Wheels for a MEMS MicroVehicle

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ABSTRACT – Inch-worm motors achieve high linear displacements with high forces while dissipating low power. Design of a wheel to achieve angular displacement from inch-worm motors is described. Test structures are then suggested to measure unknown parameters and determine how best to build wheels for a microvehicle. Conclusions and future work are then discussed.

INDEX TERMS– MEMS, MicroVehicle, MicroRobotics, Wheels, Inch-Worm Motors, DRIE process.

I. INTRODUCTION

The goal of this project is to make a microvehicle. It will utilize the inchworm motor developed by BSAC. However, instead of having a linear gear motion transfer mechanism, it will use a circular gear to generate rotary motion. This circular gear is proposed to be used as the wheel of the microvehicle. The speed and direction of the microvehicle will be controlled by inchworm motor. Change of direction will be possible by having one directional spin on one side and having opposite spin on the other. For power and control, it will use the technologies that were developed by the microrobotics project. Section II of this paper will briefly discuss motivation and applications, design and analysis will be described in section III followed by a description of the test structures that will be fabricated in section V. Section VI will detail the results expected from the structures. The paper will conclude with conclusion and a discussion of future work.

II. MOTIVATION AND APPLICATIONS

The design of a MEMS scale wheel will allow a micro vehicle to be built. Potential applications for micro vehicles include environmental monitoring and data gathering, military surveillance, and small task completion. Micro vehicles could be equipped with sensors or surveillance equipment and could drive themselves into position to gather data. Micro vehicles could also be programmed to move to desired location and perform microscopic tasks. This could be useful in assembly of other MEMS devices, microsurgery, or micro scale repair.

III. DESIGN AND ANALYSIS

The inch-worm motor designed by R. Yeh et. al. [1] achieves linear displacement of the shuttle. This motor had 80μms of displacement with hundreds of μNs of force, but was limited by the physical constraints on the shuttle, not an intrinsic limit in the motor. Using a circular gear, unlimited angular displacement is achievable. The inch-worm motor uses gap closing actuators to generate large forces and displacements with low power. The motor designed in [1] can lift over 130 times its own weight.

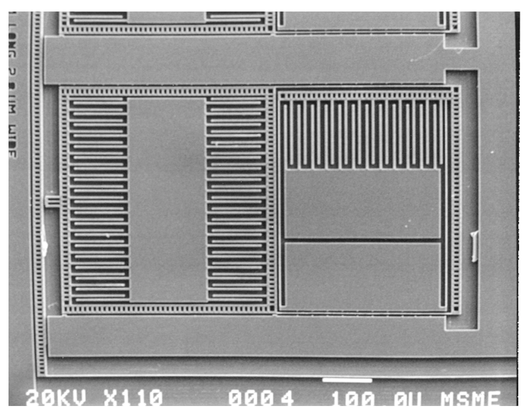

Figure 1: Inch worm motor designed by R. Yeh et.al. gives high force and displacement with low power. [1]

The Design of a micro vehicle can be broken down into four parts: wheel development, power and weight, traction, and fabrication.

III-a Wheel Development

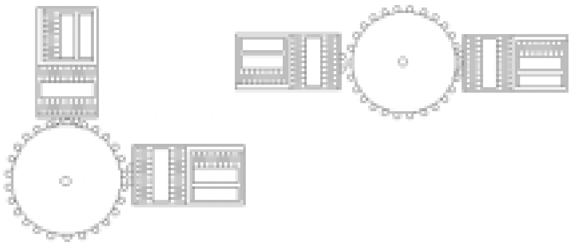

Figure 2: Two alternative placements of inch-worm motor.

The micro wheel will be actuated by two inch-worm motors. Design choices determine the locations of these motors. Two alternatives were considered, parallel or perpendicular motors, as shown in Figure 2. With perpendicular positioning as shown in the left of Figure 2, one motor has to carry the weight of the vehicle. This interferes with the engagement of the motor with the gear. When the two inch-worm motors are parallel (right of Figure 2), the weight is supported by the center pin, and the inch-worm motors contribute only to the rotation.

A four wheel design for the micro vehicle was chosen over a two or three wheel alternative for balance and assembly. A three-wheel vehicle offers good steering and balance but would be difficult to assemble due to alignment issues [6]. A three wheel assembly requires two wheels on one axis, and a third wheel forward from the other two, and positioned in a plane between the two rear wheels. This positioning would more difficult than a four wheel design, with two folded planes, as shown in Figure 3.

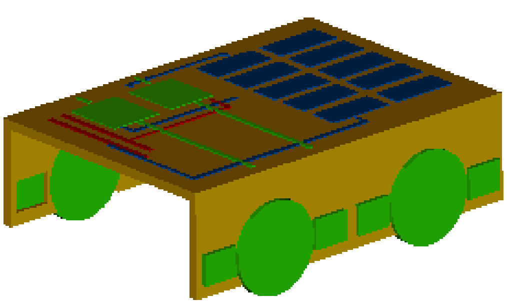

Figure 3: Four-wheel design of the micro vehicle allows for stability and easy assembly.

III-b Power and Weight

A basic micro vehicle will need to carry a power supply and a controller with its wheels. One suitable power supply would be an array of solar cells, the controller will be a small CMOS chip. Solar cells provide approximately 100uW/mm^2 in full sunlight, more than 100nW/mm^2 in average room lighting [4]. The CMOS controller and the actuators will dominate the power consumption. The CMOS controller will be a low performance very low power chip, and will contribute much less to the power consumption of the vehicle than the inch-worm motors used to drive the wheels.

To determine the power consumption, we need an estimate of the weight of the vehicle. Based on initial power consumption estimates, approximately 1 cm^2 of solar cells will be required to allow operation indoors [2]. The sides with the wheels will be 6mm long (2 wheels) and 2mm high. When the micro vehicle sits on the ground, the weight of the wheels is partially supported, and the solar cells and controller are suspended. The CMOS controller will be assumed to fit in 1 mm^2 of Silicon. This is enough space to fit a low performance microprocessor, so it should be sufficient for the necessary controller functions if they are implemented on such a processor, or as a custom processing block.

The vehicle will be fabricated using Seth Hollar's *Iolanthe Process - Glass Planarization with 2 Structural Poly Layers* [10]. This process uses an SOI wafer and a backside etch to reduce the bulk thickness and lower weight, leaving a Silicon thickness of 150µm (see Figure 4). We assume we can do a lightening backside etch to the solar cells as well.

$$\text{Mass} = \text{Area} \cdot \text{Thickness} \cdot \text{Density}$$

$$\text{Mass} = \left(A_{\text{solar cell}} + A_{\text{wheels}} + A_{\text{controller}}\right) \cdot \text{Thickness} \cdot \text{Density}$$

$$\text{Mass} = \left(1\,\text{cm}^2 + 24\text{mm}^2 + 1\text{mm}^2\right) \cdot 150\,\mu\text{m} \cdot 2330\,\text{kg/m}^3$$

$$\text{Mass} = \left(10.2 \cdot 10^{-2}\,\text{m}^2\right) \cdot 150\left(10^{-6}\,\text{m}\right) \cdot 2330\,\text{kg/m}^3$$

$$\text{Mass} = 3.56\,\text{grams}$$

$$\text{Weight} = \text{Mass} \cdot \text{Gravity} = 3.56 \cdot 10^{-3}\,\text{kg} \cdot 9.8\text{m/s}$$

$$\text{Weight} = 0.35\,\text{mN}$$

We must also consider the adhesion forces of the test structures which may be up to 100μN [3]. To ensure we can overcome this a safety factor of 10 is used, so 1mN of additional force is required. This gives a total force of 1.4mN.

We can estimate the power required to drive the inch-worm motors. The power dissipated by a gap closing actuator is:

$$P = C \cdot V^2 \cdot f$$

C is the total capacitance, V the voltage, and f the frequency of operation. To produce 1.4mN of force with a 30V supply and 3μm initial gap, a capacitance of 10pF is required [2]. The power consumed in one inch-worm motor will be 27μW. Each wheel uses two motors, so four wheels will need eight motors, consuming 216 μW. The CMOS controller can be estimated to dissipate only 17μW [4] for typical microrobotic applications. Power will also be dissipated in unwanted places by the parasitics present in the design. If we estimate this to be a 25% overhead, we reach a total power of 292μW. This can be provided by 1cm^2 of solar cells in an indoor environment.

III-c Traction

Traction of the wheel is a function of frictional forces, the contact area of the center pin. These can be estimated to give an approximate frictional force of 0.4mN. Frictional coefficients for bulk silicon have been measured between 0.1 and 0.7 [11], a starting worst case of 0.7 is used in the estimate. A normal force is found by taking the weight (1.4mN found above) divided by four (four wheels). The normal force is 0.6mN on each wheel.

$$\text{Friction Force} = \mu \cdot \text{N}$$

$$\text{Friction Force} = (0.7) \cdot (0.6\text{mN})$$

$$\text{Friction Force} = 400\mu\text{N}$$

This frictional force must be overcome by the inch-worm motors to move the micro vehicle. The traction and frictional forces will be measured by the test structures.

III-d Fabrication and Processing

The wheel was designed in Seth Hollar's Iolanthe, deep reactive ion etch (DRIE) plus planarization and two poly process [10]. This process uses an SOI wafer, that allows for a bulk silicon structural layer, two poly layers, and a backside etch. Typical process cross sections showing the structural layers and etch are shown in Figure 4. The wheel gear and the gap closing actuators of the inch-worm motors are fabricated in the high-aspect ratio silicon layer.

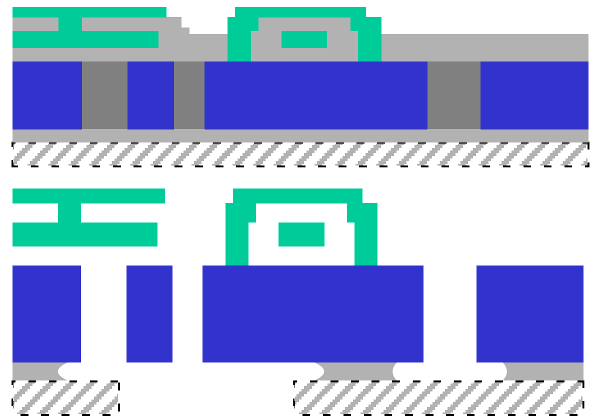

Figure 4: The backside etch in Seth Hollar's Iolanthe process cuts away the substrate and reduces weight.

The center pin holding the wheel, but allowing it to turn, is in poly 1. The first case wheel diameter was 1500μm in order to ensure a clearance of 300μm from the ground after the backside etch.

Poly 2 is used for a larger wheel around the gear that will contact the ground. The thickness of poly 2 is only 2μm, smaller than the 40μm silicon gear. This thickness may have difficulty supporting the vehicle weight, so the wheel will be tested with and without this extra surface contact layer (poly 2) to determine it's effectiveness.

IV. Test Structures

Test structures for the micro wheel will be needed to measure the traction, weight bearing and ability of the wheels to contact various surfaces. Our test

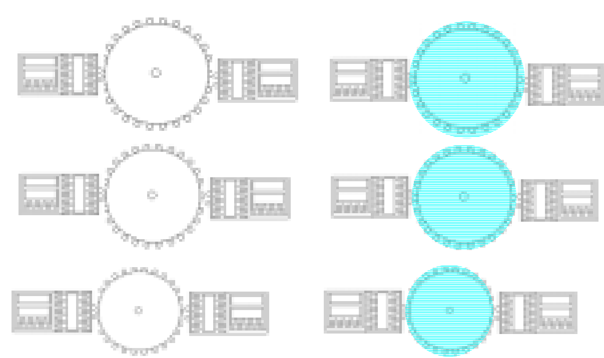

Figure 5: Test structures for the micro wheels. Shown here are variations in size and wheel contact surface. Eight wheels for each size will be fabricated.

plan consists of fabricating an array of wheels, and then measuring each wheel against three surfaces with varying roughness. Each wheel will be tested horizontally, then vertically to determine if it can support it's own weight, and then with three different loads. The Figure 5 shows the wheel variations that will be fabricated.

Inch-worm motors have been studied with various teeth shapes and spacing. Using the inch-worm design by R. Yeh [1] test structures for the wheel attempt the measure the variation of other parameters.

As described in III-d the wheel diameter was initially set to ensure clearance over the edge of the substrate after the backside etch. This diameter of 1500µm will be varied from 1300µm to 2000µm to test its impact on wheel forces and traction. Eight diameters in this range will be tested.

Another test parameter is the wheel surface that will contact the ground. The gear teeth may not be the best surface to contact the ground, so a version of the wheel with a larger poly2 wheel will be tested.

V. Expected Results

Traction, weight bearing, strength, and force of micro wheels are not well characterized. The test structures described will be measured to determine these parameters for each wheel variation fabricated. From this, optimal sizes and surfaces will be determined.

The ability of the wheel to bear weight will enable the determination maximum size vehicle that the wheels can support, and transport. With a good understanding of the power and limitations of the wheels, a micro vehicle can be designed and constructed.

VI. Conclusion and Future Work

Micro vehicles are possible by using the force and displacement of an inch-worm motor. Inch-worm motors have been developed to give large linear displacements. Much larger angular displacements are possible by using a gear structure and inch-worm motors to drive a wheel.

The size of vehicle is determined by the size of the inch-worm motor required to give the necessary force, and the size of the solar cells to power it. The vehicle should scale down as solar cells and inch-worm motor are scaled to smaller sizes.

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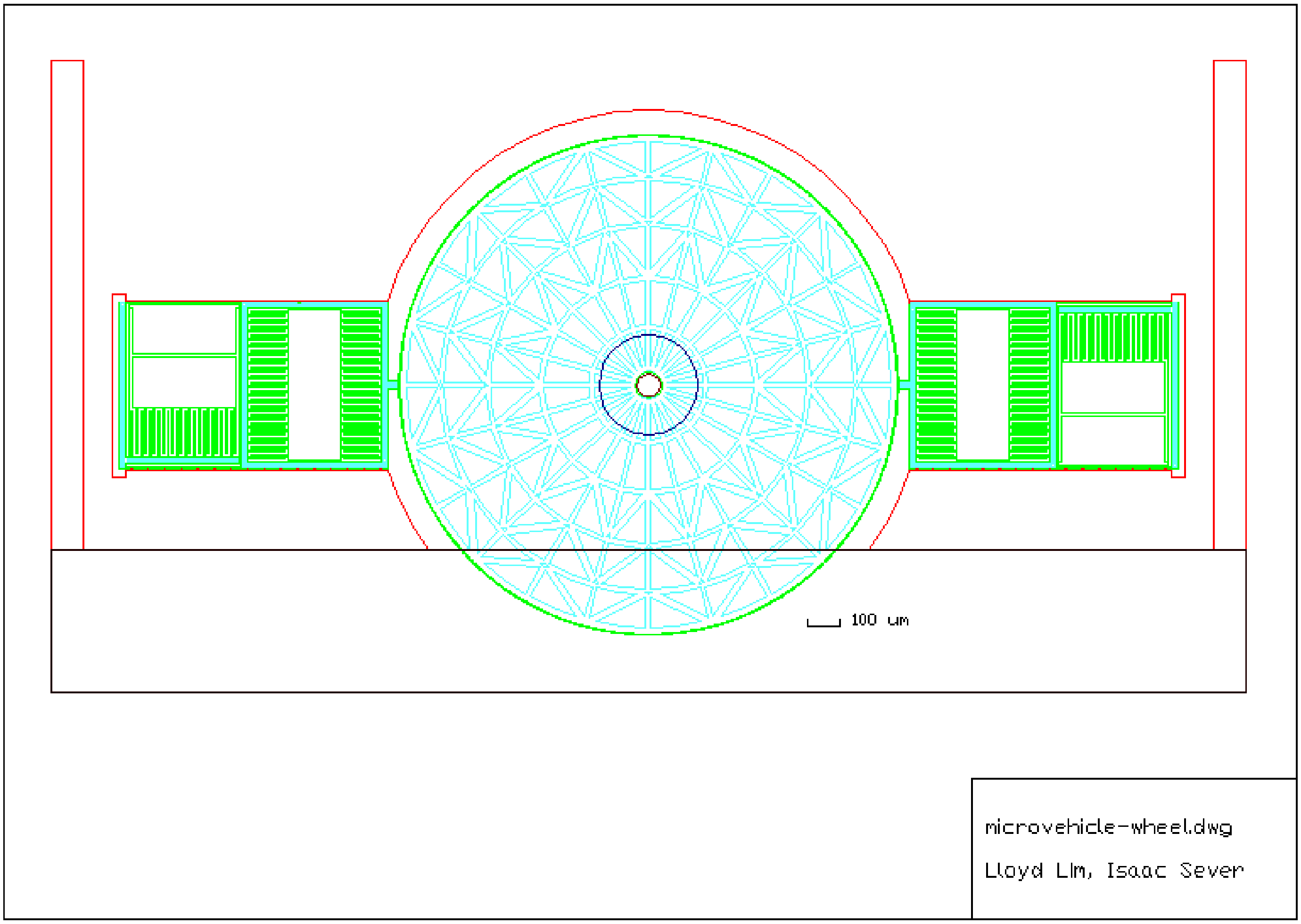
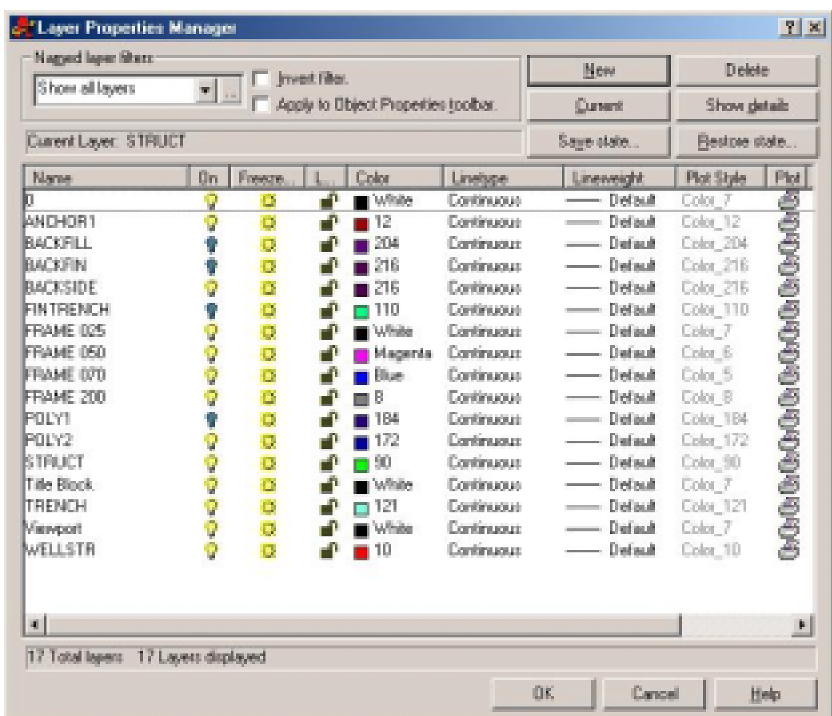
Wheel Layout

Micro Vehicle Wheel Layout





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FINTRENCH				110	Continuous	Default	Color_110	
FRAME 025				White	Continuous	Default	Color_7	
FRAME 050				Magenta	Continuous	Default	Color_6	
FRAME 070				Blue	Continuous	Default	Color_5	
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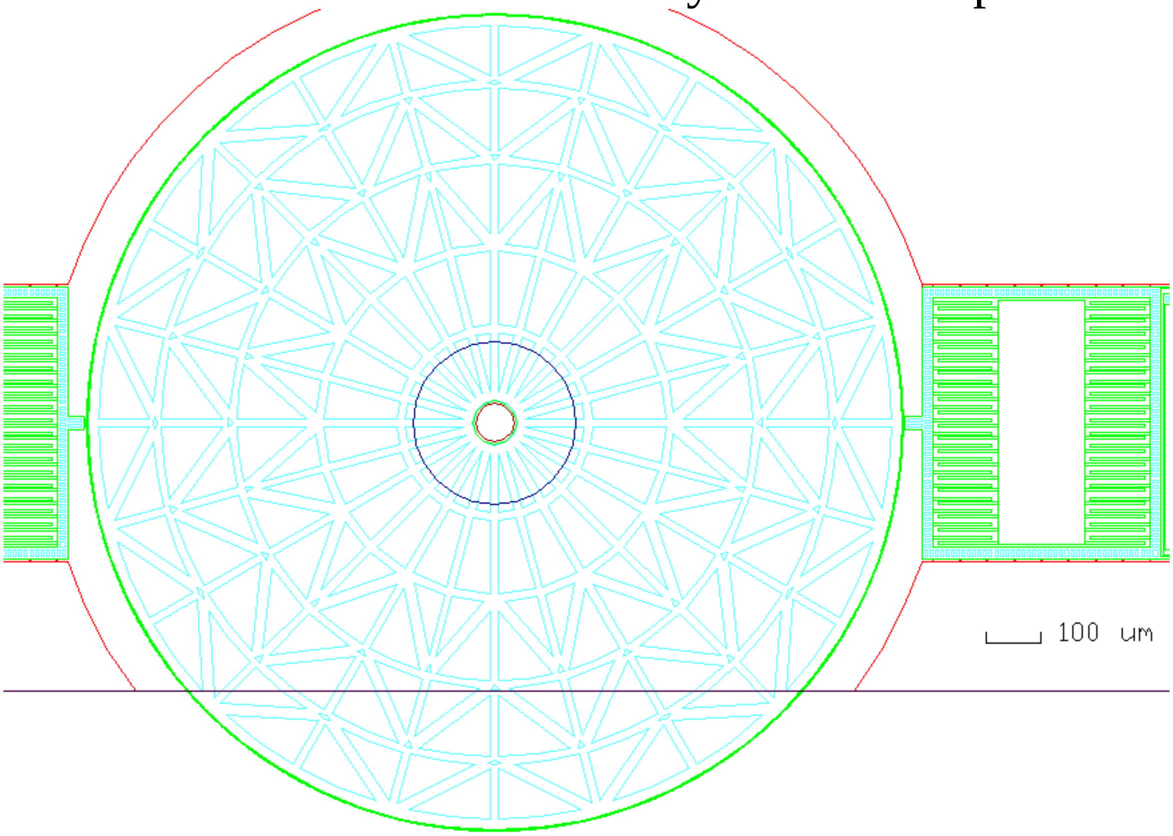
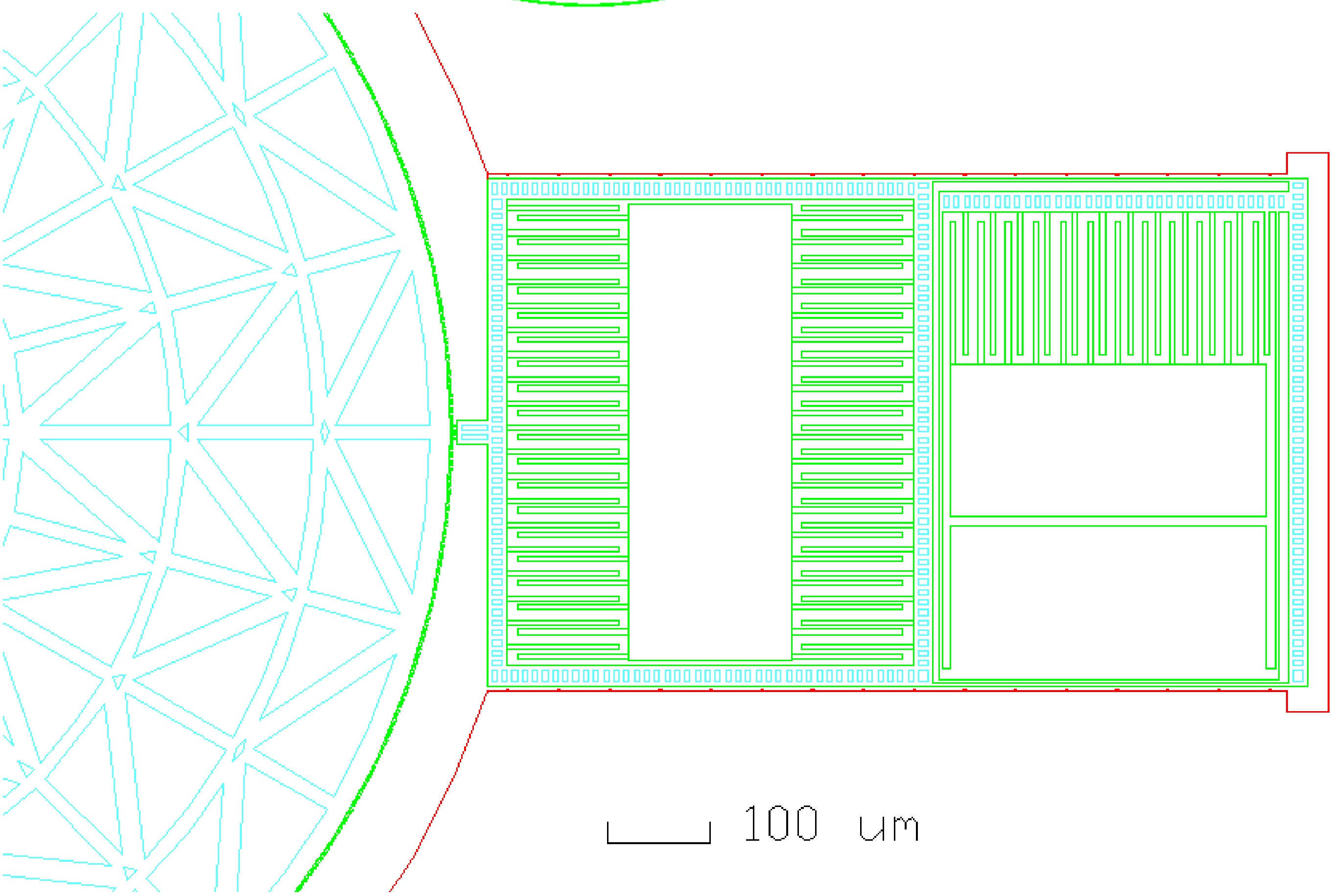
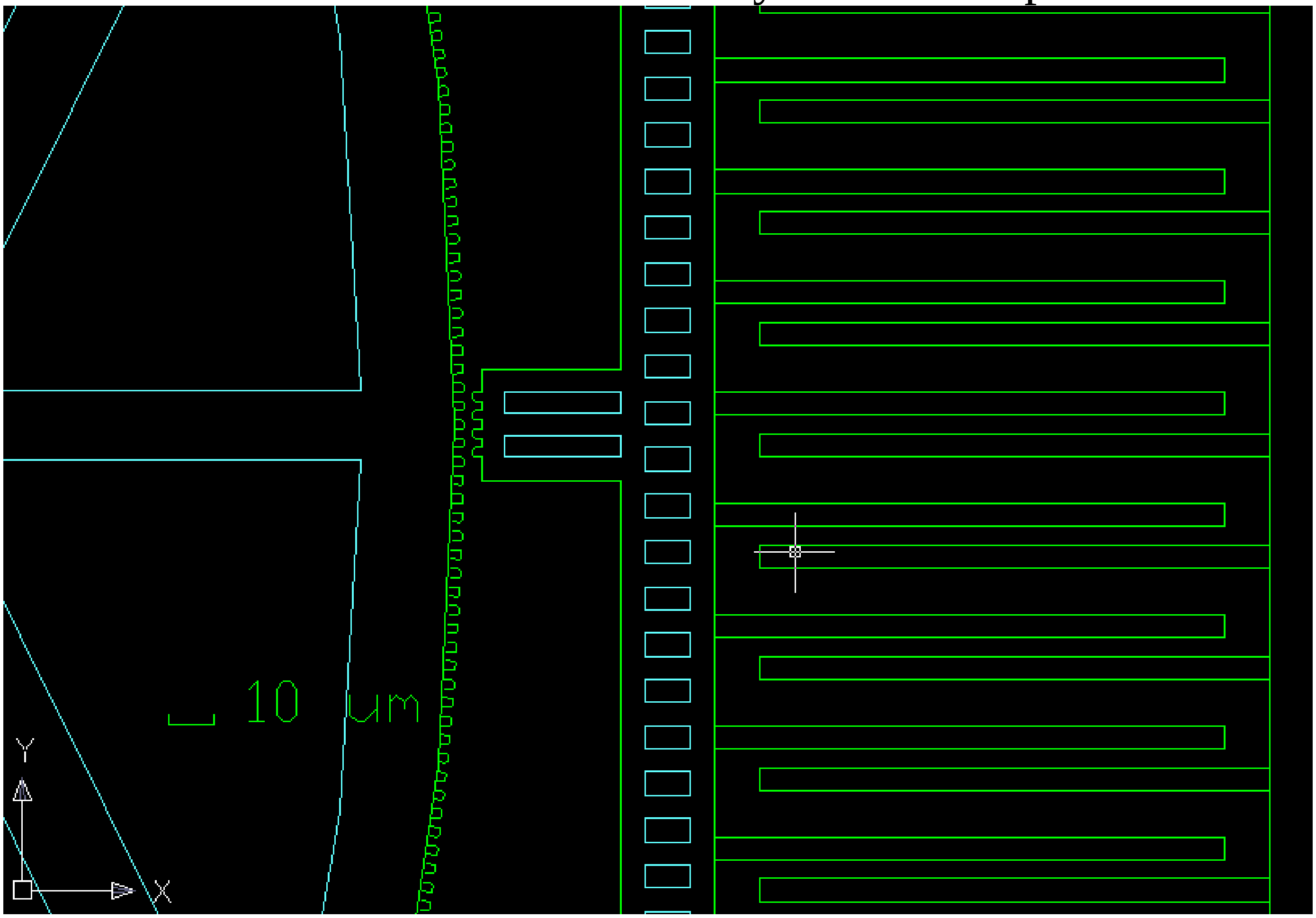
Micro Vehicle Wheel Layout Close-Ups





Micro Vehicle Wheel Layout Close-Ups



Micro Vehicle 3D Design