Novel Concept for Micro-Assembly of Optical Devices Using a Planar Motor System

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Abstract. Research and Development in recent years has led to first commercially available, magnetically levitated planar motor systems. Considering the advantages of such systems, they perfectly fit as a substitute for multi-axis fine positioning stages in high-volume productions. To address the need for solutions for high-volume packaging of optical devices, we present a novel concept for a micro-assembly station using a planar motor. To qualify a novel, vacuum-operatable planar motor system for our design, we conducted experiments regarding positioning repeatability, positioning noise, and dynamics on a pre-series system.

Keywords: maglev planar motor, micro-assembly, optical devices.

1 Introduction

The maglev (magnetically levitated) planar motor has been well-developed in recent years and is showing great potential as a precision motion system. The electromagnetic thrust in maglev planar motors is generated by the interaction between the magnetic field of a permanent magnet array (mover) and the current in a stationary array of coils (stator). Thus, the mover can be controlled in six degrees of freedom (DoF). Due to its principle of operation, the mover is entirely passive, from which the many advantages of the system can be derived. To begin with, the stator tiles can be arranged and rearranged in user-tailored machine layouts, providing production flexibility. Each mover can be assigned to an individual path through the production facility to meet customer-specific demands and realize smart manufacturing. Due to the passivity of the movers, minimal cleaning and maintenance effort is required, and they are operatable in demanding environments such as cleanrooms, vacuum environments, and in hygienic applications. The exceptional dynamics, the motion capabilities in 6-DoF, and the high positioning precision make the system not only suitable as a transport system but also as a motion unit within individual manufacturing processes [1]. The main limitations of the system concern the limited travel range in the direction perpendicular to the stator plane, and in the rotational axis that restrain the technology to specific types of tasks. Moreover, due to the magnetic levitation, modeling and controlling of the system is complex, and the motor's stiffness is limited. Given the advantages and disadvantages of maglev motors, in past works, the system was recommended for use in lithography production processes as a single-stage fine-positioning stage [2], [3]. Apart from this application, we see particular potential for the usage of the maglev planar motor in silicon photonics production. There, silicon is used as an optical medium to realize highly integrated optical devices on a microchip level. The great benefits of silicon photonics result from the manufacturing processes using well-developed and scalable CMOS production technologies, thus providing low-cost mass manufacturing capability [4]. However, the packaging of these so-called photonic integrated circuits (PICs) is significantly more challenging and currently orders of magnitude more expensive than electronic packaging. This is due to the compelling necessity of micron-level alignment of the optical components (e.g., laser diodes, glass fibers) that are to be assembled to the PIC [5]. In order to make optical products economically viable in more applications, an overall cost reduction for the manufacturing of optical devices is required. Additionally, the production volume of photonic devices is smaller compared to electronic devices, so more flexible assembly machines are desired [6]. Hence, in this paper, we present a design for an assembly station using a maglev motor that has the potential to be cheaper, more flexible, smaller in size, and more dynamic than conventional optics assembly machines.

Before we go deeper into the concept of the assembly station, we first point out current technological challenges regarding maglev motors and what challenges have been focused on in the past. Further, we provide an overview of the few commercially available systems that have emerged from decades of research on maglev motors. Based on these systems, we present a novel design for an assembly station for optical devices. In order to qualify the system for application in optical assembly processes and our design, we conducted experiments regarding positioning accuracy and dynamic behaviour on a pre-series system.

2 Maglev Motors - Research and Commercial Systems

In the following, we give a short overview about the technological challenges and the research regarding maglev planar motors (sec. 2.1). Further, we present the few commercially available systems and their industrial applications (sec. 2.2).

2.1 State of Research

The first mention of a planar motor, which is magnetically levitated and does not use aerostatic bearings, was by Kim in his doctoral thesis from 1997 [1] and in his earlier related works. The high-precision planar motor by Kim consists of a levitated mover with a Halbach array and stationary stator coils and thus can be controlled in all 6-DoF. In a Halbach array, the magnetized elements are arranged vertically and horizontally to their magnetic axis, which results in an amplification of 40 % of the magnetic field on one side of the array while cancelling the field to near zero on the other side [7]. Kim specified his motor with travel ranges in x, y, and z of 200, 200, and 0.15 mm, 1-g acceleration and a 5 nm positioning noise at 3 σ. To this day, research focuses on optimizing Halbach arrays and stator coil arrangements [8], [9], [10]. In 2012, Lu et al. presented the first cable-free 6-DoF direct drive planar motion system, in which the number of coils increases linearly (vs. quadratically in earlier solutions) with the stroke. The system is, therefore, easily scalable to meters-long X-Y strokes, enabling the technology to be used for workpiece transportation and flexible production [11]. In their prototype, Lu et al. used a 6-DoF stereo-vision-based positioning sensor to provide control feedback. Based on his experience, Lu co-founded Planar Motor Incorporated (PMI) in 2017.

A great research challenge lies in the modeling and controlling of maglev planar motors. Due to the physical functionality of magnetic levitation, the system presents a nonlinear multi-input-multi-output (MIMO) control problem. The general approach is to decouple the system equations to get six single-input-single-output (SISO) system equations that can be controlled by PID or by state controllers [2], [12], [13]. While earlier work focuses on developing analytical models, recent research presents solutions that include numerical models and data-driven control approaches [14], [3]. Besides model accuracy, also model computation time is of importance. In order to realize control for high precision positioning of a maglev planar motor, low latency and high sample times in a range of 5 kHz are required [1], [15].

2.2 Commercially Available Systems

For a few years, there have been several commercially available systems on the market. Beckhoff Automation, for example, offers the XPlanar and PMI the Planar Motor System, which B&R Industrial Automation also distributes as ACOPOS 6D. Mafu Robotics offers the M-Drive, a modified version of the planar motor from PMI, which is operatable in a vacuum environment. A maglev stage for high payloads is offered by Phillips Engineering Solutions. The development of such maglev planar motors is restricted by patents held by PMI (e.g., [16], [17], [18]). Tab. 1 shows the technical specifications of the maglev systems. Most movers are available with square as well as rectangular geometries. Depending on the mover size, the maximum payload is up to 14 kg or 100 kg in the case of the system from Phillips. Furthermore, the movers can reach speeds of up to 10 m/s. The maglev systems offer 6-DoF with a repeatability of the mover position from ±2 µm (Mafu) to 50 µm (Beckhoff) [19], [20], [21], [22].

Not much information regarding industrial applications using maglev planar motors is available in the public domain. Examples can be found for the dispersion of adhesives, and for plasma applications. In these, the needle or the plasma nozzle is fixed and the mover performs all necessary movements underneath [19], [21], [23]. Planar motors are also used for simple assembly tasks. The Eutect GmbH sells assembly lines based on the maglev motor of Beckoff that have the advantage of flexible part geometries as well as flexible process task orders. However, the planar motors are only used for simple pick and place applications but not for precision assembly. Further, they do not use the 6-DoF of the maglev motor but rely on serial robots [24].

Table 1: Technical specifications of the maglev systems commercially available

Specs/manufacturer	Mafu Robotics GmbH	Beckhoff Automation GmbH	PMI/ B&R Automation	Phillips Engineering Solutions
Mover size [mm^2]	210 x 210	113 x 113 to 235 x 235	120 x 120 to 450 x 450	500 x 500
Max. speed [m/s]	10	2	10	1
Repeatability [µm]	±2	50	±5	-
Max. payload [kg]	2	0.4 - 4.2	0.6 - 14.4	100

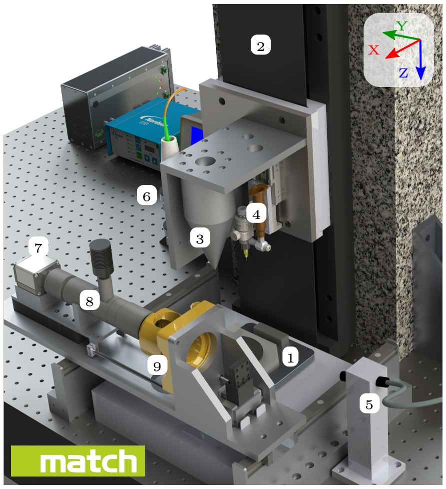
3 Concept for a Maglev Motor Micro-Assembly Station

In conventional high-precision assembly machines, part handling is typically carried out by a portal or gantry system, while alignment and assembly are performed by multi-axis high-precision positioning systems (HPPS). The redundancy of axis and the utilization of high-tech micro- and nanopositioners results in high investment costs. Moreover, process times are increased by the time needed for machine loading and unloading and by the limited motion speed of the HPPS. However, to make optical products economically viable in more applications, an overall cost reduction for machinery and manufacturing is required [6]. Thus, in this chapter, we suggest a solution for an assembly station that uses a maglev planar motor for workpiece transportation as well as an HPPS for assembly. This results in reduced investment costs regarding workpiece handling and assembly. Compared to commercially available 6-DoF HPPS, the investment costs of approx. 15,000 € for a mover and a stator are relatively low. A further advantage of the system is the compatibility with clean and especially vacuum environments, which are, in some cases, mandatory for optic manufacturing. In this context, the small footprint of the station is financially favorable. Compared to conventional assembly machines, which are normally highly specialized, the use of maglev motors enables smart and flexible production.

The following chapter presents the concept for a novel inline assembly station based on a maglev planar motor system. In sec. 3.1, the components of the station are described. Afterwards, sec. 3.2 presents the suggested assembly process.

3.1 Components of the Inline Assembly Station

Fig. 1 shows the general design of the inline assembly station. The main components are the planar motor, the vertical axis with attached tools (gripper, dispensing unit and distance sensor), an UV light source, and the camera setup. The components, as well as their tasks, are described in the following.



1 - maglev planar motor
2 - vertical axis
3 - gripper
4 - dispense unit
5 - UV light source
6 - confocal distance sensor
7 - camera
8 - telecentric lens
9 - beam splitter

Fig. 1: Components of the inline assembly station based on maglev planar motor

The maglev planar motor, especially the mover (1), is the base of the inline assembly station. The movers carry the wafers on which the components (e.g., laser diodes) are mounted, as well as the components in a workpiece tray. Alternatively, it is possible to realize part feeding with additional dedicated magazine movers. Due to the flexibility of the planar motor system, the magazine movers can overtake other movers and stations and remain in a waiting spot near the assembly station. During the assembly processes, the movers position the components and the assembly location underneath the gripper (3). In addition, the movers perform every alignment movements for the required assembly accuracy. The design of our concept is based on the M-Drive system from Mafu Robotics since it is the only system operational in vacuum environment.

An additional vertical axis (2) provides more flexibility for the assembly station because of the larger travel range (in the z-direction) compared to the movers. This, in turn, enables larger parts to be mounted on the mover. Furthermore, the vertical axis is necessary to measure gripped components with the camera (7). For this purpose, the gripper and the components are positioned on the focal plane above the camera. Additionally, the vertical axis carries the tools described in the following. The presented concept uses a linear axis with a stepper motor and a lead screw.

There are three tools mounted on the vertical axis. The first one is a micro vacuum gripper. Its purpose is to pick up the components from the magazine and place them onto the wafer. The second tool is a volumetric controlled adhesive dispense unit (4). It is mounted on a slider to move it up and down (waiting position higher than gripper; working position lower than gripper). To cure the adhesive, an UV light source (5) is implemented. The third tool is a distance sensor (6) used to level the mover for the different assembly steps. In the presented concept, a confocal sensor with a resolution of 126 nm is used.

The camera, in combination with a telecentric lens (8), is used to measure the x-/y-positions of the components and the assembly locations. A rotatable beam splitter (9) is mounted in front of the lens to look down onto the mover (component, magazine, assembly location) and up to the tools (gripper, dispense unit). The camera setup is mounted on rail guides to move it in and out of the workspace. The chosen camera setup provides a field of view of 3.32 x 2.22 mm^2 and a theoretical resolution of 0.6 µm/pixel.

3.2 Suggested Process of the Inline Assembly Station

The assembly process is demonstrated by placing a micro laser diode in front of a waveguide on a wafer. The diode has a cuboid geometry with a volume of 300 x 300 x 100 mm^3 (LxWxH). First, the mover carries the wafer and the magazine with the diodes into the assembly station and positions the diode that is to be assembled underneath the distance sensor. By measuring a few surface points, the diode plane is calculated and leveled by a tip-tilt motion of the mover. Next, the mover positions the diode underneath the gripper. Here, the x-/y-position of the diode is measured with the camera and adjusted by a movement to the gripper. The diode is gripped with the vacuum tool, and the assembly location is leveled using the distance sensor. Then, the assembly location is moved under the adhesive needle. The lateral deviation of the needle is corrected using the camera. Following, the adhesive is applied by the needle and a movement of the vertical axis. Next, the gripper is positioned above the assembly location and the x-/y-position is adjusted to the gripped part using the camera. Finally, the diode can be placed by a movement of the vertical axis.

4 Experimental Examination of a Maglev Planar Motor

Apart from a specification for the positioning repeatability of the M-Drive system, currently, there is no technical information regarding the positioning noise and the system's dynamics available. In order to qualify the M-Drive system as a suitable actor for high-precision positioning and our designed assembly station, we conducted several preliminary experiments on a pre-series system. Our experiments aimed to clarify the system's positioning repeatability, positioning noise, and dynamic behavior. To do so, we measured the proximity of the mover to a confocal sensor from Micro-Epsilon (IFS2405-3) in repetitive movements. The principal measurement setup is illustrated in fig 2. To account for measurements in the different directions of movement, the sensor was oriented in configurations A and B (highlighted in blue and yellow resp.). A parallel gauge block, which was adhered to the mover, provides a plain measurement surface. The sensor has an operating range of 3 mm starting at a distance of 20 mm from the sensor's head and is specified with a measuring resolution of 126 nm. The sensor noise was measured to be 90 nm at 1000 Hz sample frequency. Due to the status of a pre-series system, an active air or water cooling system for the stator coils was unavailable, so we had to operate the system in a thermally unstable state.

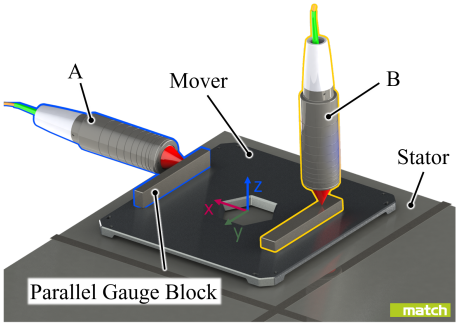


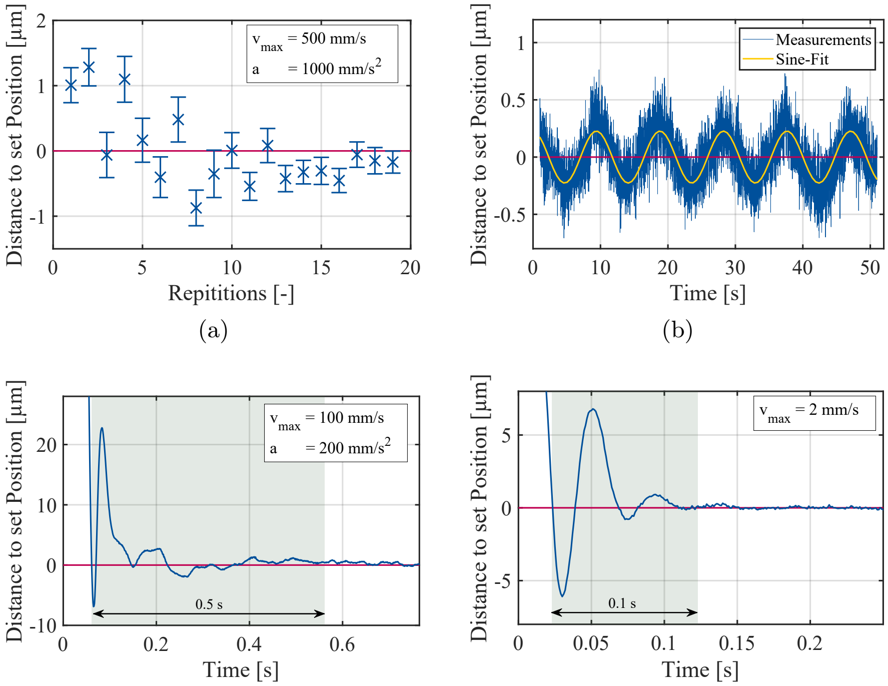
Fig. 2: Experimental setup

In order to identify the system's positioning repeatability, the mover was set up to approach the measuring position multiple times with single-axis movements (x-direction and z-direction resp.), whereby different accelerations and speeds have been tested. We recorded multiple measurement series with similar results. As an example fig. 3a shows the average positioning deviation from the commanded position for the x-direction for multiple repetitions. The average positioning deviation and positioning noise have been derived from a stabilized state of the mover. Given the measurements from fig. 3a (19 repetitions), we calculated the positioning repeatability for the x-direction of 1.8 µm at 3 σ. It is noticeable that the deviation of the distance to the nominal position decreases with the number of repetitions. Looking at the course of the measurements in fig. 3a and the significant trends in the other series of measurements, we assume a superimposition with a thermal drift which is caused by thermal expansion of the system. Consequently, the actual positioning repeatability of the system might be more precise than our experiments imply. Nevertheless, our experiments provide a first inside into the system's capabilities.

Analogous to the x-direction, we investigated the mover's positioning repeatability for z-axis movements. Our results show that the positioning repeatability increases with a decreasing air gap, which can be attributed to the sharp decrease of magnetic force with an increasing air gap. At z = 2.5 mm, we derived the positioning repeatability to be 1.6 µm, and 1 µm at z = 0.5 mm (values given at 3 σ and calculated from 16 repetitions). The acceleration of the z-movements could not be specified because of the pre-series status of the control. Analytically, we approximated the acceleration to be 200 mm/s^2 from the derived velocity.

Looking at the long-term positioning noise in the x-direction, the mover shows an oscillating behavior depicted in fig. 3b. At rest, the system oscillates periodically with an amplitude of approximately 0.23 µm with a standard deviation of 0.22 µm and a frequency of 0.11 Hz. Whether this systematic disturbance in the measuring is due to non-optimal control parameters or due to other environmental influences is still to be investigated in the future.

Our experiments regarding the positioning repeatability also provide information about the motor's dynamics. Fig. 3c and fig. 3d show the course of a



(a) (b)

(c) (d)

Fig. 3: Positioning repeatability measurements (a) and positioning noise (b) of the mover in x-direction as well as the mover dynamics in x-direction (c) and z-direction (d)

characteristic transient response of x- and z-axis movements. Regarding the x-axis, the mover stabilizes to an acceptable deviation in approx. 0.5 s with a max. positional undershoot of approx. 23 µm. It is notable that the planar motor does not show the typical behavior of a damped oscillation like traditional machine axis do. This could be referred to neglected coupling effects, inaccurate model parameters, or internal filtering of the step excitation. For the z-axis, we have determined the max. amplitude and stabilization time to be approx. 6 µm and 0.1 s at $z = 2.5$ mm. Comparing fig. 3c and fig. 3d, the z-axis oscillation appears much more harmonic. For lower z-positions, the motor's undershoot is reduced while the stabilization time and the initial overshoot remain at the same level.

Regarding accuracy requirements for optics assembly, the 1 dB planar alignment tolerance for grating couplers can be specified with ±2.5 µm and for edge coupling with ±0.5 µm [5]. Considering the positioning noise and the thermal influences on our measurements, we are optimistic that with adequate cooling and tuning of the control parameter, the precision of the planar motor is sufficient for the assembly of optical components. Further, our findings provide information regarding the stabilization time and the z-position-dependent positioning accuracy, which are essential for the operation of the system in assembly processes.

5 Conclusion and Outlook

Although the concept of maglev planar motors is old, commercially available systems have just been introduced to the market a couple of years ago. Given the high positioning precision, the system is not only suitable for flexible workpiece transportation but also as a functional positioning unit within different processes. However, as discussed in sec. 2.1, controlling maglev planar motors is still a current research topic. While research proposes to use maglev planar motors in lithography processes, we envision using them in micro-assembly of optical systems. Thus, this paper presents a novel precision assembly station that can be integrated into an inline production facility for optical devices or PIC production. The shown concept uses the maglev planar motor to handle, position and align components. An additional vertical axis performs the placing motion to extend the flexibility for larger parts. By using the planar motor for all positioning and alignment tasks, the number of stacked axis is reduced and, thereby also the complexity of the facility.

Due to the novelty of maglev planar motors on the commercial market, there are not much public information about the systems precision and their dynamics. Thus, we conducted some preliminary experiments on a pre-series planar motor regarding the system's positioning repeatability, positioning noise, and the system's dynamics. Although we could not guarantee thermal stability of the stator coils in these first experiments, we determined some key characteristics of the system and identified the motor as viable for our design. In future work, we will present a more sophisticated analysis in a thermally controlled environment. In addition to the properties already examined, we will investigate the repeatability of movements in all 6-DoF, the absolute accuracy, the path accuracy, and the motor's stiffness. Due to the coupling of the axis and the high dynamics, a mature measuring setup or an advanced sensing technology is required to record the system's movement in 6-DoF with high position resolution at a high sample rate. In parallel, we will implement our design of a maglev micro-assembly station and qualify the machine for different assembly tasks on optical devices.

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