Experiments and Simulations of Colloidal Robotics for Biomedical Applications

by
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ABSTRACT

Microrobotic systems have shown increasing promise for operation in confined, fluidic, and biologically relevant environments, with broader relevance to miniaturized biomedical technologies such as micro-robotic-assisted surgery. However, most platforms demonstrated to date remain dependent on external control and energy input. This limitation is especially significant for colloidal robots, where small device volume and complex operating environments constrain the integration of onboard function. This thesis investigates experimental and computational approaches relevant to autonomous function in biomedical microsystems, with an emphasis on colloidal robotic platforms and related responsive systems.

The thesis first turns to onboard power as one of the central enabling constraints for miniaturized autonomous systems. Microscale robotic and electronic systems require power sources that can be reduced to comparable dimensions and fabricated using compatible processes. This need is particularly important for colloidal and cell-sized devices, where conventional battery architectures are often too large or rely on materials and assembly methods that are difficult to integrate with microfabrication. We present a photolithographically fabricated picoliter-scale Zn-air microbattery platform designed for colloidal robotic and microscale electronic applications. The device uses Zn as the anode and Pt as the cathode for oxygen reduction, while relying on oxygen and electrolyte supplied by the surrounding environment to minimize onboard volume. Batteries with lateral dimensions below 100 μm and thicknesses of approximately 2 μm were fabricated in parallel and released into solution. These microbatteries with active material volumes near 2 pL delivered open-circuit voltages of 1.05 ± 0.12 V, total energies of 5.5 ± 0.3 to 7.7 ± 1.0 μJ, peak power near 2.7 nW, and energy densities ranging from 760 to 1070 Wh/L. To evaluate their functional relevance, the microbatteries were used to operate representative microscale loads, including a memristor, a bimorph actuator, chemical sensors, and a clock circuit. These results show that picoliter Zn-air batteries can serve as compact, microfabrication-compatible power sources for colloidal robotic and microscale electronic components.

This Zn-air microbattery platform is then examined for contact lens electronics. Zinc-air microbatteries are investigated in tear fluid using contact-lens-relevant form factors, and a three-slab heat transfer model is developed to define upper bounds on allowable power dissipation at the ocular surface. The model shows that device temperatures are primarily limited by heat transfer at the lens surface and dissipation into the vitreous humor. Experimentally, single-stack devices with cathode/anode dimensions from 200 × 200 μm^2 to 2000 × 2000 μm^2 were fabricated and characterized in simulated human tear fluid, producing open-circuit voltages of approximately 1.0 V and areal power densities between 0.02 and 0.06 mW/cm^2. Together, these results demonstrate zinc-air chemistry as a biocompatible battery source for contact lens electronics and establish thermal safety limits for energy discharge at the ocular surface.

The Zn-air microbattery platform is further extended from power-source development to functional integration by combining Zn-air microbatteries with onboard chemical sensing in a releasable microsystem. Here, we report a releasable 100 μm-scale microsystem that integrates a photolithographically fabricated Zn-air microbattery with a monolayer molybdenum disulfide (MoS_2) chemiresistive sensor on an SU-8 platform. After fabrication, the devices can be released and dispersed in an organic solvent for storage and activated upon exposure to an aqueous electrolyte. Exposure to triethylamine changes the conductance of the MoS_2 sensor and modulates the discharge rate of the microbattery, while optical monitoring of Zn anode consumption provides a simple readout of device state. Higher triethylamine concentrations produced faster discharge, demonstrating analyte-dependent behavior in a releasable self-powered microsystem. This work establishes a proof-of-concept platform for releasable microscale chemical sensing and provides a basis for further development of self-powered microsystems for operation in confined environments.

Beyond onboard power and sensing, autonomous microrobotic systems must also move within complex interfacial environments, where local surface conditions can strongly affect locomotion. Here, we investigate the two-dimensional surface locomotion of cell-sized self-propelled microrobots in aqueous hydrogen peroxide. Planar 15 μm microrobots were fabricated by photolithography with different structural materials and electrode configurations, and their motion was examined on substrates with distinct surface conditions. Variations in microrobot structure and substrate environment produced differences in mobility and locomotion mode, including translational, circular, and spiral trajectories. Force-balance analysis indicates that these behaviors arise from the interplay among diffusiophoretic propulsion, viscous drag, adhesion, and surface interfacial resistance. We further find that spatial heterogeneity in surface adhesion couples translational velocity to trajectory curvature, resulting in circular or spiral motion under different interfacial conditions. This behavior is captured by a reduced kinematic model and is consistent with both experiments and simulations. Together, these results provide an experimental and physical framework for understanding and tuning the surface locomotion of chemically powered microrobots.

The final portion of the thesis expands this framework to the computational evaluation of responsive biomedical systems, where glucose-dependent response and cross-species translation impose additional design constraints. Glucose-responsive insulin (GRI) and glucose-responsive glucagon (GRG) therapeutics are promising strategies for improving glycemic control and reducing the risk of therapeutically induced or severe hypoglycemia, but their development requires quantitative models that can evaluate candidate designs across physiological contexts. In this work, we use pharmacokinetic and multi-compartmental glucoregulatory models to evaluate proposed GRI and GRG systems in humans and rodents. GRI concepts are grouped into three mechanistic classes, including intrinsic GRIs, glucose-responsive particles, and glucose-responsive devices, and analyzed to identify parameter spaces that maintain glucose within the euglycemic range. Candidate GRG designs from the literature are evaluated by modeling their activation kinetics and connecting them as inputs into physiological glucoregulatory models for comparison with in-vivo data from rats and mice. These analyses reveal translational differences between rodent and human systems and show that representative physiological models require further refinement to describe coupled insulin, glucose, and glucagon dynamics. Together, these

studies demonstrate a computational framework for evaluating the clinical translatability of glucose-responsive therapeutic systems.

Taken together, this thesis establishes experimental and computational foundations for autonomous colloidal robotics and related responsive biomedical systems, including microscale energy storage, self-powered sensing, interfacial locomotion, and model-based evaluation of glucose-responsive therapeutic systems. These studies provide insights into design principles for future microscale systems operating in complex biomedical environments.

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