for the final redesign of the safety end stops.

Production

The final design for the end stops is shown in Figure 10. The edges of the new designed end stop plate do have a circular finish so there is space to drill a total of 18 holes, realizing a total of 9 different settings for each end stop, and each successive setting rotating the end stop with 10 degrees. The end stop blocks feature the elongation of the arm, making it able to lock the position with a pin in the holes, also visible in Figure 10. End stops are guided in two circular slots to ensure concentricity with the center of rotation all the time. Edges of both the end stop blocks and the hinge are made perpendicular to the axis of rotation to increase the area of impact. Material used for each part is the same as the part equivalent in the previous design. Dimension of the end stop blocks are kept the same to maintain the sufficient factor of safety reached in the previous design. Thickness of the end stop plate is kept the same. Holes with internal thread will be made in the edge of the end stop plate to be able to connect the end stop plate to the frame of the SEP. Specific dimensions are available in the SolidWorks file.

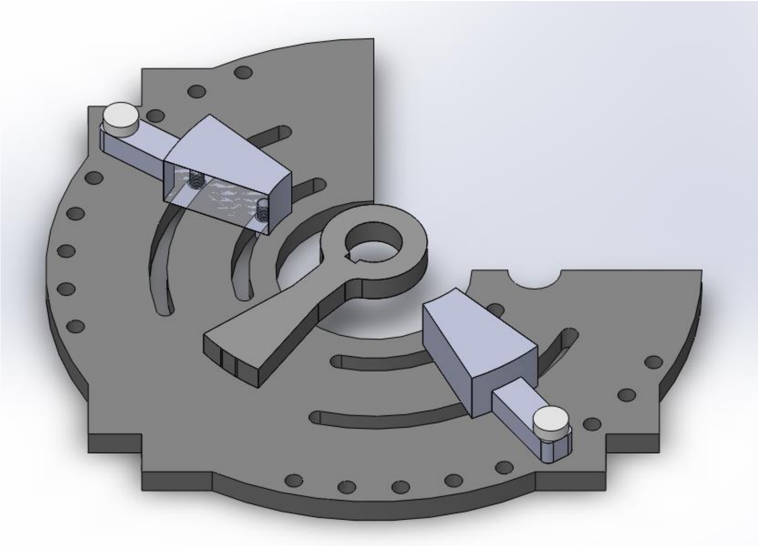


Figure 10: New design of end stops

Costs and weight of the new design of the end stops will slightly increase in comparison to the current design of the end stop. The end stop plate is somewhat larger and more complex in geometry and requires drilling of holes, therefore increasing material and the number of operation so increasing costs and weight. This same principle holds for the end stop blocks. Increases will only be relative small and therefore not deteriorate the feasibility of this final concept regarding the economical features and weight features.

Problem 4: Housing

When the SEP is ready to be delivered to the customers, a housing have to be enhanced into the design of the SEP to protect the user from the moveable Sarrus linkages. The housing has to be cheap and easy to produce and also be lightweight as much as possible. Subgoal of the design of the housing is to have a friendly appearance.

Analysis of Problem

The housing has to cover the moveable Sarrus linkages without limiting the movability of the Sarrus linkages and the rotation of the arm holder. Consequence of this is that the housing has to be mounted to the part connecting the arm holder to the frame and the housing has to move alongside the up and down motion of the frame. The point where the housing will be mounted is highlighted in the red rectangle in Figure 11 below. This part also has to be elongated so that there is room for the mounting of the housing.

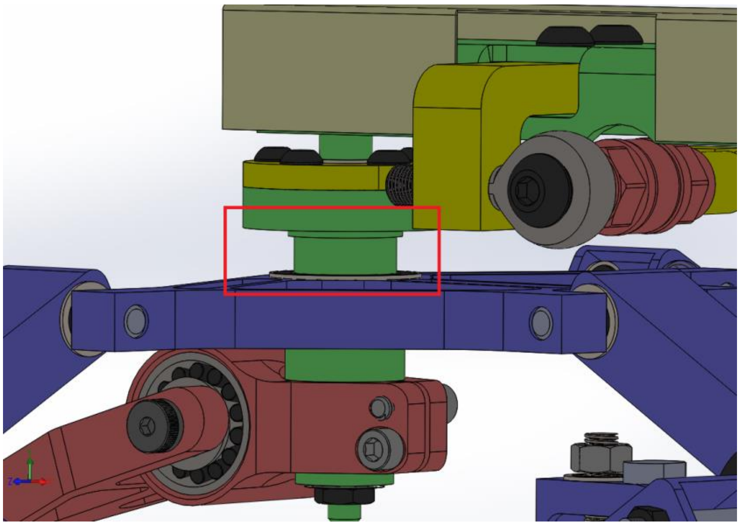


Figure 11: Mounting point of housing

To prevent that the movability of the Sarrus linkages will be limited, the housing has to have certain dimensions to ensure that in every orientation the Sarrus linkage will not hit the housing. The most protrusive Sarrus linkage with respect to the center of the mounting plate is the bottom Sarrus linkage near the gravity compensation system as highlighted with the red rectangle in Figure 12. The Sarrus linkage is in its most protrusive orientation if the arm holder is moved as low as possible, that is when the Sarrus linkage above the gravity compensation system collides with the gravity compensation system. The bottom Sarrus linkages are than orientated with an angle of 30° towards the mounting plate. Assuming that the top view of the housing has a rectangular or circular shape the minimum length and width of the housing can be determined. If the Sarrus linkages are orientated with an angle of 30° towards the mounting plate, the distance between the most protrusive point and the line perpendicular through the center of the mounting plate is 204.55 mm. Because the distance between the center of the mounting plate and the corners of the plate are 226.27 mm, a housing with a circular shape should at least have a radius larger than 226.27 mm. The line representing the distance between the most protrusive point and the line perpendicular through the center of the mounting plate is orientated with an angle of 20.4° towards the normal of the center of the mounting plate to the closest edge near the most protrusive point. If the housing would be designed with a rectangular shape, the normal distance between the center of the mounting plate and the edge of the housing closest to the most protrusive point should be at least 204.55*cos(20.4°)=191.73 mm.

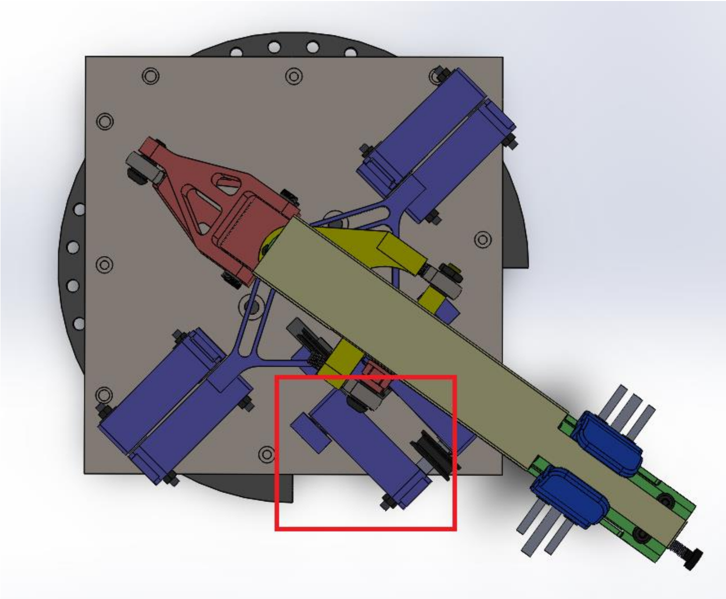
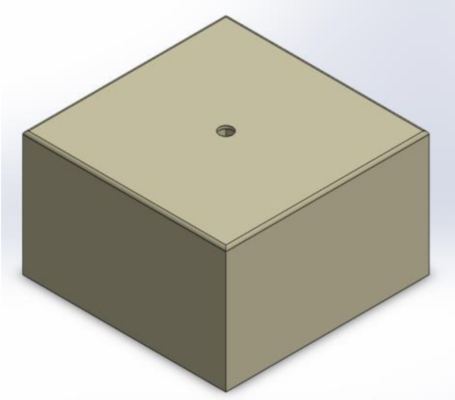
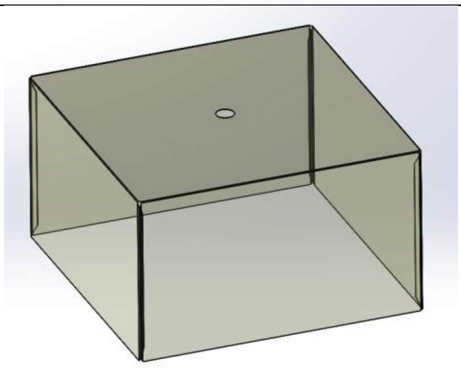
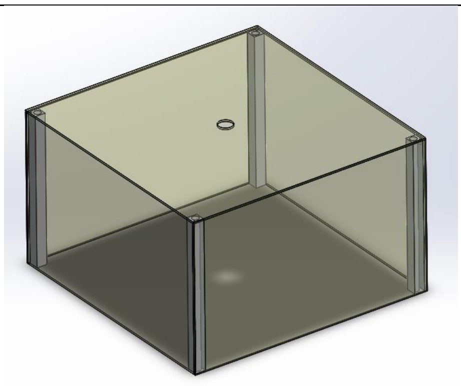


Figure 12: Most protrustive Sarrus linkage

The height of the housing should at least be that large that in every orientation the Sarrus linkages will be covered. This is when the arm holder is moved as high as possible. In this orientation the Sarrus linkages are parallel to each other. The normal distance from the mounting plate to the top of the Sarrus linkages is 226 mm. The height of the housing should therefore be at least 226 mm to cover the Sarrus linkages for every possible situation.

Concepts

Concepts are proposed for the design of the housing. The concepts are based on the difference in geometry and in producibility. Material properties are therefore not yet specified in the concepts. Wall thickness is also not yet specified in the concepts because minimum wall thickness to maintain minimum rigidity is dependent on type of material. All concepts are hollow in the inside and contain a drilled hole to be able to be mounted above the frame. An overview of pictures of the concepts with descriptions is shown in Table 9 below.

Concept number	**Assembly**	**Description**
1		Cubic housing made out of 1 piece. Depending on the material used (either metal or plastic), the production of this requires a moulding or casting process.
2		Cubic housing made by bending. More suited for metal than plastic. Design contains ribs at the corners to maintain rigidity.
3		Rectangular housing made out of plates connected to support beams. Plates can be connected to support beams by screws, gluing, welding, etcetera. Support beams can optionally function as linear guides.

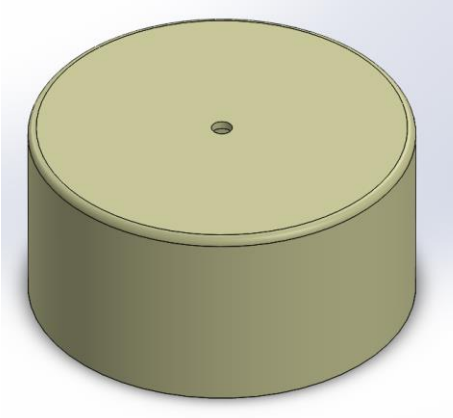
4		Cylindrical housing made out of 1 piece. Just as the cubic housing made out of 1 piece, the production of this requires either a moulding or casting process.

Table 9: Concepts for housing

Concept Evaluation

In this paragraph the proposed concepts are evaluated regarding the suitability for implementation in the new design of the SEP. The most important requirement besides to cover the moving parts is that it is inexpensive to either produce or purchase. Because the SEP will be produced in low quantity (less than 10) and end-users will be hospitals, a friendly appearance of the housing is of minor issue. Due to the fact that the final housing will be produced in low quantity, using concept 1 and concept 4 as final concept is not suited. The production of concepts 1 and 4 requires use of a mold, and the costs of a mold are that high that for low quantities this is not economically feasible. Therefore concept 1 and 4 will not be considered anymore as a suited housing for the final design of the SEP.

Weight is sought to be as low as possible. Weight depends on the density of the material used and the wall thickness. Plastics are available with lower densities than for example aluminum, but it requires larger wall thickness. Plates of polypropylene are commercially available up from 1.2 mm in thickness, which would be sufficient to maintain stiffness for concepts 2 and 3. Sheet metal plates are commercially available up from 0.3 mm in thickness, which would also be sufficient to maintain stiffness for concept 2 and 3. For example, a 1 by 1 m plate of polypropylene with a thickness of 1.2 mm would weigh 1.068 kg and a 1 by 1 m plate of aluminum of 0.3 mm would weigh 0.81 kg. Using sheet metal looks like a more suitable use for a housing regarding weight. Therefore sheet metal will be used as the material used for the housing for the final design of the SEP.

Concept 2 or 3 will be selected as the housing for the final design of the SEP. Concept 3 has the benefit that it, due to the support beams, has better stiffness than concept 2. But very good features regarding stiffness is not required, because the housing will barely endure stress during operation and otherwise it will be very low force (1 a 2 kg) acting on the housing. Besides this benefit, the support beams increase weight and optionally linear guide does not add much value. Connecting the plates with screws is costly and labor-intensive and welding or gluing is disambiguous if concept 2 is also suited, while the stiffness is not of that importance. Therefor concept 2 is the best regarding costs and manufacturability and will form the basis for the housing for the final design of the SEP.

Production

Concept 2 is chosen to be the design for the housing of the SEP. As was stated, this housing will be formed by bending. Therefore a sheet metal plate in a desired shape is necessary. A picture of this is shown below in Figure 13. A sheet metal plate of a certain thickness can be cut into this desired shape and then bent into the cubic housing. The top part of the housing will be square with edges with a length of 390 mm. A square top part will be the most easy to balance compared to a rectangle with non-uniform edge length. The length of 390 mm is large enough to prevent the Sarrus linkages to hit the housing from the inside. The side parts will have a length of 230 mm so that the Sarrus linkages will be covered for every orientation of the arm holder. The ribs will have a width of 10 mm and can be welded together at the corners. A thickness of 0.3 mm is sufficient for the sheet metal, but the final thickness of the material and the specific type material depends on what is easy for Hankamp Rehab to order/produce. The sheet metal material should not have to be of high quality regarding corrosion resistance, because this is not an issue. This can be otherwise prevented by applying paint, which also can help to increase the level of friendly appearance of the housing. A hole has to be drilled in the center of the top part so that the housing can be mounted underneath the arm holder. [6]

Figure 13: Sheet metal design of housing

Miscellaneous Problems

There are a number of issues with the current design of the SEP which can be considered as minor problems which do not need thorough explanation and can be dealt with in a simple fashion. Those issues are therefore in this chapter only elaborated briefly, compared to the previous problems.

Torque link

In the current design of the SEP, the torque link collides with the frame when experiencing a certain amount of rotation. The torque link is the red part in Figure 14 and, during operation, translates the rotation of the motor to the arm holder. Due to this issue, the arm holder cannot freely rotate and the torque link and frame can get damaged when colliding with high impact.

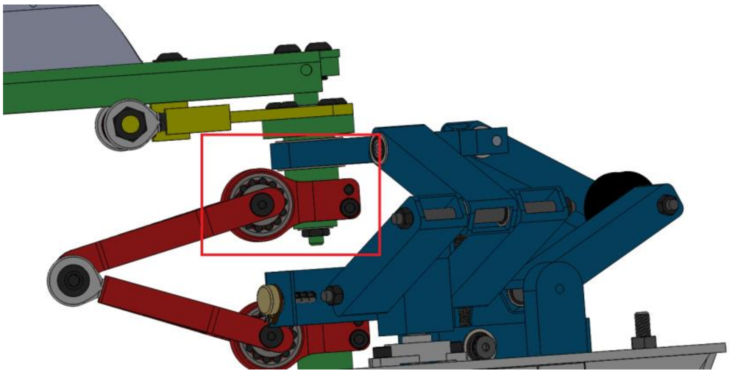


Figure 14: Collision of torque link and frame

This problem can easily be solved by elongating the axis connecting the end of the torque link to the axis of rotation of the arm holder. Besides this elongation, this axis has to be elongated so the housing can be mounted, as is discussed in the chapter *Problem 4: Housing*. The new axis will therefore be elongated with 12 mm in total. The elongation is depicted in Figure 15.

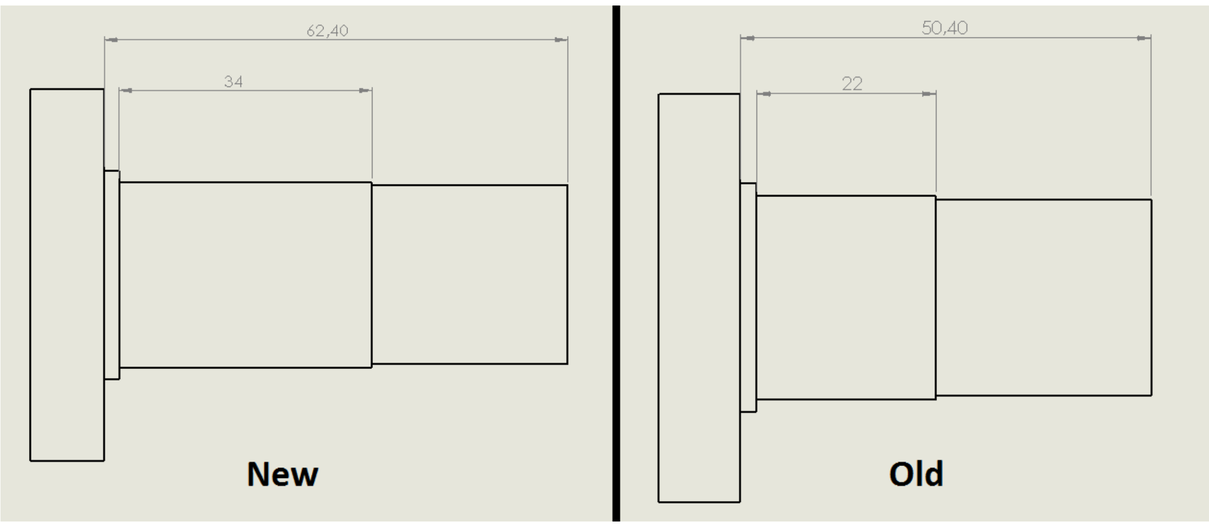


Figure 15: Representation of features in new and old part

Backlash in wrist lock

The wrist lock at the end of the arm holder experiences in the current design of the SEP too much backlash. The reason for this is that the screw-thread, on which the wrist lock is mounted so that the position can be changed, has too much backlash. The screw-thread is kept in place by guiding through 2 separate holes, which are shown in Figure 16 and highlighted by the red arrows (screw-thread not displayed in this figure). In the holes, especially the one the most near to the axis of rotation of the arm holder, the most left-one in the figure, has clear backlash easily detectable in the prototype with the human eye. The backlash can decrease by paying more attention during the drilling of the hole; making sure a sufficient tolerance is used and sufficient drilling method and equipment are use which can ensure this tolerance. Also the use of bearings can improve the amount of backlash. A use of a ball screw (see Figure 17) would be the best solution regarding backlash and it will also have low friction, but it is more expensive than regular ball bearings which are therefore a better option. The gravity compensation system also includes a screw-thread which has similar functionality as the screw-thread of the wrist lock, but this one is supported with ball bearings. A suggestion is to copy this setup to the screw-thread of the wrist lock. [7]

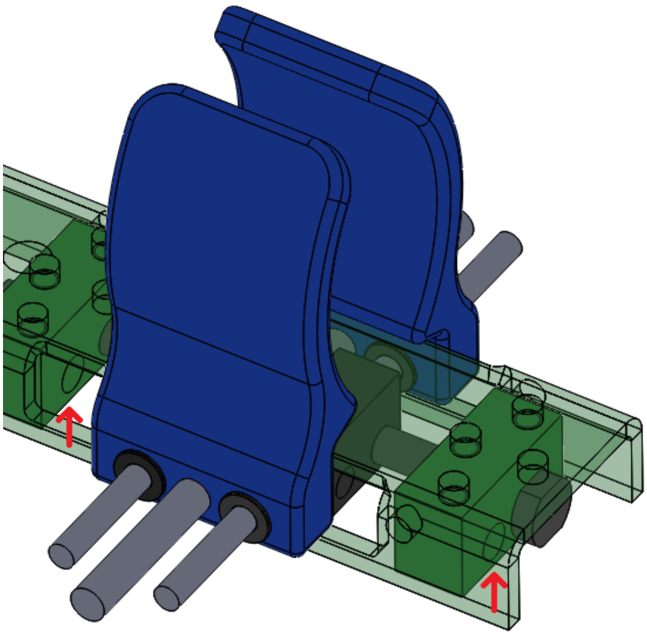


Figure 16: Guiding holes for screw thread

Figure 17: Ball screw [7]

Arm holder hood

The arm holder itself and to the arm holder several parts are mounted with bolts. Due to this, when an arm is placed on the arm holder, the arm will rest on a couple of bolt heads. Resting an arm on this does not feel comfortable and is a risk for hurting the arm. Placing a hood over the arm holder can solve this. For the design of a suitable hood, the same problems as for the design of the housing will be encountered. An inexpensive, easy to produce, lightweight and also thin hood is desired. This makes the production of a hood by bending of sheet metal also a suitable method. The same specifications regarding material properties and production as the design of the housing apply for the design of the hood. Pictures of the designed hood are shown in the figures below. Knobs of for example rubber can be mounted to the arm to support and balance the hood. The hood can be glued to the arm holder to lock position. The hood can be painted to have a more friendly appearance. Plastic strips can be put on the hood to improve the comfort of resting the arm.

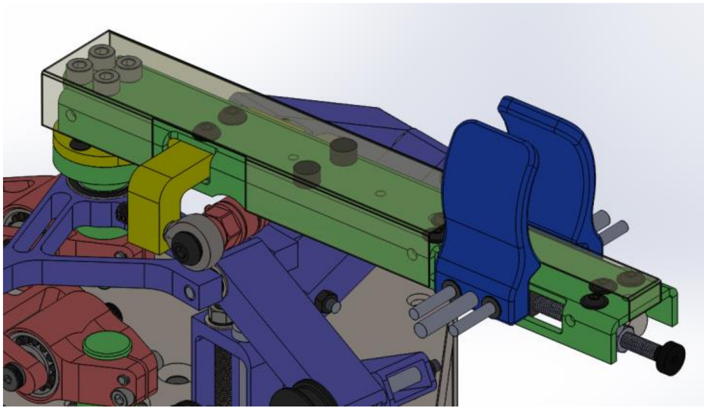


Figure 18: Transparent view of hood mounted on arm holder

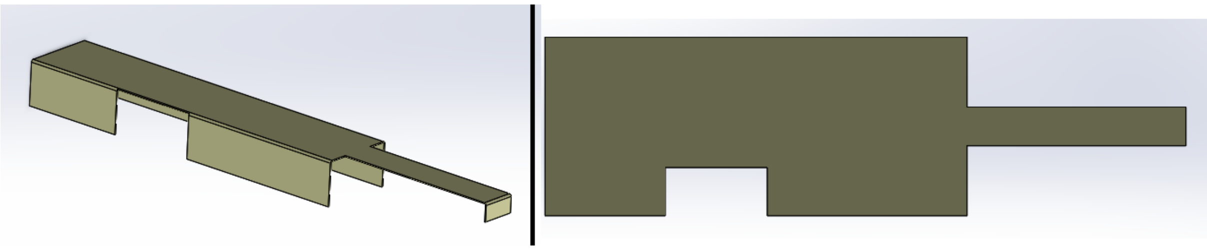


Figure 19: Views of arm holder hood including sheet metal design

Motor for GCS

The amount of compensation of the gravity compensation system can be varied by changing the position of the half pulley. The half pulley can be moved up and down by rotating a screw. This screw is driven by a motor and can be controlled at the edge of the frame. In the current design of the SEP, the motor is directly underneath the end of the screw, but because of the rotation of the GCS, as is discussed in the chapter *Problem 2: Gravity Compensation System*, this is not the case anymore. To still make is possible to translate the torque of the motor to the screw a belt will be comprehended into the design. This is represented in Figure 20.

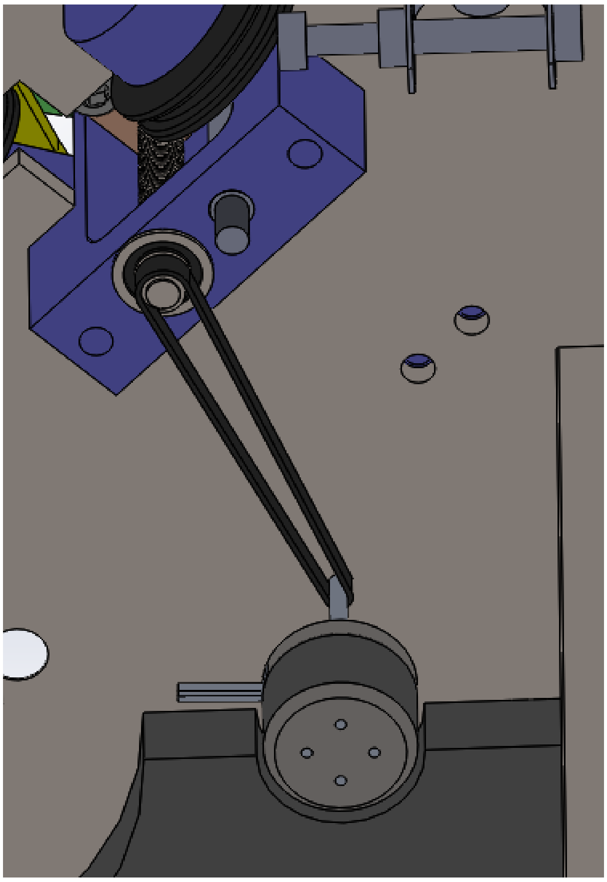


Figure 20: View on belt to translate motor torque to screw

Conclusion and Recommendations

Solutions for the several problems in the current design of the SEP are proposed. All the improvements to the SEP are processed into a new SolidWorks model. The consequences of combining each specific improvement into a final design of the SolidWorks model of the SEP will discussed in this chapter.

Pictures of the final design of the SEP are shown in Figure 21. Figure 21a shows a view with the housing and arm holder hood made transparent, while Figure 21c shows a view when those part are not transparent. Figure 21b shows the final design from the side to highlight the moved position of the end stop plate in comparison to the current design of the SEP. The motor that drives the rotation of the arm holder is not shown in the pictures because nothing is changed to this feature of the design.

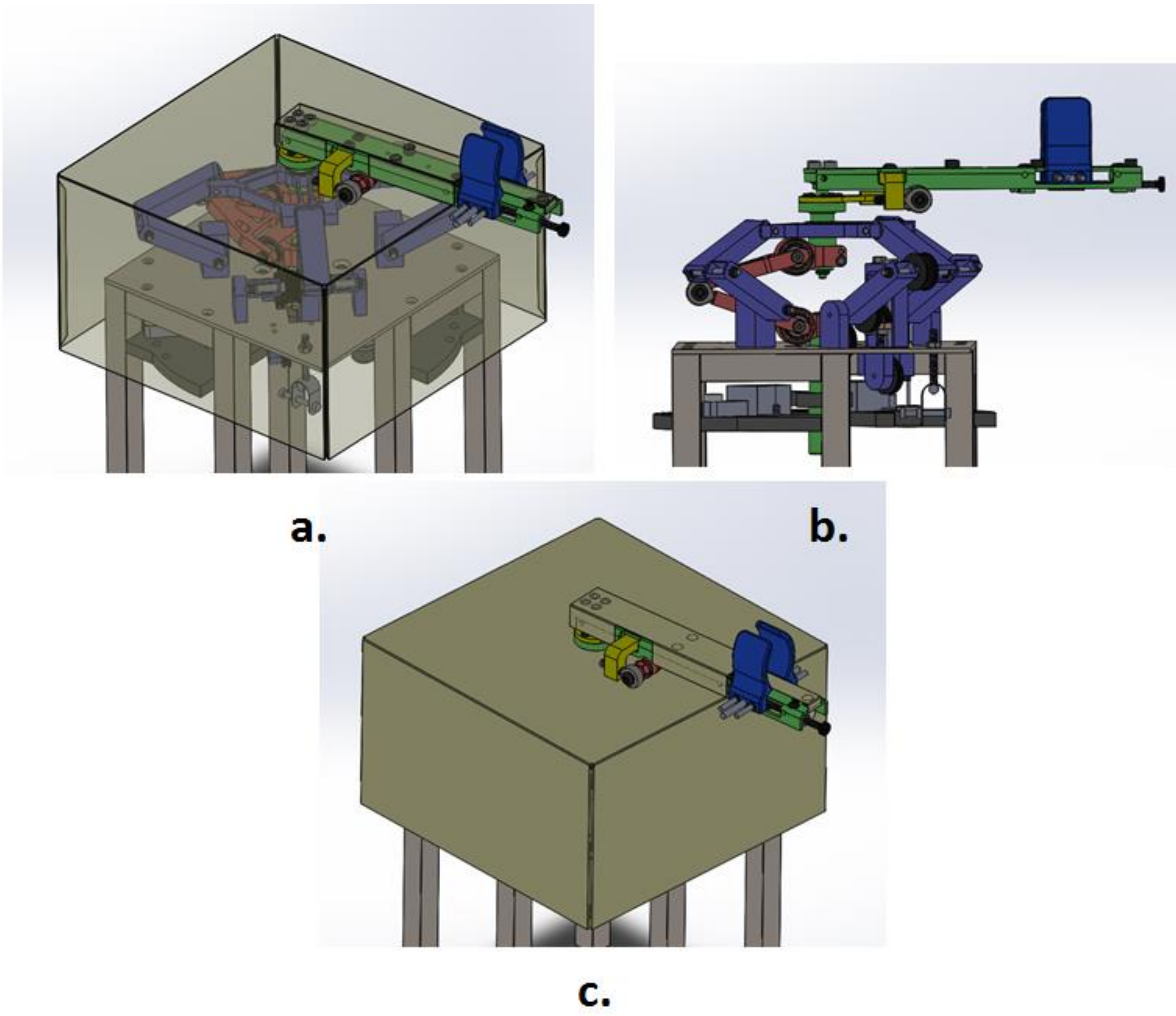


Figure 21: Several views of final design of SEP

The biggest changes to the design of the SEP are the incorporation of the additional Sarrus linkage and the rotation of the Sarrus linkages and the gravity compensation system towards the axis of rotation of the arm holder. This is clearly visible on first glance when comparing the design of the current design of the SEP with the design of the final design of the SEP. The amount of freedom of rotation is diminished by the addition of the extra Sarrus linkage, but still easily exceeds the desired minimum rotation of 120° and adds significant more stiffness to the whole construction and especially the arm holder. By connecting the torque link in such a manner to the arm holder that the rotation of the arm holder is passing directly above the Sarrus linkages, the stiffness should increase even more during operation. Production of a new prototype comprehending at least the changes to the Sarrus linkages should confirm the increase of stiffness.

Regarding the changes to the GCS, the rotation of the GCS, as discussed several times, reduced the number of pulleys by 1. Together with the new setup of the selection of bearings and the corresponding pulleys, the friction in the GCS should decrease. Testing this in a new prototype can show that this is actually a better design in real life.

The changes to the end stops make it easier to change the position of the end stops. The main features of the end stop block are not change significantly so the factor of safety of the current design of the SEP should be maintained. The end stops are changeable if the arm holder is in an enough elevated position such that the housing is not blocking the entrance to the end stops. This same principle holds for the changing of the amount of compensation of the GCS; if the arm holder is elevated enough the motor is reachable and the motor can be controlled.

All the changes onto the final design of the SEP are of similar costs as the corresponding design used in the current design of the SEP. The same will hold for the total weight of the final design of the SEP compared to the current design of the SEP. This will also not significantly change. So those two factor are not deteriorating the feasibility of a newly to produce prototype.

Next to do for the development of the SEP is for Hankamp Gears to decide which changes to the design will be comprehended into a new prototype. Then a new prototype can be produced and be tested in real life to see if the prototype can be suitable to become actual a product.

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