Proceedings of "3rd International Conference on Micro Opto Electro Mechanical Systems" Mainz, Germany, 1999

Ultra small positioning system for high force, high velocity and long travel range with a built-in linear encoder

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ABSTRACT

Micro positioning systems play an important role for a broad variety of optical applications. Examples are mechanisms for adjusting, focussing or zooming and devices like fiber-optical switches or robots and grippers for the assembly of optical systems.

At the Institut für Mikrotechnik Mainz GmbH (IMM) a micro positioning system with dimensions of only 4 mm x 6 mm x 40 mm has been developed which offers a travel range as long as 20 mm. Travel speeds up to 40 mm/s and forces up to 0.7 N have been reached. A built-in linear encoder allows the direct measuring of the position within an accuracy of ±5 µm.

The high performance of this ultra small positioning system could be realized by using an electromagnetic micromotor with an integrated planetary gear. A micro gear motor with an outer diameter of 1.9 mm was developed in cooperation between IMM and the German motor producer Dr. Fritz Faulhaber GmbH & Co. KG. Recently, this company started to fabricate and to distribute this type of micromotor.

In order to integrate a linear measuring system into the ultra small stage the principle of incremental optical encoder with transilluminating IR light was chosen. The glass scale (5 µm lines and spaces) could be realized with a thickness of only 100 µm. The laser diodes and the photo detectors are situated outside the stage. They are connected to the glass scale via a combined fiber and free-space optics. Therefore, the measuring system inside the stage has a cross section of only 1.2 mm x 1.3 mm.

The micro positioning system with built-in encoder was developed for FESTO AG in Germany. Both micro positioning system and the optical encoder can be applied as components of a construction kit in order to built up various MOEMS.

Keywords: micro positioning system, linear encoder, rotary encoder, micromotor, motion transformer, MOEMS

1. INTRODUCTION

In the growing market of MOEMS there is a strong demand for ultra small positioning systems. Additionally, for a clan of applications such systems have to travel quickly and precisely over a positioning range of some centimeters and against load forces up to 1 N on the one hand. On the other hand, ultra small positioning systems must fit to the rather low price of the whole optical system. Typical application fields for ultra small positioning systems are production and handling of semiconductors, laser technique, optical mechanisms, fiber optics, assembly operations and micro manipulation. Very common miniaturized positioning systems are piezo translators [1] which offer a high accuracy but travel ranges only up to 1 mm. Another kind are pneumatic [2] or hydraulic [3] actuators which reach long travel ranges but only a low accuracy. A third working principle is used by electromagnetic positioning systems. One approach is to utilize linear motors [4] as direct drives for miniaturized positioning systems. The advantages of the linear motor are high velocity and high acceleration. On the other hand linear motors offer only low forces. Additionally they are not self-locking. But the main drawback is that almost each "micro application" needs a complete new and cost intensive development with a careful design of actuator, guidance and measuring system due to their strong dependence of the load, friction or damping behavior.

An alternative to linear motors is the combination of rotary micromotors [5] with miniaturized motion transformers like belt drives or gear racks. Even for those micro systems, the single components are more and more designed for the use in a construction kit [6]. The application of these elements allows the quick and cost-efficient realization of various positioning systems with different dimensions, traveling ranges, maximum speeds or maximum forces. As a key element of the ultra small positioning system an electromagnetic micromotor with planetary gear [7] developed by IMM and Faulhaber [8] has turned out. This micro drive offers a high performance compared to its small dimensions in the millimeter range.

2. REALISATION OF AN ULTRA SMALL POSITIONING SYSTEM

Apart from the ultra small size the main goals of the development of the micro positioning system were:

- high travelling speed,
- long travel range,
- high force and
- high accuracy.

The dimensions of this ultra small positioning system amount to only 4 mm x 6 mm x 40 mm. On the other hand this miniaturized stage offers a travel range as long as 20 mm and travel speeds up to 40 mm/s. To drive the stage a micromotor with a LIGA [9] made planetary gear is used. The micromotor works as an electromagnetic synchronous motor with rare-earth magnet rotor. By the transformer the rotary movement of the motor is turned into a smooth linear motion of the moving table. A view of the built-up positioning system is given in Figure 1. In experiments the performance of the ultra small positioning system was measured. Therefore, the maximum force at certain travelling velocities has been registered. The measured force depending on the velocity is illustrated in Figure 2.

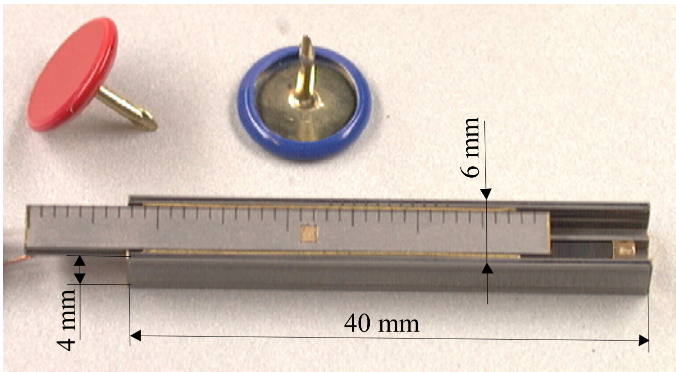


Figure 1: Built-up ultra small positioning system

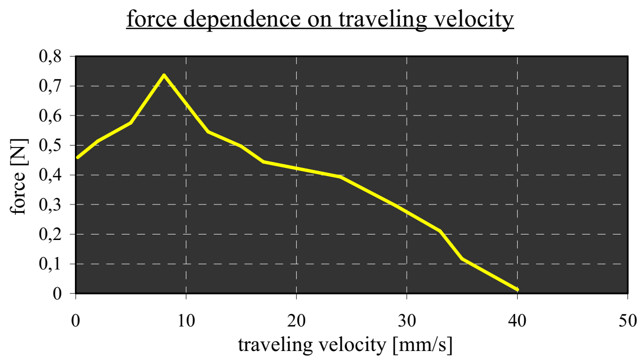


Figure 2: Characteristic curve of force

The development of the ultra small positioning system was carried out for the German company FESTO AG & Co. To illustrate the high performance of this miniaturized stage at the fair HANNOVER MESSE 1999 a compactly designed demonstrator device was built-up. The device enables a freely programmable control of the stage. Any values for the position or the velocity of the stage can be entered and executed with this device. The device with it’s input field, display and the ultra small positioning system is shown in Figure 3.

Figure 3: Freely programmable control of the stage

3. ARCHITECTURES FOR POSITIONING CONTROL

Open loop or closed loop are both architectures to realize a positioning control of a linear stage. Open loop is a control technique which does not measure the position of the moving table. Stepper motors are often used as driver systems with open loop control technique because the angular position of the rotor is determined by the motor´s construction. The position of the moving table results from the amount of steps carried out by the motor. A former IMM development of a micro linear stage is working with open loop control technique. The micro linear stage could be realized with a size as small as 3.5 mm x 24 mm x 5 mm and a travel range of 7.5 mm. This micro linear stage is illustrated in Figure 4. The stage is driven by a micromotor which operates in a micro step mode. The steps of the micromotor are used to determine the position of the moving table.

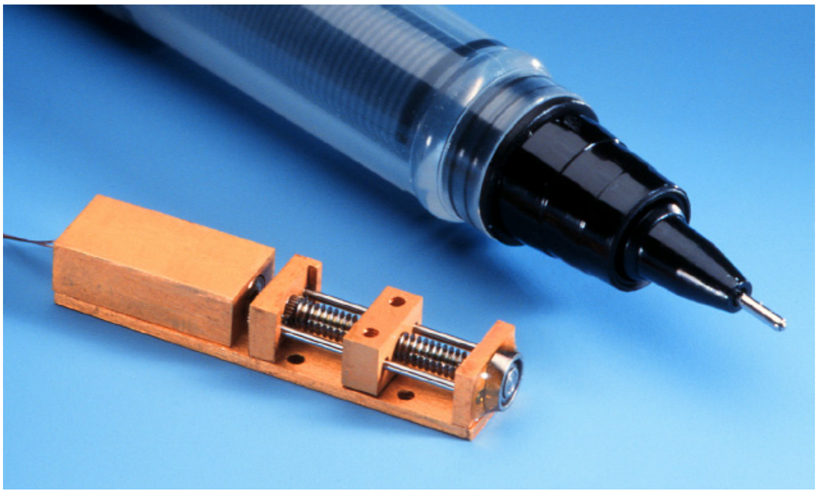


Figure 4: Open loop controlled linear stage compared to a pencil

A stage using open loop control can not compensate positioning errors of the drive system which may result from:

- Backlash in the motion transformer.
- Transmitting errors in the motion transformer caused by tolerances of fabrication.
- The synchronous mode of the motor control, which does not recognize stepping errors caused by an overload.

Due to the errors of the drive system the former realized micro stage with open loop control reaches an accuracy of ±20 µm.

The closed loop control technique allows to compensate positioning errors of the drive system because the position of the moving table is directly measured and compared to the desired one. Due to this a high accuracy can be reached by the use of a closed loop control. A direct measuring system with feedback gauging system has to be built-up to realize a closed loop control.

4. LINEAR ENCODER

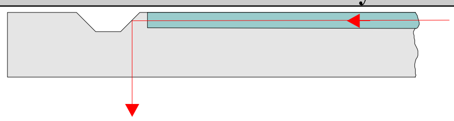
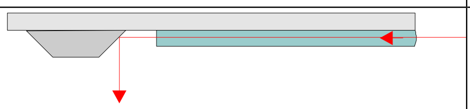
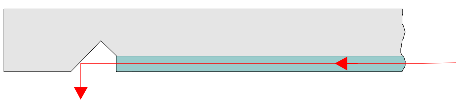
A measuring system was developed to realize a closed loop control of the position of the micro stage. The measuring system represents another key element of the ultra small positioning system. Due to the small dimensions of the stage, the measuring system has to be extremely miniaturized. Therefore, a suitable working principle was chosen: The optical encoder with through-going IR light. The realized system consists of following components:

- Lightsource;
- Glass scale with phase grating of lines;
- Index grating;
- detectors.

In order to achieve a miniaturized measuring system the laser diodes and the photo detectors are situated outside the stage. Only the beam steering components, the glass scale and the index grating are situated inside the positioning system. The beam is guided by fiber optics from the laser diodes into the stage and back to the photo detectors. Inside the stage the fibers run parallel to the glass scale to achieve a compact measuring system.

During the development of the linear encoder various possibilities for beam steering have been tested. The constructions and fabrications of the variants of the mirror units are schematically illustrated in Table 1.

Table 1: Various possibilities for beam steering of the linear encoder

Possibility for beam steering			fabrication
1		PMMA-prism with total reflection	Laser structured PMMA
2		Mirror made of brass mounted on a carrier	The 350 µm thick polished prisms are mounted together with the fibers on a 100 µm thick carrier
3		Aluminum unit with integrated mirror	Ultra precision milled by a diamond cutting tool

The free-space optics actually used consists of specially adapted input and output fibers and two mirror units made of aluminum by ultra precision milling with diamond tools. By the mirror unit the beam is reflected perpendicular to the glass scale and the index grating. After passing the glass scale and the index grating the beam is steered by the second mirror unit into the direction of the output fiber which guide the light to the photo detector. Additionally, the mirror units are equipped with structures for adjusting and fixing the fibers. The glass scale and the index grating could be realized with a thickness of only 100 µm and a width of 1 mm. The glass scale and the index grating carry a phase grating of chromium lines with a pitch of 10 µm on their upper sides. On the index grating two areas of phase grating are arranged which are displaced about 2.5 µm relatively to each other. Therefore, the two optical signals are 90° phase-shifted. The mirror unit has the outer dimensions of 22 mm x 0.5 mm x 1 mm. Due to this extremely miniaturized components the linear optical encoder requires a cross section of only 1.2 mm x 1.3 mm inside the positioning system. The photo detectors convert the optical information into two electrical signals. By using only the crossovers of the sinusoidal electrical signals the resolution of this extremely miniaturized linear optical encoder amounts to 2.5 µm.

The functional principle and the components of the optical linear encoder are illustrated schematically in Figure 5.

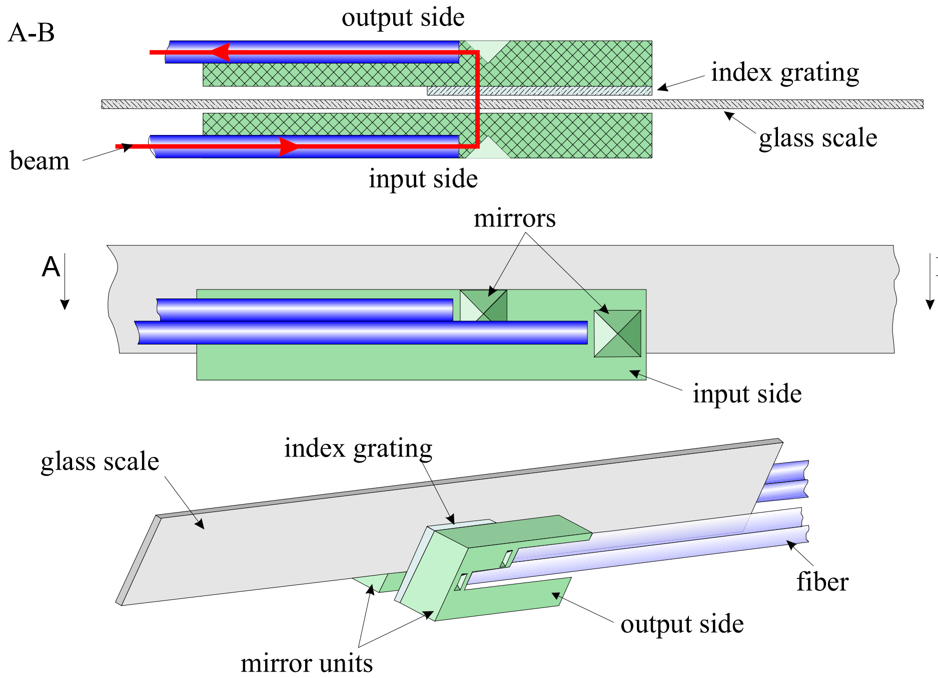


Figure 5: Functional principle of the optical linear encoder

By the developed positioning system the principle of separation of the moving and electrical system was realized. The optical parts of the encoder are connected by fibers with the electronic components. Because no electrical connection exists between the electronic system and the positioning system the following advantages could be achieved:

- no electrical noise is added to the signal,
- no disturbing signals from other sources are overlaid to the measured devolution of the signal and
- the mechanical and optical components have ultra small dimensions.

5. RESULTS

Due to the built-in linear encoder and the smooth travelling of the moving table the ultra small positioning system reaches an accuracy of ±5 µm and a resolution of 2.5 µm. To measure the accuracy of the positioning system a reference scale was installed on the moving table of the positioning system. The reference scale was observed by a CCD-camera to determine the deviation of the position of the moving table.

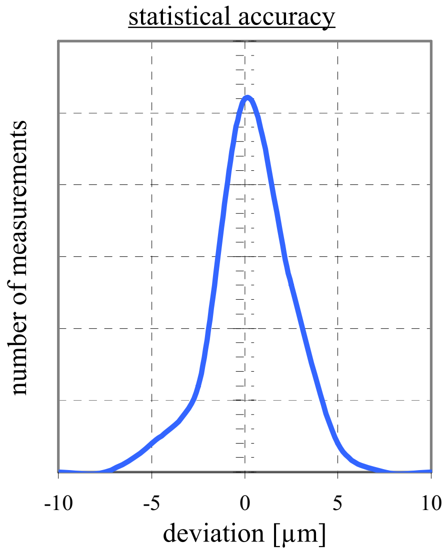


Figure 6: Accuracy of the stage

The distribution of the measured deviation is illustrated in Figure 6. In Figure 7 and Figure 8 the electrically measured signal of the photo detectors is shown. Figure 7 shows the two sinusoidal signals which are shifted 90° in phase. In Figure 8 both measured signals are superposed to an x-y graph.

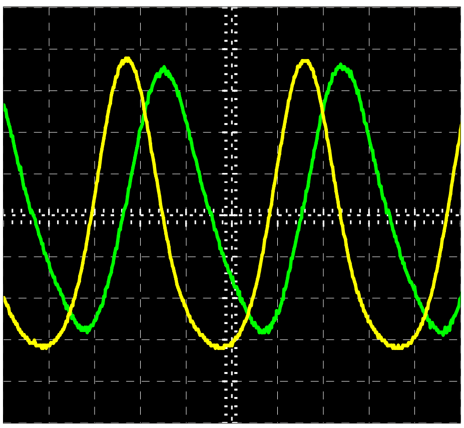


Figure 7: 90°-phase shifted signals of encoder

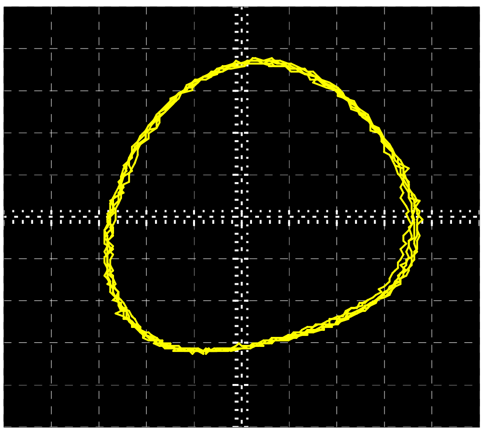


Figure 8: x-y superposition of measured signals

6. OUTLOOK

Further developments will be carried out, e.g. the electronic analysis of the measuring signal to increase the resolution reached. By the realized linear encoder only the crossovers of the measuring signals are used to count the covered distance of the moving table. Therefore, the length of the smallest step which can be measured amounts to 2.5 µm. To increase the resolution of the linear encoder an electronic interpolation of the sinusoidal signals can be applied. An electronic interpolation can be realized up to the factor of 200 rather easy. This leads to a smallest measurement step of only 12.5 nm. For a further miniaturization a linear encoder would be advantageous which is based on the principle of a reflective system. A reflective working system needs only one of the mirror units and an even smaller encoder can be realized. The principle of this optical encoder can also be utilized for ultra small rotary measurement systems. The presented ultra small positioning system and miniaturized optical encoder can be applied as components of a construction kit of micro electro mechanical systems. Additionally, these components establish an excellent basis to built up more complex micro systems like micro robots.

7. REFERENCES

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