Magnetic and Optical-Fluorescence Position Sensing for Planar Linear Motors

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Abstract

Planar linear motors, e.g. *Sawyer motors, operate in an open-loop stepping manner. This mode of operation makes them i) susceptible to loss of steps, ii) unable to reject external disturbances, iii) unable to provide controlled forces, and iv) unable to provide high stiffness. These limitations, in turn, restrict their usefulness in a wide range of robotic applications. Suitable position sensing and control technology, when added to such motors, can to a large degree eliminate these problems. In this paper we present two new sensor technologies for planar motor systems: one uses an ac magnetic technique, the other uses an optical fluorescence technique. The magnetic sensor has achieved 1 μm position resolution and is compact and easy to fabricate. The optical fluorescence sensor has the advantage of complete insensitivity to nearby motor fields. Either technology has the potential to greatly improve future robotic systems that are based on planar linear motors.*

1 Introduction

Planar linear magnetic motors enable motion over a planar surface chiefly in two translational degrees of freedom, but with small rotation as well [Fig. 1(a)]. The usual arrangement combines four linear-motor sections into one *forcer* assembly that is capable of producing forces and torques in the plane [Fig. 1(b)]. The forcer is magnetically attracted to a patterned iron platen surface while being forced away from the surface by an air bearing film; the equilibrium separation being typically 10 to 15 μm. The motor sections have fine teeth [typically 0.5 mm (.020 in.) wide on a 1.0 mm (.040 in.) pitch] and the platen has a two-dimensional array of square teeth of corresponding width and pitch. A typical planar motor platen has the structure shown in Fig. 2(a). After chemical machining, the platen surface is planarized using epoxy to form the air-bearing surface as shown in Fig. 2(b). The combined motor sections making up the forcer ride above or hang below the platen (stator) surface, and typically operate on a flux-steering principle in open-loop microstepping mode. These developments are chiefly due to Sawyer [1, 2], and date from the late 1960s.

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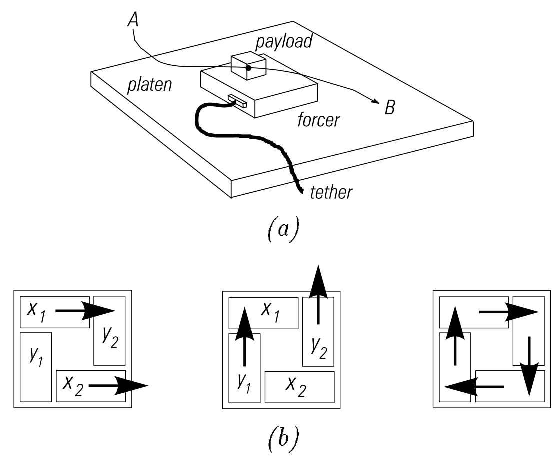

Figure 1: Planar linear motor. (a) General view, moving payload from point A to point B along a specified trajectory, (b) schematic plan views of forcer, showing four motors that generate forces and torques.

Recently, the Sawyer principle has attracted considerable attention in robotics because of its many desirable attributes. RobotWorld [3, 4] uses forcers carrying vertical and rotational axes and vision cameras suspended from a platen ceiling for automated assembly. Similar systems have been developed by AT&T [5] and Megamation [6] for a wide variety of automation applications such as the placement of surface-mount components on circuit boards [7].

While offering many benefits, current planar motion systems are severely limited because of their open-loop stepping operation which prevents the achievement of maximum potential performance. To help ensure against loss of synchrony (missing steps), only two-thirds to three-fourths of the available force margin is used, reducing the forcer's potential maximum acceleration and velocity. Even so, the forcer motors remain susceptible to loss of synchrony if large enough unanticipated external forces are acting. Additionally, settling times after moves are longer than desirable and there is no way to reject low-frequency external disturbances. The forcer has only moderate stiffness requiring high power dissipation when holding a position.

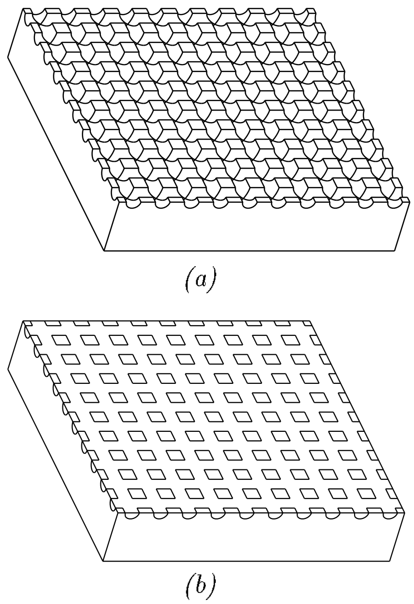

Figure 2: Oblique drawing of platen surface (highly magnified). (a) Orthogonal groove pattern, (b) after epoxy backfill, showing the array of square teeth.

These problems can be alleviated by incorporating a suitable position sensor. Such a sensor could greatly improve performance if it could accurately measure the relative displacements of forcer and platen at a high enough bandwidth to be used for servo control. Among the possible sensing strategies are laser interferometry, tracking from light sources attached to the forcer, optical sensing of teeth in the platen, capacitive sensing of teeth, and magnetic sensing of teeth. Despite these possibilities, it would appear that viable closed-loop control of planar linear motors has yet to be achieved. We believe this is due to the lack of satisfactory position sensors—hence the motivation for the work described in this paper.

Interferometric or other optical tracking techniques are expensive and run into trouble when multiple forcers are used in a cluttered environment. On the other hand, sensors that are self contained and can be mounted on or incorporated into the forcer would appear to be the most desirable. Such sensors could use either magnetic, capacitive or optical principles to generate electrical output when the forcer is driven over the platen array. The output signals, either pulses or continuous waveforms, would correspond to the platen array dimensions. These could be used for closed-loop coarse distance control by pulse counting and/or intratooth fine control by interpolating the analog waveform.

Sawyer himself recognized the desirability of a platen tooth sensor and patented a method based on magnetic induction [8]. A technique based on sensing capacitance between patterned electrodes and the platen teeth was developed by Miller [9, 10]. A magnetic sensing technique was developed by Brennemann, et al. [11]. An optical technique using colored stripes similar to that used by an optical mouse device

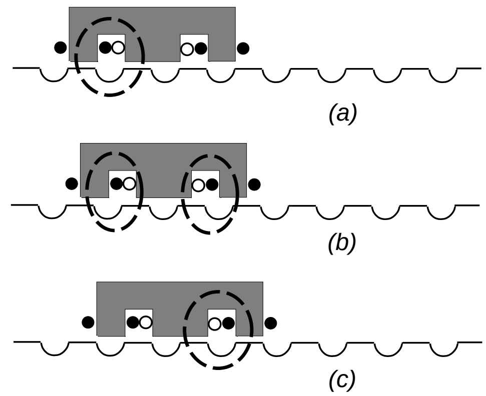

Figure 3: Principle of magnetic position sensor. Drive wires are shown as open circles ∘, sense wires are shown as closed circles •: (a) maximum coupling for left sense winding, (b) equal coupling for each sense winding, (c) maximum coupling for right sense winding.

was patented by Hoffman and Pollack [12]. Another optical technique based on reflected light was developed by Nicolson, et al. [13].

None of these sensing techniques have met with any reasonable degree of success. Each of them is sensitive to external disturbances. The magnetic and capacitive types are disturbed by either stray magnetic or electric fields. The magnetic sensors are bulky and sensitive to the motor drive currents. The optical reflection sensors are sensitive to platen surface irregularities causing extraneous signals and high spatial noise.

In this paper we describe a new ac magnetic position sensor [14] and a new fluorescent-dye-based optical sensor [15], both of which overcome many of the present problems, and either of which can provide the noise/bandwidth characteristics suitable for use in planar motion systems. Additionally, they can be easily integrated and readily manufactured.

2 Magnetic sensor

The new magnetic sensor measures the relative position of the forcer, carrying its toothed motors, with respect to the toothed platen. The basic physical principles are well known and in use, for example, in the LVDT (Linear Variable Displacement Transducer) available commercially, but here the geometry is adapted to the planar situation.

The sensor is comprised of i) a magnetic structure preferably of manganese zinc ferrite, ii) coil structures for excitation and pickup, and iii) a shield structure.

Figure 3 illustrates the sensor principle. There is an E-shaped magnetic structure with a central drive tooth equal in width to the spatial period of the platen, and two sense teeth of width equal to the platen tooth width. The central tooth is encircled by a single-turn planar drive coil, and serves as a source of ac magnetic flux with approximately constant coupling to the platen as a function of position. A high frequency ($\sim$100 KHz) drive signal can be used.

When the sensor is in the position shown in

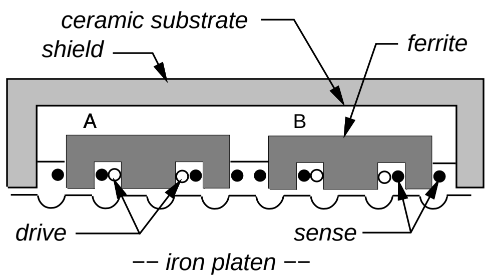

Figure 4: Cross section of as-built magnetic sensor. A and B sections are positioned in quadrature phase relationship.

Fig. 3(a), most of the drive flux is coupled through the left sense tooth, inducing an ac voltage in the single-turn sense coil encircling the left pole. A smaller leakage flux is induced in the coil encircling the right sense tooth. As the sensor is moved to the right by 1/2 tooth width, as shown in Fig. 3(b), a symmetrical flux coupling ensues with equal coupling to left and right coils. If these coils are wound in opposite senses and connected in series, the resulting output will be zero. As the sensor is moved farther to the right as shown in Fig. 3(c), displaced by a full tooth width in relation to (a), most of the drive flux is coupled through the right sense pole and coil. Assuming a series-opposite connection of sense coils, the resultant sensor output will be a smoothly varying periodic function centered on zero, with period equal to the period of the platen structure. Such a function can be characterized as "quasi-sinusoidal," easily expressible, for example, as a Fourier series.

To provide a quadrature output signal, which is necessary for tracking direction of motion and absolute position, two sections of the sensor can be spaced $n-1/4$ platen periods apart, where $\{n|n=0,1,2,...\}$. A cross-section of this arrangement is shown in Fig. 4, which represents the sensor as it was built. For symmetric output, this requires a total of four sense windings corresponding to spatial displacements of 0°, 90°, 180°, and 270°.

Sense and drive teeth were machined out of a block of ferrite material, with the sense teeth having 0.5 mm (0.020 in.) width and the drive teeth having 1.0 mm (0.040 in.) width. Gaps between the drive tooth and the adjacent sense teeth were 0.5 mm (0.020 in.). Tooth length was approximately 15.2 mm (0.600 in.). (There is a trade-off between increasing the sensor length which increases signal and averages over more teeth, but decreases the ability to operate at large skew angles.)

Sections A and B are of ferrite, epoxied to a machinable glass substrate and surrounded by the shield, which in this case was soft iron. The two sections of the sensor were separated by 0.75 mm (0.030 in.) to create a quadrature phase relationship between their outputs, and to provide some degree of isolation between sections. Each of the six teeth comprising the sensor was wound with a single turn copper coil (shown as small circles in Fig. 4) with the drive windings on the opposite side of the sensor with respect to the sense windings. The sense windings of each section were connected in series-opposite polarity to subtract their outputs and cancel common-mode external fields.

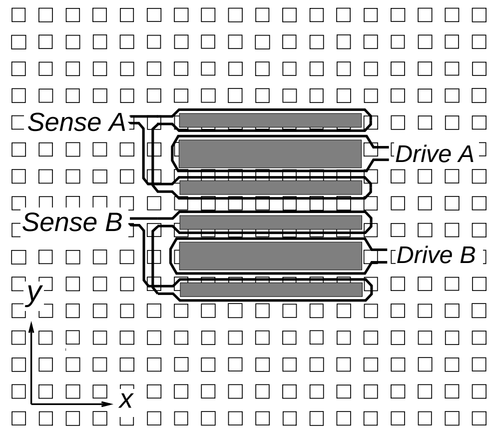

Figure 5: Schematic plan view of magnetic sensor positioned in relation to the platen tooth pattern. Motion along the y axis produces position signals; motion along x produces some unwanted signals (approximately 4% modulation).

All teeth in the sensor and platen were potted in epoxy and planarized (not shown). As shown in Fig. 4, the shield covers the sensor and extends down to the same height as the teeth to provide a degree of shielding from external motor fields in the air, and to provide a parallel flux path for motor fields in the platen.

Sense and drive windings were brought out to small connectors attached to the shield/housing. An attempt was made to make all coil loops of consistent shape and equal area, but this was achieved only to a level of about 20% because of the manual technique used. Unfortunately, one of the sense wires was exposed by the grinding process and was nearly ground in two. This adversely affected the operation of the as-built sensor (see Section 3). If photolithographic techniques were used instead of the manual technique, it is likely that the coil areas would match to within 1% of each other.

A schematic plan view of the magnetic sensor is shown in Fig. 5. Here, the cross-hatched rectangles represent the magnetic teeth, and the drive and sense windings are on opposite sides to minimize direct coupling effects. The magnetic shield layer is not shown. If the sensor is moved in a direction orthogonal to the measurement direction, only weak modulation occurs because of fringing effects. This was approximately 4% of the signal in the measurement direction.

3 Magnetic sensor results

Several experiments were run to measure the effectiveness of the sensor. The sensor was mounted on a precision stage allowing accurate translation along a Sawyer motor platen. A gap of 37 μm (1.5 mils) between the sensor and the platen was maintained using a non-metallic shim. The drive windings were ex-

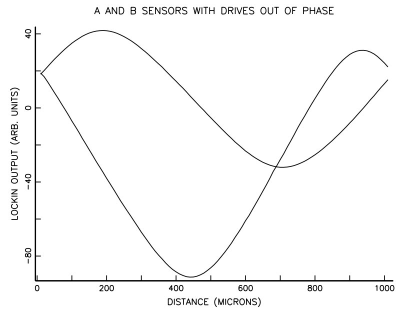

Figure 6: Magnetic sensor output vs. position.

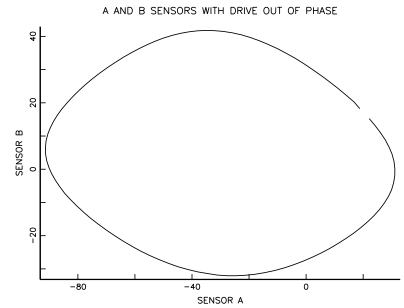

Figure 7: Magnetic sensor A output vs. B output.

cited with a 90 KHz sine wave signal, and detection was done with a lock-in amplifier. Figure 6 shows the lock-in outputs as a function of distance along the platen. Several features are noticeable. The signals are quasi-sinusoidal as expected, and are very smooth (noise level much smaller than line width). The A and B signals are very close to having a quadrature spatial phase relationship. One of the signals is nicely centered around zero output (indicating good balance between the two sense teeth), however the other signal goes more negative than positive, and has a much higher amplitude.

Figure 7 shows the A and B outputs plotted against one another. The ideal output would be a circle or symmetric loop centered at (0,0).

Experiments were performed in which the phase of the A and B drive circuits were reversed. This had a large effect on the offset of the sensed signals, indicating fairly large couplings between the drive of one section, and the sense of the other. The coupling could be reduced by adding a shield between the sections, or moving them farther apart. Also, it was surmised that the badly mis-positioned and thinned sense winding in the as-built sensor contributed to the different amplitude signals. Finally, some sensitivity to external fields was investigated. It was found that nearby motor fields effected the sensor outputs by perhaps 6% for reasonable placement positions. This could likely be improved by using μ-metal, which has a much higher permeability, instead of soft iron in the shield.

Despite these caveats, the as-built sensor provided reproducible high-resolution (approximately 1 μm) position sensing along the platen and there is no doubt that it could serve well in an integrated sensor/forcer.

The signal from the sensor has significant components both in-phase (resistive) and out-of-phase (reactive) with the drive current. The size of the signal compares very favorably with the intrinsic noise for this sensor. A suitable type of preamplifier for such a sensor is that used in magnetic disk drives. These have a noise level of about 0.2 microvolts rms in a 10 KHz bandwidth, giving a signal to noise of 500:1. The resistance of the sensor is extremely small (0.2Ω) giving it an intrinsic noise level about 10 times smaller than the preamplifier. The proper choice of input transformer could allow this noise level to be reached [16].

4 Fluorescence-based optical sensor

We describe a new fluorescence-based optical technique that can sense position relative to the array pattern of the planar motor platen surface. The sensed information can be used for commutation and control. The sensor does not use reflected light and therefore is not sensitive to the platen surface irregularities which have plagued previous attempts at optical position sensing.

The sensor uses two optical wavelengths and a fluorescent dye material. Conceptual elements are shown in Fig. 8(a). The platen is an array of square magnetic teeth of nominal width W spaced on centers of $2W$, surrounded by grooves of width W as in Fig. 2(a). The grooves are filled with a polymer or similar material [Fig. 2(b)] containing a fluorescent dye. The remaining components are mounted on the forcer and collectively move in either x or y relative to the platen.

A primary light source of wavelength λ_1 illuminates the platen through a slit in the mask. The dye absorbs some of the primary wavelength and emits fluorescent light at a longer secondary wavelength λ_2 and the remainder of λ_1 is reflected. A filter with a sharp high-pass cutoff removes λ_1 and allows λ_2 to reach the photodetector. The amount of λ_2 is a function of the mask slit dimensions and its x, y position relative to the platen.

The unidirectional operation of the sensor is illustrated in Fig. 8(b) for a single slit of dimensions $W \times L$ ($10W$) with the detector output shown in Fig. 8(c). The output is proportional to the light from the area of exposed fluorescent material and is modulated by the slit position along the y-axis. As shown, the slit is aligned with a row of 5 teeth and 5 fluorescent squares corresponding to slit position $y = 0$ in Fig. 8(c) with the output at 0.5 maximum. Moving the slit in the y direction a distance W causes the output to increase from 0.5 maximum to the maximum. Moving the slit farther in y from W to $2W$, the output decreases from maximum to 0.5 maximum. Ideally, the output is a triangular function of the slit position for one cycle of the array and is repeated for larger y displacements. Thus the position of the slit can be determined using conventional electronic circuits to count cycles for large excursions and to interpolate the waveform for intra-teeth locations. The output is essentially independent of the x-axis position of the slit. Two of these devices in spatial quadrature are required for a bidirectional position sensor.

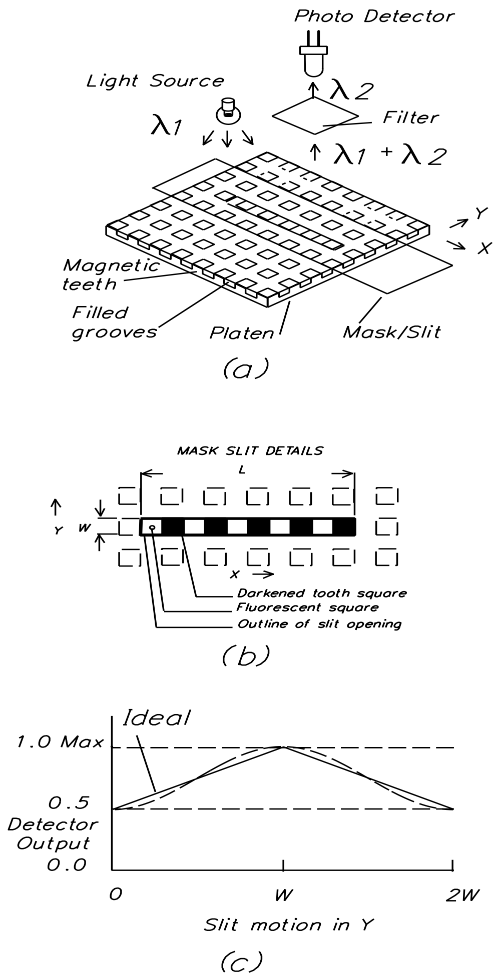

Figure 8: A dual wavelength optical planar motor sensor: (a) basic principle, (b) slit detail, (c) normalized output.

Operation of the sensor depends on selection of a fluorescent dye with good quantum efficiency and wide separation of absorption and emission peaks. Figure 9 shows the spectral characteristics of Rhodamine R-610 which was selected for this study. The solid trace at the left is the normalized absorption with its peak at 545 nm. The emission dashed trace at the right peaks at 565 nm.

The sensor principle was demonstrated using a simulated platen surface with an array of 0.5 mm (0.020 in.) square teeth on a 1.0 mm (0.040 in.) grid machined into a steel bar. The surface was illuminated by passing white light through a blue sharp-cutoff low-pass filter at 500 nm and the reflected light was passed through a sharp-cutoff high-pass filter at 550 nm. The platen grooves were filled with a quick-setting epoxy containing Rhodamine R-610, available from Kodak. The dye absorbs light in the blue-green region and fluoresces in the orange-red.

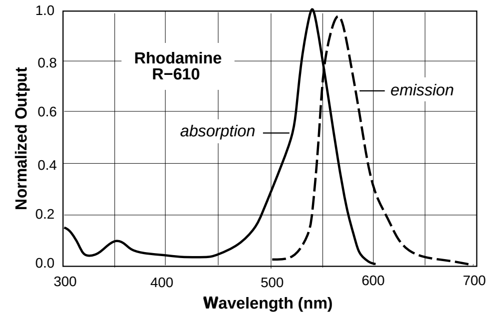

Figure 9: Spectral characteristics of Rhodamine R-610 dye (after Kodak brochure JJ-169).

5 Optical fluorescence results

The optical fluorescence position sensing technique was evaluated by taking a number of photomicrographs. The photographs of Figures 10, 11, and 12 are typical of those taken of a platen surface whose grid was filled with epoxy containing Rhodamine R-610 dye in a solvent.

Figure 10 was taken with white-light illumination where the view contained the combined reflected and fluorescent light. Numerous surface irregularities in both the teeth and the epoxy are evident. These defects would prohibit deriving a reliable position signal.

In Fig. 11, the same surface was illuminated with blue light. The photograph consists of reflected blue light and fluorescent light. As in Fig. 10, surface irregularities are again evident; in particular, numerous scratches in the magnetic teeth are visible.

Figure 12 is a view that was taken through an orange-red filter of the blue-illuminated surface of Fig. 11. The reflected blue has been almost completely removed leaving only the induced fluorescent orange-red. With no reflected light in the scene, the magnetic teeth appear as high-contrast black squares in the presence of the fluorescent background. Contrast is greatly improved over methods based on reflected light. Scratches in the tooth surfaces have vanished.

The design of an optical sensor based on the above principles requires optimizing the quantum efficiency of the dyes, choosing the proper filter characteristics, selecting the appropriate detectors and designing a compact package for use with a planar linear motor forcer.

6 Future work

The illustration in Figure 13 is a conceptual design of a compact sensor unit. In Fig. 13(a), diodes D_a, D_b with selective filters and source L are shown. In Fig. 13(b), two units are shown mounted back to back to provide a pair of quadrature signals per axis. The slotted mask in Fig. 13(c) is positioned on the bottom of the unit next to the platen surface.

Light source L of wavelength λ_1 illuminates the platen through the mask, exciting the dye at wavelength λ_2. Diodes D_a, D_b receive filtered light of wavelength λ_2 and generate a pair of signals corresponding to mask positions 0° and 180°. A quadrature signal is

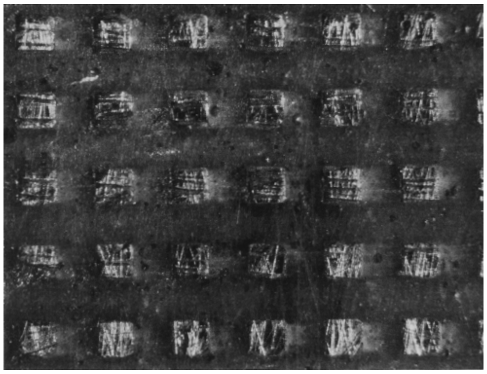

Figure 10: Photomicrograph of the platen surface using white light only.

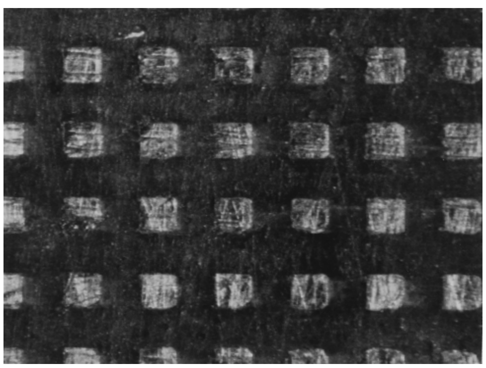

Figure 11: Photomicrograph of the platen surface using blue light.

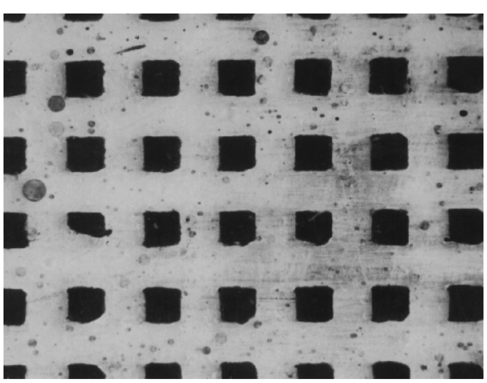

Figure 12: Photomicrograph of the same area as the previous figure seen through a sharp orange-red high-pass optical filter.

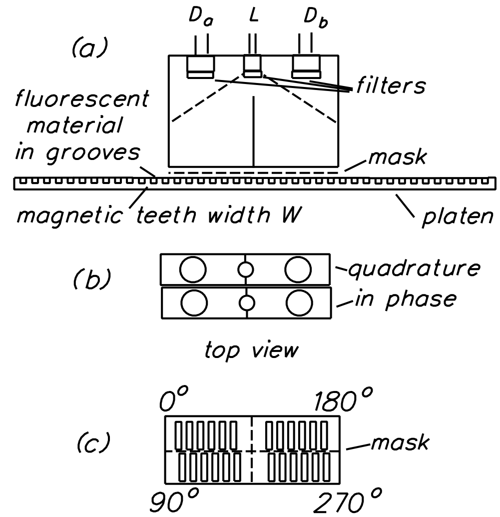

Figure 13: Optical sensor design concept: (a) side view, (b) top view, (c) quadrature mask.

produced from the other sensor for the mask positions of 90° and 270°.

A package for a single-axis unit could be 0.5 cm × 1.0 cm × 1.5 cm and be molded from inexpensive plastics.

7 Conclusions

This paper reports a new magnetic sensor, and a new optical fluorescence position sensing technique. Both of these developments can be applied to position sensing in a planar motor system, to which they are particularly suitable. The magnetic sensor senses the planar motor platen teeth using an ac principle. The optical sensor uses a fluorescent dye in the epoxy backfill of the planar motor platen to eliminate the spatial noise problems of optical reflection sensors.

The magnetic technique has several distinct advantages (+) and disadvantages (–):

- (+) Measurements on the as-built sensor show motion resolutions of 1 μm (1/1000th of platen pitch) or better.
- (+) The sensor depends on sensing flux through *individual teeth* rather than through poles which have many teeth. Because of this, the sensor is about an order of magnitude smaller than previous designs. The small form factor is essential for minimizing the volume and moving mass of an integrated forcer/sensor.
- (+) The small size of the sensor allows operation at high frequencies (100 KHz or more). This is important in the detection electronics since the carrier frequency can be well-separated from both the PWM frequency of the motor drives (several tens of KHz) and the periodic frequencies associated with high-speed motion (several KHz).
- (+) The two sense coils occupy an area approximately 100 times smaller than previous designs.

Thus, modulation from unwanted external fields is relatively uniform over the coils. Since the two coils can be connected in series opposition, common mode pickup will be rejected.

- (+) The essentially planar form of the sensor makes it amenable to manufacture. Single-turn planar drive and sense coils are used which can be easily fabricated in printed-circuit form and assembled with the magnetic portion in a single operation. For very small sensor/platen periods, the coils and the magnetic structures can be fabricated in integrated form, for example by plating through masks. In fact, the sensor design is amenable to batch fabrication of hundreds of sensors per wafer in parallel, with later dicing into individual sensors. These considerations lead to a sensor which could potentially be low in cost.
- (–) There is an approximately 4% unwanted modulation for motion in the orthogonal motion axis. This can be largely corrected through software.
- (–) There is an approximately 6% unwanted magnetic pickup from nearby motor coils. Again, software corrections can be applied.

The optical fluorescence technique has several distinct advantages (+) and disadvantages (–):

- (+) The emitted light is not sensitive to platen surface irregularities as it is in previous reflected light schemes.
- (+) The contrast of the image of the teeth and the grid area is improved as there is no reflected secondary wavelength light from the tooth surfaces.
- (+) The technique is insensitivive to electric and magnetic motor fields.
- (–) A very pure dye and epoxy must be used which is free of voids and inclusions, otherwise there will be a spatial noise component.
- (–) The technique cannot be used with existing commercial platens.
- (–) The sensor is more difficult to miniaturize.

We envision that further refinements of these techniques, combined with modern digital control methods will lead to planar motor systems with much higher and more robust performance. In this form, such systems can be used in a wide variety of important applications including high-speed electrical circuit testing, precision placement of very fine-pitch surface-mount components, and tabletop factories for assembly of precision products, where both fine position and force control is needed.

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