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Row-bot: An Energetically Autonomous Artificial Water Boatman

Hemma Philamore[1,3], Jonathan Rossiter[1,3] Andrew Stinchcombe[2,3] and Ioannis Ieropoulos[2,3]

***Abstract*— We present a design for an energetically autonomous artificial organism, combining two subsystems; a bio-inspired energy source and bio-inspired actuation. The work is the first demonstration of energetically autonomy in a microbial fuel cell (MFC)-powered, swimming robot taking energy from it's surrounding, aqueous environment. In contrast to previous work using stacked MFC power sources, the Row-bot employs a single microbial fuel cell as an artificial stomach and uses commercially available voltage step-up hardware to produce usable voltages. The energy generated exceeds the energy requirement to complete the mechanical actuation needed to refuel. Energy production and actuation are demonstrated separately with the results showing that the combination of these subsystems will produce closed-loop energetic autonomy. The work shows a crucial step in the development of autonomous robots capable of long term self-power. Bio-inspiration for the design of the Row-bot was taken from the water boatman beetle. This proof of concept study opens many avenues for the further development of the subsystems comprising the Row-bot, and the functionality of the robot itself.**

I. Introduction

Fig. 1. Water boatman (James Lindsey, Hesperocorixa castanea from Commanster, Belgian High Ardennes, April 11, 2009 via Wikipedia, Creative Commons Attribution)

A significant challenge in robotics research is extending the length of time for which robots are able to function autonomously and without the need for human assistance. A key inhibiting factor is the energy demand of a robotic system. Most robots require re-charging or refuelling, often requiring human involvement. Energetic autonomy will extend the range of operation of autonomous systems in fields such as marine and space exploration, treatment of contaminated environments and remote environmental monitoring. This is particularly beneficial in reducing the need for human presence in hostile environments such as conflict or contamination zones.

Looking to nature, foraging presents a promising solution for fuelling autonomous robots. For example, Symbiotic Machine is a floating robot that uses algae foraged from the fluid surrounding it to provide electrolyte for the redox reaction between the copper and gold electrodes of a galvanic cell. The electricity generated is used to power motorised breakup of algae and propulsion [1]. However, the sacrificial electrode required for this reaction means that the system will gradually degrade. The use of MFCs to power robots such as Gastrobot [2] and the Eco-Bot robot series [3] demonstrates robots utilising a symbiotic bacterial relationship to generate their own electricity, minimising their negative environmental impact. The most recent generation of the Eco-Bot series used a stack of batch fed MFCs to power sensing, navigation and wheeled motion to static fuel and water reservoirs. However the robot can only operate within a structured arena limiting the robot's operation to within range of the purpose built feeding station. Furthermore, the stacking of MFCs for increased power output increases the size and complexity of the robot and the complications associated with stacking cells such as voltage reversal [4]. In an MFC, electrical charge is generated using electrons mobilised by the redox reaction that takes place in electrogenic bacterial anabolism. This charge is then stored and can be used for pulsed operation of electromechanical actuator, sensor and communication systems. Raw organic biomass is used as both an inoculant for the bacterial culture and the anolyte that fuels the reaction resulting in an environmentally biocompatible means of electricity generation. The relationship between substrate type/concentration and electrical output has been the subject of multiple studies [5], [6]. MFC technology has been demonstrated using inoculum and anolyte from a range of naturally occurring aquatic environments such as seawater [7], marine and freshwater sediment [8] and waste water [9] so is suited to powering foraging robots in many different fluidic environments. Additionally, MFC technology has been demonstrated in treatment of water with pollutants such as algae [10], petrochemicals [11] and sewage [12] while simultaneously extracting energy for electrical power. Past studies have documented MFCs showing improved power generation as the MFC matures and the biofilm develops [13], demonstrating their suitability for installation as an artificial stomach for an energetically autonomous robot capable of long term, unassisted, operation. Furthermore, previous work has shown MFCs functioning in remote unstructured environments for extended periods of time [14]. We present the design of an MFC-powered artificial organism, inspired

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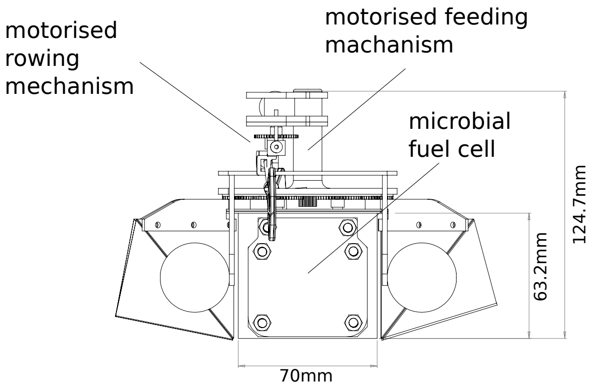
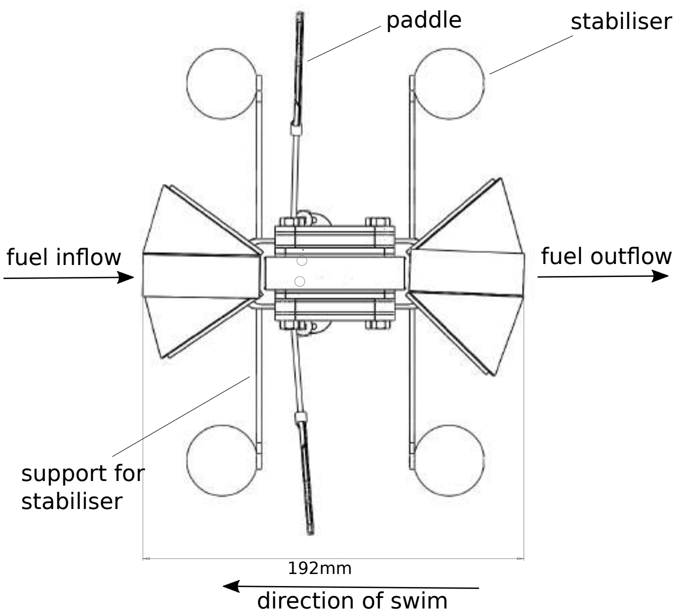
[1]University of Bristol, Bristol, UK
[2]Bristol BioEnergy Centre, University of the West of England, Bristol, UK
[3]Bristol Robotics Laboratory, Bristol, UK

by the water boatman beetle (Figure 1). The Row-bot demonstrates the fundamental requirements of energetic autonomy using two subsystems which are presented separately.



(a) Side view



(b) Top view

Fig. 2. CAD model showing the dimensions of the Row-bot with the mouth open

The first subsystem demonstrates the power generation capability of the robot. A second replicate system shows actuation to refuel and move the robot with an energy requirement that is less than the energy generated by the first system. This is achieved by ingesting chemical energy contained in its surrounding fluid to support microbial metabolism inside the MFC. Hence, the robot exhibits competence for complete autonomy in an unstructured aquatic environment provided enough energy is available in the fluid. In contrast to previous MFC-powered robots, the Row-bot (Figure 2) employs a single fuel cell, minimising system geometry and mass as well as reducing complexity and susceptibility to cell reversal, thus contributing to a more robust system design.

II. Methods and processes

A. Design of the Row-bot

Fig. 3. Row-bot with mouth open (inset shows mouth closed)

A fluidic environment was chosen to demonstrate the robust operation of the Row-bot due to the abundance of bio-matter suspended in environments such as ponds. These environments are the natural habitat of water beetles such as the water boatman (Notonecta) which swims on its back, the lesser water boatman (Corixidae) (Figure 1) that swims in a similar manner but on its front, diving beetle (Dytiscidae), dragonfly nymphs (Sympetrum frequens) and whirligig beetle (Coleoptera Gyrinidae). The propulsion mechanisms of these organisms have been studied extensively for use in underwater robots [15] [16], [17] due to their high efiiciency and impressive velocity [16] which involves synchronous paddling using the hind legs. The side-paddling propulsion mechanism of the water boatman was selected over those of the other beetles as it best suited the morphology of the MFC stomach. The MFC configuration comprised an established batch fed MFC design for a cuboid analytical style MFC, previously described in [13], adapted to include wide mouth openings at its anterior and posterior ends to sweep in fresh fluid from its surroundings (Figure 2). Mimicking the water boatman's feeding mechanism, which employs a broad beak-like mouth to sweep in both fluid and suspended particulate matter [18], the Row-bot feeds the MFC stomach by opening and closing the mouth-like orifice at each end of the MFC through the bending of a flexible acetate envelope structure (Figure 3). This was actuated by the rotation of two sets of arms at the posterior and anterior of the robot through 67 degrees.

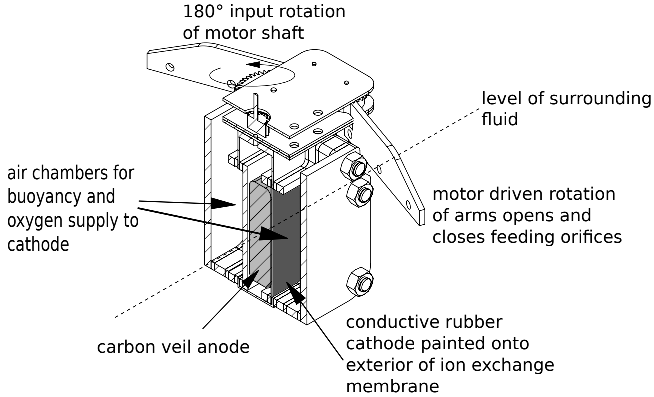


Fig. 4. CAD model: Section view of microbial fuel cell component of Rowbot with component features labelled.

The water boatman floats at the surface of the water, and traps air pockets on its thorax, beneath its wings for breathing when submerged [19]. To emulate this, the Row-bot had, two air chambers, each of volume 29.9cm^3, (Figure 4) for buoyancy and to provide oxygen to the cathode. The air entry holes and feeding orifice (when closed) remained above the surface of the fluid. Polystyrene floats were added laterally for stability.

Two replicate systems were tested in separate environments to demonstrate the electrical output of the MFC generation and the swimming actuation independently:

1) Energy Generation in Robotic MFC Stomach: The anode chamber of the MFC stomach held 25mL of anolyte, and was open on one side, where a cation exchange membrane (Membranes International Inc.), with a projected area of 20cm^2 was attached. An open to air cathode, made from conductive latex, using a method derived from [20], was used to maintain a continuous redox reaction without the need to hydrate the cathode electrode. A polyurethane-based rubber coating (Plasti-Dip, Petersfield UK) was mixed with white spirit and micronised graphite powder in the mass ratio 2:3:1, and painted onto the air side of the membrane. Stainless steel mesh was pressed into the un-cured conductive, rubber electrode to provide an electrical connection. The anode electrode was made from carbon fibre veil and had a surface area of 270cm^2, folded to give a projected area of 7cm^2.

A static MFC was inoculated with sewage sludge (Wessex Water, Saltford UK) mixed with nutrient broth and placed under a 10kΩ load. 5ml of fluid was removed daily from the anode chamber and replaced with 5ml of 25mM acetate stock solution, mixed with 1% tryptone, 0.5% yeast extract. After 5 days the entire content of the anode chamber of each MFC was evacuated using a syringe and replaced with 25ml of 5mM acetate solution, mixed with 0.2% tryptone, 0.1% yeast extract. Following this inoculation period, the static MFC was transferred to the floating Row-bot housing. The housing comprised the MFC and the feeding actuators, which were driven by a standard hobby servo (Carson). The floating MFC was placed in a rectangular container (40mm by 30mm) of de-ionised water containing 10L of 5mM acetate solution, mixed with 0.2% tryptone, 0.1% yeast extract, with a depth of 80mm. For the purpose of this experiment we assume homogeneous nutrient content of the surrounding fluid.

The orifices at each end of the MFC were opened, taking 17 seconds, then left open for 3 minutes. Fishing wire traversing the length of the container between two pulleys, driven by a continuous rotation servo motor (Parallax), was then used to transport the MFC (20cm) linearly, at an average velocity of 2.5cms^{-1}. The MFC then remained open for 1 minute before the sides were closed again, taking 17 seconds. An Uno micro controller board (Arduino) based on an ATMega328 microcontroller (ATMEL) with was used to control the motor driven actuation using manual switch inputs.

An EH4295 Micropower Step Up Low Voltage Booster Module (Advanced Linear Devices), with a fixed load of 950Ω, was used to amplify the MFC voltage. The booster module's rated minimum input voltage was 60mV, with a step up to 5.5V at this voltage. The rated power efficiency of the converter is 48% at nominal voltage of 250mV. At this efficiency, input energy equal to the mean of the energy produced by the MFC stomach over 10 feeds would produce output energy of 5J from the step up converter. The equation for capacitive energy storage $E = CV^2/2$ was used to determine a value of 0.33F to charge the output capacitor to the maximum voltage output of the step up converter (5.5V) to maximise the torque output of the DC motors when driven directly from capacitor discharge. Super capacitors were used to minimise leakage.

A 34972a LXI data acquisition/switching unit (Agilent) was used to measure the voltage produced by the MFC under the load of the energy harvester (950Ω) and the output of energy harvester which charged the 0.33F capacitor. Two consecutive charges, each from a single batch of anolyte were recorded. The output capacitor was discharged in between. The recorded energy conversion efficiency of the boost converter was 30%, resulting in the charge of the 0.33F capacitor to 4.1V. At this efficiency a capacitance of 0.18F is calculated to reach the desired voltage of 5.5V.

2) Row-bot Motion Test Bed: The replicate Row-bot for testing actuation lacked the active components for power generation using an MFC. It was operated in a rectangular container (1000mm by 440mm) containing water, with a depth of 80mm. For simplicity, the effect of the boundary on viscous drag and reflected force was neglected in the results of the current proof of concept study. Actuation of the feeding mechanism was driven by a 0.75 Watt, brushed DC motor (Maxon) with a plastic planetary gearhead (gear ratio 1024:1). The polarity across the motor was reversed in order to switch between opening and closing actuation. In contrast to the system for energy generation, which used pulleys fixed to the periphery to transport the MFC through the fluid, untethered propulsion was generated by using bio-inspired paddling mechanism (Figure 5). Momentum was imparted to the surrounding fluid using the paddles. The propulsion mechanism was driven by a brushed DC motor (Escap) and gearhead (gear ratio 98.7:1). DC motors were used in the Row-bot in place of the servo motors in the aforementioned energy generation subsystem as they consumed less energy than that which was harvested from the MFC. In contrast the energy used by the servos used in the energy generation system (11.6J) exceeded the energy produced by the MFC and therefore were unsuitable for use in the energetically autonomous system design. The hind legs of the water-boatman (Corixidae) extend frontally and are swept back with a rowing motion from +50 to -87.7 degrees to the lateral axis of the beetle, for propulsion, while maintaining a high angle of attack to maximise the drag surface throughout the power stroke [21]. To mimic this, the Row-bot generates thrust using a pair of oars of length 71mm, driven in a rowing motion through an angular range of +19.5 to -19.5 degrees, with an orthogonal angle of attack to the water surface. The drag of the water boatmans's limbs is increased during the power stroke and decreased during recovery by increasing the angle of the oar beneath the water surface from 30 degrees during the recovery stroke to 55 degrees to the water surface, during the power stroke [19]. This mechanism was adopted in the design of the Row-bot which changed the angle of the oar from 35.6 degrees to the water surface, during the power stroke, to 16.3 degrees during the recovery stroke. The rowing mechanism was driven by a quick return rotation mechanism, with two, gear coupled crank drives. This extended the legs laterally during the power stroke and retracted them during the recovery stroke to change their angular position with respect to the surface of the surrounding fluid.

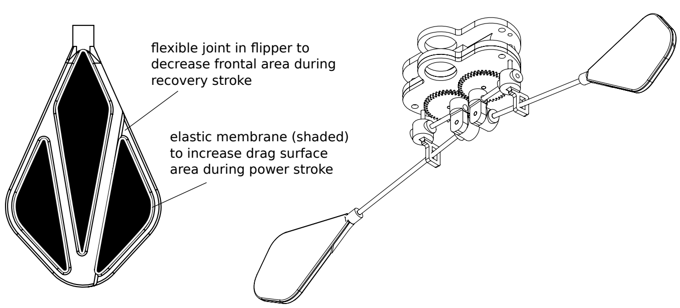


Fig. 5. CAD model of motorised rowing mechanism with enlarged detail of paddle

The legs of the water boatman are covered by swimming hairs which span laterally to maximise drag during the power stroke and collapse to minimise drag during the recovery stroke [21]. The design of the Row-bot's paddles was inspired by this mechanism. Each paddle was made as a 3D printed composite structure with a rigid frame (Vero White 3D printed, acrylic based photo-polymer (Polyjet)) that supported an elastic membrane (Tango Black 3D printed, acrylic based photo-polymer (Polyjet)) which stretched to increase the paddle surface area during the power stroke. Additionally, the elastic membrane formed a hinge that changed the angle of attack of the portion of the paddle that remained submerged during the recovery stroke, to reduce its frontal area. A NI USB-6229 data logger (National Instruments) was used to measure the controlled direct discharge of the 0.33 F capacitor charged to 4.1V and a separate 0.18 F capacitor charged to 5.5V, to the motors driving feeding and propulsion. Manual switches were used to operate the discharge of the capacitors into the motors.

III. Results

A. Energy generation in robotic MFC stomach

The electrical output to the 0.33F capacitor via the boost converter was measured during two consecutive batches of feeding, using a 34972a LXI data aquisition/switching unit (Agilent) (Figure 6). The average electrical energy output from the MFC was 8.82J per cycle. The output capacitor was charged to an average voltage of 4.1V, demonstrating an energy conversion efficiency for the step up boost converter of 30%.

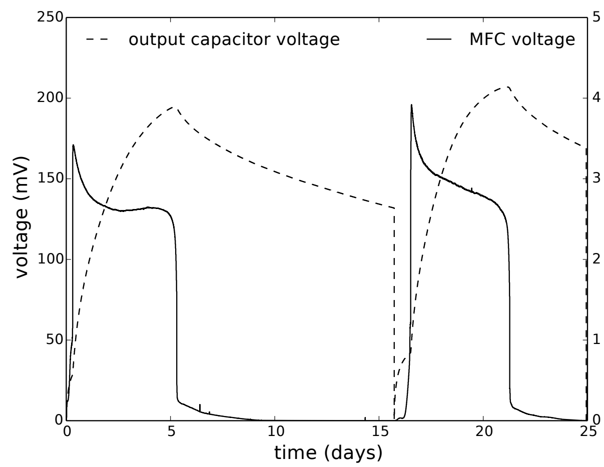


Fig. 6. Voltage output from MFC and corresponding voltage of step-up converter (to output capacitor, 0.33F) over two batches of anolyte

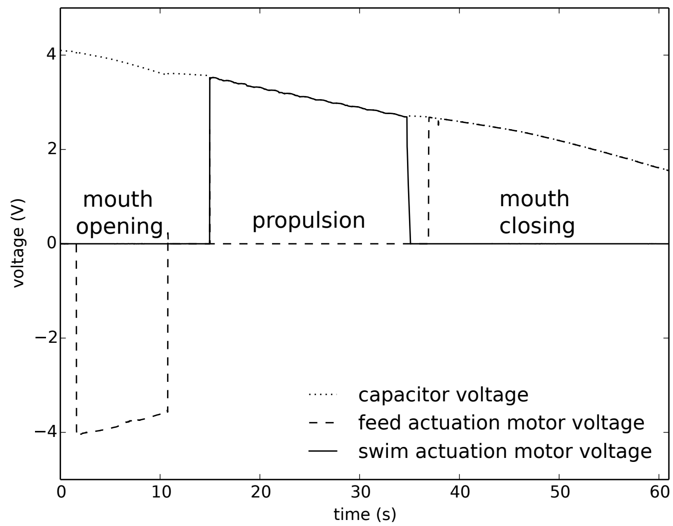
B. Rowbot Feeding and Swimming Actuation

The operations used to feed and move the robot in Section II-A.1 were successfully repeated using a replicate robot which used oars for propulsion in place of a pulley system to allow untethered locomotion. DC motors were used in place of hobby servos for higher electromechanical efficiency. The energy consumed in actuation of the DC motors Section II-A.2 was less than the energy harvested from the MFC, demonstrating the potential to combine these subsystems, resulting in an energetically autonomous, MFC-powered robot. The duration of individual swimming strokes increased as energy was depleted from the capacitor. The submerged paddle area ranged 2.20 to 12.11cm^2 throughout one stroke cycle causing the dynamic drag of the paddle and hence the paddle velocity, V_p to vary throughout the stroke. The power required to produce the paddle dynamic drag, T_p which can be expressed as a function of its linear velocity, V_p and the forward velocity of the Row-bot, U such that $P = T_pV_p = \frac{1}{2}\rho V_p(V_p - U)|V_p - U|S_pC_D$ [19], where S_p is the area of the paddle and C_D is its drag coefficient and ρ represents the density of water (1000kgm^{-3}). The body drag of the artificial water boatman is equal to the thrust generated by paddling at constant velocity and may be given as $D = T_p = \frac{1}{2}\rho U^2 S_T$ where S_T refers to the wetted surface area of the artificial water boatman. Hence the work done in propelling the the water boatman is $W = DU = \frac{1}{2}\rho U^3 S_T$. The hydrodynamic efficiency can be defined as $\eta_h = W/P = U/V_P = \frac{1}{1+\sqrt{S_T/(S_P CD)}}$. The electromechanical efficiency can be defined as $\eta_{em} = \frac{W}{E_{in}} = \frac{2W}{CV^2}$ where C and V are the capacitance and voltage of the supply capacitor, respectively. An estimation of the hydrodynamic efficiency was made using the average angular velocity, and the assumption that the centroid of the submerged oar remained the same radial distance from the fulcrum throughout the duration of the stroke.

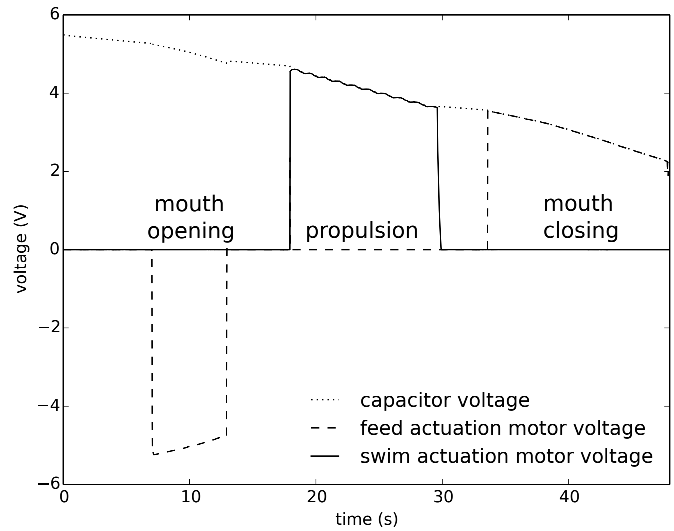
Case 1: 0.33F capacitor charged to 4.1V 2.12 J of energy was depleted from a 0.33F capacitor charged to 4.1V in actuating the feeding mechanism of the Row-bot to open (0.60J) then propel the Row-bot a linear distance of 20cm, using 12 strokes, with an average frequency of 0.6Hz (σ = 0.05)(0.81J). This resulted in a mean body velocity per cycle of 1.66cms^{-1} meaning the robot travelled 0.09 of it's body length per cycle, before closing again (0.71J) (Figure 7(a)). The feeding actuation took 9s to open the mouth, and 32s to close again, reversing the polarity across the motor to actuate it in the opposite direction (Figure 7). This left 0.58J of surplus energy in the capacitor after completing all actuations described in Section II-A.1 The hydrodynamic efficiency during propulsion was approximately 0.12. The mechanical efficiency was 0.0007.

Case 2: 0.18F capacitor charged to 5.5V 1.8J of energy was depleted from a 0.18F capacitor charged to 5.5V in actuating the feeding mechanism, to open each end (0.41J), then propel the Row-bot 20cm, using 10 strokes, with an average frequency of 0.83Hz (σ = 0.04)(0.70J), before closing again (0.69J). This resulted in a mean body velocity per cycle of 2cms^{-1} meaning the robot travelled 0.10 of it's body length per cycle, (Figure 7(b)). The feeding actuation took 5.82s to open the mouth, and 14.64s to close again. This left 0.9J of surplus energy in the capacitor after completing all the actuations, described in section Section II-A.1. The hydrodynamic efficiency during propulsion was approximately 0.14. The mechanical efficiency was 0.0023.

In both cases the performance of the Row-bot was inferior to that of the real organism, which produced a mean body velocity of 3.92cms^{-1} meaning it travelled 4.6 times it's body length per stroke at a stroke frequency of 10Hz. The total energy from paddling was 13.2 x 10^{-7}J per stroke resulting in a hydrodynamic efficiency of 0.52 [21], suggesting that the ratio $\frac{S_T}{S_P C_D}$ is smaller in the case of the real organism than the Rowbot.



(a) Actuation of the Row-bot powered by a 0.33F capacitor charged to 4.1V



(b) Actuation of the Row-bot powered by a 0.18F capacitor charged to 5.5V

Fig. 7. Supply capacitor, and motor voltages during feeding and propulsion actuation

IV. Discussion

The results show the potential for the combination of the energy generation and actuation subsystems in an energetically autonomous robot. Therefore, next stage in this work is the direct integration of these subsystems with the addition of switching circuitry also powered by the MFC. The resulting Row-bot can be developed for applications such as remote sensing and environmental monitoring and clean-up. As mentioned in Section I, MFC substrate type has a significant impact on energy output, with raw environmental pollutants shown to produce lower power output than synthetic feedstocks [5]. The electrical isolation of both electrodes in the Row-bot from the surrounding fluid means that multiple MFCs could be configured in series in a fluid environment to achieve tasks requiring higher voltages. The morphology of the design was chosen to allow direct comparison to the cuboid analytical style MFCs, previously described in [13], resulting in large body drag. Future design will reduce the body drag of the Row-bot to increase its propulsive efficiency by further emulating the water boatman's morphology. This may include the low body to paddle drag ratio of the beetle and its hydrophobic skin. The system powered by a 0.18F capacitor showed significantly better efficiency than the one powered by a 0.33F capacitor, suggesting that higher operating voltage provided by the former set-up targeted a more efficient point of the power curve of the motors. Future work could further exploit this behaviour to improve the electromechanical efficiency of the system. This could be achieved using voltage regulation hardware, which would also provide more precise motor velocity control than the direct capacitor discharge used to power the current system, at the expense of energy used in the regulator circuit. The use of paddles with direction-dependent variation in component flexibility is discussed as a means of reducing the paddle drag surface during the recovery stroke. The study demonstrates the use of 3D printing to fabricate materials with inhomogeneous stiffness as a single component. However, the material showed low fatigue resistance when used to fabricate thin flexible components (thickness = 1mm). Furthermore, the stiffness was too high to facilitate adequate flexibility for the mechanism to function as designed. Quantifying the fatigue life and material stiffness of this and other 3D-printed materials is a possible way to improve the fabrication of this mechanism, however this material characterisation is beyond the scope of this study. Additionally, the bio-inspired features of the robot could be further developed to improve overall system behaviour. For miniaturisation of the driving mechanism, the Row-bot oars had an angular range of 72.85 to 107.15 degrees about the longitudinal axis of the Row-bot. This range of operation was significantly smaller than that of a water boatman (40 to 177.7 degrees) and increased angular displacement could be used to generate more thrust per actuation. Furthermore, a larger crank radius in the paddling mechanism would result in a larger angular velocity ratio of the power to recovery stroke, mimicing the behaviour of fast swimming organisms such as the whirligig beetle.

V. CONCLUSION

The work presented shows a viable system for use as an energetically independent autonomous robot. A modular system has been used to rigorously demonstrate the anabolic, propulsive and feeding mechanisms of an artificial, water boatman-inspired organism, the Row-bot. The energy generated has been shown to exceed the energy required to refuel. It is the first practical robotic application to use a single MFC and as such demonstrates the potential of the technology as an energy supply. biomimicry of the water boatman beetle has driven key design features resulting in system optimisation including morphology to suit the drag profile required for power and recovery propulsion phases and combined floatation and oxygen supply. This work demonstrates a suitable system for robots operating autonomously for extended periods in the environment and presents many avenues for development of the various subsystems and the robot as a whole.

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