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Synthesis of a Micro Motor Actuated by Remote Resonant Magnetic Fields

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***Abstract*—It is believed that micro actuators and robots might introduce revolutionary changes in many advanced applications, such as nano manipulation and minimally invasive medicine. Many prototypes were recently developed, which could be powered either by micro organism, by onboard mechatronic systems or by remote magnetic fields. This paper presents two evolving designs, aiming at producing a micro motor which can be selectively remotely actuated by weak resonant magnetic fields. The core design concept is to design a spring-mass structure to transform the vibrations of a soft magnet into rotary outputs. The generated rotation can then be used to form revolute joints or to drive propellers. The proposed designs convert magnetic energy directly into mechanical work, avoiding complex components from tradition motor units such as windings, batteries, etc.**

I. Introduction

Micro robots could find many potential applications in minimally invasive medicine, such as performing diagnosis and treatments in intracranial cavities and vascular systems [1, 2]. In order to realize these visionary functions, micro robots should be able to swim through low-Reynolds-number regions [2, 3] and perform manipulation tasks. Both locomotion (such as intravascular swimming or crawling) and manipulation of a micro robot require properly integrated actuation. Locomotion actuation schemes of many existing micro robots fall into one of the following categories:

- Engineered micro organisms (such as bacteria) were used to provide propelling actuation, as in [4-7]. Ensuring controllability and biological safety of such robots is still quite challenging.
- It is also possible to design a standalone micro robot with an onboard power and a controller, such as the designs in [1, 8-10]. Fabrication complexity and difficulty might be a real obstacle when such a micro is further downsized.
- Strong magnetic fields could also be used to drive micro robots. The micro robots made from magnetic materials could be dragged by a static magnetic gradient (e.g. the designs in [11-13]). Or a rotating or an oscillating magnetic field can be used to spin or swing a micro robot so that its helical or flexible tail can generate thrusts for swimming (e.g. the designs in [14, 15] [16-18]). However, individual control of a swarm of robots can be quite difficult.
- A few promising solutions were presented in [19-21], where an oscillating magnetic field was used to trigger a resonant vibration between a micro robot's mass blocks made from soft magnetic materials and the collision was modulated to provide thrusts. Different resonant frequencies can be used to control different robots. However, the operational requirement of a frictional surface puts practical limitations for its future applications.

Inspired by the results from the aforementioned work as in [19-21], this paper presents two evolving designs as shown in Fig. 1, aiming at producing a micro motor which can be selectively remotely actuated by weak resonant magnetic fields. With such micro motors fabricated and equipped, micro robots might then be able to actively navigate around (swim or crawl) and perform manipulation tasks.

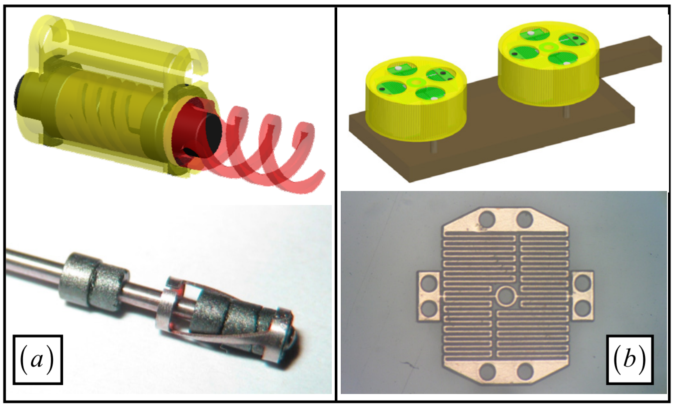

Figure 1. Two evolving designs with their fabrication attempts: (a) the alpha design with a helical spring, and (b) the beta design with a planar spring

The main contribution of this paper is the proposal of fabricating micro motors which essentially directly harvest magnetic energy in space to perform mechanical work. These motors consist of mass-spring structures using properly arranged soft magnetic and nonmagnetic materials. Success of the proposed idea could lead to the development of micro motors which could be remotely controlled by oscillating magnetic fields with different frequencies. And such micro motors would find wide applications in both minimally invasive medicine and other fields.

The paper is organized as follows. Section II presents the working principle of the design concepts. Section III presents the coil design for the generation of oscillating magnetic fields. Section IV and Section V present the alpha design and the beta design, including design simulations and fabrication attempts. Conclusion and future work are summarized in Section VI.

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II. WORKING PRINCIPLE OF THE DESIGN CONCEPTS

Working principle of the design concepts is shown in Fig. 2. Components with non-negligible masses made from soft magnetic materials are connected by a non-magnetic spring. When an external magnetic field is applied, the mass blocks made from soft magnetic materials are magnetized. An attraction force is hence generated between the blocks to compress the non-magnetic spring which connects the blocks. When the external magnetic field is removed, magnetization of the blocks disappears and so does the attraction force. The compressed spring generates a repulsion force to push the blocks apart.

When the external magnetic field is switched on and off at a frequency that matches the resonant frequency of the mass-spring system, mechanical energy (kinetic energy of the blocks and elastic potential energy of the spring) will accumulate within the system. When the accumulated energy exceeds a threshold, a designed structural feature will allow the output of the energy via a collision or modulated friction.

Following this working principle, two conceptual designs are presented in later sections, aiming at producing a micro motor which can be selectively remotely actuated by magnetic fields. The designs essentially directly harvest magnetic energy to perform mechanical work. With such micro motors fabricated and equipped, micro robots might then be capable of swimming or crawling around and performing manipulation tasks.

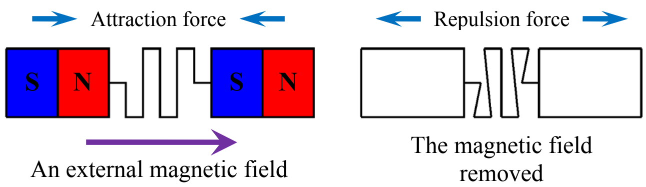

Figure 2. Working principle of the design concepts

III. COIL DESIGN FOR THE MAGNETIC FIELD

According to the working principle of the proposed designs, a fast switching magnetic field will be needed to actuate the micro motors. Then a coil system for such a magnetic field and its actuation circuits will be designed and implemented. Since the magnetic field will be primarily used to test the micro motors that generate rotary outputs without moving around, the uniformity of the magnetic field is not that concerned. This work hence chose to apply a pair of Helmholtz coils.

According to [20], a magnetic field with the magnetic flux density as weak as 2mT is capable of driving the micro robots with planar movements. 2mT is hence selected as the design goal of this work. Since the magnetic flux density matters the strength of the magnetization and hence affects how fast the harvested energy accumulates within the motor system, a slightly weaker or stronger magnetic field should be always capable of driving the motors, as far as the principle works.

As shown in Fig. 3, a Maxon motor amplifier (LSC 30/2) working in its current mode was used to drive the pair of Helmholtz coils. Since the current output of the amplifier is limited to ±2A, the coils are assumed to have a 1.5A current while finalizing the coil parameters following the approach as in [22]. Each coil in the Helmholtz pair has a diameter of 30mm and 45 turns (distributed in 6 layers as 8-7-8-7-8-7 turns per layer). Distance between the center planes of the coils is also kept 30mm, as shown in Fig. 3-(b).

Referring to Fig. 3-(a), square-wave signals at specific frequencies from the signal generator are connected to the V_{set+} and V_{set-} ports of the Maxon amplifier. Motor+ and Motor- ports of the Maxon amplifier are connected to the Helmholtz coils and a resistor serially. Voltage on the resistor is monitored by an oscilloscope to indicate the current flowing through the coils. P_{gain} and N_{max} knobs of the amplifier (serving as the coefficients of the inherent PD controller) can be adjusted for the current to better follow the desired signal. Using this setup, an on/off current of 1.5A can be driven to follow a square-wave signal with a frequency up to 3.3 KHz, as shown in Fig. 4.

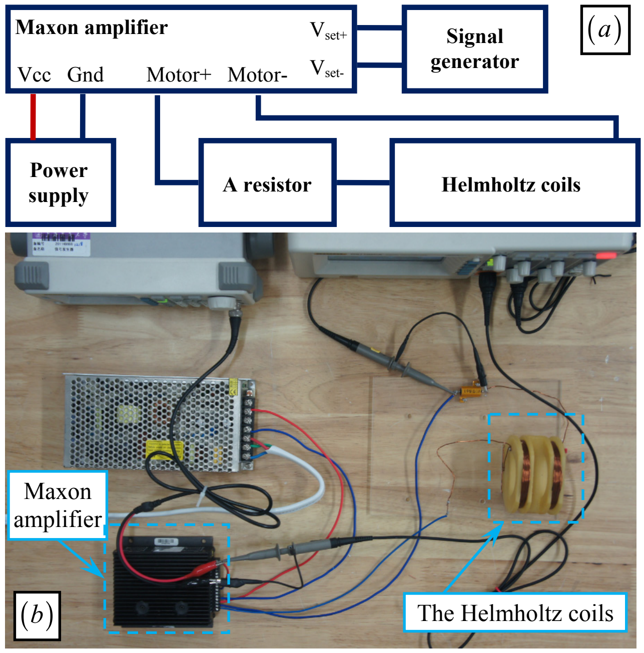

Figure 3. The Helmholtz coil design with the actuation circuit: (a) the schematic, and (b) the actual system

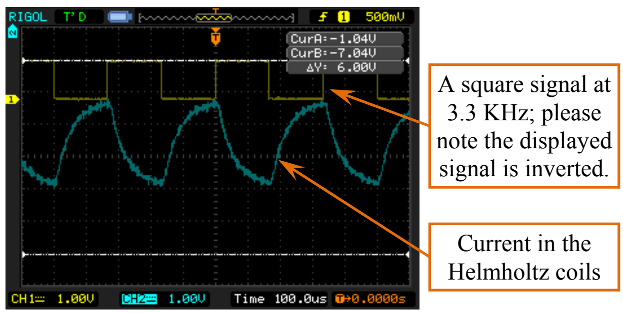

Figure 4. Wave form of the on/off current in the Helmgoltz coils following a 3.3KHz square-wave signal

IV. The Alpha Design with a Helical Spring

A. The Alpha Design Concept

Following the aforementioned working principle, the alpha design was conceived as shown in Fig. 5, whereas the total assembly with the casing is shown in the inset (a).

The stator and the vibrator are made from soft magnetic materials (e.g. produced by powder metallurgy using nickel zinc powders). And the stator and the vibrator are connected by a non-magnetic helical spring (e.g. brass). When the external magnetic field is switched on and off at a frequency that matches the resonant frequency of the stator-spring-vibrator system, the vibrator is expected to vibrate in a helical manner: the vibrator translates along the axis of the stator as well as rotates about this axis. When the amplitude of the vibration becomes big enough, the vibrator will collide with the output ring. Since the motion of the output ring is constrained by the casing in the axial direction, the output ring is expected to generate a rotary output. Then the output could be connected to a tail to generate swimming thrusts.

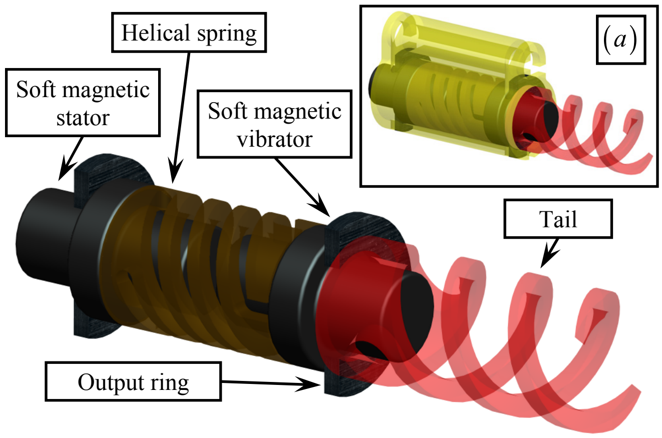

Figure 5. The alpha design with a helical spring

B. Design Drawbacks and Challenged Fabrication Attempts

The design was found to have an intrinsic drawback that the output is only unidirectional. Determined by the right-handed or the left-handed helical spring, the output can only be counterclockwise or clockwise.

Additional design/fabrication dilemma was also spotted after the simulations for the design concept verification were carried out. The insets (a) and (b) of Fig. 6 show two possible designs of the helical spring which connects the stator and the vibrator. Both spring designs deform in the desired helical pattern: the spring can be axially compressed with a desired parasite twist. However, when the dimensions of a brass tube (OD[1] 3.20mm & ID 2.80mm) are big enough so that the design from Fig. 6-(a) can be fabricated using wire EDM as in Fig. 7-(a), the spring is so stiff that the resonant frequency is more than 820 KHz, which is way above the capability of the coil driving circuit (3.3 KHz).

In order to reduce the resonant frequency, a spring should be fabricated using a finer tube with a thinner wall thickness. As shown in Fig. 7-(b) and Fig. 7-(c), a brass tube with an OD 0.7mm and an ID 0.6mm was eventually machined in Japan. The helical structure in Fig. 7-(b) has a width of 0.12mm and a lead of 0.4mm, whereas the helical structure in Fig. 7-(c) has a width of 0.06mm and a lead of 0.2mm. However, no suppliers were identified to fabricate the stator and the vibrator using powder metallurgy at such a small size with a fitting tolerance. Fabrication attempts for the alpha design were not successful.

Since the alpha design has a spatial helical structure, MEMS fabrication techniques could not help. This also completely eliminates the possibility for further miniaturization of this design. No matter whether the design concept works or not, the design is useless if further miniaturization is not possible. Plus the design drawback of a unidirectional output, the alpha design was abandoned.

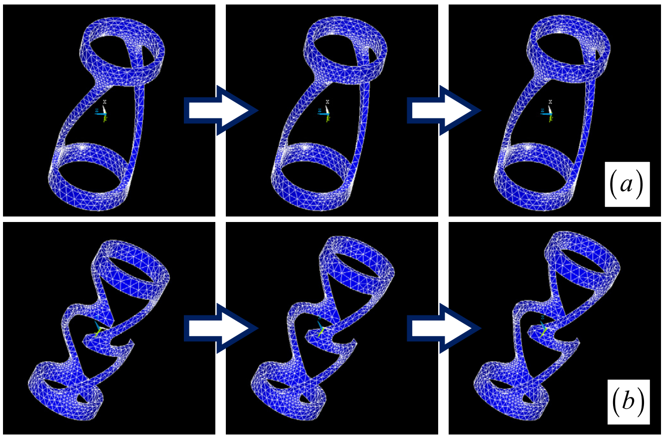

Figure 6. Simulations for the design concept verification: desired deformation patterns of the spring which connects the stator and the vibrator

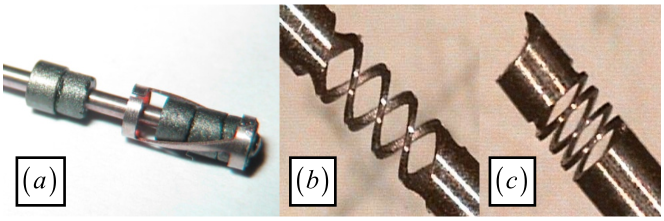

Figure 7. Manufacturing attempts of the alpha design

V. The Beta Design with a Planar Spring

A. The Beta Design Concept

Following the same working principle as explained in Section II, the beta design shown in Fig. 8 was conceived to take the advantages of MEMS fabrication techniques.

The beta design consists of a base, an output rotor, two vibrators and two asymmetric planar springs. The vibrators are made from soft magnetic materials (electrically deposited nickel) and the springs are made from non-magnetic materials (electrically deposited copper). The nickel vibrators are sandwiched by the two copper springs.

When the spring-vibrator system is placed in an oscillating magnetic field (a fast switching on/off magnetic field), different resonant frequencies of the spring-vibrator system will lead to different vibration patterns. Making use of these

[1] OD stands for outer diameter and ID stands for inner diameter

different vibration patterns, the beta design is expected to generate clockwise and counterclockwise rotary outputs when the magnetic field is switched on and off at different resonant frequencies.

Finite element simulations were carried out in the next sub-section to verify this design concept.

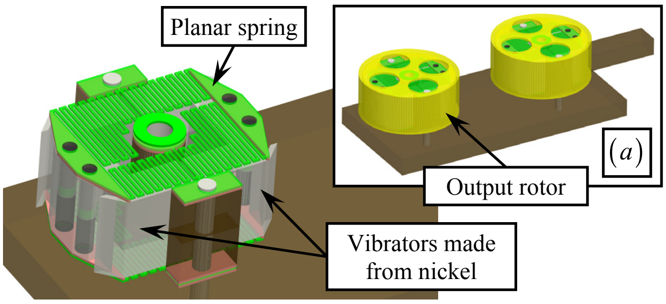

Figure 8. The beta design with a planar spring; inset (a) shows the two fully assembled micro motors

B. Design Simulations

Back view of this beta design is shown in Fig. 9-(a) for better indication of the geometrical dimensions of this design.

- The output rotor has an outer diameter of 1mm (1000um).
- The Ni (nickel) vibrator blocks have a width of 600 um. The gap between the two Ni blocks is 20um. An attraction force of about 1.2×10^{-6}N will be generated when the Ni blocks are magnetized in a magnetic field of 2mT.
- Pointed corners are designed for the Ni vibrators so that kinetic energy can be better transferred to the output rotor through collisions when the vibration amplitude of the vibrators becomes big enough under resonant frequencies.
- Width and layer thickness of the Cu spring are both 10um. There are two holes with a diameter of 70um for relative positioning of the Cu spring and the Ni block.

Vibration patterns of the spring-vibrator system under different resonant frequency were simulated in COMSOL.

As shown in Fig.9-(b), when the magnetic field is switched on and off at a resonant frequency of 561.8Hz, the nickel vibrator is oscillating in a rotary pattern with the center of motion located at the left side (indicated by the dark blue dot). When the vibration amplitude becomes bigger under this resonant excitation, the pointed corner at the right side (this side is with the wider spring pattern) will hit the inner wall of the output rotor first. A continuous counterclockwise rotation is then expected from such repeated collisions.

Similarly, at a higher resonant frequency of 1441.9Hz as shown in Fig. 9-(c), the nickel vibrator is oscillating with the center of motion located at the right side. At this higher frequency, the side with a narrower spring pattern (the stiffer side) has a bigger vibration amplitude and the pointed corner at this side is expected to hit the inner wall of the output rotor first. Such repeated collisions are then expected to generate continuous clockwise rotation outputs.

The gap between the pointed corner of the nickel vibrator and the inner wall of the output rotor is kept 6 to 10 um. At non-resonant frequencies of the spring-vibrator system, amplitudes of the vibrators will not be big enough to hit the inner wall of the output rotor. Hence no rotation outputs are expected when the external magnetic field is switched on and off at non-resonant frequencies.

Holes and cavities can be included in the nickel vibrators to change its mass distribution. This will lead to changes in the resonant frequencies as well. Then the micro motors working under different excitation frequencies can be designed.

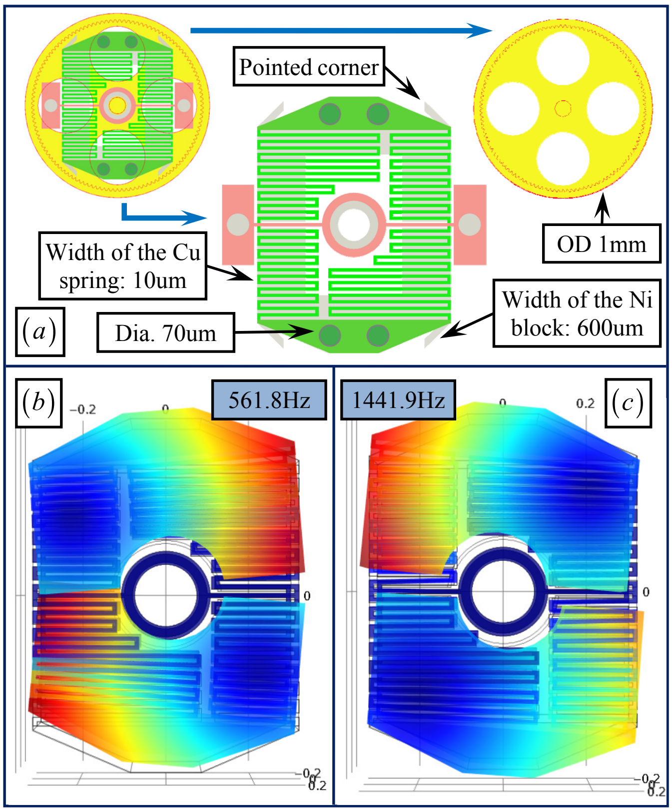

Figure 9. Resonant vibrations of the beta design: (a) geometrical dimensions, (b) the vibration pattern in an oscillating magnetic field at 561.8Hz, and (c) the vibration pattern in an oscillating magnetic field at 1441.9Hz

C. Fabrication and Assembling Attempts

As shown in Fig.8 and Fig. 9-(a), it will be a challenging and costly process to fabricate the beta design as one piece in consecutive steps. In order to lower the fabrication costs and increase the success rates of the MEMS fabrications, it was decided to fabricate the components of the beta design separately and later assemble the components.

Some fabrication results are shown in Fig. 10.

- The output rotor, the rectangular spacer blocks and connecting poles as in the insets (a) to (c) were fabricated via lithography using photoresist SU-8 (UV LIGA). The output rotor has been produced at several versions with various inner diameters.
- The nickel vibrator shown in the inset (d) was produced by lithography followed by electrical deposit of nickel. The thickness is 360um.
- The copper spring and copper spacer as in the insets (e) and (f) were produced by lithography followed by electrical deposit of copper. The thickness is 10um.

Tolerances of these fabricated components are all within ±5um. After picking components with fitting tolerances, it is possible to assemble these components to form the beta design using a micro positioning device.

The proposed assembling process is shown in Fig. 11: a) the connecting poles will be firstly inserted into the holes in the base; b) the removable spacers (the blue ones) and the structural spacers (the pink ones) will then be placed; c) the copper spring can now sit on top of the spacers; d) then another layer of the structural spacers (the pink ones) and the connecting poles will be placed; glue droplets will be applied and cued to bond the spring to the poles; e) the rectangular block spacers (the brown ones) and the removable spacers (the blue ones) will be placed; f) the nickel vibrator blocks will be placed on the connecting poles with another layer of the structural spacers (the pink ones); glue droplets will be applied again in the holes for the connecting poles; g) the top spring can now be placed; h) after the glue is set, the removable spacers (the blue ones) will be pulled out; and i) the output rotors will be assembled as the last step.

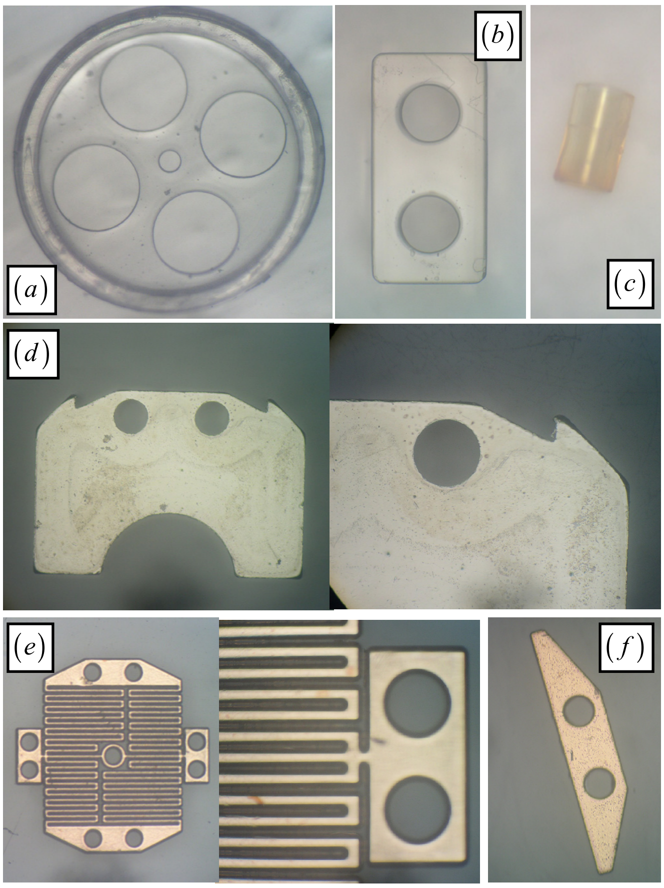

Figure 10. Partial fabrication results of the beta design

Positioning of these components can be realized using a motion control device from the Thorlab Inc. (e.g. the XY-R multi-axis platform XYR1/M with a manual stage for the Z axis translation mounted). Then a slim metal beam with a flat tip will be attached to the positioning device with a generator for static electrical charges connected. Static charges in the metal beam will pick up these tiny components for the assembling tasks.

Then the assembled micro motors will be placed inside the coils from Section III for experimental validations and tests.

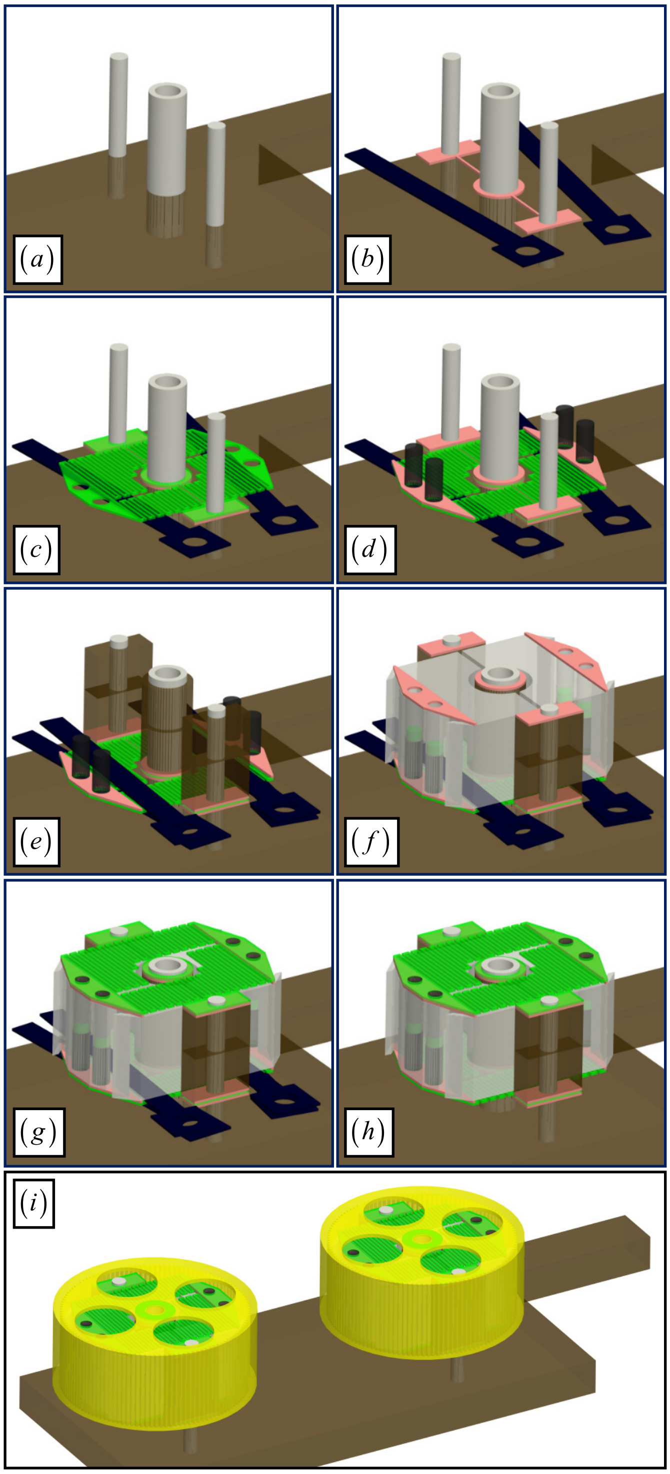

Figure 11. Proposed assembling process of the beta design

VI. Conclusion and Future Work

The paper presents two evolving designs, aiming at producing a micro motor which can be selectively remotely actuated by weak resonant magnetic fields. If the proposed idea succeeds, these micro motors can essentially directly harvest magnetic energy from space to perform mechanical work and they will find wide applications from MEMS manipulation to minimally invasive medicine.

The alpha design has a spatial helical spring structure. After careful considerations of its design characteristics and fabrication challenges, the design was abandoned due to the intrinsic design drawbacks and difficult fabrication processes.

The beta design has a planar spring structure. It is feasible to fabricate such a design using MEMS fabrication techniques. However, in order to prove the design concept in a cost-efficient way, it was decided to fabricate individual components separately and try to assemble them.

Several components have been fabricated and the immediate future work is to assemble the beta design when fabrications are completed. Then a series of experimental verifications and design characterizations could be carried out, investigating the i) feasibility, ii) speed of the rotation output versus strength of the magnetic field, iii) payload capability, iv) dynamic responses, v) further miniaturization possibility, etc.

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