High-precision 'flying carpet'

Since 2002, Eindhoven University of Technology has been investigating fully contactless *xy*-positioning systems. These magnetically levitated planar actuators consist of a single carrier with permanent magnets that is levitated above an array of coils and can move fast and accurately over long distances in the *xy*-plane. Because the magnets are moving, there are no cables or cooling hoses connected to the moving part. Nevertheless, data and energy can still be transferred, using contactless links. This high-precision 'flying carpet' was one of the subjects in the lecture programme at the Precision Fair 2008.

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Most multi-degree-of-freedom (multi-DOF) positioning systems are constructed of several single-DOF linear and rotary actuators with air bearings. All these individual actuators are coupled using complex mechanical structures. However, the demand for higher accuracies, higher accelerations, and vacuum compatibility triggers actuator solutions with multiple degrees of freedom and magnetic bearings integrated in one actuator, a concept resulting in a low moving mass.
An example of such a novel actuator is a magnetically levitated planar actuator. This actuator has only one moving body, the translator, which is suspended above a stator with no support other than magnetic fields. The translator can move over long distances in the *xy*-plane and is controlled in six degrees of freedom. There are two options for the planar actuator configuration. The actuator has either stationary magnets and moving coils, or stationary coils and moving magnets. The advantage of the second configuration is that it is truly contactless because of the absence of cables connected to the moving part.

The Electromechanics and Power Electronics (EPE) group and the Control Systems (CS) group of the Department of Electrical Engineering at Eindhoven University of Technology (TU/e), the Netherlands, have been conducting research into these moving-magnet planar actuators since 2002 within the framework of two IOP-EMVT projects (Innovation-directed Research Programme ElectroMagnetic Power Technology, funded by the Dutch Ministry of Economic Affairs). In the first research project, the modeling, design and control frameworks for this type of actuator have been established and proven on a fully operational prototype. Afterwards, it has been demonstrated that data and energy can be transferred to the translator using contactless links. These results were so promising that recently an industrial project was started to investigate whether this technology can be used to construct a single-stage, nanometer-accurate, long-stroke *xy*-positioning system.

Planar actuator

Magnetically levitated planar actuators with moving magnets are coreless actuators that are solely constructed of coils and permanent magnets. A schematic overview of a moving-magnet planar actuator is shown in Figure 1. This planar actuator topology has been patented by TU/e and has 84 stator coils which are arranged in a herringbone pattern. For that reason it is named Herringbone Pattern Planar Actuator (HPPA) [1][2]. Onto the translator, 385 NdFeB permanent magnets are glued in a two-dimensional array with a quasi-Halbach magnetization. Because only the coils below the surface of the magnet array effectively contribute to its levitation and propulsion, the set of active coils (in this case 24 coils) is switched during movement in the *xy*-plane. The stroke of the planar actuator can simply be increased by adding extra stator coils.

The three-dimensional magnetic fields and the lack of symmetries and periodicity in the electromechanical structure of moving-magnet planar actuators, require a different design approach as compared to standard linear and rotary actuators. Moreover, all degrees of freedom are intrinsically coupled. Contrary to many other magnetically levitated systems such as maglev trains, the bearing and propulsion functions are not separated into different parts of the actuator. Only the force production in the *xy*-plane can be physically decoupled by applying rectangular coils as shown in Figure 1.

To design the planar actuator, research in two different directions was carried out. Firstly, an electromagnetic modeling framework was created that can be used for a fast prediction of the force and torque produced by the actuator. Because the actuator is coreless, 3D finite-element simulation turned out to be very slow and time-consuming. Instead, several accurate semi-analytical models were created that can be used for both design and real-time control. These models allow the derivation of simple design rules for the coil and magnet dimensions.

Secondly, research was carried out into commutation and coil switching algorithms. Because all degrees of freedom are intrinsically coupled, standard decoupling algorithms

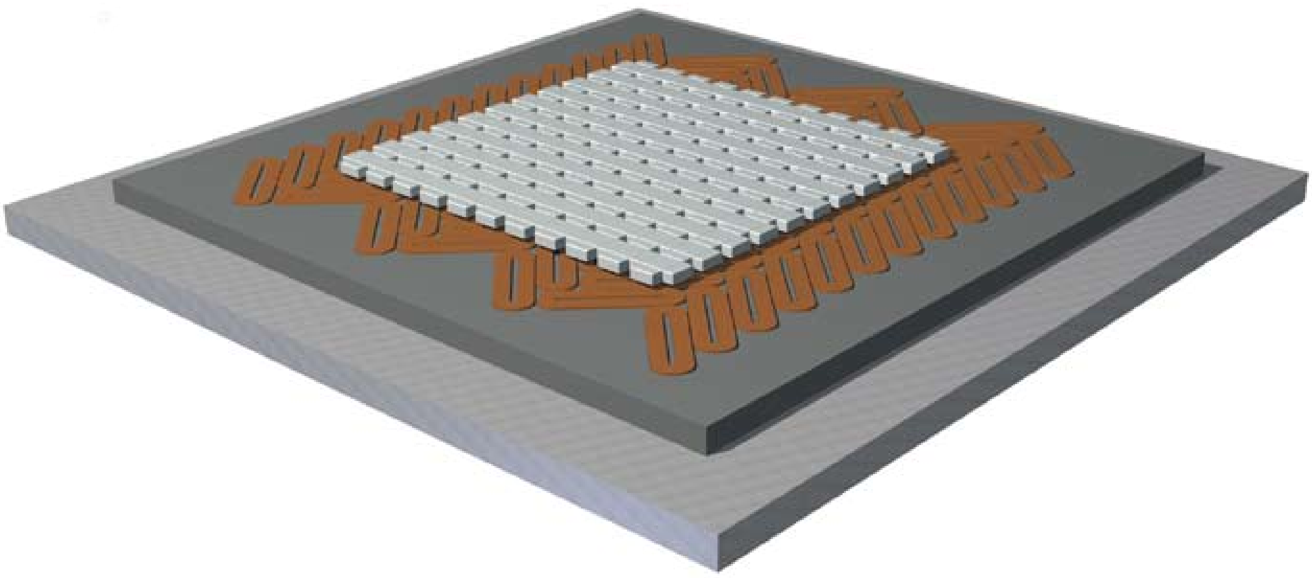

Figure 1. Overview of the Herringbone Pattern Planar Actuator.

for synchronous machines cannot be applied to the planar actuator to decouple the force and torque components. Therefore, a novel commutation algorithm was derived that inverts a fully analytical mapping of the force and the torque exerted by the set of active coils as a function of translator position and orientation. This algorithm guarantees a minimal energy dissipation by the actuator and smooth switching between different sets of stator coils. With this algorithm the controllability of different topologies could be tested. The combination of both the electromagnetic modeling framework and the commutation algorithm turned out to be an excellent tool to evaluate many different planar actuator topologies and to predict performance indicators fast. In several hours, a full planar actuator could be evaluated on thousands of different positions.

Figure 2 shows the prototype that was built to verify the developed theories. Its topology is shown more clearly in Figure 1. The translator has a size of 300 by 300 mm and a mass of 8.2 kg. It consists of an aluminum construction, with mechanical eigenfrequencies of 785 Hz and higher, onto which the magnets are glued. It can move in the *xy*-plane with a stroke of 230 by 230 mm. The maximum velocity and acceleration in the *xy*-plane are 1.4 m/s and 14 m/s^2, respectively.

The position of the translator is reconstructed on the basis of data from eight inductive sensors that are mounted on an external *xy*-robot and from the encoders of the *xy*-robot itself. Because the inductive sensors only have a range of 2 mm, the *xy*-robot follows the same *xy*-trajectory as the planar actuator during long-stroke measurements. However, the planar actuator and *xy*-robot are controlled independently and do not make contact. At standstill the position and angular error of the planar actuator was approximately 0.1 µm and 1 µrad rms, and during high-speed trajectories less than 30 µm and 0.1 mrad. During these measurements, six SISO controllers with a 35 Hz bandwidth were used to control the six degrees of freedom of the planar actuator. The power dissipation for levitating the translator 1 mm above the stator is approximately 40 W.

Planar actuator with manipulator

Although a planar actuator with moving magnets can be applied as a position stage, many applications require sensors on top of the stage. It would be a waste of all the effort that went into creating a fully contactless stage, to install power supply and data cables to these sensors. To demonstrate that both power and data can be transferred without any contact to a moving-magnet planar actuator, a planar actuator with a manipulator on top of it is investigated in the still ongoing second IOP-EMVT project. In this actuator system, three contactless technologies have been combined: magnetic levitation, contactless energy transfer and wireless communication [3].

Figure 3 shows a photo of this system. Below the black surface the stator coils are located. Although rectangular coils are more efficient for a planar actuator, round coils

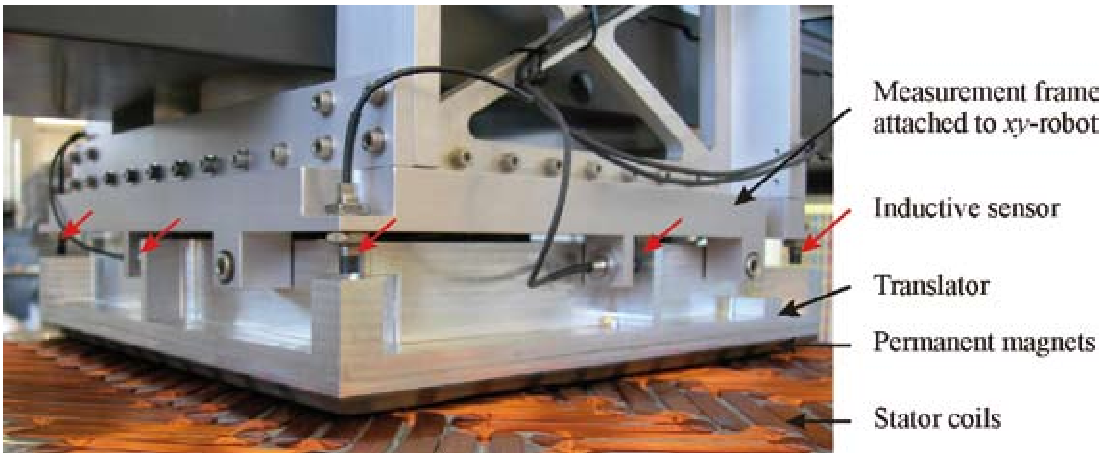

Figure 2. Herringbone Pattern Planar Actuator and measurement frame

were chosen to simplify the contactless energy transfer. Some of these stator coils are wire wound and some are Litz wire wound. The Litz wire coils have two functions. They can be used to produce force for the planar actuator when they are below the permanent magnets, and to transfer power when they are below the secondary coils of the contactless energy transfer system. The inductive energy transfer system is a coreless transformer with multiple primary coils that operates at 158 kHz. The secondary coil of the transformer is the large coil that overlaps several primary coils and is mounted at the side of the planar-actuator translator. The transferred power is rectified and used to drive a two degree-of-freedom manipulator that is placed on top of the translator. This system can transfer 100 W with an efficiency of 72%. The controller of this manipulator is placed on the fixed world. Hence, position data and current setpoints have to be transmitted from and to the current amplifiers on the moving platform. This data is transmitted with a 1.5 Mbit low latency 2.4 GHz wireless link. Because the data transfer is in the loop of the controller, IP-based protocols that are applied for W-LAN could not be used because of their large delays (several milliseconds). Consequently, a new protocol for data transmission was written, having a delay of 0.3 milliseconds. Furthermore, a very fast infrared link (VFIR) was designed, having a data rate of 16 Mbit and a transmission delay of only 7 μs [4]. Also for the VFIR link a custom communication protocol was written. For transmitter-receiver distances smaller than 0.7 m, the optical link is significantly more reliable than the radio link and has a CRC error rate of less than 10^{-7}.

Advanced Single-stage Planar Actuator

Nanometre-accurate stages often consist of a short-stroke nanometre stage on top of a micrometer-accurate long-stroke stage. Because of the absence of disturbing hoses and cables connected to moving-magnet planar actuators, the main question after completing the first planar-actuator project was if this technology could be applied to realize a long-stroke nanometre-accurate stage with only one moving part. In April 2008, the third planar-actuator project was granted by the Ministry of Economic Affairs (‘Pieken in de Delta’ programme) to investigate the possibility of an Advanced Single-stage Planar Actuator (ASPA).

In this project several industrial partners, ASML, Prodrive, Tecnotion and VDL-ETG, will participate together with the EPE and CS groups of the Electrical Engineering Department and the Control Systems Technology group of the Mechanical Engineering Department of TU/e, to investigate and realize this nanometre-accurate single-stage

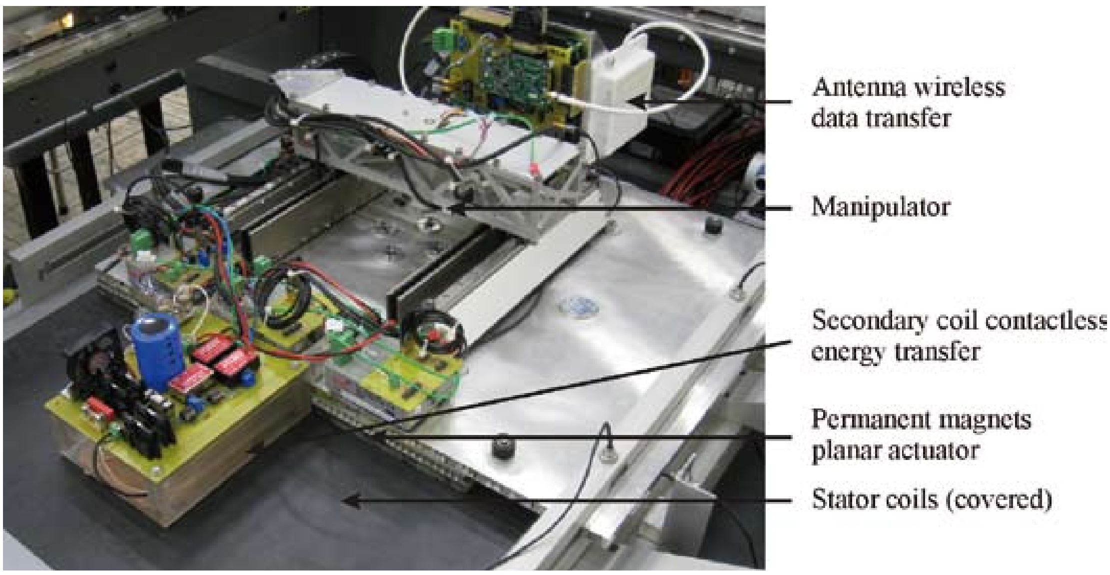

Figure 3. Planar actuator with manipulator and wireless energy and data transfer.

planar actuator. Whereas in the previous projects rigid-body dynamics was assumed, this assumption does not hold in the new project as flexible modes of the moving translator should be actively compensated by over-actuation to achieve the desired accuracy. Hence, the force distribution should be controlled over the surface of the translator as illustrated in Figure 4. Furthermore, the modeling and design of the planar actuator has to be improved and the influence of model inaccuracies and production tolerances on the closed-loop performance has to be investigated and minimized. Another important aspect is the reduction of the number of amplifiers in the system. As only a small part of the stator coils are energized simultaneously, it is not economic to have each coil connected to its own amplifier. In the project an integral design approach will be followed, combining electromechanics, control design and mechanical design.

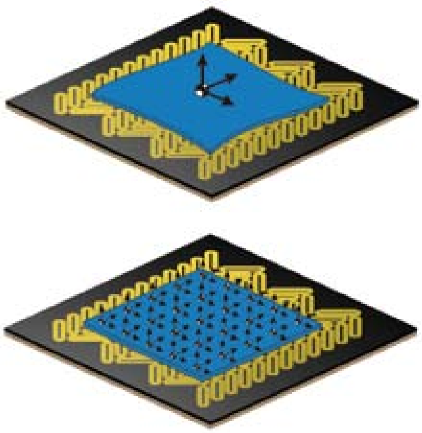

Figure 4. Schematic representation of the use of over-actuation to compensate flexible modes.

Because the measurement system of the planar actuator shown in Figure 2 limits the accuracy of this actuator, it will be equipped with a laser interferometer system to re-measure its performance. These measurements will be the starting point of the research, which will hopefully result in a new generation of highly accurate positioning stages based on moving-magnet planar-actuator technology.

Authors' note

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