FRAGILE AND COOL

A novel design of a retractable imaging device that is able to facilitate a fragile image sensor has been developed. Two major design challenges characterise this design project. Firstly, the designing of a statically determined support for the fragile image sensor that ensures a low thermal resistance to meet the strict cooling requirements. Secondly, designing a non-overdetermined linear retraction mechanism with appropriate pretension and without collision forces at the end of its stroke.

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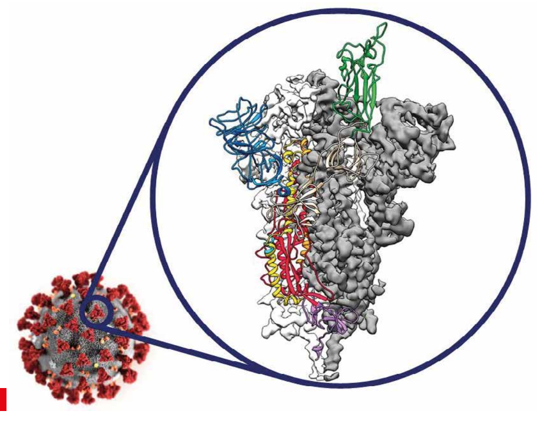
Imaging devices are used for capturing samples within, for example, structural biological or fundamental material research. Prodrive Technologies develops and manufactures such imaging devices. Figure 1 shows an example of the importance of the project described here. On the left, the Covid-19 virus is shown with its red crowns on top, depicting the S-proteins. On the right, a 3D reconstruction of an S-protein is shown, which was generated from approximately 3,000 images that were captured by such an imaging device.

The image sensor considered here is highly fragile, and should be able to withstand extreme temperature differences and thermal cycles while operating in a vacuum environment. Therefore, this sensor requires proper support. Furthermore, the imaging device should be able to insert and retract the image sensor with high repeatability.

Two major design challenges

A system decomposition resulted in two major design challenges to solve. Firstly, designing a statically determined support of the fragile sensor, including its strict requirements on cooling. Secondly, designing a high-precision linear retraction mechanism with a well-defined pretension and without end-of-stroke collision forces.



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A 3D reconstruction of the S-protein of the Covid-19 virus, which was generated from approximately 3,000 images captured by an imaging device [1] [2].

AUTHOR'S NOTE

Teun van de Sande graduated in mechanical engineering from the Eindhoven University of Technology (NL). For his master thesis work, supervised by Nick Rosielle, he received the Wim van der Hoek Award 2020. Currently, he is working as a mechanical system architect at Prodrive Technologies in Son (NL). The author acknowledges the support of Ron Hendrix of Prodrive Technologies.

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For confidentiality reasons, no further details on the design challenge and the specifications can be provided.

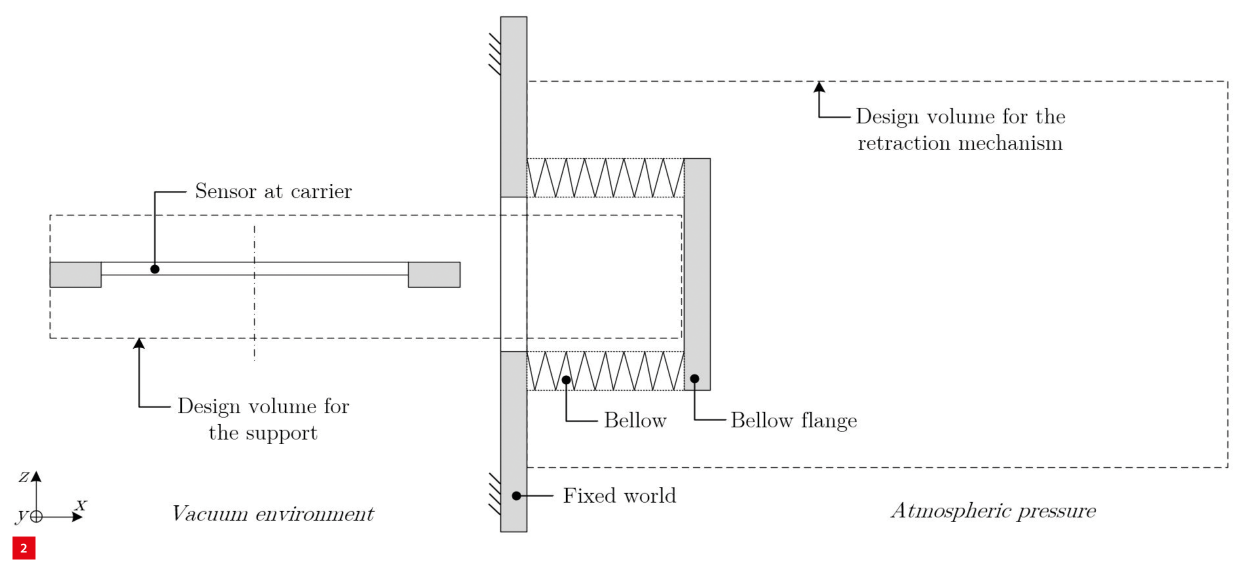
Figure 2 shows a simplified schematic section view of the proposed imaging device. The outer dimensions of the device are 200 mm x 150 mm x 75 mm (*x*, *y*, *z*). The image sensor is attached to a carrier and located in a vacuum environment. A vacuum bellow is used to separate the vacuum from atmospheric pressure. One end of the bellow is connected to the interface flange, which is the fixed world. The other end is closed by the bellow flange. As a result, only a minimal number of components is located in the vacuum, which minimises potential outgassing inside the vacuum environment.

Stress-free support of the image sensor

Minimising deformation during thermal cycling is critical in enhancing the lifetime of the imaging sensor, as this sensor is highly fragile. The induced stress can be minimised by choosing the right material. The image sensor is attached to a carrier with a comparable coefficient of thermal expansion (CTE) value. As the CTE values of both materials are comparable, low relative thermal deformation between the sensor and its carrier will occur. Moreover, the sensor's printed circuit board assembly (PCBA) is thermally decoupled from this carrier.

The carrier is attached to a heatsink that absorbs the dissipated heat. The extreme temperature changes require a stress-free and statically determined mounting of the carrier to the heatsink. Having thermal interface material between the heatsink and carrier ensures low thermal resistance, while allowing stress-free movement of the sensor and carrier.

Figure 3 shows this attachment. Three slotted holes in the carrier construct a thermal centre at the centre of the image sensor, which minimises thermal stresses and pixel movement at the same time. The thermal centre is indicated by the crossing of the dashed lines. The sensor's PCBA contains a flexible part to prevent constraining any degree



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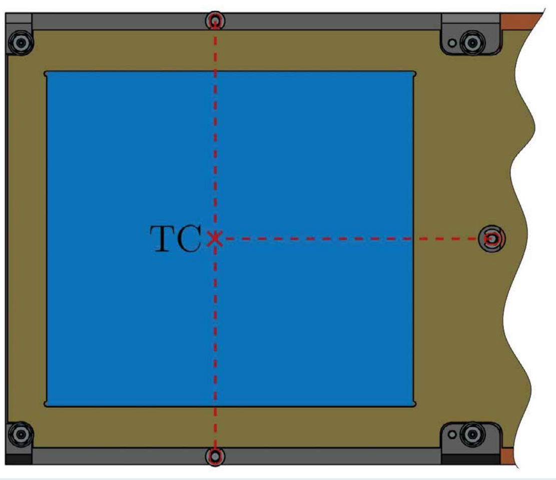
Schematic section view of the proposed imaging device, including the design volumes for the two major design challenges: sensor support and retraction mechanism.

of freedom (DoF) of the sensor assembly. In this way, the position of the sensor assembly is only defined by the support. Compared to, for example, a flexure mechanism for creating a thermal centre, this is a compact and robust design that eases assembly and manufacturability.

The support has a constant temperature during operation, which means that thermal deformation of the support can be considered negligible. Therefore, it is acceptable that the mechanical and thermal paths are not entirely uncoupled within this part.

Statically determined linear guide

Preferably, the motion path is defined mechanically to ensure no collision will occur during the movement. The stroke in x-direction is approximately 100 mm. Moreover, the bellow flange should be supported close to the interface flange at the inserted position to acquire considerable stiffness and to achieve the required repeatability. Figure 4a shows a typical guidance concept based on two conventional linear bearings, preloaded using preload screws. However, this preloading method will establish a form-closed construction, in which misalignment or wear can affect the preloading. This could result in unpredictable preloading with variations over the stroke (or over time), which negatively affects the dynamic behaviour in the inserted position. Moreover, this preloading method could be disadvantageous for thermal behaviour, as the sideways alignment is defined at the left linear bearing instead of at the mid-plane.



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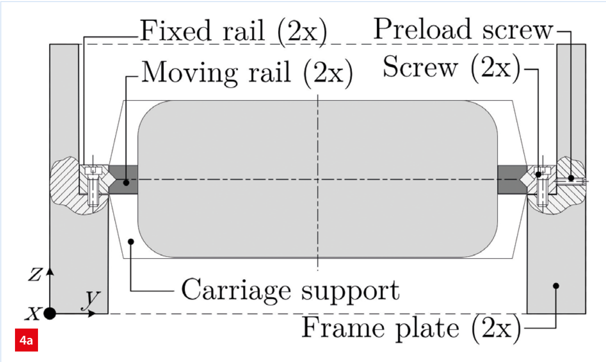
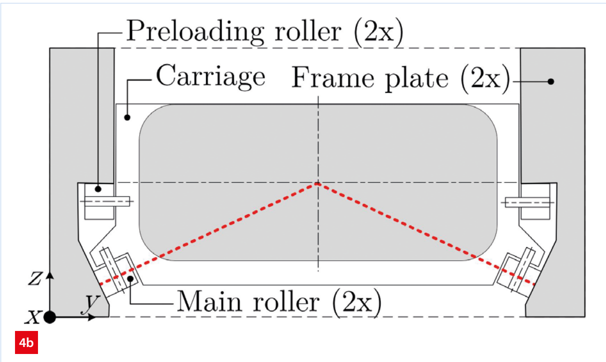
Top view of the cooling assembly. The crossing of the dashed lines indicates the thermal centre.

The linear bearings are constraining five DoFs each, which is considerably over-constrained. The degree of over-constraint should be diminished by strict manufacturing tolerances. Moreover, this linear guide will over-constrain the bellow as well. The bellow constrains one DoF, namely the rotation R_x around the direction of motion.

Over-constraint is not preferred as it induces internal stresses, which could negatively affect repeatability and result in damage in the long term. The linear guide as proposed in Figure 4b does not have these drawbacks, since it only constrains four DoFs (y, z, R_y, R_z) by pointing crowned track rollers towards the centre of the bellow.

Figure 5 shows the proposed design of the linear guide in an isometric view. The sensor assembly is mounted to a carriage that is guided on the frame plates using two sets of steel rollers, which are mounted to the left and the right side of the carriage. A set of rollers consists of two main track rollers at the bottom and one preloading track roller at the top. The preloading track roller is – viewed from above, along the z-axis – centred between both main track rollers.



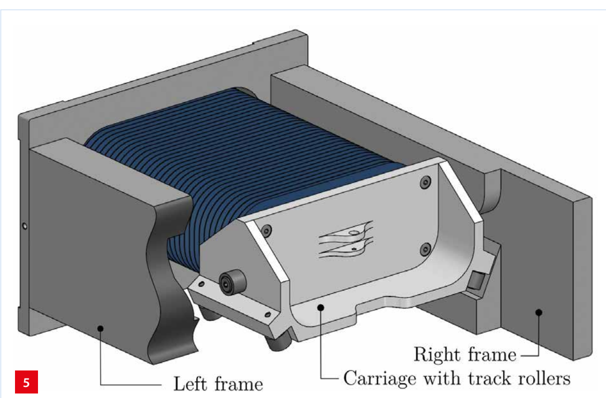


Schematic rear view of the linear guide concepts.
(a) Linear bearings.
(b) Track rollers.

This linear guide is symmetric and free to rotate the bellow in R_x, which minimises internal stresses. The bellow is attached to the linear guide, which is close to the interface flange in the inserted position to provide considerable stiffness at this position.

A bi-stable crank mechanism as drivetrain

The desired motion in the x-direction is performed by a crank mechanism, as shown in Figure 7. The crank is assisted by a compensation mechanism for the relatively high constant force on the bellow flange resulting from the pressure difference between the vacuum and the atmospheric pressure. A motor with a gearbox drives the crank mechanism.



Isometric view of the linear guide based on track rollers pointing to the centre of the bellow.

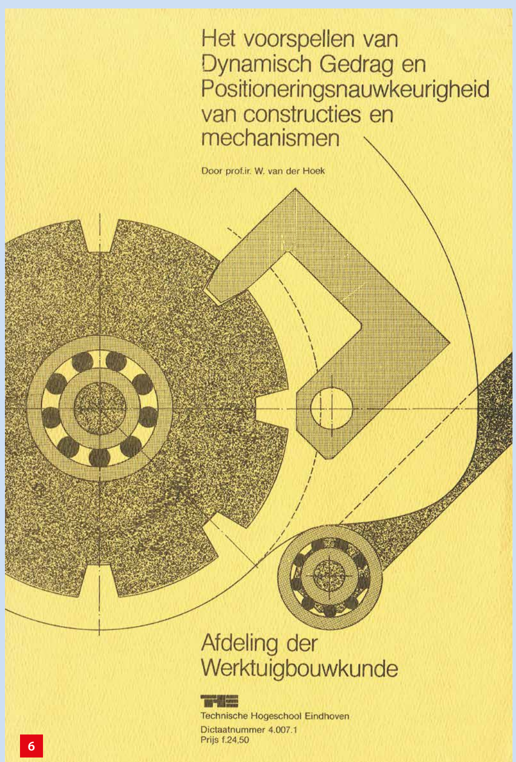
Personal note: Passion for precision engineering

It has been an honour to receive the Wim van der Hoek Award for this work. My already substantial enthusiasm and passion for precision engineering grew extensively thanks to Nick Rosielle's passionate lectures on design principles. Precision engineering inspires me, as it enables us to push the boundaries in high-performance systems within extreme environments, which is the key to creating cutting-edge technologies.

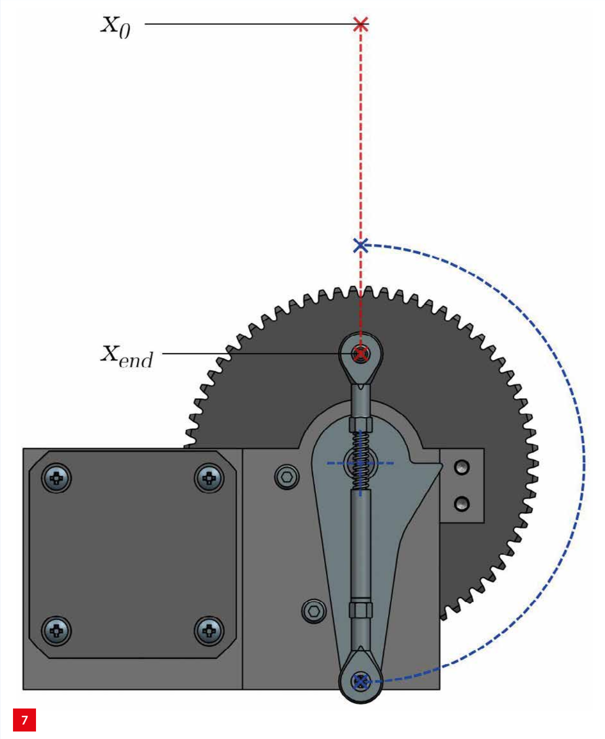
The considerations for the linear guidance concepts presented here are a nice example of different design strategies. The first strategy is based on a commonly used off-the-shelf solution that over-constrains the construction, where the over-constraining should be diminished by tight manufacturing tolerances and assembly procedures. This is acceptable in most situations.

However, what if we create a statically determined design? Another strategy is to use an off-the-shelf solution and add, for example, a flexure to release the over-constrained DoFs. This results in less internal stresses and internal moments, which is beneficial for the predictability and durability of the design.

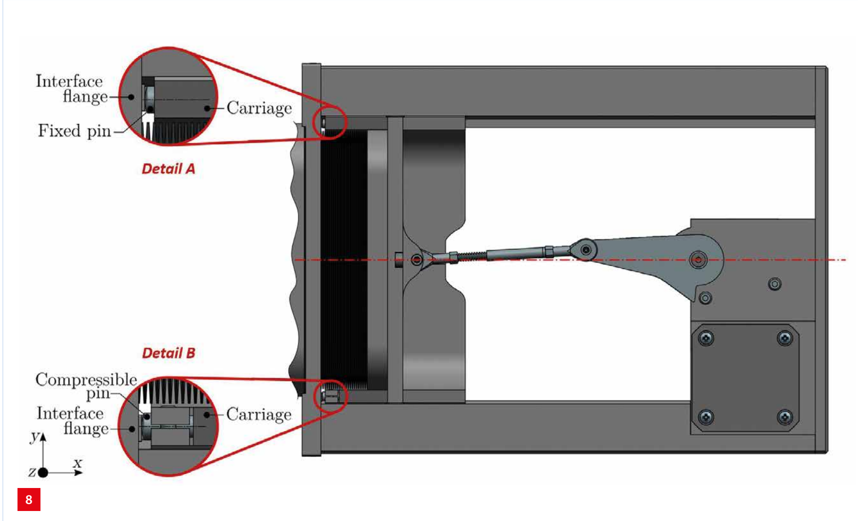
Nevertheless, what if the released over-constrained DoFs were never constrained at all? I think, that is designing according to Wim van der Hoek's design principles: a design strategy to create a construction or mechanism that exactly constrains the desired DoFs. Thinking one step ahead leads to an even lighter, stiffer and more compact design, while a statically and thermally determined design leads to beneficial dynamical behaviour and low hysteresis effects.



Van der Hoek's lecture notes (in Dutch), titled "Predicting Dynamic Behaviour and Positioning Accuracy of constructions and mechanisms", includes "The Devil's Picture Book", his collection of good designs from a dynamics and positioning point of view.



Top view of the crank mechanism and its motion paths, which are visualised by dashed lines. The stroke of the mounting point of the connecting rod is indicated by the red dashed line. The blue dashed line describe the rotational motion of the crank during the stroke.



Top view of the retraction mechanism slightly before the end of stroke. The landing principle is shown by details A and B.

The crank mechanism has a relatively high stiffness in the inserted and retracted positions, as the connecting rod and the crank are aligned in these positions. This drivetrain design is compact, which enables its placement behind the carriage to correctly align the actuation force and the force acting on the bellow flange. In this way, no internal moments are induced. Despite these advantages, the crank mechanism causes a force perpendicular to the actuation force during the motion. However, this force is fully absorbed by the linear guide in the proposed design.

Landing without end-of-stroke collision forces

The velocity of the crank mechanism at the start and end of its stroke goes to zero by design, which ensures a collision- and shock-free movement of the sensor assembly. Naturally, the mechanism locks the sensor assembly in the retracted position.

At the end of the stroke, adequate landing at the interface is essential for minimising the induction of vibrations to the image sensor and for providing considerable stiffness in the direction of motion. Figure 8 shows a top view of the retraction mechanism slightly before the end of stroke, to explain the landing principle. Depending on the actual manufacturing tolerances, it is possible that the carriage has already landed at the interface, while the crank mechanism still needs to rotate a few degrees. In that case, the crank mechanism can finish its stroke by compressing the connection rod, without inducing internal stresses. During the stroke, the connecting rod is able to endure the tension stresses.

As a result, the collision velocity is not exactly equal to zero. However, the velocity of the carriage is sufficiently low if the crank mechanism is a few degrees before the end of its stroke. Therefore, the collision force will be within the order of 1 N, which is considered low enough.

The carriage has two rounded landing pins at the front end, which are able to land on a hardened surface of the interface flange. Both landing pins provide a point contact. The pins at the carriage should copy the (potentially misaligned) angle information of the interface flange in R_z to not over-constrain the linear guide, which significantly minimises internal stresses during landing. This is realised by one fixed landing pin (Figure 8, detail A) and one compressible landing pin (detail B), which are both placed symmetrically with respect to the mid-plane. The compressible pin needs to be fixed with a screw after installation to copy the angle information of R_z.

In conclusion, the sensor assembly support is statically determined while ensuring a low thermal resistance. At the inserted position, the landing interface provides considerable stiffness to the sensor assembly in the direction of motion (x), as close as possible to the interface flange. The bellow constrains one DoF (R_x), and the linear guide with track rollers stiffly constrains the other four DoFs (y, z, R_y, R_z).

REFERENCES

[1] D. Wrapp et al., "Cryo-EM Structure of the 2019-nCoV Spike in the Prefusion Conformation", *www.biorxiv.org/content/biorxiv/early/2020/02/15/2020.02.11.944462.full.pdf*

[2] *phil.cdc.gov/Details.aspx?pid=23311*