Contactless Planar Actuator with Manipulator

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Abstract

The accuracy and reliability of high-precision machines is compromised by friction and disturbances due to cables to moving machine parts. These problems can be solved by applying three contactless techniques in one system: contactless generation of forces and torques, contactless energy transfer to a moving load and wireless control. This paper presents an overview of the research performed at Eindhoven University of Technology to create a contactless planar actuator with manipulator, a system which combines all three contactless techniques.

Introduction

Most high-precision machines are positioning stages with multiple degrees of freedom (DOF), which often consist of cascaded long and short stroke linear actuators that are supported by mechanical or air bearings. Usually the long stroke actuator has a micrometer accuracy, while the submicron accuracy is achieved by the short stroke actuator.
There is a continuous push to increase productivity of high-precision machines in order to lower production costs and processing time. Two common methods are available to improve productivity of a machine.

1. Develop faster machines, leading to more powerful motors and a bulkier design, since mechanical and thermal stresses increase as well.

2. Increase the batch size of production process, e.g. use a larger wafer so more chips fit on one wafer. This results in machines with actuators that have a longer stroke.

Both methods compromise the accuracy of the machine. The use of more powerful motors means higher forces and higher speeds, thereby increasing vibrations and disturbances e.g. by larger cables to the motor. Increasing the stroke of the actuator makes it more difficult to align all components, thus making the actuator more expensive or less accurate. In addition, both methods make the machine heavier, which is especially a problem when several actuators are cascaded.
Another possibility to increase productivity is to use parallel processing, i.e. movement and positioning in parallel with inspection, calibration, assembling, scanning, etc. With parallel processing it is possible to increase the performance of the machine without the need of increasing the machine size or speed. However, it makes the machine more complex since it requires real-time synchronization of multiple actuator systems to ensure proper operation.
To build a high-precision machine, as much disturbances as possible should be eliminated. Disturbances that can not be prevented should be known exactly so they can be countered by advanced feed-forward controls. Common sources of disturbances are vibrations, coulomb and viscous friction in bearings, crosstalk of multiple cascaded actuators and cable slabs that guide the power and sensor cables to the moving parts of the machine.

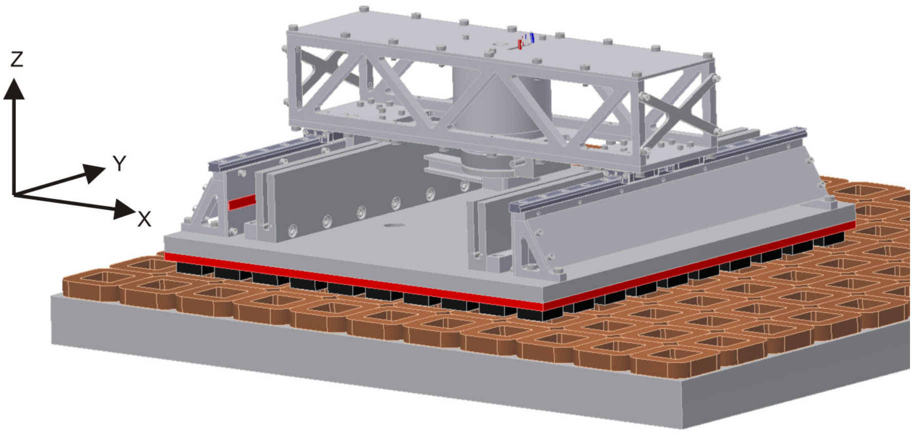


Figure 1: Contactless planar actuator with manipulator

Contactless Technology

Contactless techniques can greatly improve the flexibility of high-precision machine design. There are three contactless techniques:

1. Contactless generation of forces and torques by magnetic suspension and propulsion.
2. Contactless energy transfer using an inductive coupling.
3. Wireless control with low-latency wireless data links.

Each technique operates in a different frequency level of the electromagnetic spectrum. The magnetic bearings use permanent magnets and coils with a current loop of several kHz. The energy transfer uses inductive coupling and AC currents around 100 kHz and finally, the data is transmitted using a RF-transceiver operating at 2.4 GHz. The combination of contactless energy transfer and wireless control allow the design of machines and robots without cables to the moving parts, hence improving reliability and dynamic performance. Combining all three techniques results in a contactless planar actuator with manipulator, which is shown in Figure 1. The platform is suspended and propelled by magnetic bearings, with moving magnets and stationary coils. The energy to operate the manipulator is provided by contactless energy transfer, which can continuously supply energy while the platform is moving by means of inductive coupling. The communication between the ground controller and the manipulator is done by a low-latency wireless link. All three facets are currently being investigated at Eindhoven University of Technology and an overview of this research is given in this paper.

Magnetic Suspension and Propulsion

First of all, forces and torques can be applied without contact to the moving part of the machine by means of magnetic suspension and propulsion. An example of this are contactless planar actuators that are currently being developed for the next generation of lithography machines [1], [2], [3], [6]. Such a planar actuator is based on repulsive forces between magnets and coils and has six degrees of freedom (DOF). It can make a long-stroke movement in a plane and short-stroke movement perpendicular to the plane. In addition, it can realize small rotations about all three axes. Such a device is capable of achieving submicron precision, without the need of cascaded long- and short-stroke actuators. A contactless planar actuator with stationary coils and moving magnets is shown in Figure 1.

The current in each coil is controlled by a separate power amplifier and such a drive can typically supply currents with a bandwidth up to several kHz. Only coils that are overlapped by the magnet array are activated to supply forces and torques on the magnet array.

The main problem in controlling the planar actuator is the mapping of the desired force vector and torque vector to the required current in each coil to realize them. Since all 6 DOF have to be controlled, it is not possible to use a Park-transformation as in regular 3-phase synchronous AC machines, because this transformation would result in disturbance torques destabilizing the platform [5]. Therefore, it is necessary to calculate real-time the force and torque per ampere each coil exerts on the platform.

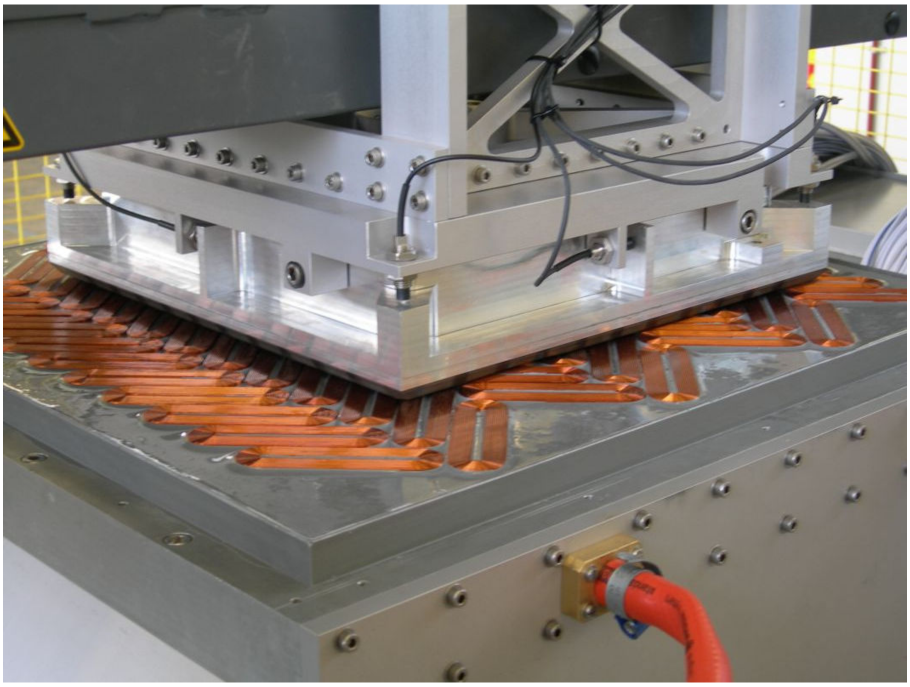


Figure 2: Planar Actuator Prototype by Helm Jansen and Nelis van Lierop [4]

A first prototype is developed at Eindhoven University of Technology, without additional system on top of the floating platform [3], [4], which is shown in Figure 2. This prototype was developed to minimize the power dissipation in the coils and force and torque ripples, which results in a coil structure with rectangular coils [2], [3], [4].

Contactless Energy Transfer

The second contactless technique is contactless energy transfer. Most machines need cables to supply energy to the moving parts. These cables can compromise reliability, since they break after a certain number of movements. In addition, they are a source of undesirable disturbances, because of friction and elasticity in the cables. Removing these power cables would greatly increase the reliability and dynamic performance of the machine. Contactless energy transfer (CET) by means of inductive coupling is commonly used. However, to be applicable in high-precision planar actuators, such a system must have long-stroke energy transfer capability in a plane, should not produce disturbance forces and must supply energy to a moving load.

For the contactless energy transfer a secondary coil is attached next to the magnet array. The primary coils are the same coils which are used for supplying forces and torques. However, only the primary coil that is overlapped by the secondary coil will transfer energy. Therefore, a stationary coil provides either forces and torques or energy, but never forces, torques and energy simultaneously. No iron or ferrites can be used in combination with a contactless planar actuator, since it is based on repulsive forces. Therefore, the inductive coupling between the coils is low, so a high frequency of more than 50 kHz is necessary to get a highly efficient energy transfer. This requires special attention in the design of the coils. The geometry of the secondary coil is optimized to minimize the position dependence of the coupling.

This concept is demonstrated in a separate test setup (see Figure 3) transferring power up to 250 W with an efficiency of 90 % [7]. The contactless energy transfer consists of an array of three primary coils with each a series resonant capacitor driven by a half-bridge square wave voltage source. A secondary coil is attached to a linear motor that moves the secondary coil over the array of primary coils. Due to the geometry of the coils, the coupling between the primary coil and secondary coil remains fairly constant (ca. 25 % variation) over a large area (black square in Figure 4). This allows the secondary coil to move over a matrix of primary coils, while transferring power. Only the primary coil that is completely overlapped by the secondary coil is active. The energy will be used to power a small manipulator on top of the planar actuator.

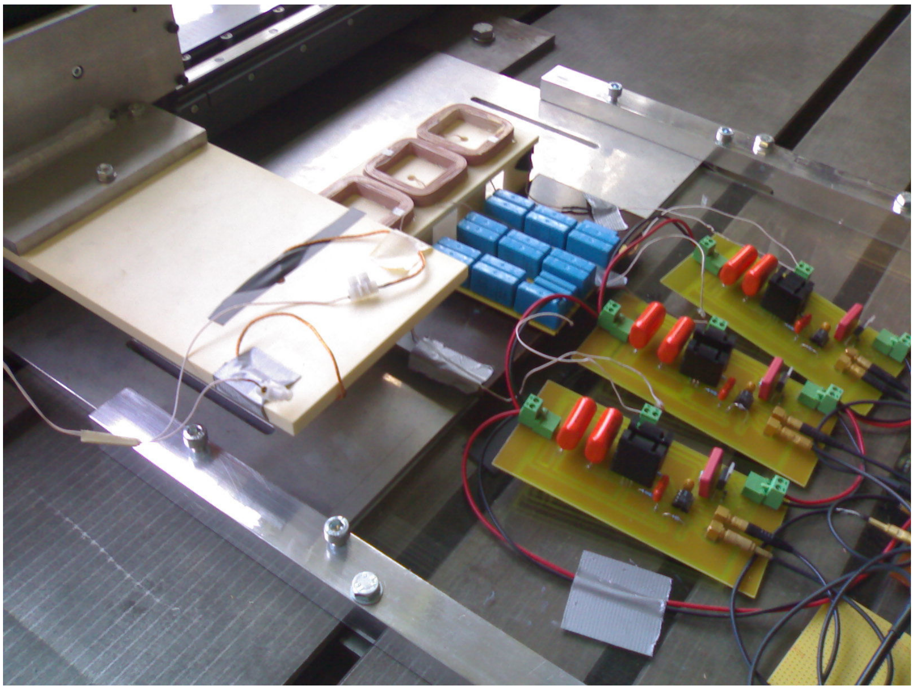


Figure 3: Experimental setup for contactless energy transfer

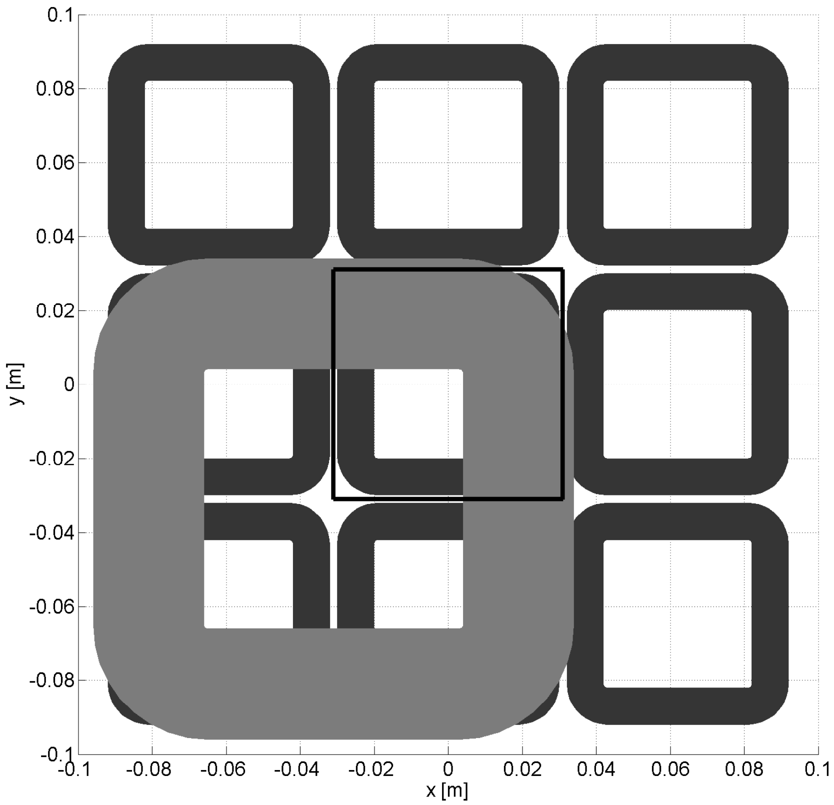


Figure 4: One secondary coil above nine primary coils

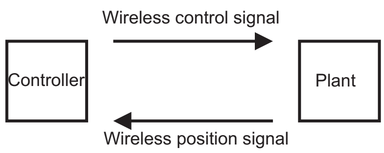


Figure 5: Schematic of wireless control system

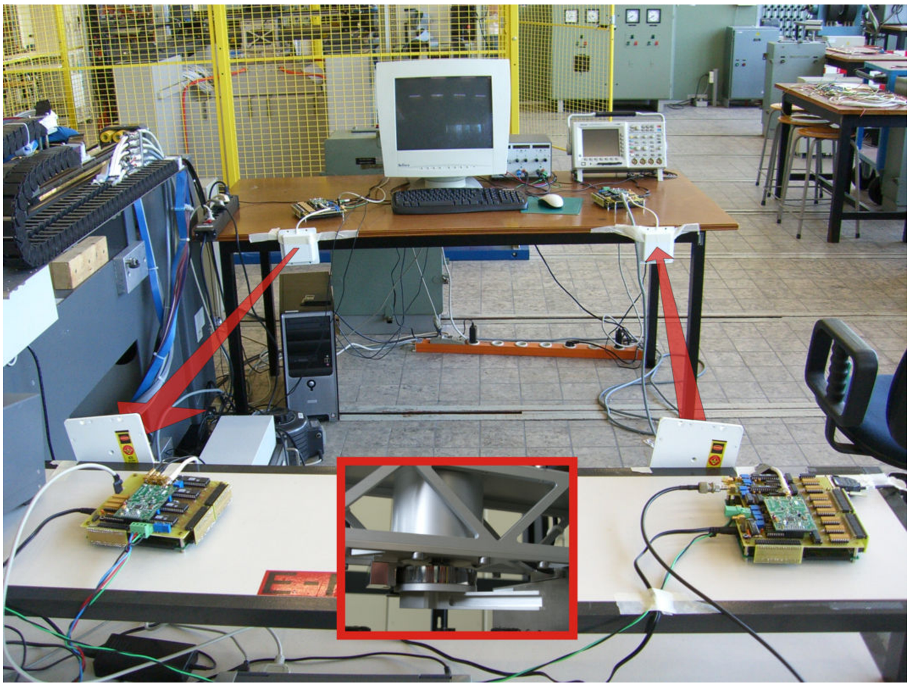


Figure 6: Experimental setup of wireless control system

Wireless Control

The third technique is wireless control and it also aims at removing cables to the moving part of the machine. By sending data over a wireless channel, signal cables can be removed, hereby improving reliability and machine dynamics. There are several techniques available for wireless data transfer, e.g. WLAN, Bluetooth and Ultra Wide Band (UWB). However, all these wireless systems are optimized for high data throughput not for low latency (delay). Even for the fastest wireless system (UWB), the delay is several milliseconds, due to the large protocol overhead. Most sensors in a machine are part of a control system which have a closed loop delay of less than 1 ms, so none of these existing wireless techniques are suitable to be used in a control loop. A schematic of a wireless control system is shown in Figure 5. The delay, introduced by the two wireless data links between the controller and the plant, should be as small as possible.
A wireless system is developed that operates in the 2.4 GHz ISM (Industrial Scientific Medical) frequency band with a custom protocol that minimizes latency. A test setup with the aim to prove the principle and tune the hardware and software is built consisting of a controller, two wireless links and a plant to test the wireless system. The plant is a three phase AC synchronous motor which has no physical connection to the controller. A picture of the setup is shown in Figure 6. The wireless system can send packages with 64 bits of data at sample rates from 6 kHz up to 12.5 kHz, depending of the bandwidth of the wireless channel (0.768 Mbit/s up to 1.536 Mbit/s). The delay in a one way transmission varies between 80 μs and 160 μs at a bandwidth of 1.536 Mbit/s and 0.768 Mbit/s, respectively. The reliability of the link is also dependent on the bandwidth. At the highest speed the packet loss is about 10%, at the lowest speed it is only 0.015%
The transfer function of the wireless system is measured at different data rates and the result is shown in Figure 7. Compared to the wired system, the wireless links introduce additional delay in the loop, which is visible at additional phase lag in the transfer function. The higher the data rate of the wireless link, the lower the phase lag as is clearly visible in Figure 7.

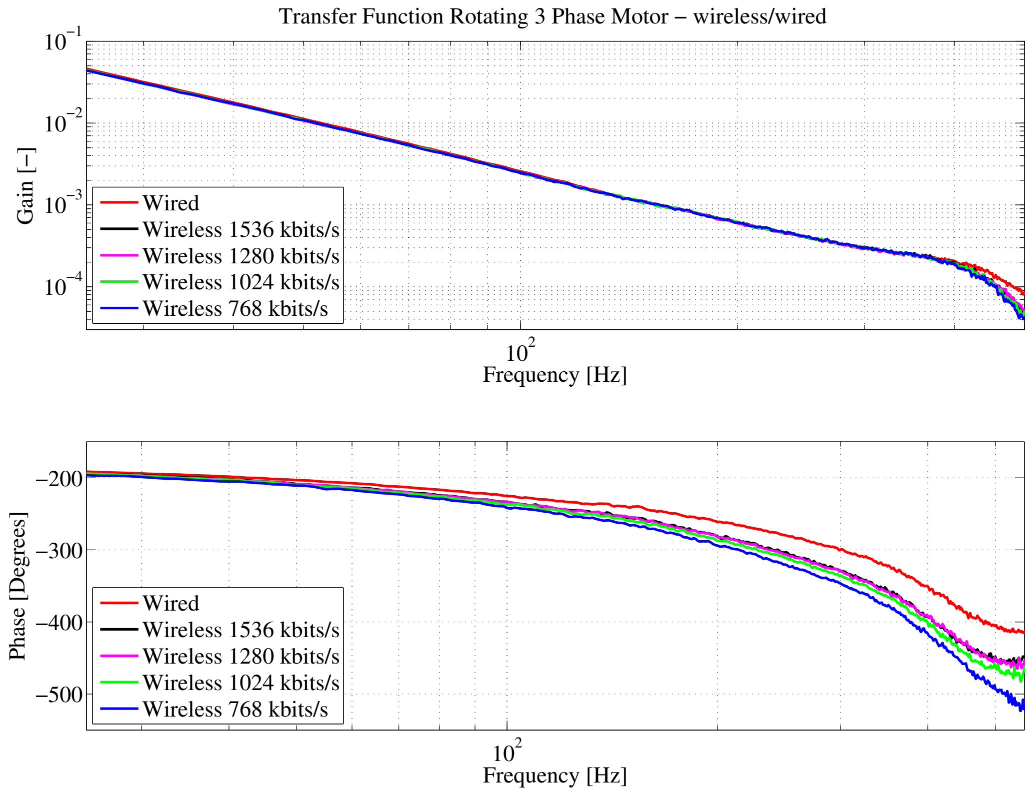


Figure 7: Transfer function of 3-phase motor at different wireless data rates

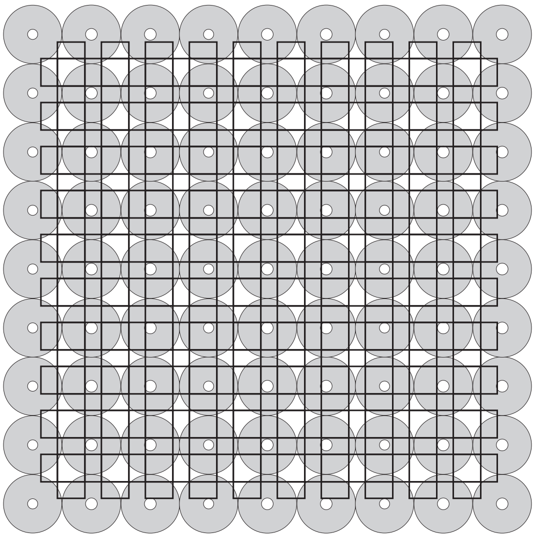
Contactless Planar Actuator with Manipulator

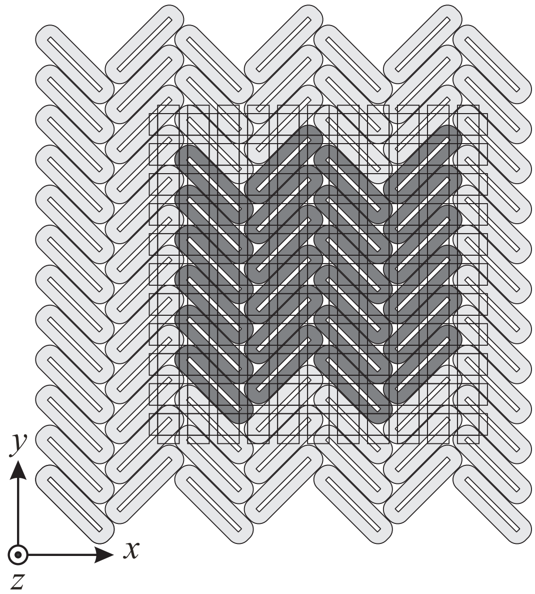
At Eindhoven University of Technology a project is started to demonstrate all three contactless techniques in one integrated system. The system consists of a contactless planar actuator with manipulator and the three contactless techniques and their interaction are addressed in this section.

The Design of the Planar Actuator

The weight of the manipulator and the contactless energy transfer greatly influence the design of the planar actuator. The additional levitated mass will require larger and thicker magnets. Moreover, the coils will have to be able to generate forces and additionally to transfer energy to a moving secondary coil. The rectangular coils are not suitable for energy transfer, since the resulting array of primary coils does not allow to have a sufficiently high coupling (higher than 20%) between one primary coil and one secondary coil at every position. Therefore, square or round coils must be used to be able to implement the contactless energy transfer principle discussed previously. The disadvantage of square or round coils (Figure 8(a)) is the higher power dissipation in the coils to lift a certain mass, compared to rectangular coils (Figure 8(b)).

The contactless energy transfer is done at high frequencies, therefore regular solid wire would result in unacceptable eddy current losses. This can be prevented by using litz wire instead of solid wire, since the strands in the litz wire bundle are individually isolated to prevent eddy current losses due to the skin and proximity effect. However, for a litz wire bundle, only 50% of the bundle cross-section is copper. Considering that for a regular coil only about 75% of the cross-section is copper, for a litz wire coil this is reduced approximately by a factor two, increasing the power dissipation with a factor four. Together with the lower efficiency of the non-rectangular coils, this creates significant thermal problems, which will have to be addressed in the design. Current densities in the coils can reach up to peak values of 20 A/mm^2 during acceleration. Water cooling is therefore required to keep the temperatures in the coil below 100°C during continuous operation. The most important criteria for the design of the planar actuator is the minimization of the maximum current density in the coils to minimize the thermal stresses.


(a)



(b)

Figure 8: Planar actuator with round coils (a) and width rectangular coils (b) [4], respectively.

Contactless Energy Transfer

The contactless energy transfer is integrated with the magnetic suspension, where the stationary coils provide force when overlapped by the magnet array and energy when covered by the secondary coil. If the primary coil is operating as suspension coil it is connected to a single phase current amplifier, which controls the current in the coil with a bandwidth of several kHz. For an efficient contactless energy transfer, the current in the coil will be sinusoidal with a frequency higher than 50 kHz. In order to force such a high frequency current through the coil a resonant capacitance is necessary. Instead of a current source, a square-wave voltage source must be connected to excite the resonant circuit. The square-wave voltage over the resonant circuit is generated by a full-bridge that switches with a 50% duty cycle.
Some switching between these two functions must be implemented, especially since the resonant capacitor should be excluded from the circuit, if the coil is connected to the current source. These switches can be either mechanical relays or electronic switches like MOSFETs. A major point of concern is the high voltage in the resonance itself from which the current amplifier must be protected. Care must been taken to ensure switching between the two amplifiers is done only when there is no current flowing through the coil.

Manipulator

The manipulator on top of the planar actuator is an H-drive, that consists of a beam propelled by two linear motors and an arm on the beam that is driven by a rotating motor. The arm of the manipulator can move in the x-y plane and can be equipped with a tool, e.g. a camera or laser for inspection or measurements on the platform. A picture of the total system is shown in Figure 1.
The movement of the manipulator and the movement of the platform will influence each other according to Newton's second law. Therefore, the magnetic suspension will have to compensate for the disturbance forces generated by the movement of the manipulator. First, a model is derived that describes the multi-body dynamics of the total system. This model is used to determine the force and torque vector that the suspension must generate in order to counteract the movement of the manipulator.
A setup is built to measure disturbance forces and torques on the platform while the manipulator is moving, which is shown in Figure 9. The setup consists of the manipulator, which is fixed on top of a 6DOF Force-Torque sensor. The sensor operates as an ideal magnetic suspension since it keeps the manipulator base frame steady while it is moving. The necessary forces and torques are measured and compared with the predictions of the multi-body dynamic model. The most significant force and torque are related to the movement of the beam and are F_y and T_x, according to the coordinate system in Figure 1. The measured and predicted values of F_y and T_x for a certain trajectory are shown in Figure 10(a) and Figure 10(b), respectively.

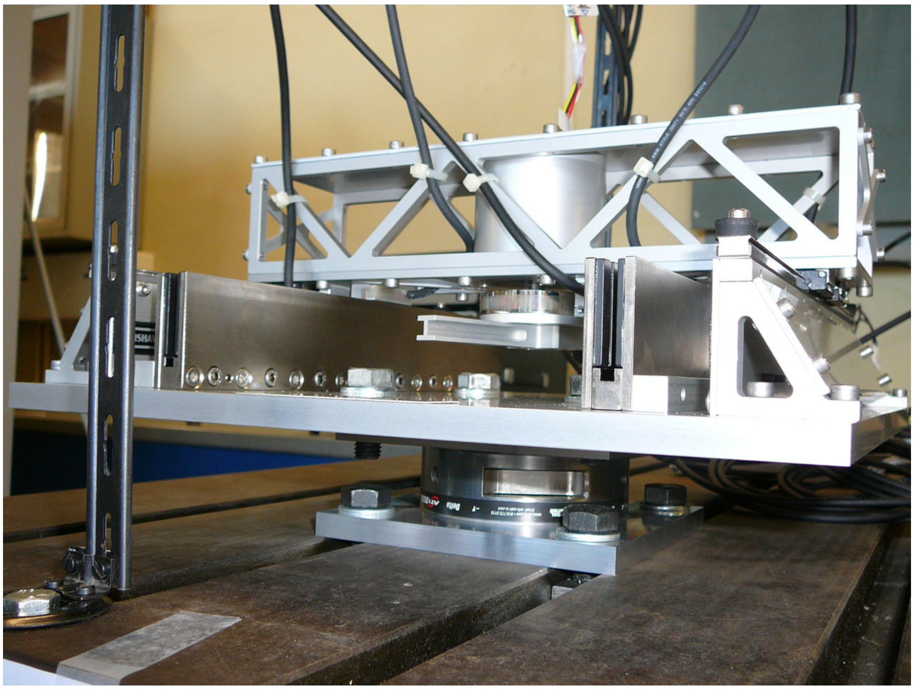
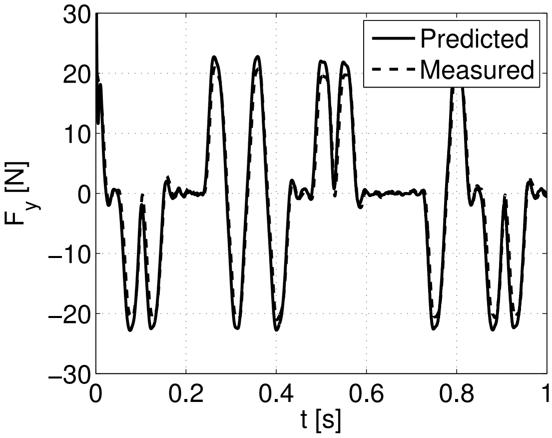
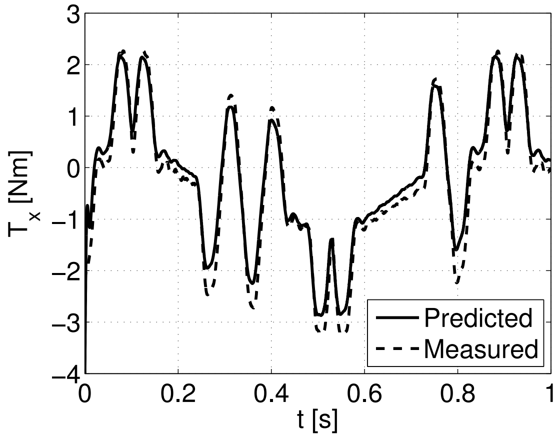


Figure 9: Manipulator with 6 DOF Force/Torque sensor



(a)



(b)

Figure 10: Measured and predicted value of F_y (a) and T_x (b), respectively.

Control of the Total System

Since the movement of the manipulator will generate disturbance forces and torques on the planar actuator, the controller of the magnetic suspension needs to know these movements in order to compensate for these disturbances. The synchronization of the manipulator and the magnetic suspension controllers must be real-time. The short delay in the wireless link, which has a maximum of 160 microseconds one way, allows for a wireless real-time feedback loop. The position, read by the incremental encoders on the manipulator is sent back to the ground controller and the current commands to the manipulator are sent by a second wireless link. In addition, the encoder readings are used to estimate the disturbance forces on the moving platform, which can be used as a feed forward control action for the magnetic suspension. Finally, this control strategy allows to accurately move the tool center point (the tip of the arm) to any position in the workspace in real-time, since there is no local manipulator control-loop on the platform that is unsynchronized with the ground controller.

Power Electronics

The energy that is transferred at high frequency using the contactless energy transfer system needs to be conditioned to several DC voltages in order to power the electronics on the platform. The amplifiers that drive the 3-phase motors of the manipulator need 60V to operate. Furthermore, the motors can operate as generators when braking, so a large buffer capacitor is necessary at the +60V bus to account for the power fluctuations. In addition, the incremental encoders and the logic of the wireless link need +5V. The amplifiers are voltage controlled current sources, so each amplifier needs two analog control signals between +/-10V. The signals are sent digitally using the wireless link and the DA-conversion needs +/-15V to generate the required voltage references. These four voltage levels, +5V, +/-15V and +60V are generated by a resonant LLC converter of which one inductance is the primary side of a transformer. The secondary winding ratios determine the output voltages which are then regulated to ensure the +/-5% accuracy of the output voltages.

Conclusion

Combining the contactless application of forces, contactless energy transfer and wireless control into one system is very complicated and requires a unique system approach. It involves three different electromagnetic frequency levels for forces ($<$ 3kHz), contactless energy transfer (50 - 200 kHz) and communication (2.4 GHz). These techniques facilitate the design of high-precision machines of greater complexity, accuracy and flexibility. Moreover, it can increase the reliability by removing cable slabs to moving machine parts.

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