An Insect-Scale Self-Sufficient Rolling Microrobot
Palak Bhushan and Claire Tomlin

Abstract—We design an insect-sized rolling microrobot driven by continuously rotating wheels. It measures 18 mm × 8 mm × 8 mm. There are 2 versions of the robot - a 96 mg laser-powered one and a 130 mg supercapacitor powered one. The robot can move at 27 mm/s (1.5 body lengths per second) with wheels rotating at 300°/s, while consuming an average power of 2.5 mW. Neither version has any electrical wires coming out of it, with the supercapacitor powered robot also being self-sufficient and is able to roll freely for 8 seconds after a single charge. Low-voltage electromagnetic actuators (1V-3 V) along with a novel double-ratcheting mechanism enable the operation of this device. It is, to the best of our knowledge, the lightest and fastest self-sufficient rolling microrobot reported yet.

Index Terms—Micro/Nano robots, mechanism design, compliant joint/mechanism, wheeled robots.

I. INTRODUCTION

The future is filled with milligram-scale microrobots (or, microbots) doing things like active remote sensing, searching for earthquake and other disaster survivors, and exploring other planets. These applications are mainly due to their small size, but this size also turns out to be challenging for their mobility in natural terrains. Robustness to tough terrains generally increases the less the bot interacts with the environment. Fliers minimize this interaction by flying over and avoiding the obstacles in contrast with earthworms (and ants) which have to crawl (and walk) over each little bump.

Among insect-scale microbots, the flying kind are well heard of due to their promise for robust navigation, visually appealing flapping wing kinematics, together with the inherent difficulty in making them owing to the high power demand of flight [1]–[4]. Thus insect-scale flying microbots are all tethered with the exceptions of [5], [6] but even those take off just for a split second on photovoltaic power before falling to the ground.

The power and, thus, the design requirements for ground-based microbots are much more relaxed compared to those of flying ones [7], in part due to the fact that they are not required to lift their own weight. Yet we have seen few 100 mg-scale robots that are self-sufficient [8]. Most of the electrical-powered designs are tethered [9], [10], due to the high-voltage, high-current, and/or, high-power demands on the drive electronics and the power source.

There have been prior works that are untethered but these mostly require a controlled environment, like a changing external field [11] or an electrical grid surface [12] to function, restricting their global operation. Recently a self-sufficient bot was reported [13] weighting 200 mg with a supercapacitor as its power source. It crawls at 2 mm/s just like a bristlebot, that is, using anisotropic forward versus backward friction coefficient between its legs and the ground. But this makes the bot’s motion very sensitive to the surface properties, with rougher surfaces potentially rendering it useless.

Rolling and walking locomotions are more robust than crawling to changes in the environment’s surface [14], but producing these motions requires generating a continuously rotating motion in contrast to the small-displacement oscillatory actuators available at milligram scales. So we design a new double-ratchet mechanism that converts small periodic motions to large continuous rotations by anisotropically adding up the small motions. The principle behind is similar to some other designs like the inchworm motor [15], [16] which converts tiny motions of an actuator to large motions of a shuttle. Note that we still use anisotropy in our mechanism, but it has been shifted from the environment to inside the mechanism which we can fully control.
The double-ratchet constructed here turns only on clockwise inputs.

In order to simplify the drive electronics, we take a low-voltage actuation route by using electromagnetic actuation, that is, a magnet plus coil system. Low-voltage approach has previously been taken with flying microbots [2]–[4] but not with ground based ones. The use of a double-ratchet to keep the magnet displacements low ensures higher average magnetic fields seen by the coil. Use of the mechanical advantage principle to keep the actuation forces low ensures low current in the coil. Both these strategies further simplify the electronics unit by lowering the current and power demands, allowing the use of off-the-shelf components.

Low-voltage and low-current requirements enable the use of onboard low-power light-weight power sources. The laser-powered version of the bot can operate indefinitely using a 1 mg photovoltaic (PV) cell, but the laser needs to be pointed accurately on to the PV cell which becomes a challenge when the bot is moving fast. Thus to demonstrate an untethered motion that is not intermittent we use an onboard 24 mg supercapacitor that can power the bot for 8 seconds.

II. DESIGN

This section is organized as follows. We first construct a ratchet (see Figs. 2 & 3) whose shaft is free to rotate in only one direction, and locks in place when tried to rotate in the other direction. The backlash of this ratchet is estimated (see Fig. 4). Then we use two such ratchets to make a double-ratchet (see Fig. 5(a)) which has (a) a defined ground, (b) a provision to supply an input to it, and, (c) a common shaft that acts as its output. When the input is rotated clockwise, the output engages with the input and rotates clockwise with it. But when the input is rotated anti-clockwise, the output disengages with the input and remains stationary. An electromagnetic actuator is constructed to drive this input periodically (see Fig. 5(c)), which results in the output continuously rotating clockwise and thus rotating the wheels (see Fig. 9). The minimum actuator current required to drive the double-ratchet is computed. An electronics unit is then constructed (see Figs. 7 & 8) to drive the actuator by periodically switching the actuator’s connection polarity with the power source.

A. Micro-Ratchet

The basic building block of our mechanism is a ratchet with its cross-section portrayed in Fig. 2. The inner shaft is free to rotate relative to the outer ring when it is rotated in a clockwise direction relative to the ring. Under this operating condition, the elastic protrusions emanating from the shaft slide over the zig-zag patterns on the inner perimeter of the ring. These elastic beams are bent by 25 μm more (in addition to any pre-deflection) when encountering the peaks in the pattern. When rotated anti-clockwise, the shaft locks relative to the ring. In this reverse operation, the elastic beams push the falling edge.
of the pattern head-on, and motion can only be achieved if the beams buckle. This buckling requires orders of magnitude higher torque compared to the simple sliding motion from before and this configuration can be considered as locked for the purposes of this letter.

Fig. 3(a) shows the construction of the inner shaft. 12 tabs are laser-cut on a 12.7 μm-thick Kapton sheet. This laser-cut sheet is then rolled on to a 2 mm-diameter Kapton tube and glued in place. The rest of the sheet adheres to the curved surface of the tube due to the glue, but the unglued tabs retain their planar shape thus acting as our desired elastic protrusions. Rectangular slots cut into each of the 12 tabs will help in keeping the outer ring in place as will be seen next.

Rings with patterned holes are laser cut using 25 μm-thick Stainless steel. These rings slide into the slots previously cut in each of the tabs as seen in Figs. 3(b) & (c). The slots prohibit any sideways motion of the rings, but there is still a slight ‘give’ due to the clearances between the slot and ring, that is, due to the ring being thinner than the slot width. This play can cause the rings to not be perpendicular to the shaft. Thus, we later add some constraints in the mechanism to reduce this play and avoid any parasitic motion, that is, to ensure the perpendicularity of the rings and the shaft.

B. Backlash
Backlash is the maximum amount the shaft can rotate in the anti-clockwise direction before locking to the ring. From Fig. 2 one would expect the elastic beams to slide up to 4° before hitting a falling edge. However, this number is generally smaller since the elastic beams are not spaced apart at exactly 60° relative to each other due to assembly imperfections. If the beams are spaced apart at x°, then in the worst case the contact points of the 6 beams are distributed over the 4° gap as: S = {0°, x°, 2x°, 3x°, 4x°, 5x° (modulo 4°)}. The distance to the next falling edge is then given by 4° – max(S). For x uniformly distributed over the interval 55° ≤ x ≤ 65°, the numerically computed cumulative distribution function (CDF) of the backlash is shown in Fig. 4. The backlash is ≤ 1° with a probability of 75%.

C. Double-Ratchet
Now we seek a mechanism whose output rectifies and adds up the provided input motions. This is done by using two ratchets in conjunction (see Fig. 5(a) & (b)). The left ratchet’s ring is grounded. Input is provided at the central ratchet’s ring, and the common shaft acts as the output. When the input is rotated clockwise (see Fig. 5(a)), the central ratchet locks to the shaft but the left ratchet is free to rotate relative to the shaft. Thus, the shaft rotates clockwise. When the input is rotated anti-clockwise (see Fig. 5(b)), the central ratchet is free to rotate relative to the shaft but the left ratchet locks to the shaft and prohibits it from rotating anti-clockwise. Thus, the shaft remains stationary. Providing periodic clockwise plus anti-clockwise motion at the input results in the shaft adding all the clockwise motions and neglecting any anti-clockwise motions.

D. Electromagnetic Actuator
The coil is custom made from a 12 μm-thick Copper wire which is array wound n_a = 96 × 16 number of times. It has an inner diameter of 1.9 mm, an outer diameter of 2.45 mm, and a height of 1.6 mm, with resistance ≈ 1500 Ω. The NdFeB magnet is of grade N52 with 1.6 mm diameter and height. The left ratchet’s ring is attached to the rectangular base plate made from 50 μm-thick Aluminum sheet. The shaft is further supported by a non-patterned ring at the right side to ensure the shaft’s perpendicularity to the left ring.

The input ring is attached via a long moment arm to the magnet (see Fig. 5(c) & (d)) which is concentric to the coil in its rest state. The fully deflected position of the magnet is chosen such that one of its pole faces is still almost inside the coil. For a 8 mm long moment arm this corresponds to a maximum deflection of ≈ 12° (see Fig. 5(e)). Since this deflection is greater than the backlash, the shaft is expected to rotate continuously instead of just wiggling in place.

A 50 μm-thick Al alignment plate, shown in Fig. 5(e) & (f), is used to ensure that the moment arm (and hence the input ring) always moves in a plane perpendicular to the shaft. This is accomplished by constraining the moment arm to only move through a narrow slot (100 μm-wide) in the alignment plate.
This slot also limits the magnet from moving completely out of the coil.

E. Starting Torque & Mechanical Losses

Three types of torques need to be overcome in each ratchet to produce motion. One is the friction torque arising from the contact between the elastic beams and the ring. Another is due to the energy dissipated in the deflected elastic beams when they are released after crossing over the peak (in the patterned hole) into the falling edge. And lastly to lift the weight of the magnet against gravity.

1) Friction: Each of the elastic beams is l = 0.5 mm long and w = 1 mm wide, hence their bending stiffness is \( k = \frac{2.5GPa \cdot \text{mm}^2}{2} \approx 10 \text{ N/m} \). When inside the patterned hole, they are pre-deflected (pre-tensioned) by an amount no larger than \( \Delta y = 0.2 \text{ mm} \) (estimate), corresponding to a contact force of \( F_{\text{contact}} = 2 \text{ mN} \) per beam. Assuming a friction coefficient of \( \mu_s = 0.1 \), this corresponds to a starting torque of \( \tau_{\text{friction}} = 6 \cdot \mu_s \cdot F_{\text{contact}} \cdot r_{\text{shaf}} = 1.2 \mu\text{Nm} \) per ratchet.

2) Elastic Dissipation: During a rotation of \( 4^\circ \approx 0.07\text{ rad} \), each of the 6 beams are released from the peak into the valley of the pattern (see Fig. 6). Since the beams are themselves \( \approx 13 \mu\text{m} \) thick, they fall by \( 18 \mu\text{m} - 13 \mu\text{m} = 5 \mu\text{m} \) when snapping into the valley. Thus, an energy of \( 6 \cdot \frac{1}{2} k(\Delta y + 5 \mu\text{m})^2 - 6 \cdot \frac{1}{2} k\Delta y^2 = 0.06 \mu J \) is dissipated. By energy equivalence, this corresponds to a starting torque of \( \tau_{\text{elastic}} = \frac{0.06 \mu J}{2} \approx 0.86 \mu\text{Nm} \).

3) Gravity: The 25 mg magnet at the end of the 8 mm long moment arm, which always remains almost horizontal, exerts a torque of \( \tau_{\text{gravity}} = 0.25 \text{ mN} \cdot 8 \text{ mm} = 2 \mu\text{Nm} \) due to its weight.

The total estimated starting torque is the sum of the above three and thus \( \approx 4.06 \mu\text{Nm} \). Experimentally it is found that when the central ratchet is released from its top extreme position (as shown in Fig. 5(b)), the torque due to gravity exerted by the magnet (\( = 2 \mu\text{Nm} \)) is sufficient to overcome the friction and elastic torques and cause the central ratchet to return to its neutral position (as shown in Fig. 5(a)). Thus, \( \tau_{\text{friction}} + \tau_{\text{elastic}} < \tau_{\text{gravity}} \Rightarrow \tau_{\text{net}} = \tau_{\text{friction}} + \tau_{\text{elastic}} + \tau_{\text{gravity}} < 2\tau_{\text{gravity}} = 4 \mu\text{Nm} \). Any discrepancy between the estimated (\( \approx 4.06 \mu\text{Nm} \)) and the actual starting torque (\( < 4 \mu\text{Nm} \)) is expected to be due to deviations in the modeling parameters (\( \Delta y \) and \( \mu_s \)). This required starting torque now determines the minimum coil current needed to produce motion.

Using finite element simulations we find the average magnetic field seen by the coil to be \( B_{\text{avg}} \approx 0.1 \text{ T} \). This average is not low because the magnet undergoes only small displacements never being very distant from the coil. The 8 mm long moment arm greatly reduces the force the coil needs to generate to produce 4 \( \mu\text{Nm} \) of torque. \( F_{\text{coil}}(\text{needed}) = 4 \mu\text{Nm}/8 \text{ mm} = 0.5 \text{ mN} = \tau_{\text{friction}} \cdot B_{\text{avg}} \cdot I_{\text{coil}} \cdot 2\pi r_{\text{coil}} \Rightarrow I_{\text{coil}} \approx 0.5 \text{ mA} \). The heat loss in the coil at this current value will be \( I_{\text{coil}}^2 R_{\text{coil}} = 0.38 \text{ mW} \), and the voltage across the coil will be \( V_{\text{coil}} = 0.75 \text{ V} \). However, the off-the-shelf electronics components used in this letter can’t operate below 1 V and thus the voltage across the coil would be \( V_{\text{coil}}(\text{actual}) = 1 \text{ V} \Rightarrow I_{\text{coil}}(\text{actual}) \approx 0.6 \text{ mA} \) which is more than the current required to guarantee function.

F. Electronics Unit

Fig. 7 shows the schematic of the 3 constituent components of the driving electronics. An 11 m\text{F} supercapacitor from Seiko (CH3225 A) is used as a power source for our device. It has an internal resistance of 160 \( \Omega \) and can be charged up to 3.3 V. A resistive divider with \( R_s = 5.6 \Omega \) is used to provide a virtual ground. An opamp based oscillator circuit is used to generate a 20 Hz oscillating waveform. Time period of oscillations is given by \( T = 2 RC \ln(\frac{1+\beta}{\beta}) \), where \( \beta = \frac{R_2}{R_1+R_2} \). Choosing \( R_1 = R_2 = 56 \text{ k}\Omega \) sets \( \beta = 0.5 \) and \( T \approx 2 RC \). Choosing \( R = 10 \Omega \) and \( C = 2.2 \mu\text{F} \) sets \( f = \frac{1}{2\pi} \approx 20 \text{ Hz} \).

This periodic waveform is then fed to an H-bridge made out of 2 opamps which alternates the connection polarity of the coil to the supercapacitor at 20 Hz. The supercapacitor discharges through the coil and the opamps stop functioning below a supply voltage of 1 V at which point the coil stops receiving alternating supply voltage and the device stops functioning.

A 12.7 \( \mu\text{m} \)-thick Kapton sheet with an 18 \( \mu\text{m} \)-thick double-sided adhesive film attached to it acts as the substrate of our circuit. The copper traces acting as wiring are laser cut from a 25 \( \mu\text{m} \)-thick Copper sheet and then bonded to the substrate using heat and pressure, as seen in Fig. 8. The surface mount opamps, 0402 resistors, 0603 capacitor and 0402 zero resistance jumpers are glued to the substrate and then soldered to the Copper wiring using solder paste and a hot air gun. Jumpers are used to make electrical connection paths that otherwise intersect with existing copper traces. The double opamp (TLV342 RUG) and the single opamp (TLV341 DRL) units each weight around 2 mg and are the heaviest parts in the circuit.
G. Assembly

The completed electronics unit is glued on to the Al base plate in the space below the moment arm as seen in Fig. 9. Spiked wheels 8 mm in diameter, laser cut from 50 μm-thick Al, are attached to the double-ratchet’s shaft. Smaller 3 mm diameter wheels, with CF rod as axle and free to rotate inside a Kapton tube, are added to the front to balance the robot. This makes the robot a rear-wheel-drive. The masses of all the constituents after the assembly can be seen in Table I.

### III. Experiments

#### A. Rolling Using Photovoltaics

Before trying the supercapacitor powered version of the bot we tried an alternate power source which is a 1 mm × 1 mm infrared PV cell (MH GoPower 5S0101.4-W) that produces current when a 976 nm wavelength laser light (MH GoPower LSM-010) is shone on it. The laser intensity is increased until the PV cell outputs ≈ 1.5 V while driving a 1.5 kΩ load. The robot’s operation was intermittent since the onboard PV cell moves out of the laser spot (seen as the green spot on the infrared indicator card in Fig. 10) as soon as the robot rolls forward, and then needs to be repointed which is done manually. So to test the operation we allow the smoothed out rear wheels of the robot to slip in a gap/valley between two cards so that its wheels rotate but the robot doesn’t move forward and its PV cell remains in the laser spot. Because of the absence of the spikes on the rear wheels and the heavy supercapacitor, this version of the robot weights 96 mg. Note that even while in motion if the laser is somehow shone continuously on the PV cell then a continuous forward motion would be expected.
The supercapacitor is charged up to 3 V (in 1 minute) using an external function generator. After this charge, the voltage across the supercapacitor drops from 3 V to 1 V in 8 s due to it getting discharged via the coil. During this phase, the magnet drives the input of the ratchet at 20 Hz resulting in the rear wheels rotating and the robot rolling forwards as seen in Fig. 11. Any given spoke in the wheel (out of a total of six spokes) is observed to rotate approximately by 5 full turns in 6 seconds, giving the wheel speed as $\approx 300^\circ/s$. The known length of the robot (18 mm) is used as a unit for on-screen measurement, and in 2 seconds the robot is seen to move forwards by approximately 3 body lengths, giving its forward velocity as $\approx 27$ mm/s. If we had a constant 1 V battery, then the robot can be kept operating while consuming 0.6 mW of power. But since we don’t have a constant voltage battery, the average power consumed in the 8 seconds is greater at 2.5 mW since the capacitor starts with a higher voltage.

IV. CONCLUSIONS AND FUTURE WORK

The wheels and the supporting structures in the robot weight 40 mg and can be made much lighter by using carbon fiber or using the material more sparsely. The bot could be made to consume an even lower power if the electronics could function below 1 V, but we didn’t find any lower voltage light-weight opamps.

The mechanical work done by the actuator to overcome the mechanical losses in the mechanism is negligible compared to the Joule heat loss in the coil. This Joule heat loss is independent of the actuator frequency. Thus, the wheels can be made to rotate much faster simply by increasing the operating frequency of the actuator, and still consume almost the same amount of power while rolling forwards much faster.

The added friction due to the use of a contact-based double-ratchet mechanism can be a disadvantage of this actuator. This friction, however, is estimated to be low in magnitude as is computed in the letter. If the bot is used to carry a large payload much heavier than itself, it can cause the elastic beams in the ratchet to deflect more leading to increased contact friction in the ratchet, in turn requiring more mechanical power from the actuator to function. The shaft can potentially be supported using tiny bearings to avoid this. Another disadvantage is that energy is wasted when the magnet collides with the limiter (that is, when the magnet flips its rotation direction twice per cycle).

The proposed double-ratchet can work with any other actuator and convert small periodic motions to continuous rotation. Using the same principles, one can make a much smaller rolling robot as well but we expect the availability of off-the-shelf electronics components to be very restricting at smaller scales, and custom chips would have to be made. We can now use continuous rotation motion as a building block for making more complicated robots, for example, walking and jumping bots.

ACKNOWLEDGMENT

The authors would like to thank Prof. R. Fearing for his help and insightful discussions.

REFERENCES

[1] K. Ma, P. Chirarattanant, S. Fuller, and R.J. Wood, “Controlled flight of a biologically inspired, insect-scale robot,” Science, vol. 340, pp. 603–607, 2013.
[2] Y. Zou, W. Zhang, and Z. Zhang, “Liftoff of an electromagnetically driven insect-inspired flapping-wing robot,” IEEE Trans. Robot., vol. 32, no. 5, pp. 1285–1289, Oct. 2016.
[3] P. Bhusan and C. J. Tomlin, “Milligram-scale micro aerial vehicle design for low-voltage operation,” in Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst., Madrid, Spain, Oct. 2018, pp. 1–9.
[4] P. Bhusan and C. J. Tomlin, “Design of the first sub-milligram flapping wing aerial vehicle,” in Proc. IEEE 32nd Int. Conf. Micro Electro Mech. Syst., 2019, pp. 2–5.
[5] J. James, V. Iyer, Y. Chukewad, S. Gollakota, and S. B. Fuller, “Liftoff of a 190 mg laser-powered aerial vehicle: the lightest untethered robot to fly,” in Proc. IEEE Int. Conf. Robot. Autom., Brisbane, Australia, May 2018, pp. 1–8.
[6] N.T. Jaferis, E. F. Hebling, M. Karpelson, and R. J. Wood, “Untethered flight of an insect-sized flapping-wing microscale aerial vehicle,” Nature, vol. 570, pp. 491–495, 2019.
[7] M. Karpelson, G-Y. Wei, and R. J. Wood, “A review of actuation and power electronics options for flapping-wing robotic insects,” in Proc. IEEE Int. Conf. Robot. Autom., Pasadena, CA, USA, May 2008, pp. 779–786.
[8] S. Hollar, A. Flynn, C. Bellew, and K. S. J. Pister, “Solar powered 10 mg silicon robot,” in Proc. 16th Annu. Int. Conf. Micro Electro Mech. Syst., Kyoto, Japan, 2003, pp. 706–711.
[9] D. S. Contreras, D. S. Drew, and K. S. J. Pister, “First steps of a millimeter-scale walking silicon robot,” in Proc. 19th Int. Conf. Solid-State Sensors, Actuators Micr. Syst., 2017, pp. 910–913.
[10] K. Saito, K. Iwata, Y. Ishihara, K. Sugita, M. Takato, and F. Uchikoba, “Miniaturized rotary actuators using shape memory alloy for insect-type MEMS Microrobot,” Micromachines, vol. 7, no. 4, p. 58, 2016.
[11] R. S. Pierre, W. Gosrich, and S. Bergbreiter, “A 3D-printed 1 mg legged microrobot running at 15 body lengths per second,” in Proc. Hilton Head Solid-State Sensors, Actuators Micr. Syst. Workshop, Hilton Head Island, SC, Jun. 2018, pp. 59–62.
[12] B. R. Donald, C. G. Levey, C. D. McClary, I. Paprotny, and D. Rus, “An untethered, electrostatic, globally controllable MEMS micro-robot,” J. Microelectromech. Syst., vol. 15, no. 1, pp. 1–15, 2006.
[13] M. Qi, Y. Zhu, Z. Liu, X. Zhang, X. Yan, and L. Lin, “A fast-moving electrostatic crawling insect,” in Proc. IEEE 30th Int. Conf. Micro Electro Mech. Syst., Las Vegas, NV, USA, Jan. 2017, pp. 761–764.
[14] S. Bergbreiter, “Effective and efficient locomotion for millimeter-sized microrobots,” in Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst., Nice, France, Sep. 2008, pp. 4030–4035.
[15] R. Yeh, S. Hollar, and K. S. J. Pister, “Single mask, large force, and large displacement electrostatic linear inchworm motors,” J. Microelectromech. Syst., vol. 11, no. 4, pp. 330–336, 2002.
[16] I. Penskiy and S. Bergbreiter, “Optimized electrostatic inchworm motors using a flexible driving arm,” J. Micromech. Microeng., vol. 23, no. 1, pp. 1–12, 2012.

Fig. 11. Microrobot rolling forwards in real time. The bot is operated over a piece of paper for better traction and to avoid any slipping between the spiked wheels and the level surface.