Expanding Engineering Education through Undergraduate Research Experience in Micro-Robotic Drug Delivery

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Abstract

This paper examines the use of MEMS research in bio-medical micro-robotic drug delivery as an education vehicle for expanding the effectiveness of undergraduate engineering education in order to meet advancing challenges of the future. Micro-robotic drug delivery is a diverse area of research with emerging applications in intraocular surgery and cancer treatments. This research requires integration of engineering sciences such as bio-systems, fluid mechanics, thermodynamics, chemistry, material sciences, and more. This allows various engineering disciplines to utilize their classroom knowledge in direct research with real, innovative applications in technology. This method of complimenting engineering education with curricula-related research has shown improvement in engineering accomplishment and learning that is advantageous to the future success of undergraduate engineering education.

Introduction

Engineering focuses on the development and discovery of important resources such as energy, materials, and information in order to provide tools and technology in service of advancing human civilization. Consequently, engineering activity has a global impact due to the international utilization of innovative discovery. For this reason, engineering education has the objective of presenting not only the engineering sciences but also how to apply them to direct applications in a manner that is judicious and conscience of societal and environmental impact[1]. In order to meet the future challenges of an advancing engineering industry, undergraduate education needs to prepare students in a vast spectrum of sciences and technical skills. This requires collaboration between classroom knowledge and laboratory practice. By utilizing the opportunities for undergraduate research projects, students can significantly advance their education by applying first-hand the curricula they are learning in class. This approach allows for a greater understanding of the advanced sciences and an early exposure to the laboratory skills, both technical and practical, utilized by the professional engineering industry.

One way of accomplishing this is through the pursuit of research in microelectromechanical systems (MEMS) and the technologies it encompasses. MEMS research is an innovative research area for undergraduates because it incorporates a diverse range of technical skills in various engineering fields and represents many current and emerging applications in society. With a history of over 30 years, MEMS research has supported the development of technologies such as switches, displays, pressure sensors, accelerometers, gyroscopes, inkjet printer heads, and lab-on-a-chip chemical detection systems. Discoveries such as these have not only inspired the industrial world, but have given rise to interest among academic institutions in incorporating MEMS into their curriculum[2,3]. MEMS research has an interdisciplinary nature originating from the need to design and integrate electrical, mechanical, optical, and chemical sub-systems into a functional device[1]. This paper focuses on the use of MEMS principles in Micro-Robotic research as an innovative education vehicle to attract top students from various engineering backgrounds and give them the opportunity to expand their education by being actively involved in an exciting research project.

MEMS Micro-Robotic Research

MEMS research is a broad field with multiple areas of critical development and investigation. It requires a collaborative effort spanned by engineering disciplines such as robotics, automation, ultrasound, fluid dynamics, modeling, kinetics, magnetism, bio-systems, and other curricula as reviewed in table 1. In recent years, MEMS technologies have been integrated into many bio-medical applications. One of these applications is the development of micro-robotic drug delivery systems. The purpose of these systems is to provide a means for wireless, targeted drug delivery to various areas of the human body. These systems are of interest to the medical industry because they could provide less adverse methods for cancer treatment[4], replace high-risk intraocular micro-surgeries[5], and provide great improvements in future technologies such as those reviewed by Gilles[6]. The development of these systems requires a collaborative grouping of research in areas such as structural design, assembly, bio-compatibility, encapsulation, steering and guiding, imaging and tracking, insertion and retrieval, and actuation. Consequently, this MEMS research incorporates a diverse range of engineering disciplines. Of these areas, micro-robotic actuation has been one area of undergraduate research success. This aspect of research focuses on the investigation of alternative drug release mechanisms to improve the remote triggering of drug release from the robot structure. Existing methods use diffusion[7] and magnetic modulation as a means for triggered release but have shown disadvantages relating to release time and magnetic interference with emerging steering and guiding systems[8]. For these reasons, ultrasound is being investigated as an alternative actuation mechanism for drug delivering micro-robots. This research project is ideal for undergraduate student research because it involves knowledge and curricula from general chemistry, biology, physics, and core engineering sciences. It also presents an affordable opportunity for innovative research and undergraduate learning experience.

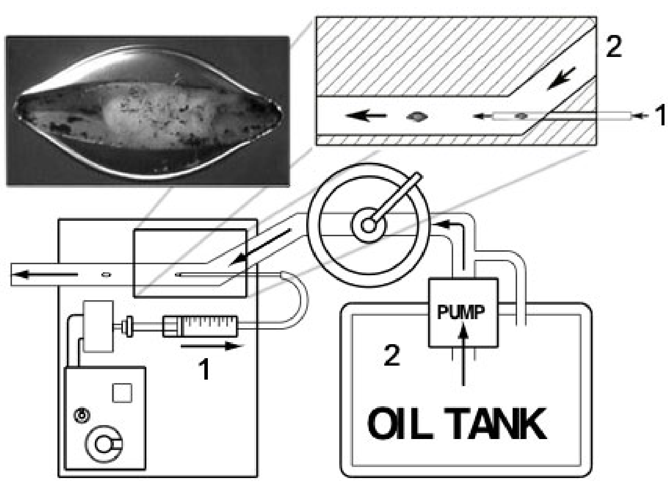

Fig. 1: Micro-robot encapsulation system showing fluid manifold and encapsulated micro-robot. 2 – Continuous Oil Phase. 1 – Sodium Alginate Disperse Phase

Subject/Curriculum	Relation to MEMS Micro-Robotics Research
Intro. Mechanics	Newton's Second Law
Fund. Tech of Chemistry	Kinetics, Beer's law of absorbance. Spectroscopy and concentration measurements.
Intro. Electricity and Magnetism	Magnetic forces and torques, circuit analysis.
Intro. CAD / Graphics	Photomask design, conceptual graphics
Differential Equations	Force derivation and modeling
Elements of Electrical Engr.	Electromagnetics and driving circuits.
Thermodynamics	Diffusion kinetics
Fluid Dynamics	Characterizing flow regimes, motion in low Reynolds number environments.
Instrumentation Lab	Control of B-Field and gradients
Fund. Of Engr. Materials	Bio-polymers: processing/use
Senior Lab	Device testing and analysis
Control Systems	Closed-loop position control

Table 1: MEMS disciplines and applications of engineering curricula.

The technical aspects of the this research focus on the development of a bio-compatible surface skin with the purpose of inhibiting drug leakage prior to remote actuation, the mechanisms inducing the drug dispersion, and the measurement and analysis of the release characteristics. The bio-compatible coating materials derive from the protocol reported by Saslawksi [9] and are used in a series of chemical soaks to induce the formation of a polymer based outer coating. The method of coating is also an important research area to ensure consistency of release characteristics and uniformity. The most efficient method implements encapsulation by means of a co-fluidic extrusion system (figure 1). This system was designed to disperse Sodium Alginate drug complex into a continuous oil flow via a capillary tip. This method allows the experimenter control of the droplet size and disperse frequency thus making it ideal for encapsulation of various micro-robots and MEMs devices. The development of this system employed many concepts from fluid mechanics and required an in-depth analysis to characterize the performance as a direct result of design parameters. This required an undergraduate researcher to apply fluid mechanical concepts, such as flow regimes, Reynold's numbers, and interfacial tension forces, to an actual design concept. Another aspect of the project focused on bio-compatible chemicals to use in the drug delivery process. Horseradish Peroxidase was chosen as a drug substitute and is contained in the Alginic coating during this extrusion process. The encapsulated micro-robots are then soaked in a 0.1M Calcium Chloride ($CaCl_2$) solution for up to 15 minutes. This salt solution promotes cross-linking with the NaAlg. and creates a drug-containing, durable surface shell surrounding the magnetic robot structure. The robots are then transferred into a polyethylenimine (5% wt.) solution for approximately 4 minutes. During this soak, a protective polymer coating forms and serves to isolate the drug containing sub-layer from the surrounding fluidic environment. The droplets are finally soaked in a Poly-l-lysine (2% wt.) solution where the poly-l-lysine is hypothesized to leak into the $CaCl_2$- $NaA\text{lg}$. cross-linking and strengthen it. This aspect of the project utilized various chemistry concepts that govern the underlying principles of the surface skin formation. The undergraduate researcher had to familiarize himself with these concepts in order to understand the formation process and optimize the relative effects of chemical concentration and soak times on skin formation. After the formation of the protective surface barrier, the droplets are prepared for drug release studies. Visual release results showing the effectiveness of the protective surface skin are shown below in figure 2.

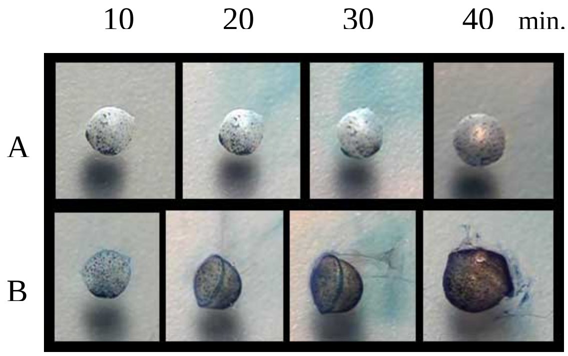

Figure 2: Visual release experiment showing the impact of the protective surface skin on release kinetics. **A** droplets have a protective surface skin while **B** droplets are bare. Drug release is observed by color change in surrounding fluid.

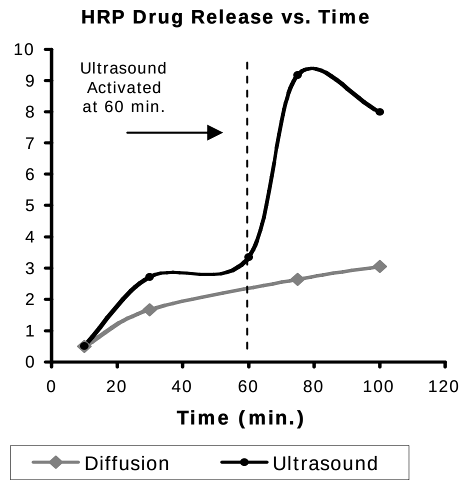

Figure 3: HRP drug release vs. time for both diffusion and ultrasonically stimulated micro-robots.

In order to test ultrasound as a proposed release mechanism for encapsulated micro-robots, undergraduate research assistants faced the task of designing affordable and efficient test experiments. This approach requires undergraduate students to use their scientific knowledge to assess the affordability of research practices and ensure efficient methods of hands-on experimentation. Student research assistants did this by using an ultrasonic bath designed to utilize ultrasonic cavitation as a mechanism for cleaning lab glassware and equipment. They tested the drug release effectiveness by sonicating robot samples for various time intervals and observing the robot behavior and release dynamics. In order to assess the ultrasonic power and effective causes of release, students had to employ research and analysis methods to characterize the results of their experimentation. They used spectrophotometry techniques and a selected chromogenic substrate, Tetramethylbenzadine (TMB), to quantitatively measure the amount of released drug with respect to ultrasound exposure time. This gave students the opportunity to apply common engineering instrumentation methods to discover and report the success of ultrasound as an alternative drug release mechanism for bio-medical micro-robots. The results of ultrasound as an actuation mechanism are shown above in figure 3.

Educational Impacts of Undergraduate MEMS Research

This project and other MEMS research areas present many advantages to engineering education and the advancement of learning in undergraduate engineering disciplines. One of these advantages is the heightened understanding of classroom curricula. By applying first-hand the engineering knowledge taught in the classroom, undergraduate students are able to increase their scope of understanding in industry applications and practical laboratory procedures. This not only expands ones understanding but also increases excitement and motivation in the curriculum due its apparent utilization in real, innovative research. This increased excitement also permeates into the students overall perspective on their engineering education as a whole and serves as a backbone to further engineering accomplishment. Undergraduate involvement in research also gives students an early exposure to laboratory instrumentation and experimental procedures commonly undergone by the engineering industry. This allows students to develop significant technical and practical laboratory skills that are of interest to many engineering employers. It also promotes a clearer understanding of the discovery process and the steps undergone to make an engineering idea become a developed product. Another advantage offered by undergraduate research is the knowledge gained from technical research and reporting. Since research often leads to novel discoveries, undergraduate students are also exposed to the procedures encompassed in technical writing and publicizing new research. This creates a great opportunity for undergraduate students to submit papers to conferences and gives them the potential to be invited to conference proceedings for poster or oral presentations. Such an engineering experience also serves to enhance the chances that undergraduate engineering students will pursue their education up to masters or PhD proficiency. This is due to the inspiration that derives out of technical achievement and premises the engineering mindset that aspires for life-long technical excellence. Overall, the opportunity for undergraduate research presents many advantages to aid in the betterment of engineering education.

Conclusion

Undergraduate education is perhaps the most critical aspect of higher education because its purpose serves to educate and train the next generation of professionals that will confront advancing challenges of the future. For this reason, engineering education must continue to improve in order to prepare future engineers for the vast range of technical challenges they will address. One way of achieving this goal is by providing undergraduate engineering students with rewarding research opportunities to heighten their educational understanding and gain early experience with technical procedures currently taking place within the modern engineering industry. Active research projects can provide undergraduate students with many advantages such as increased achievement, greater motivation, broader understanding of engineering sciences and disciplines, and a mindset of technical excellence. Research areas within MEMS technologies present one of the most effective opportunities due to the variety of disciplines that are applied and the large range of emerging applications. Within MEMS technology, Micro-robotic drug-delivery research has shown great success in its purpose of expanding a mechanical engineering student's perspective on education, technical knowledge and skills, and engineering aspirations. By expanding engineering education beyond the limits of core curriculum, universities can greatly improve the success of many engineering graduates and ensure the development of a strong next generation of engineers who are technically trained to meet the advanced challenges of the future. This can be achieved by implementing programs that support and reward undergraduate engineering research as an effective approach to greatly enhancing engineering education and heightening the life-long success of future engineers, the engineering industry, and most importantly, the discoveries made to further advance humankinds understanding of the world and universe.

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