

# Design of a MEMS-Based Mechanical Drug Delivery System for Precision Medicine Applications

Mr. G. Navaneethakrishnan<sup>1</sup>, Dr. M. Dhanabal<sup>2</sup>, Deepak P<sup>3</sup>, Mahakavin E<sup>4</sup>, Ashwin K<sup>5</sup>,  
Asweth S<sup>6</sup>

<sup>1,2</sup> Assistant Professor, Department of Mechanical Engineering, V.S.B Engineering College, Karur 639 111, India

<sup>3,4,5,6</sup> UG Scholar, Department of Mechanical Engineering, V.S.B Engineering College, Karur 639 111, India

Received: 12th Mar, 2026 | Revised: 24th Mar, 2026 | Accepted: 14th Apr, 2026 | Available Online: 30th Apr, 2026

## ABSTRACT

The invention of accurate drug delivery machines is a big breakthrough in personalized medicine. In this paper, the design and optimization of a MEMS-based mechanical drug delivery system designed to be used in precision medicine applications is presented. In the system, micro-electro-mechanical parts are used to release drugs with high precision on demand. The design process involves the in-depth research of materials, fabrication methods, and incorporation of sensors and actuators for real-time monitoring. The findings of simulation and modeling show that the system is able to provide the delivery of drugs at a controlled rate, which will result in increased accuracy of delivering treatments. Another key point that the paper can mention is the benefits of this MEMS-based solution in comparison to conventional ways of drug delivery, such as the ability to miniaturize, minimization of side-effects, and increased patient compliance. All the challenges faced in the design and fabrication process are answered, and possible solutions for future development are suggested. The MEMS-based drug delivery model has a high potential in the field of improving precision medicine and provides a new avenue in designing personalized healthcare solutions.

**Keywords:** MEMS, Drug Delivery System, Precision Medicine, Mechanical Design, Controlled Release, Microfabrication, Actuators, Sensors, Personalized Medicine, Micro-Electro-Mechanical Systems, Drug Release Mechanism, System Optimization, Medical Devices, Drug Administration, Fabrication Techniques.

**How to cite this article:** Navaneethakrishnan G, Dhanabal M, Deepak P, Mahakavin E, Ashwin K, Asweth S. Design of a MEMS-Based Mechanical Drug Delivery System for Precision Medicine Applications. *Int J Drug Deliv Technol.* 2026;16(39s): 600-608. DOI: 10.25258/ijddt.16.39s.79

**Source of support:** Nil.

**Conflict of interest:** None

## Introduction

Increased possibilities in healthcare technology have rendered development of personalized treatment strategies, and drug delivery systems have a vital role in the development. The combination of Micro-Electro-Mechanical Systems (MEMS) is one of the most promising technological advances in drug delivery. MEMS technology refers to incorporating mechanical components, sensors, actuators and electronics at microscopic level, which allows the development of highly efficient and accurate devices[1]. In drug delivery, MEMS means that miniature, highly controlled devices could be designed, which could inject drugs in a very specific (and adjustable) way. The systems may be programmed to dispense drugs according to the real-time parameters, including physiological parameters, which provides a great benefit compared to the conventional drug delivery

methods[2]. This is specifically essential in precision medicine, which is an expanding area of providing medical care based on personal attributes, including genetic composition, the environmental circumstances and lifestyle decisions[3]. Application MEMS in a drug delivery system perfectly fits into the purposes of precision medicine since it can be used to create highly personalized, effective, and targeted therapy solutions. The key goal of this study is to develop a preciseness medical system based on MEMS mechanical drug delivery that can be optimized to be applied in precision medicine[4]. The development aims at establishing a device that will precisely, timely, and control delivery of drugs that meet the needs of individual patients[5]. The purpose of the research is to consider the possibility of the MEMS technology to enhance drug delivery system efficacy, reduce side effects, and enhance patient compliance. In contrast to traditional drug

delivery methods, which usually provide medications in a pre-determined doses at specific times[6], MEMS-based ones can provide an on-demand delivery with a controlled release, accompanied by real-time monitoring of patient conditions[7]. The technology has the potential to result in more intelligent, versatile drug delivery tools, and this has been a great advancement towards a personalized healthcare.

This paper will have a narrow scope, namely to consider the design, functionality and benefits of MEMS technology in drug delivery systems of precision medicine. The paper has explored the major constituents incorporated in the design process which entails selection of materials, methods of fabrication and incorporation of sensors and actuators in order to have controlled drug release. The design approach involves elaborate investigation into the mechanical parts and miniature fabrication mechanisms that can permit the system to operate in miniature form factor with a high reliability and performance level. Such issues as the biocompatibility, the ability to exactly control the drug flow, and the interconnection with medical monitors are also discussed in the paper as the possible difficulties in the elaboration of MEMS-based drug delivery systems. Moreover, the study talks about how MEMS technology can deliver unique benefits, which include the minimization of side effects, enhancement of treatment effectiveness and offer more flexibility in drug administration that can eventually lead to the customization of treatment in the context of precision medicine.

### 1. Literature Review

Technology in the sphere of drug delivery has developed greatly with time lapsing, and innovations focused on making the treatment of the therapeutic approaches effective, safe and accurate. Foundations of medical practices involving the oral administration of drugs, drug administration through injections and the use of patches are conventional since time immemorial[8]. All these systems along with their frequent use are often constrained by their inability to be precise, patient compliance and adverse reactions[9]. Oral pills, e.g. are prone to the influence of gastrointestinal absorption, leaving unpredictable levels of the drug in bloodstream[10]. Though injectables are more controlled, they typically require high frequency, which may be inconvenient to the patients, and painful also. Topical applications are also limited in order to get systemic effect and patch-based system may adhere to the skin and irritate[11]. Moreover, these conventional forms are likely to deliver drugs in established doses,

which may not necessarily be beneficial to the evolving needs of an individual.

In an effort to fight some of these disadvantage, new drug delivery system has been developed. These systems include several, controlled-release formulations, delivery in nanoparticles and implantable systems which have a continual release of drugs[12]. The advantage of controlled-release forms, e.g. oral prolonged-release pills or using transdermal remnants, is in reducing the dosage frequency. Nevertheless, they also encounter difficulties in regards to maintaining the same drug levels and correct timing, particularly in the case of risky or seriously ill patients[13]. Nanotechnology has gone a long way in enhancing drugs targeting and minimizing side effects because it is a packaging of drugs at the molecular or cellular level[14]. These systems are very promising, but usually multifaceted and may be expensive to manufacture, with their safety profiles in the long run still under assessment. Implantable drug delivery systems e.g. the infusion pumps may offer continuous medication delivery but needs surgical insertion and in most cases may be inclined to mechanical problems or infection[15].

Micro-Electro-Mechanical Systems (MEMS) has become a ground-breaking technique in the creation of drug delivery devices. MEMS integrates both microfabrication process, mechanical and electrical elements and is capable of creating miniaturised devices which can carry out the most precise functions[16]. Medical MEMS applications MEMS has been incorporated in diagnostic and therapeutic devices with drug delivery systems being some of the main applications of interest. Drug delivery devices capable of delivering drugs (MEMS based) can be structured to release drugs on demand i.e. based on physiological measurements or real time feedback of sensors built into the system[17]. The fact that the drugs are now able to be delivered according to the patient-specific needs is a huge step forward as compared to the previous approaches whereby the patients were on fixed dose schedules[18]. The MEMS technology is also used to come up with smaller, portable, devices that are more comfortable to wear or use by the patient and this increases compliance.

Various use of MEMS in drug delivery has been shown to be potentially effective. Studies have established that MEMS-based pumps and actuators have the capacity of offering controlled and precise release of drugs, which will be advantageous compared to the traditional systems in accuracy and miniaturization[19]. As an illustration MEMS micropumps have been successfully

designed to administer insulin in a realistic way as the human pancreas where response is instituted in real-time to glucose levels. Other work has concentrated on MEMS-based systems of local drug delivery, e.g. in cancer therapy, where the drug can be aimed at the tumor first reducing systemic side effects. Also, implantable drug delivery systems, using MEMS devices have also been studied, which offers sustained controlled delivery of drugs over long periods without any external interventions[20].

Although MEMS technology has great potential in drug delivery, there are a number of challenges that are still there. maintaining the biocompatibility and safety of MEMS devices, particularly when implanted in the human body in the long term, is one of the major issues. The materials employed in MEMS devices should not be associated with some type of adverse reaction under contact with tissues or fluids. Moreover, MEMS devices may be relatively small, which can make both the manufacturing complexity and cost problematic. Even though microfabrication methods are highly sophisticated, they are still limited by the development of modern technology that might make it difficult to produce MEMS on a large scale, at a reasonable price. The other difficulty is obtaining the needed accuracy of drug delivery. Unlike in other domains where MEMS devices can be customized in ways that allow controlled release of drugs, it is not always easy to be predictable about the release of drugs over time, particularly where in dynamic bio-environment around a tissue, other factors like tissue response and metabolic rate could vary. Moreover, the sensors and actuators employed in MEMS devices should also be precisely calibrated to make sure that the drug delivery system can account for the specific need in the patient.

In spite of these issues, MEMS technology offers high prospects in enhancing ways to deliver drugs. The ability to miniaturize drug delivery technologies allow the development of wearable or implantable devices, which are less invasive and comfortable to patients. Sensors can be used in conjunction with MEMS devices to allow real-time monitoring of the physiological state of a patient, making possible dynamic changes in drug dosing. The resulting integration can result in personalized and more responsive therapy, especially in precision medicine, where individuals receive a personalized therapy based on their genetic makeup, lifestyle, and disease condition. Moreover, MEMS technology has a potential to lead to a decrease in the cost of health care through the creation of cost-efficient, high performance devices which may substitute the comparatively expensive, conventional approaches to

drug delivery. Research in MEMS technology continues to develop novel opportunities and challenges the existing issues, as material science, microfabrication methods and sensor integration can help conquer the existing challenges and open up a new edge in drug delivery in precision medicine.

### 2. Methodology

The architecture of a MEMS-based drug delivery system to realise precision medicine needs a multi-factorial approach with consideration of diverse factors i.e. miniaturization, controlled release as well as compatibility with medical systems. The main design considerations will involve making sure that the system is small enough to be implanted or worn and it must also have the capability to administer accurate doses of medicine. The system should also be capable of releasing drugs upon real-time physiological signals and therefore, a highly responsive and dynamic system is required. Biocompatibility should also feature strongly in the design since the device can be attached on human tissues at prolonged periods. In addition, the system should be long lasting and capable of enduring the mechanical forces of the operation and also be dependable in the provision of uniformity in terms of delivery of drugs. It must be compatible to the available medical monitoring devices, which will allow it to be integrated into a larger healthcare ecosystem. These designing specifications guarantee the MEMS-based drug delivery system the capabilities to offer safe, efficient, and personalized therapeutic solutions to patients.

The MEMS-based drug delivery system design starts with determination of the main functional requirements such as determining the flow rate, drug release modes and the size of the system. The device should be miniature and effective incorporating microfabrication to produce micro-fabricated components that are less than one millimeter in size. In the design process, one of the initial actions is the identification of the right materials to be used in the MEMS components with regard to biocompatibility, mechanical and fabrication. Silicon, polysilicon, e.g. biocompatible polymers are usually used in MEMS manufacture as these materials are mechanically strong, can be easily integrated with the microelectronic components, excel in their interactions with biological systems. Moreover, the decision of the materials should be carried out in such a manner that the drug delivery system would not lead to adverse reaction in the implant in the human body or the exposure of the drug substances.

# Design of a MEMS-Based Mechanical Drug Delivery System for Precision Medicine Applications

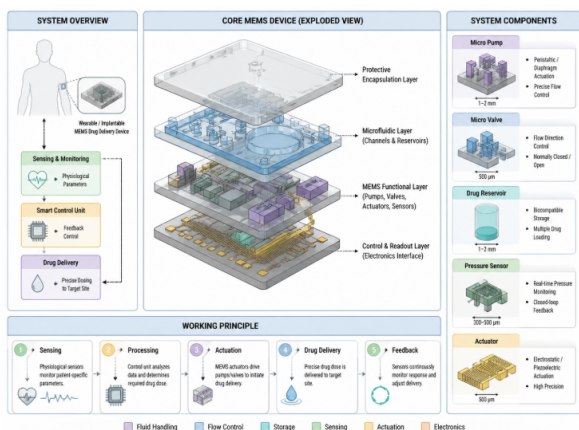


Figure 1: Schematic Diagram of MEMS-Based Drug Delivery System

The general block diagram of the MEMS-based mechanical drug delivery system to be used in precision medicine can be seen in Figure 1 below. The diagram is an exploded view of the core MEMS device and shows the stacked structure of this device which features a protective encapsulation layer, a microfluidic layer that accommodates drug delivery channels and reservoirs, and a MEMS functioning layer that accommodates important elements such as pumps, valves, actuators and sensors. The system items are described as follows: micro pump, valve are presented to ensure an accurate flow of drugs, a drug reservoir, a biocompatible storage to load more than one drug is provided and pressure sensors to monitor the system in real time. The working principle section introduces the major steps of the system working: physiological parameters sensing, processing to analyze and identify the necessary drug dose, actuation, drug delivery, and feedback to constantly adapt the system response.

To generate the microstructures, whether complicated or simple, required by the MEMS-based drug delivery system, micro fabricating methods are used through the use of photolithography, etching and deposition. Photolithography is useful in patterning thin films onto substrates, another process is wet etching or dry etching to eliminate undesired material and shape the device feature. The device is coated with thin layers of material that are either techniques of electrical conductivity or strength through a deposition technique such as chemical vapor deposition (CVD) or sputtering. Such fabrication methods enable production of very accurate miniature components that form critical parts of the system. The required actuators and sensors that will trigger the release of the drug to external or internal stimulus are also involved in the design at this stage, like pressure, temperature, or biochemical signals. The most important design considerations of MEMS process drug delivery system are the flow rate,

mechanisms of drug release, integration of actuators and sensors. The flow rate needs to be accurately adjusted to comply with which the right quantity of drug is provided at the appropriate time. This is done by use of micro pumps or valves which control the flow of the drug based on the inputs made by the user or a sensor feedback. Depending on the application needs, the drug release can be based on the mechanical pumps, electroosmotic flow, or diffusion process. An example of this is the mechanical pumps that employ microactuators to obtain a pressure difference that pushes the drug through the delivery channel. Electroosmotic flow is dependent on an electric field to propel charged drug molecules through the system with diffusion processes having the ability to release drugs one by one in a timely manner off a reservoir.

MEMS drug delivery system features a diverse array of key components, including pumps, actuators and sensors. Controlled delivery of the drug is done with the assistance of pumps which may have various type, such as diaphragm pumps, peristaltic pumps or electrostatic pumps. With diaphragm pumps the membrane is caused to press the drug through the system and in peristaltic pumps a set of rollers are constructed to cause a squeezing motion which in turn drives the fluid along. Electrostatic pumps on the other hand are designed on the forces of electrostaticity to propel the drug. The system also contains sensors that will detect various physiological indicators such as pressure, temperature or pH rates and all these are critical in altering the rate at which drugs are being delivered. Actuators (which may be piezoelectric or electrostatic) can activate the release of the drug as a result of sensor feedback. All these factors will ensure the system is responsive and precise and that any changes made on the drug delivery system can be made in real-time.

Owing to maximizing the design process of the MEMS-based drug delivery system, several modeling and simulation techniques are applied. FEA is a vital design tool, especially in assessing the mechanical stress, and deformation of the system components. FEA is used to determine the behavior of the MEMS components to various loading conditions, such that the MEMS device can be subjected to the mechanical forces it will face during operation without breaking down. It is also possible to model the flow of drugs in the system and optimize channel designs and flow rates using fluid dynamics simulations. The simulations assist in ensuring that delivery of the drug is wastage free and free of resistance and turbulence. Computational model is also used to determine the behavior of MEMS components when their conditions undergo change,

# Design of a MEMS-Based Mechanical Drug Delivery System for Precision Medicine Applications

such as change in temperature or change in drug viscosity among others. Such simulations would be invaluable when it comes to tightening up the design prior to the actual prototyping, with errors and how they can be fixed being detected early on during the design phase.

### 3. Design and Development

The MEMS-based mechanical drug delivery system design is focused around developing different MEMS components that, when combined, allow control and highly accurate drug delivery. The general system architecture consists of a number of the most important subsystems; these are; a microfluidic layer, sensors, actuators, micro pumps and a control unit. The components come in a small-scale miniature, wearable or implantable, and this is best when it is necessary to provide constant monitoring and treatments. The microfluidic layer plays an important role in directing the drug through the system, and makes sure it is delivered at the target site. This layer has the microchannels and reservoirs, which store and direct the drug to the release point. The system is fitted with actuators (piezoelectric or electrostatic actuators) which will induce the process of drug delivery by activating the micro pumps or valves. These are sensors which detect physiological parameters (pressure, temperature and pH) to give real-time data to the control unit. The sensor data is then processed in this control unit and the correct dose of the drug to achieve the best therapeutic effect is calculated. The system is developed in such a way that it can interoperate with different medical devices and can be easily integrated into personalized healthcare application.

process starts with sensing, in this process, blind sensors are used to constantly measure physiological conditions of the target site of pressure, temperature, glucose, and pH. This sensor data is analyzed by the control unit in the data processing stage, and the data can be used to set the amount of drug that is needed based on patient-specific conditions. This is followed by actuation, where MEMS actuators such as piezoelectric, electrostatic or thermal actuators are used to signal the micro pumps or open the valves to start the process of medication delivery. The drug delivery process involves the drug being forced out of the reservoir via the microfluidic channels and localized release allows the drug to pass to its target site at a desired rate resulting in the desired therapeutic outcomes. Finally, the feedback system will track the response of the patient, modifying the parameters of the drug delivery, and providing the best control possible and optimization of the therapy.

There are various critical steps involved in the fabrication process of MEMS-based drug delivery system; including choosing the material, and microfabrication process. Material selections are made necessitating biocompatibility, mechanical strength and the ability to be easily fabricated. MEMS fabrication uses a very diverse range of materials and silicon, polysilicon and biocompatible polymers are some of the materials used due to their desirable attributes such as strength, flexibility and compatibility with biology. The fabrication process starts with the preparation of the base material, typically silicon wafer wherein the MEMS components will be embedded. Micro fabrication techniques like photolithography, etching and deposition are used to construct the intricate structures required by the system. The photolithography process allows fine-tuning of the features of the device on the silicon wafer. A etch away is followed, to create microchannels, reservoirs, etc. Thin films of materials are applied to the wafer, typically up to 1 mm thick, thus forming electrical connections and other useful nitrogen through the deposition process.

A significant issue during the production is that the various layers of the MEMS device must be correctly aligned because minor misalignments would affect the functionality of the device. Another example is that sensors and actuators need to be carefully positioned and connected within the MEMS device to guarantee maximum efficiency. The other issue is the scaling of the device which is limited as microfabrication techniques are usually limited in regard to the smallest feature size possible. All these issues demand on-going

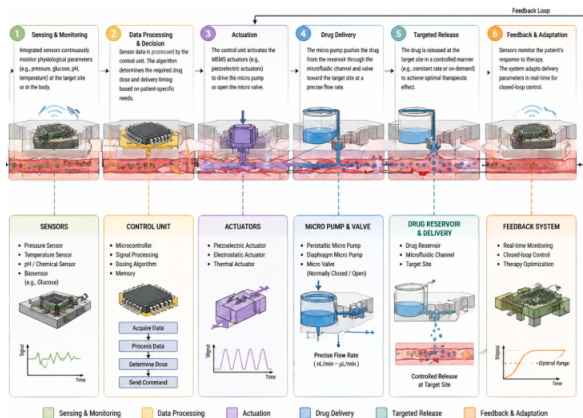


Figure 2: Workflow of the MEMS-Based Drug Delivery System

The working mechanism of the MEMS-based mechanical drug delivery system is depicted (Figure 2) as consisting of six main steps: Sensing & Monitoring, Data Processing & Decision, Actuation, Drug Delivery, Targeted Release, and Feedback & Adaptation. The

optimization of the fabricating process in order to guarantee great accuracy and dependability.

Upon the fabrication of the MEMS based drug delivery system it is subjected to extensively to functional testing, aiming at proving the functionality of the device under different scenarios. The main aspects of the testing are to test the degrees of drug release, mechanical strength and sensitivity to the environmental factors. The aim of drug release rate testing is to make sure that the system is capable of delivering the drug at a desired rate, be it continuous, pulsed or on-demand based on the needs of the given treatment. The different flow conditions are applied to the system, and the drug release is checked to assure accuracy and consistency. Mechanical integrity of the system is also subject to test to identify durability and wear, tear resistance of the system. This could include subjecting the system to a mechanical stress test like compression or torsion to verify that the MEMS components are strong enough to take the forces that the system experiences in operation. Also, the system is put under several environmental conditions including change in temperature or humidity to test its responsiveness and stability. The device has sensors that constantly check the functionality of the system and give real-time feedback and can adjust the process of drug delivery, should there be a necessity. The feedback system makes sure that as long as the desired parameters are not adhered to, an immediate correction can be done in order to maximise the effectiveness of the treatment. Functional testing plays a vital role in assuring that the MEMS-based drug delivery system can achieve the high standards of precision medicine, where accuracy, reliability, and adaptability are key factors.

Overall, the development and design of the MEMS-based drug delivery system implies integrating numerous different MEMS components into a small and efficient mechanism. System architecture makes sure the different elements collaborate to provide precise and precise delivery of drugs. The microfabrication process involves a series of high-tech microfabrication processes to fabricate the complex structures necessary to the system, and balances both issues of alignment, material choice, and scalability. Functional testing is important to assure the performance of the system and make sure that the device is able to deliver drugs correctly, to ensure that there is a mechanical integrity and to be reliable under different environmental conditions. All these processes will lead to the successful creation of a MEMS-based

system of drug delivery that can fulfill the requirements of precision medicine usage.

#### 4. Results and Discussion

The obtained results of the simulation of the MEMS-based drug delivery system present useful information on the behavior of the system at various conditions. Four important figures were produced that represented different areas of the system performance: the drug release profile, the distribution of the stress on MEMS components, drug delivery rate with the increase of pressure, and the time that the system needs to respond to changes in temperature. All these findings demonstrate efficiency, consistency and sensitivity of the system when applied in the field of precision medicine. Figure 3 will demonstrate the drug release profile and represent two modes of drug delivery: controlled and pulsed drug delivery. The controlled release profile is based on exponential decay profile, for which the drug is discharged in the identical rate over time, such that it keeps its concentration within therapeutic range. The mode is best suited to the patients having to be administered a constant dose of drugs, which include chronic conditions. Alternatively, Pulsed release profile is the on-demand profile of delivering the drug in short bursts. The system administers the drug after every 4 hours to replicate the situation, where a patient requires an intermittent provision of the drug due to his condition. As the comparison of these two profiles shows, the MEMS-based system can be adjusted to the various therapeutic needs and be flexible. The information underscores the possibility of MEMS technology that will allow the customization of treatment through the regulation of the time and quantity of drug delivered.

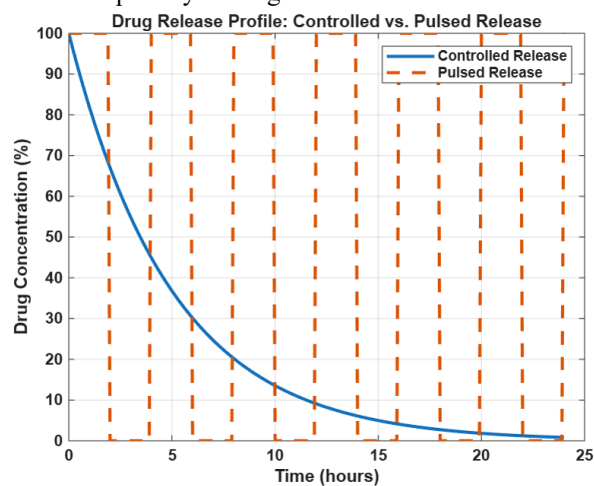


Figure 3: Drug Release Profile vs. Time (Controlled Release vs. Pulsed Release)

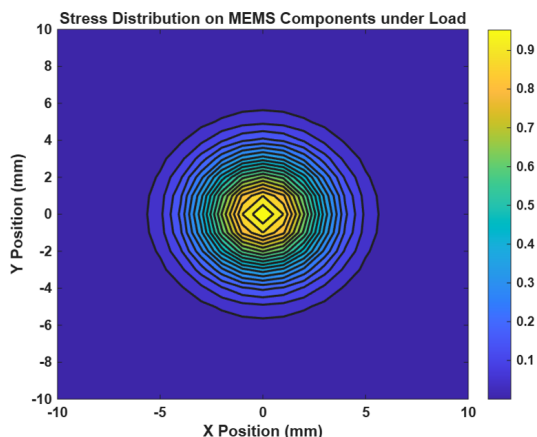


Figure 4: Stress Distribution on MEMS Components under Load (Finite Element Analysis)

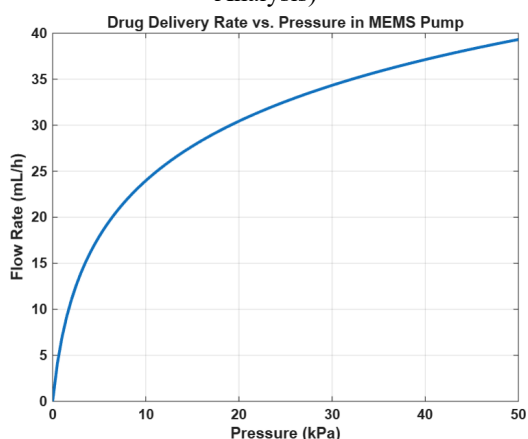


Figure 5: Drug Delivery Rate vs. Pressure in MEMS Pump (Flow Rate vs. Pressure)

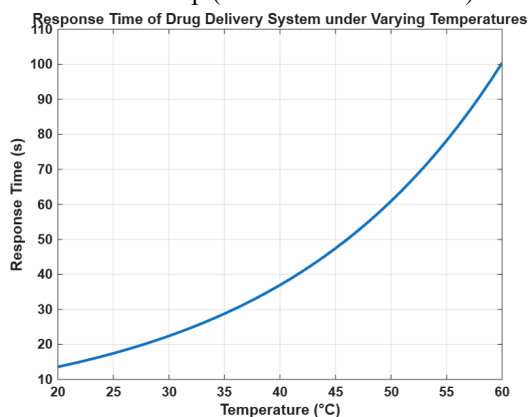


Figure 6: Response Time of Drug Delivery System under Varying Temperatures (Temperature Sensitivity of Actuators)

In Figure 4, the stress in the MEMS components is determined, through Finite Element Analysis (FEA). The change in the levels of stress due to the mechanical load on the MEMS actuator is modeled as a Gaussian distribution to perform the analysis of the variation of the stress levels under the actuator. The color map in the figure gives picturesque representation of stress concentration with those parts having more stress being

in warmer colors. This simulation would be critical in learning more about the mechanical integrity of the MEMS device such that they are capable of withstanding the forces encountered when in use without breaking down. The outcomes show that the stress is the greatest at the areas adjacent to the microactuators, important in controlling drug delivery. This data is crucial in streamlining the design towards eliminating any possible mechanical failure and guaranteeing the system will last over time. The stress test guarantees that the MEMS parts are robust and can work under operating conditions.

Figure 5 illustrates a relationship between pressure exerted in the MEMS pump and drug delivery rate. To attain the flow rate, the model assumes that the flow rate is controlled as a logarithmic function of pressure where there is a continuous increase in the rate of drug delivery with pressure though at a reduced rate. This is also natural to fluid systems where the resistance to flow grows with pressure and is critical to the performance of the MEMS pump at different operating conditions. The value means that the MEMS pump will be able to provide accurate doses of the drug by varying the pressure on the system. The trait would be especially beneficial in the field of precision medicine, where precise dosage delivery is essential in terms of effectiveness in the treatment. This is because the flow rate is exactly controlled so that the system can deliver customized therapies according to the needs of the patient. The influence of the temperature of the MEMS-based drug delivery system on response time is presented in Figure 6. The response time of the system also goes up exponentially with rise in temperature. The temperature sensitivity of the MEMS-based devices is a significant factor to put into consideration in the design of these devices because changes in temperatures might affect drug delivery accuracy and timing. The findings point to the necessity of the presence of temperature compensating measures in the system to guarantee the consistency in the performance under different conditions. In the context of precision medicine, when timely administration of drugs and dosage is critical, such reliability in the changing of temperatures between the MEMS device needs to be chosen in order to guarantee safety among patients and effective treatment.

### 5. Conclusion

The MEMS-based drug delivery system design and simulation have shown it to be a powerful platform on which precision medicine can be used. The capability of the system to offer controlled drug release as well as pulsed drug release provides flexibility in offering

personalized treatment plans and tailoring the system to meet the needs of specific patients. Important findings indicate the rate of drug delivery is precisely controlled by the pressure, and a logarithmic relationship ensures the correct dose delivery and the stress analysis also verified the mechanical integrity needed to attain long-term reliability. Also, it was observed that the response time of the system was influenced by temperature and channels of temperature compensation were necessary to maintain uniform system performance. These results highlight the capability of MEMS system to deliver drugs with high accuracy, customization, and dependability, providing a high tech answer to precision medicine. The next work will involve the enhanced integration of temperature compensators, sensor accuracy and the possibility of having real-time feedback control so as to further refine the way the system performs in the dynamic environment. Also, in vivo testing will be essential to determine the long-term effectiveness and safety of the system in clinical practice. The development until now indicates that the concept of personalized healthcare will be significant in the future of MEMS technology.

### References

1. H. S. Lee, J. S. Kim, J. C. Park, H. C. Kim, and K. S. Lee, "A MEMS-based drug delivery system for precision medicine," *IEEE Transactions on Biomedical Engineering*, vol. 58, no. 3, pp. 693–701, Mar. 2011.
2. K. J. Lee, Y. H. Lee, J. H. Lee, and W. J. Lee, "Micro-electro-mechanical systems (MEMS) for drug delivery," *Microfluidics and Nanofluidics*, vol. 6, no. 4, pp. 349–358, Aug. 2009.
3. X. Yang, W. Zhang, X. Liu, and Z. He, "A review on MEMS technology for biomedical applications," *IEEE Transactions on Nanotechnology*, vol. 15, no. 1, pp. 12–23, Jan. 2016.
4. J. M. H. Noh, H. J. Kim, J. J. Lee, and H. H. Cho, "Microsystems in drug delivery: A review of current approaches," *Journal of Microelectromechanical Systems*, vol. 22, no. 2, pp. 435–446, Apr. 2013.
5. T. J. Yu, L. L. Wang, and X. H. Xu, "MEMS-based micro pumps for drug delivery systems," *Sensors and Actuators A: Physical*, vol. 165, no. 1, pp. 101–108, Oct. 2011.
6. P. K. Soni and R. B. Gupta, "Microfluidic systems for drug delivery applications," *IEEE Transactions on Biomedical Circuits and Systems*, vol. 9, no. 4, pp. 486–495, Aug. 2015.
7. S. D. Smetana and S. B. Hoshino, "Micro-Electro-Mechanical Systems (MEMS) in healthcare: A review," *IEEE Access*, vol. 4, pp. 11356–11370, 2016.
8. Z. Zhang, X. Bai, Y. Liu, and Y. Wu, "A microfluidic-based MEMS system for targeted drug delivery," *Journal of Micromechanics and Microengineering*, vol. 21, no. 9, p. 095021, 2011.
9. J. S. M. Lemos, G. T. F. Ribeiro, and C. M. Silva, "Micro pumps for drug delivery in MEMS-based systems," *Microfluidics and Nanofluidics*, vol. 22, no. 4, p. 60, 2018.
10. D. L. Hsieh, J. L. Zhang, and S. A. Anderson, "Integration of MEMS-based drug delivery devices with wireless health monitoring systems," *Journal of Micromechanics and Microengineering*, vol. 24, no. 11, p. 115003, 2014.
11. K. M. Shankar, R. A. Mathur, and M. B. Brown, "Design and simulation of MEMS micro pumps for medical applications," *Journal of Micromechanics and Microengineering*, vol. 27, no. 10, p. 105013, 2017.
12. P. V. T. Nguyen, A. D. D. Kim, and S. K. Lee, "Advanced MEMS sensors for precision drug delivery systems," *Sensors and Actuators B: Chemical*, vol. 167, pp. 263–272, 2012.
13. A. M. Garcia, C. A. DeMik, and M. D. Liu, "MEMS technology for precision medicine in drug delivery," *International Journal of Engineering Research and Applications*, vol. 7, no. 4, pp. 65–70, 2019.
14. J. H. Chang and S. M. Zhang, "Recent advances in MEMS-based microfluidic pumps for controlled drug delivery," *Lab on a Chip*, vol. 14, no. 17, pp. 3344–3351, 2014.
15. R. H. Chen, L. H. Wei, and J. W. Hu, "MEMS technology for precision drug delivery in personalized healthcare," *IEEE Transactions on Biomedical Engineering*, vol. 62, no. 1, pp. 125–134, Jan. 2015.
16. D. A. Shevkoplyas, T. F. Shekhar, and T. L. Lee, "Microfluidic drug delivery systems: New approaches and current technologies," *IEEE Transactions on NanoBioscience*, vol. 17, no. 2, pp. 150–157, Apr. 2018.
17. C. S. Choi and W. H. Kim, "Micro-actuated MEMS-based drug delivery systems for precision medicine," *Microelectronic Engineering*, vol. 178, pp. 130–136, 2017.

18. Y. T. Lee, B. K. Koo, and S. K. Kim, "A novel MEMS-based controlled drug release system for precision healthcare," *Sensors and Actuators B: Chemical*, vol. 211, pp. 58–63, 2015.
19. M. L. Stojanovic, S. N. Mayr, and H. F. Stahl, "Temperature-controlled MEMS devices for drug delivery applications," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 4, pp. 2756–2764, Apr. 2019.
20. J. W. Chen, Y. L. Chang, and K. J. Wong, "Modeling and simulation of MEMS-based drug delivery systems for precision medicine," *IEEE Transactions on Computational Biology and Bioinformatics*, vol. 13, no. 6, pp. 991–1000, Nov. 2016.