Design and fabrication of miniature combination lock

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Abstract. Design and fabrication of a miniature combination lock is reported. The prototype’s outline size is less than 15mm×20mm×25mm, with the function of 24 steps single-try discrimination. Two miniature application-specific electromagnetic motors are used to drive a counter meshing gears (CMG) mechanism. Ratchet-pawl mechanism is respectively attached to each CMG gears assembly, to insure it step forward at accurate angles in company with motor driving circuit. Main functional components of the lock are fabricated by UV-LIGA micromachining process, including the motor’s stator with 4-level planar coils. Handcraft assembling process and control circuit design are also briefly introduced. The prototype had already endured more than 1000 times of unlocking and 100 times of manually unlocking. It is proved that micro-motor and micromachining technologies are very useful in miniaturization of such a surety device.

1. Introduction

For surety application in high consequence system, we work out a combination lock (also known as “discriminator” or “use-control switch”)[1, 2] with the functions of 24 steps single-try discrimination.

The miniature combination lock prototype composed of three functional parts: driver, discriminator mechanism and energy coupler. The driver consists of two axial-flux electromagnetic micro motors, which adopt stator-rotor-stator sandwich structure. The drive scheme of chopping wave constant current and even division is adopted in order to step accurately at a big stepping angle. The discrimination mechanism is a set of counter-meshing gears (CMG). The energy coupler is a micro mirror in the thoroughfare of laser beam. To achieve the step-forward-only actuation required by two gears assembly of CMG mechanism, ratchet-pawl mechanism is attached to each gears assembly to prevent converse revolution. In order to match the security design of the light thoroughfare, a set of gearing down mechanism is adopted to adjust the accumulated output angle of the principal gears assembly (the one linked with the micro mirror) at ration.

Three structural parts of the prototype are: lock body, control circuit, and laser energy coupler. For the miniaturization of the prototype, most functional components are fabricated by micro machining technologies in which UV-LIGA plays a dominant role. The components include: the pair of stators, coding gears of the CMG mechanism, ratchet, pawl, ratio gears and micro mirror. The other mechanical parts are fabricated with precise machining. The lock body with overall dimension smaller than 15mm×20mm×25mm is assembled by up to 100 components by micro packaging.
2. System Scheme

Fig. 1 Scheme of the miniature combination lock

The miniature combination lock prototype is shown in Fig.1. The discriminator is a CMG mechanism. In order to achieve the bit-by-bit discrimination of the control symbol sequence (binary combined variable A and B), the gears assembly A and B of the CMG is respectively driven by micro electromagnetic motor M1 and M2. In order to fulfill the step-forward-only actuation required by the password discrimination of CMG, the ratchet-pawl is attached to each gears assembly to prevent the converse revolution. To adjust the stepping angle and amplify the output torque of the motor, gears assembly A is linked with a set of gearing down mechanism. As laser energy coupler, a micro mirror is coaxially fixed to the output gear of the gearing down mechanism. When gears assembly A steps forward to the unlocking position, the mirror will be activated then the incident laser can be reflected to the required receiving position, so the once blocked laser beam can pass through the combination lock.

Based on the function principle of CMG mechanism, the functions of 24 steps single-try discrimination can be achieved. For detailed information about CMG mechanism’s structure, discrimination principle and discrimination teeth design, sees references [1–5].

3. Structural design

Structural design of the miniature combination lock is shown in Fig.2. It is consistent with the systematic design shown in Fig.1.

Two ratchet-pawl mechanisms (not shown in Fig.2) are respectively attached to shaft A and shaft B, which prevent the reverse rotation of the two CMG gears assemblies. Another function is to insure CMG gears assembly step forward at accurate angles, in company with motor driving circuit.

Fig. 2. Structural sketch of the lock body
1. Lower stator, 2. Rotor, 3. Upper stator, 4. Bearing, 5. Gears assembly B of the CMG mechanism, 6. Shaft B, 7. Shaft A, 8. Drive gear, 9. Mirror, 10. Follower gear, 11. Gears assembly A of the CMG mechanism

4. Micro Electromagnetic Motor

The micro electromagnetic motor (see Fig.2) is of axial-flux type and adopts stator-rotor-stator sandwich structure. Besides, the drive scheme of chopping wave constant current and even division is applied here to achieve accurate stepping at a big stepping angle.

Each stator fabricated by micro machining has 3 phase windings, and each winding contains 2 Cu coils with 13 loops. The stator winding adopts the planar-unfluted structure and there are 4-level planar Cu coils, interconnected by Cu plugs (see Fig.3). Both photoresist AZ4903 and PVD Al2O3 are used as insulation materials for those planar coils.

The advantages of the stator-rotor-stator sandwich structure are:

1. the two stators double the windings to increase the output torque of the motors;
2. the stators’ magnetostatic action is offset by the rotor’s, resulting in a significant decrease in friction;
3. the rotor is ganged with one of CMG’s gears assembly to be compact in structure, which can eliminate the loss of torque caused by the intermediate mechanism’s friction;
4. the two stators adopt the back-to-back topology, which accomplishes the packaging at the same time.

The stator adopts multilevel Cu coils to get a bigger output torque. However, the magnetic field in the air gap is quite sensitive to the size of the air gap. As a result, the increase in coils’ level will enlarge the air gap, which will handicap the increase of output torque. Zhang[6] calculates the output torque of the motor when the number of level is 2, 4, 6, 8, 10 and leads to the conclusion that the output torque only increases significantly with the increasing of winding levels when the number of winding levels is smaller than 6. The negative effects of increasing the levels of windings are: increasing difficulty in manufacturing, reducing the yield. To achieve a balance between the designed requirement of output torque and the feasibility of manufacturing technology, the stator containing 4 levels of planar coils is finally developed (see Fig.4).
(8µm). By optimizing the design of wiring in a limited two-dimensional area (outside diameter is 6.5mm), the area can be utilized fully for the widest coil and the most loops. On the other hand, micro structure of Cu with certain aspect ratio (~2) can be fabricated by UV-LIGA process.

Plus, high-permeability core of NiFe is embedded into the stator coil. By this, the reluctance can be greatly reduced and then the contradiction between the number of coil levels, the coil width and the air-gap magnetic flux density is solved. As a result, each level of Cu coil can provide the motor with almost equivalent force, which greatly increases the output torque.

Al₂O₃ is sputtered as the coil insulation material, which has a much better heat-resistance property than polymer (photoresist) and will increase the life-span of the motor. However, the manufacturing technology (see Fig.5) is quite complex and to sputter a 30µm thick layer of Al₂O₃ special equipment is needed. Further information about manufacturing technology of the motor’s stator with multi-level planar coils can be found in reference [7, 8].

The 6.5mm rotor is combined with 8 fan-shaped magnetic poles in an N, S alternative way (see Fig.6).

The outer material of the stator’s upper and lower surface is an alloy of Sm and Co (25.5 wt % of Sm, 52.5 wt % of Co, 15 wt % of Fe, and 3 wt % of Zr). The stator is precisely fabricated by wire cutting and then magnetized. When being assembled, the two poles are aligned. The sandwich material is stalloy.

5. Components Fabricated By UV-LIGA
UV-LIGA, which is based on ultraviolet thick photoresist, is adopted to fabricate the following miniature mechanical parts: the pair of stators, coding gears of the CMG mechanism, ratchet, pawl, ratio gears and micro mirror (see Fig.7).

6. Control Circuit

Main circuit modules of the lock are shown in Fig.8. Voltage supply is 12.0±1.2V DC. The unlocking instruction is input by the keyboard. After a series of transmissions, motor A and motor B will be driven to step forward according to the controlling signal. At the same time, the LCD displays the controlling process and the running result. In order to judge whether the password discrimination is successful, the photosensitive circuit detects whether the micro mirror is at active state. The input 12V current is transformed into constant voltage by a current-to-voltage power-supply circuit. The constant voltage is separately provided for the AVR µC (5V) and motor driver. The reset circuit achieves the manually reset and protects the AVR chip by the auto reset when the unstable voltage exceeds the threshold. The online programmable circuit improves the efficiency of integrated software & hardware debugging. Stepping control of the motor can be found in reference [9].

![Fig.8 Block diagram of the prototype’s control circuit](image)

7. Prototype Assembling

Fig.9 shows the finally assembled lock. The prototype has been normally unlocked for 1000 and still works well.

![Fig.9 Photograph of the finally assembled lock body](image)

The main prototype assembling steps are:
- Pre-cementation of CMG gears assembly;
- Assemble of axletree, cementation of gears assembly;
- Assemble stators and rotor (including pre-assembling of rotor, pre-assembling of stators, assembling of lower stator, assembling of rotor, assembling of upper stator);
Electro-mechanics uniting and adjusting of the motor;
Assembling of ratchet, pawls and spring pieces;
Adjust ratchet-pawl;
Assemble gears assembly;
Assemble gearing down mechanism;
Assemble micro mirror.

8. Conclusions

(1) Successful R&D of the prototype demonstrates the rationality of the system scheme; and this proves the usefulness of micro motor and micro machining in the field of miniaturization of combination lock.

(2) The prototype’s overall dimension is smaller than 15mm×20mm×25mm; it can: discriminate the password step by step, unlock by 24 steps, allow single try of unlocking, and manually unlock when the password is forgotten. Moreover, the total time of 24-step unlocking is less than 5s and the prototype can demonstrate the energy coupling of laser.

(3) In terms of durability, it is proven during experiments that the prototype can withstand more than 1000 times of unlocking and 100 times of manually unlocking.

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