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TASTINGS AND THEORY

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Ferrofluid bearings have recently been successfully implemented in precise positioning systems. This article gives an overview of systems built in the Department of Precision and Microsystems Engineering at Delft University of Technology in the Netherlands. Most applications are in microscope stages, where high accuracy is important while stroke and speed attain only moderate levels. Furthermore, some basic theory is provided on ferrofluid bearings that can help engineers incorporate ferrofluid bearings in their designs.

STEFAN LAMPAERT, RON VAN OSTAYEN AND JO SPRONCK

A ferrofluid is a type of fluid with magnetic properties, and its most important property is that it is attracted by a magnet (Figure 1). This is due to the tiny magnetic nanoparticles about 10 nm in size suspended in the fluid. Ferrofluids can be used to make bearings that generally differentiate themselves from other bearings by their simplicity, low cost, inherent stability, viscous damping with low friction and absence of stick slip [1] [2]. These characteristics make ferrofluid bearings a low-cost alternative in systems with a moderate stroke and speed that are currently using air bearings or magnetic bearings to achieve similar specifications.

Precise positioning systems

The first in the Delft series of precise positioning systems with ferrofluids was built by M.Sc. student Simon van Veen (Figure 2) [4]. The primary goal of his work was to understand and demonstrate the behaviour of ferrofluid bearings. The complete absence of stick slip and pure viscous friction made it a very interesting and simple linear bearing concept for precise positioning. The final system could be positioned in one degree of freedom (DoF) with a precision of σ = 10 nm over a range of 20 mm.

This 1-DoF system was followed by a (2+4)-DoF positioning system built by Max Café [5]. This system was able to make two large translational movements (10 mm x 10 mm) and four small correctional movements in the other


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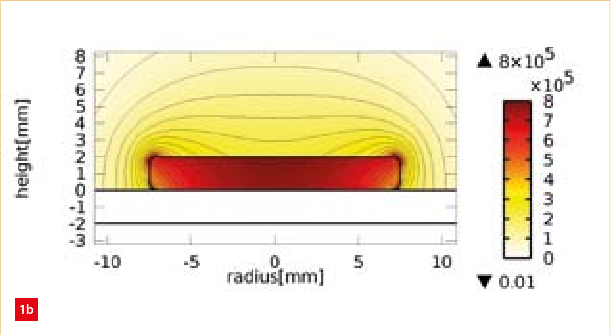
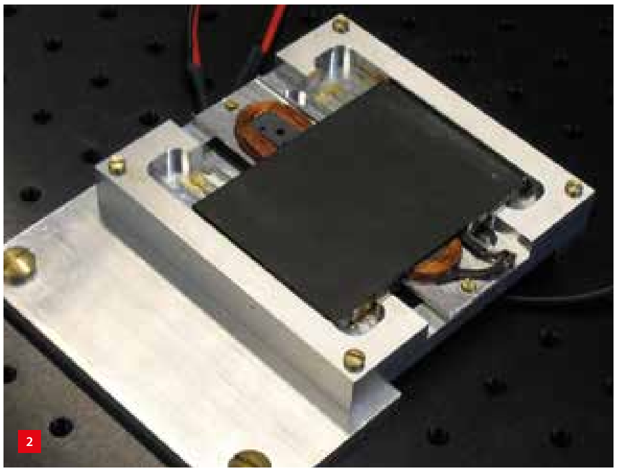


1b

1 *Ferrofluid bearing principle.*
  (a) A disc magnet with ferrofluid on a steel plate. The ferrofluid (black) is drawn towards the highest magnetic field strength, at the edge of the magnet. The disc positioned in the centre is the magnet.
  (b) The associated magnetic field. The colours show that the magnetic field intensity is highest at the corners of the magnet, which confirms that the ferrofluid follows the contour lines of the magnetic field. The model was made using COMSOL Multiphysics® [3].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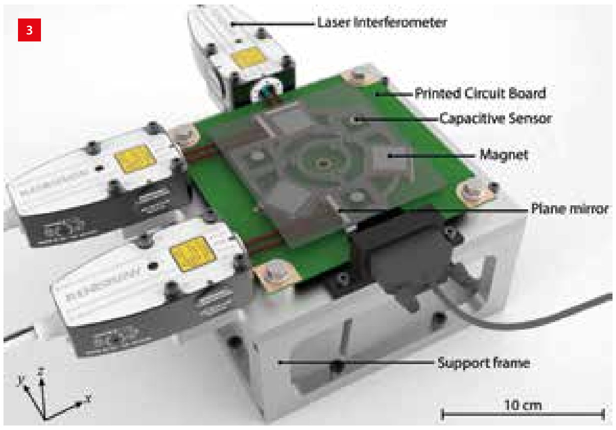
2 *Overview of the 1-DoF positioning system built by Simon van Veen [4]. The black body in the middle is the dynamic part of the system. The system is actuated electromagnetically; the coil is visible underneath the black body.*

3 *Overview of the (2+4)-DoF positioning system built by Max Café [5]. A printed circuit board with coils is used to actuate the magnets placed on the moving part of the system. The magnets are additionally used to create a ferrofluid bearing. Three laser interferometers and three capacitive sensors are used to measure the position and orientation of the system.*

4 *The actuation system of Figure 3 consists of three magnets and six coils in a PCB board: two layers contain coils for the out-of-plane actuation and two layers contain the coils for the in-plane actuation. Both sets of coils use the same magnet, which is also used to hold the ferrofluid for the bearing [5].*

5 *Renderings of the planar 2-DoF positioning system built by Gihin Mok [6].*
(a) Overview of the complete stage.
(b) The base.



DoFs (Figure 3). In this system, the magnets fulfil a dual role: they hold the ferrofluid for the bearing function and they provide the magnetic field for the coils of the 6-DoF Lorentz actuators (Figure 4).

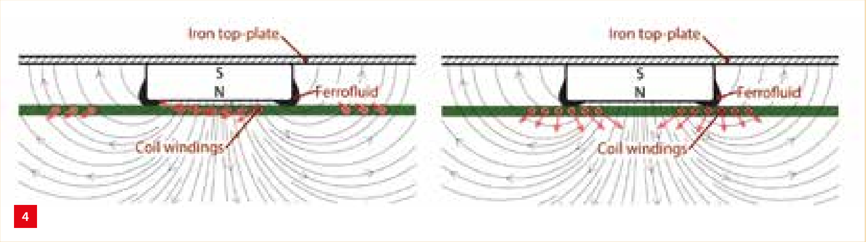
The primary goal in this instance was to understand and demonstrate the behaviour of the ferrofluid bearings in a multi-DoF positioning system. An additional goal was to solve the problem of so-called trail formation of the bearing. When moving, the ferrofluid bearing leaves behind a trail of ferrofluid on the contact surface that reduces the amount of ferrofluid actually used in the stage's support. This causes the bearing to slightly decrease in fly height, i.e. 2 μm per mm translation for this system. This decrease in fly height can be compensated for by active control of the Lorentz actuators. The final system was able to take in-plane steps of 0.1 mm with a control bandwidth of 500 Hz with a 1% settling time of 0.02 s, and out-of-plane steps of 250 nm with a bandwidth of 100 Hz with a 1% settling time of 0.1 s.

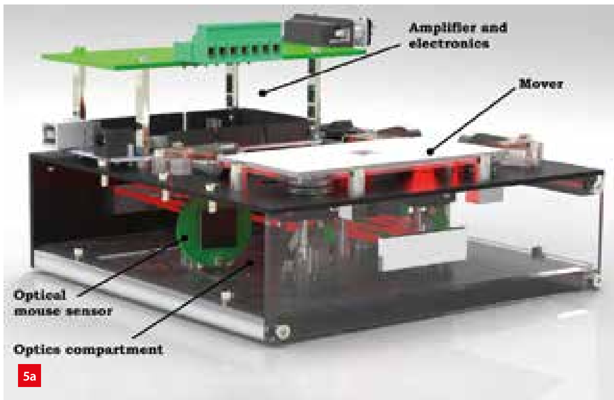
The system's planar performance was mainly limited by the performance of the actuator and the sensors, and not by the performance of the bearings. This showed that the ferrofluid bearing is an interesting concept for high-speed precise positioning in multiple DoFs. It also showed that good system integration can be achieved by using the magnets required for Lorentz actuation to also generate the magnetic field used in the ferrofluid bearings.

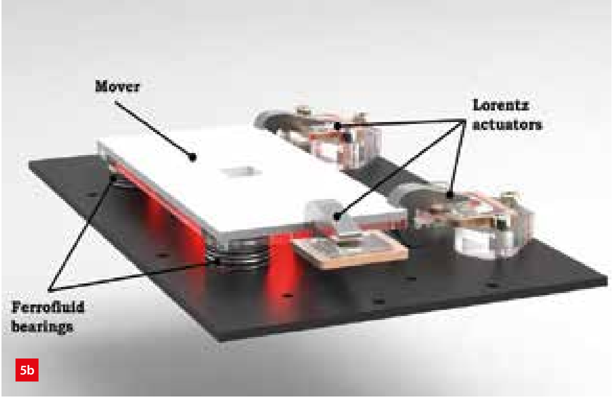
The successful completion of these projects created a certain confidence in the properties of ferrofluid bearings. As a result, ferrofluid bearings have been used in subsequent projects as a simple bearing solution in positioning systems. One such example is Gihin Mok's project [6], which examined the potential of using a low-cost optical mouse sensor for a positioning sensor. A full stand-alone positioning system with two DoFs was realised, using three ferrofluid bearings to accommodate planar movements only (Figure 5).

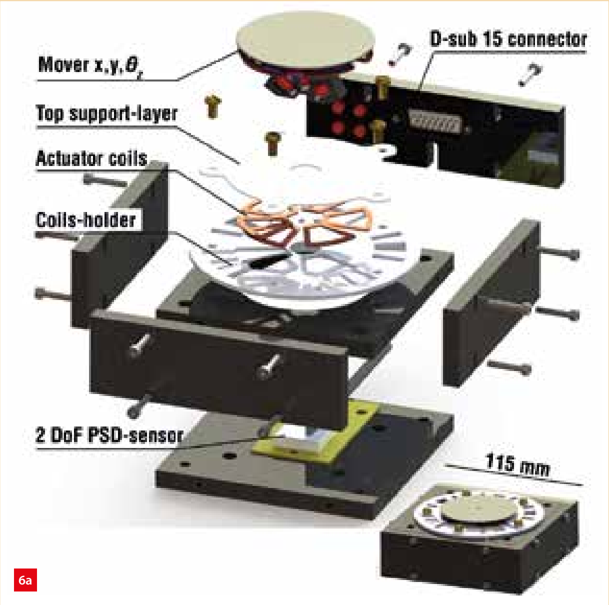
A second example is Haris Habib's project [7], in which an XY360 3-DoF positioning system was designed, built and tested. Here, the goal was to demonstrate the concept of measuring a planar position and orientation with a 2-DoF optical position-sensitive detector (PSD) (Figure 6). The sensor and actuation system allowed for a full rotation in combination with a translational range of 9 mm x 9 mm.

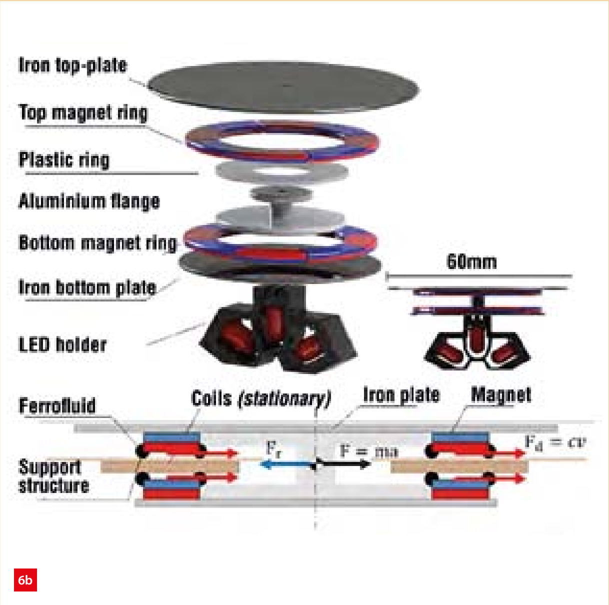
The final system was able to take planar steps of 0.1 mm with a settling time of less than 0.1 s and with an accuracy of 0.2 μm (3σ). A rotational step of 10° took 0.18 s to settle with an accuracy of 0.15 mrad (3σ). The speed of the system was mainly limited by the friction in the bearings. This friction was apparently higher than was modelled using the basic model developed in advance. This eventually caused excessive heat to develop during operation.











6 *Renderings of the XY360 3-DoF positioning system built by Haris Habib [7].*
(a) Overview.
(b) Cross-section showing two LEDs used to sequentially illuminate the PSD so that the location and the orientation can be measured, and a third LED used to increase the range of motion.

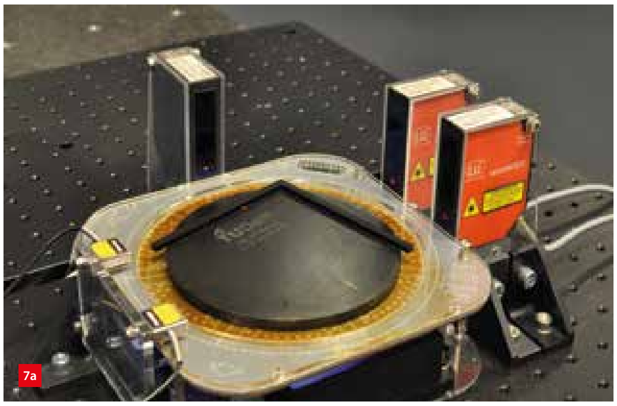
For this reason, a new project was launched by Stefan Lampaert, the aim of which was to draw up improved theoretical models to be used for generating an accurate prediction of the bearing properties (see below) [8]. This work resulted in validated models that accurately describe the load and stiffness of ferrofluid bearings. A friction model directly derived from these improved models was later validated in [2] [9] by a redesign of the system presented in [4] to obtain an accurate measurement for the friction of the bearings.

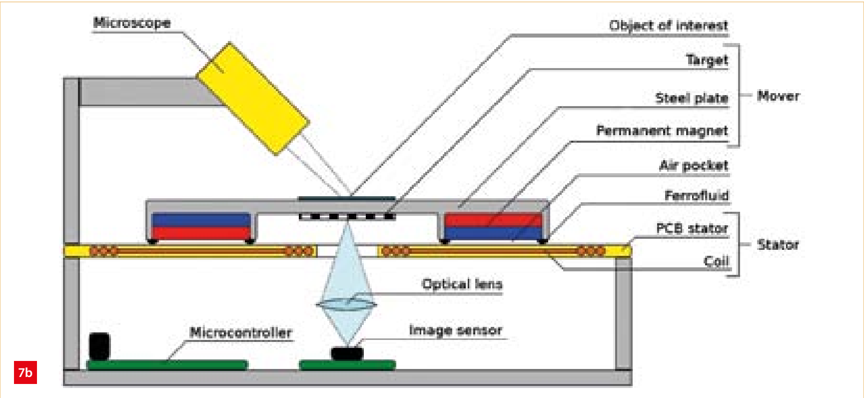
A third example in which ferrofluid bearings and an improved understanding of their functioning has been used is Len van Moorsel's project. Here, the newly derived models of ferrofluid bearings were used in the design of a 3-DoF precise positioning system using fully contactless vision with a single image sensor as position sensor [10]. The final system had a mover that could be actuated in all the in-plane DoFs; commutation of the Lorentz actuators made it possible to make infinite rotations (Figure 7). All the remaining DoFs where constrained using a ferrofluid bearing. The theoretical models facilitated a more balanced design between actuator and bearing so that no excessive heat developed during operation.

Basic theory

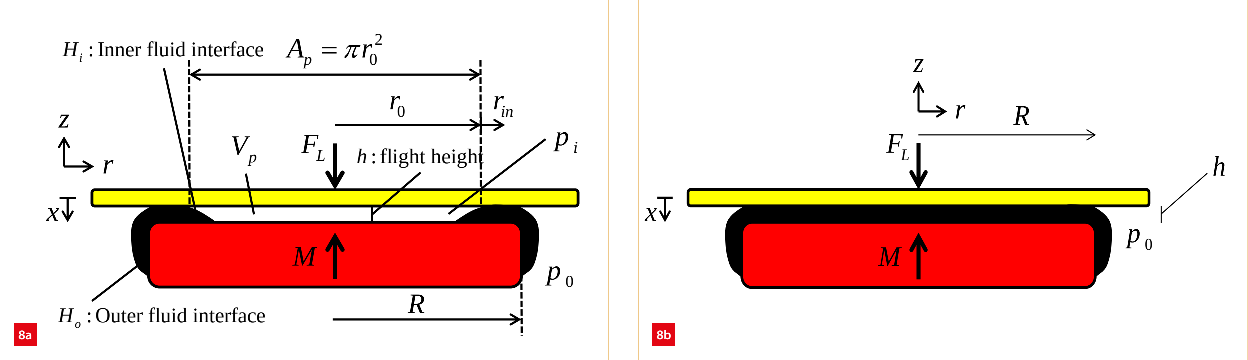
A ferrofluid can basically be used in two different types of bearings [11] [12]. In both bearing types, the ferrofluid acts as a lubricant and a load-carrying component, even at zero speed. The first bearing type is the so-called ferrofluid pocket bearing that encapsulates a pocket of air to carry a load (Figure 8a). The second one is a so-called pressure bearing that works solely by floating the mover on a layer of magnetically pressurised ferrofluid (Figure 8b).

The load capacity of a pocket bearing ($F_{L,\text{pocket}}$) is generally a function of the surface area of the pocket of air A_p and the pressure difference that is built up across the seal. This pressure difference is a function of the magnetisation strength of the fluid (M) and the difference in field intensity between the inner fluid interface (H_i) and the outer fluid interface (H_o). The load capacity of a ferrofluid pressure





7 *The 3-DoF (XYθ) positioning system built by Len van Moorsel [10]. The moving part of the system contains magnets that are used for the ferrofluid bearing and the Lorentz actuator. The other half of the Lorentz actuator consists of a PCB board in which coils have been etched.*
(a) Overview showing the black body in the middle as the moving part of the system.
(b) Rendered cross-section showing the image sensor, located underneath the black body, used for contactless optical measurement of the position of the system.



8a

8b

8 *Schematic representation of two types of ferrofluid bearing [8].*
(a) Pocket bearing: the load is carried by an encapsulated pocket of air.
(b) Pressure bearing: the load is floated on a layer of magnetically pressurised ferrofluid.

bearing ($F_{\mathrm{L,pressure}}$) is solely defined by the pressure built up in the fluid due to the magnetic field at the load-carrying surface of the bearing.

$$F_{\mathrm{L,pocket}} = \mu_0\, M\, A_{\mathrm{p}}\, (H_{\mathrm{i}} - H_{\mathrm{o}})$$

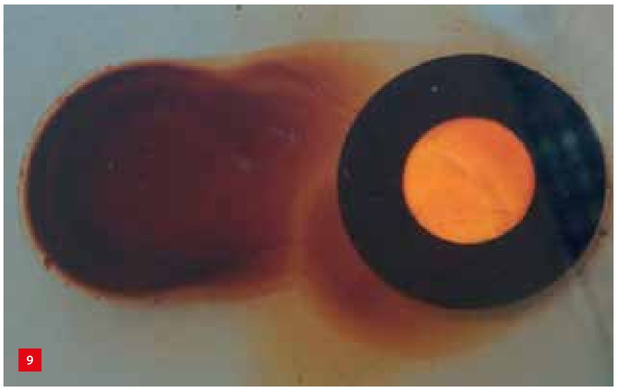
$$F_{\mathrm{L,pressure}} = \mu_0\, M \int H\, dA$$

The stiffness for a pocket bearing (k_{pocket}) is mainly defined by the change in pressure across the seal with a change in fly height. This means that this stiffness is mainly defined by the gradient of field intensity across the seal. In general, only the inner fluid interface contributes to the stiffness. The term dr_0 / dz in the formula below is called the pneumatic leverage and relates to the movement of the inner fluid interface with the change in fly height. The stiffness for a ferrofluid pressure bearing (k_{pressure}) is mainly defined by the gradient in the magnetic field at the load-carrying surface.

$$k_{\mathrm{pocket}} = -dF_{\mathrm{L,pocket}} / dz = -\mu_0\, M\, A_{\mathrm{p}}\, (dH_{\mathrm{i}} / dr_0)\, (dr_0 / dz)$$

$$k_{\mathrm{pressure}} = -dF_{\mathrm{L,pressure}} / dz = -\mu_0\, M \int (dH / dz)\, dA$$

Translating the bearing leaves behind a trail of ferrofluid that has three effects on the bearing's performance (Figure 9). The first is a reduction in fly height due to a reduced load capacity caused by less fluid being available for levitation. The second is an increase in damping due to the reduced fly height. The third effect is a time- and path-dependent force between the ferrofluid trail and the magnet. Upon translation of the bearing, it appears that the majority of the fluid remains between the bearing surfaces.



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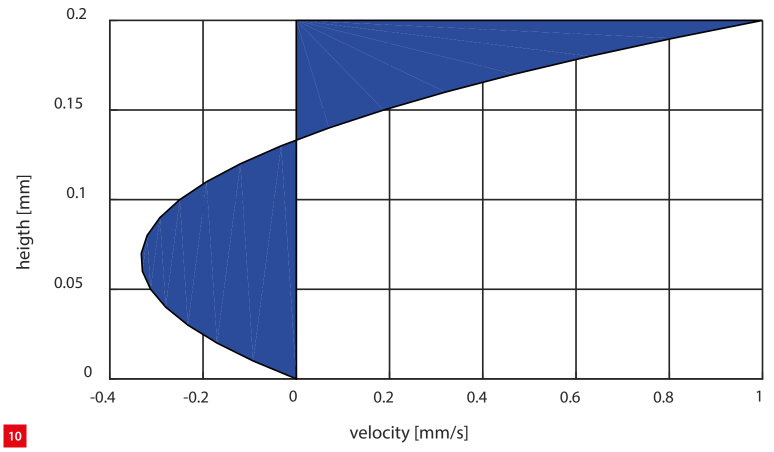
9 *Translating the bearing leaves behind a trail of ferrofluid [8].*

This means that there is a fluid flow with no net fluid transport along the length of the bearing. Figure 10 presents the flow profile that meets this condition. This flow profile basically consists of the summation of a Couette flow caused by the relative movement of the bearing surfaces and a Poiseuille flow caused by the magnetic body force. The model is validated by the work presented in [2] [9]. The viscous-like friction force can be described as follows:

$$F_{\mathrm{fric}} = c\, U = 4\, \eta\, (A / h)\, U$$

Conclusion

The various systems described in this article demonstrate that ferrofluids can provide a simple and cost-effective bearing solution for high-precision positioning. The models presented can be used in the design of ferrofluid bearings. The equations show that the magnitude of the magnetic field is important for the load capacity, while the gradient of the magnetic field is important for the stiffness. The model for the friction shows that the bearing can be taken as a pure viscous damper.



10

10 *Fluid flow profile with no net fluid transport along the length of the bearing [8].*

Current and future developments

What started as a simple research project on ferrofluid bearings is now growing into a new research area at Delft University of Technology. Projects have been started that focus on the application of magnetic fluids in different industries. These projects now also include the application of magnetorheological fluids, a type of non-Newtonian magnetic fluid that becomes more viscous in response to a magnetic field. Applications currently being investigated include seals, large-scale bearings and active dampers. ■

REFERENCES

[1] S.G.E. Lampaert, J.W. Spronck, and R.A.J. van Ostayen, "Load and stiffness of a planar ferrofluid pocket bearing", *Proc. Inst. Mech. Eng. Part J J. Eng. Tribol.*, vol. 232 (1), pp. 14-25, 2018.

[2] S.G.E. Lampaert, B.J. Fellinger, J.W. Spronck, and R.A.J. Van Ostayen, "In-plane friction behaviour of a ferrofluid bearing", *Precis. Eng.*, under review, 2018.

[3] *www.comsol.com*

[4] S. van Veen, "Planar Ferrofluid Bearings for Precision Stages", M.Sc. thesis, Delft University of Technology, 2013.

[5] M. Café, "Nanometer precision Six Degrees of Freedom Planar Motion Stage with Ferrofluid Bearings", M.Sc. thesis, Delft University of Technology, 2014.
S.G.E. Lampaert, M. Café, R.A.J. van Ostayen, and J.W. Spronck, "(2+4) DOF precision motion stage with ferrofluid bearings", *2016 Spring Meet. Precis. Mechatron. Syst. Des. Control*, pp. 7-10, 2016.

[6] G. Mok, "The design of a planar precision stage using cost effective optical mouse sensors", M.Sc. thesis, Delft University of Technology, 2015.
A. Alvarez-Aguirre, G. Mok, S.H. Hosseinnia, and J.W. Spronck, "Performance improvement of optical mouse sensors for position measurement", *euspen Int. Conf.*, 2015.
A. Alvarez-Aguirre, G. Mok, S.H. Hosseinnia, and J.W. Spronck, "Performance improvement of optical mouse sensors: Application in a precision planar stage", *2016 Int. Conf. Manip. Autom. Robot. Small Scales, MARSS 2016*, 2016.
G. Mok, "Mouse precision", *Mikroniek*, vol. 56 (6), pp. 14-18, 2016.

[7] H. Habib, "Design of a three Degrees of Freedom planar precision stage using a single Position Sensitive Detector", M.Sc. thesis, Delft University of Technology, 2015.
S.G.E. Lampaert, H. Habib, J.W. Spronck, and R.A.J. van Ostayen, "XY360 planar positioning stage with ferrofluid bearings", *DSPE Conference on Precision Mechatronics 2016*, pp. 57-61, 2016.

[8] S.G.E. Lampaert, "Planar Ferrofluid Bearings Modelling and Design Principles", M.Sc. thesis, Delft University of Technology, 2015.
S.G.E. Lampaert, J.W. Spronck, and R.A.J. van Ostayen, "Load and Stiffness of a Ferrofluid Pocket Bearing", *17th Nord. Symp. Tribol.*, p. 11, 2016.
S.G.E. Lampaert, J.W. Spronck, and R.A.J. van Ostayen, "Friction and trail formation of a planar ferrofluid bearing", *Leeds-Lyon Symp. 2016*, 2016.
S.G.E. Lampaert, "Modelling and Design Principles of planar ferrofluid bearings", *DSPE Conference on Precision Mechatronics 2016*, pp. 157-158, 2016.

[9] B.J. Fellinger, "Validation of in-plane friction behaviour of a ferrofluid bearing", M.Sc. thesis, Delft University of Technology, 2017.

[10] L. van Moorsel, "A planar precision stage using a single image sensor", M.Sc. thesis, Delft University of Technology, 2017.
L. van Moorsel, N. Saikumar, H. Polinder, and J.W. Spronck, "Axial Flux Permanent Magnet Motor Design for 30mm Planar Translations and Infinite Rotation", *IEEE Trans. Ind. Electron.*, under review, 2018.

[11] R.E. Rosensweig, "Bearing arrangement with magnetic fluid defining bearing pads", U.S. Patent 3,612,630, 1971.

[12] K.D. Ridler, A.B. Gosling, and G.M. Edge, "Linear bearing for parallel tracking arm", U.S. Patent 4,065,188, 1977.