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Research Article

Comparative Study to Analyze MEMS Based Microrobot Using Fuzzy TOPSIS Approach

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With the emergence in the field of developing small-scale systems, microrobots are gaining enormous attention due to their small size, wide number of application, and negligible effects on the surrounding. MEMS and microrobots both have electrical and mechanical parts which are situated on a single device and chip. This makes MEMS based microrobots and an excellent device due to its ease of fabrication and small size. MEMS-based microrobots have a wide number of applications in the field of bio-medical special drug delivery and invasive surgery. These tiny robots can be sent into the human body to send any medicine inside the human body. Various types of MEMS based microrobot can be used in drug delivery applications including magnetic nanoparticles based microrobots, magnetized spirulina microrobot, and electro-magnetic microrobots. However, the suitability of all these robots for drug delivery applications depends on the locomotion, navigation controlling, shape transformation, actuation requirement, and amount of drug wasted before moving to the destination. In this work, fuzzy rules based system is performed to confirm the dependence of the parameters including the locomotion, navigation controlling, shape transformation, actuation requirement, and amount of drug wasted on the working of microrobots in drug delivery applications. Similarly, fuzzy TOPSIS based study is performed to compare and analyze the most suitable microrobot for drug delivery application. Piezo-electric and electro-magnetic microrobots are considered the most suitable option with relative closeness to the ideal solution of 0.71 and 0.66, respectively, owing to their better shape transformation and movement.

1. Introduction

Automation in the industry is getting enormous attention owing to its excellent use in increasing the productivity and efficiency of industrial units [1, 2]. To achieve automation, robotic systems are widely used in industry. These robotic systems range from large size as well as nano-sized robots with different functionalities [3]. Among these types of robots, microrobots consist of mechanical and electric parts which is similar to the micro-electromechanical system (MEMS) [4]. Microrobots on a single chip with both electric and mechanical parts are categorized as MEMS microrobots [5, 6]. MEMS based system is designed on the basis of their actuation, sensing, structural, and electronic circuit. On microscale, microrobots also consist of these components in which they sense the environment based on the microstructure properties, and the electronic circuit then responds to the sensing data by actuating it.

Actuating can be moving from one place to another or to carry out a work based on the sensing data. The basic components along with their few basic types for MEMS based systems are shown in Figure 1. MEMS technology is expected to have an impact on microrobots in three ways. These ways include providing sensing and actuation, introducing a better and intelligent system, and providing autonomous distributive systems. With its small size and excellent applications, microrobots are considered an important constituent in the bio-medical industry. It has several applications in disease diagnosis, health monitoring, tissue engineering, invasive surgery, drug delivery, and cell manipulation [7–10].

Reported small-scale bio-medical robot sizes use range from tens of micrometers to several centimeters. Typically, the dimensions of a single biomedical MEMS microrobot are less than 1 mm and larger than 1 μm that can work on microscale forces. Thus, for microrobots, bulk forces such as inertial forces and buoyancy are negligible in comparison with its size. These parameters include surface tension, adhesion, viscous forces, friction, and drag. Microsized medical robots are used in surgical procedures which can be static or moveable [11, 12]. There are two main ways of designing, building, and controlling moveable biomedical microrobots including the following:

(i) On-board approach: similar to a typical robot which is self-contained and self-propelled, the miniature robot with components on-board has the capability to operate on its own.
(ii) Off-board approach: off-board microrobots have their components attached externally. All the actuation, sensing, and controlling parts are externally connected to the sensor.

In the various fields of biomedical engineering, drug delivery is considered as an important method to send various different types of drugs and medicines to various different parts of the human body. Microrobots of various different actuation principles have been used in the biomedical engineering field. Figure 2 shows microrobots of different types used in bio-medical applications. Various on-board as well as off-board microrobots have been reported in the literature which can be used in drug delivery using microrobots. Microrobots have the potential which makes them usually for application including real-time tissue controlling and complex drug delivery to the human body [13, 14]. However, it faces issues including its proper locomotion within the human body, navigation controlling, shape transformation, drug wastage, ease of fabrication, difficulty in controlling, and actuation principle as well as design.

Various MEMS based magnetic and piezo-electric robots are used which helps in providing an ease in drug delivery throughout the human body. However, their work is highly affected by the use of different types of actuation principles as well as materials to fabricate the microrobots [20, 21]. Various different types of microrobots that can be used for drug delivery include hydrogel microrobot, piezo-electric microrobot, magnetic nanoparticles based microrobots, magnetized spirulina microrobot, and electro-magnetic microrobots [22–26]. These various robots show issues in terms of drug wastage, slow motion and navigation, requirement of high actuation, and shape transformation. Koleoso et al identify various different types of microrobots which can provide magnetic actuation for drug delivery as well as for different other biomedical applications. In terms of MEMS based microrobots, these different microrobots can be defined in terms of a single lab of chip device (under the on-board approach) and can be categorized as an excellent way to improve the use of microrobots in drug delivery applications.

In this work, various different microrobots used for drug delivery including hydrogel microrobot, piezo-electric microrobot, hydrogel microrobot, and electro-magnetic microrobots are categorized in terms of MEMS based microrobots. The effect of the above-stated robots on the basis of 3D locomotion, stationary controlling, navigation controlling, shape transformation, drug wastage, ease of fabrication, and magnetic field requirement is analyzed using TOPSIS. The proposed system has application in the field of bio-medical including drug delivery, invasive surgery, dental, and other applications.

2. Methodology

In this work, the selected microrobots are analyzed for their dependent parameters using a fuzzy rule based system. After analyzing the effect of the parameters on the microrobot, the best microrobot for bio-medical application is analyzed using the TOPSIS study. The block diagram of the work is shown in Figure 3.

2.1. Fuzzy Analysis. The fuzzy analysis is carried out in the MAMDANI model for the three different microrobots and its effect on the output including 3D locomotion, navigation controlling, ease to fabricate, shape transformation, and drug wastage. The input hydrogel microrobot, piezo-electric microrobot, and electro-magnetic microrobots and output parameters are shown in Figure 4. Three membership functions are defined for all the inputs and outputs as shown in Figures 5 and 6. The ranges for the inputs and outputs are selected from 0 to 1. The membership function includes low, medium, and high. The low membership function has a range of 0–0.25, the medium membership function has a range of 0.20–0.80, and the high membership function has a range of 0.7–1.

Totally, 27 rules are then defined in terms of literature and theories. On the basis of the theories, 3D graphs are plotted which show the relationship between inputs and outputs. The graphs show that the robots significantly affect the motion, movement, and working of the robot. The rule viewer based on the fuzzy analysis is shown in Figure 7.

Based on the simulated values, the output crisp values are calculated based on the input crisp value from the rule viewer and the MAMDANI formula. The Minimum membership function for the MAMDANI formula is calculated using the input crisp values from the rule viewer.

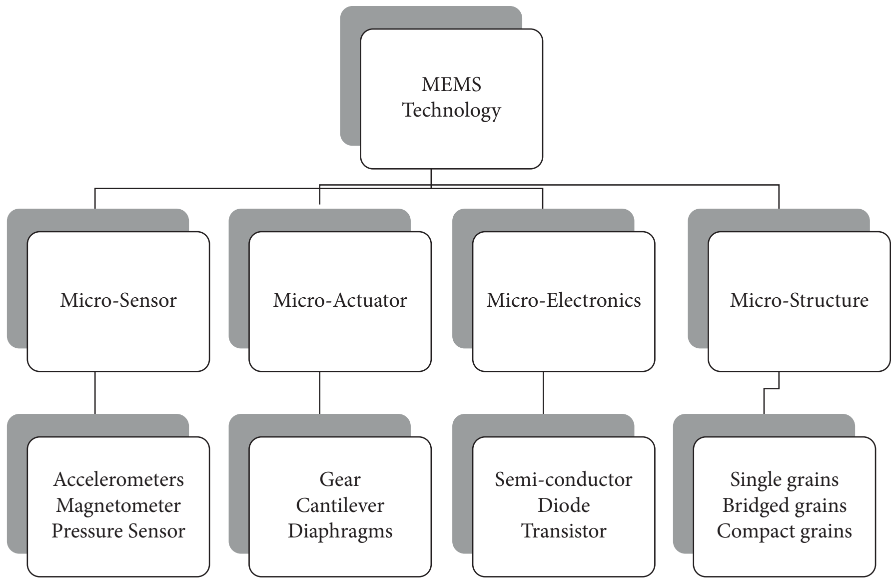

Figure 1: Basic components of MEMS based systems.

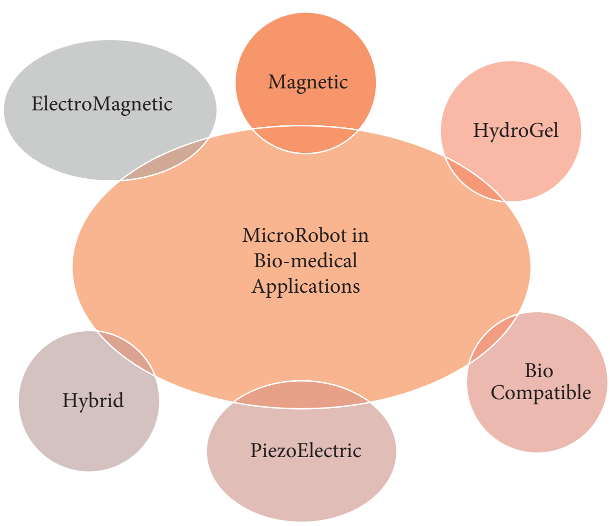

Figure 2: Microrobots used in bio-medical applications [15–19].

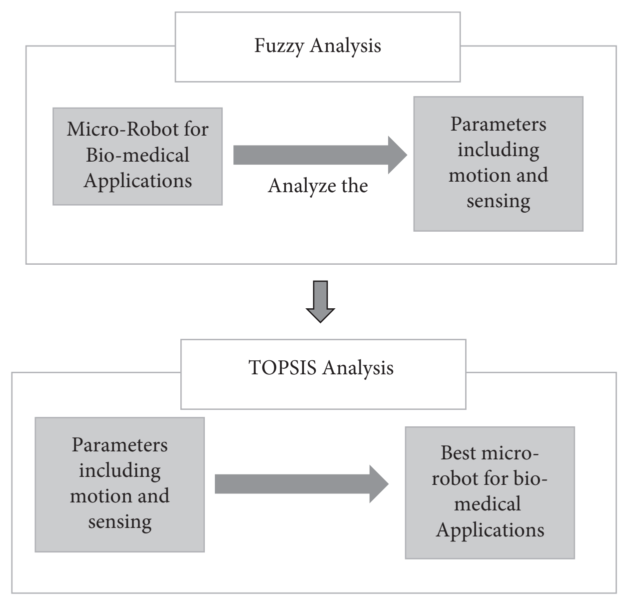

Figure 3: Block diagram for the proposed methodology.

Table 1 shows the simulated values from the crisp values and calculated values using the MAMDANI model. The error between the values is less than 1% which shows the accuracy of the system. Similarly, the dependence of all the three inputs microrobots also depends on the output 3D locomotion, navigation controlling, ease of fabrication, shape transformation, and drug wastage.

2.2. TOPSIS Study. TOPSIS is considered a way to do multicriteria decision-making for the determination of an ideal solution. To carry out the TOPSIS study, the following steps are taken.

(1) Various different criteria and attributes are selected. In this work, attributes include piezo-electric, electro-magnetic, and hydrogel microrobots, and the criteria on which the attributes are checked include 3D locomotion, ease of fabrication, navigation controlling, shape transformation, and drug wastage.

(2) After finalizing the attributes and criteria, the relative behavior of each factor is analyzed.

(3) The attributes are now checked based on the feedback from the literature review and experts to check the effect of attributes on the criteria. The marked attributes on the basis of criteria are in terms of 0–10.

(4) With the rating, the average attributes are finalized along with the decision matrix.

(5) The entities in the decision matrix are calculated as Xij.

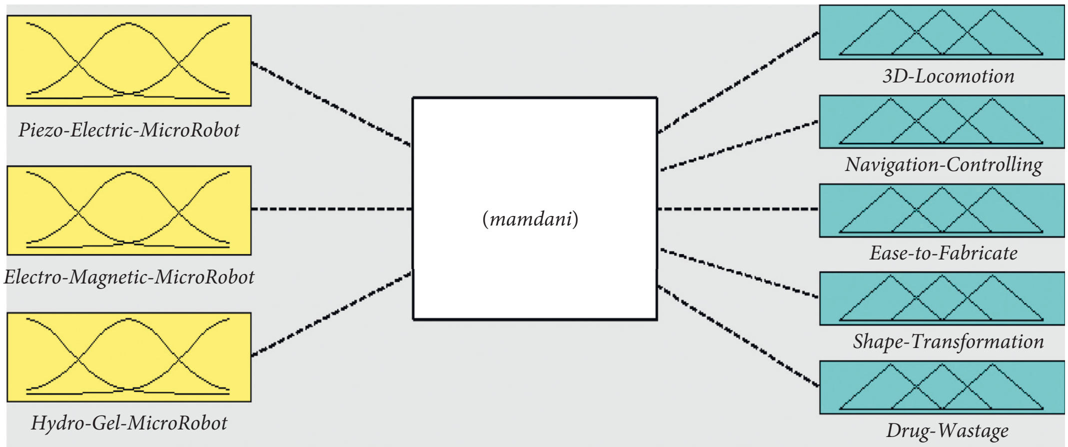

FIGURE 4: FIS figure of the fuzzy rule based system.

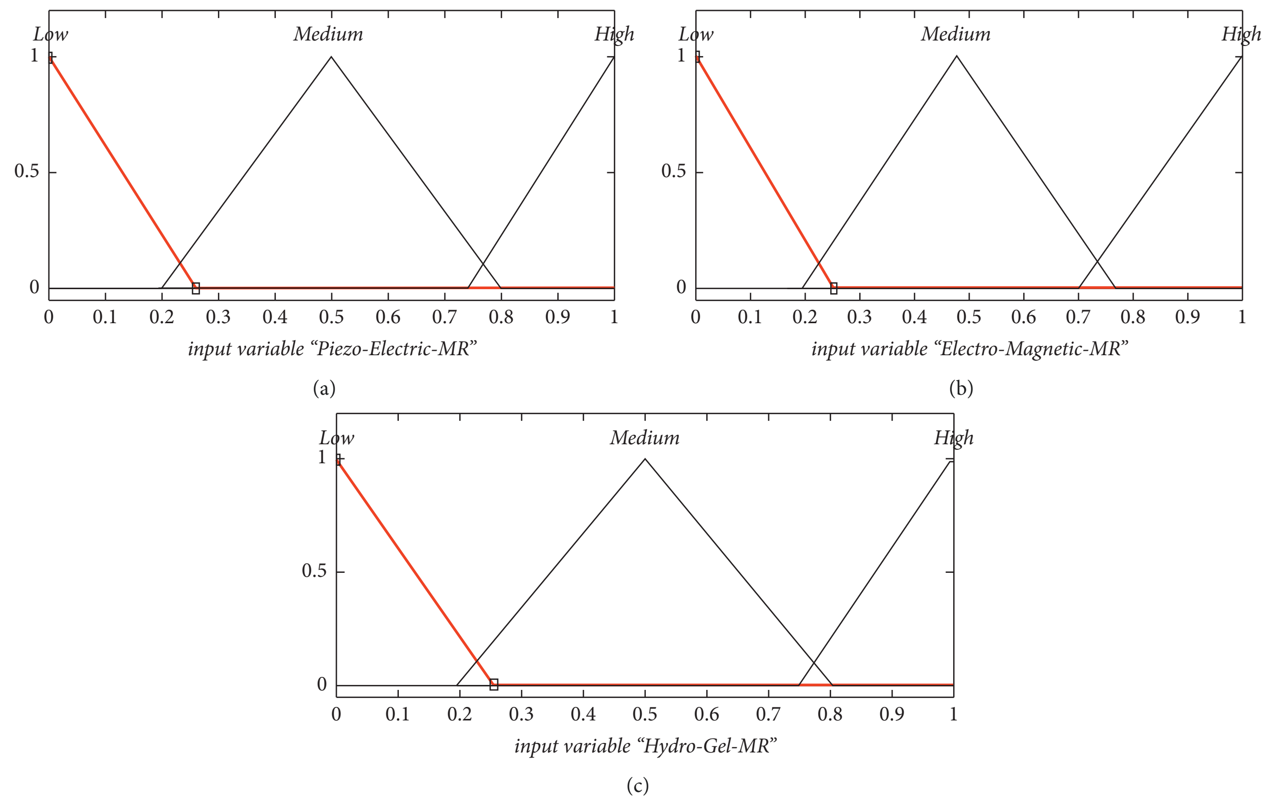

FIGURE 5: Membership function for input. (a) Piezo-electric microrobot. (b) Electro-magnetic microrobot. (c) Hydro-gel microrobot.

(6) After the entities are calculated, they are multiplied with each weight attributed.

(7) The ideal and nonideal solutions are calculated. The ideal solution is calculated by using the formula stated in the following equation:

$$S_i^+ = \sum_{j=1}^{m} \left[\left(V_{ij} - V_J^+ \right)^2 \right]^{0.5}, \tag{1}$$

where the positive ideal solution is represented by Vj^+, and the positive ideal solution is represented by Vj^-.

(9) The separation to the ideal solution is then determined using the formula in the following equation:

$$S_i^- = \sum_{j=1}^{m} \left[\left(V_{ij} - V_J^- \right)^2 \right]^{0.5}. \tag{2}$$

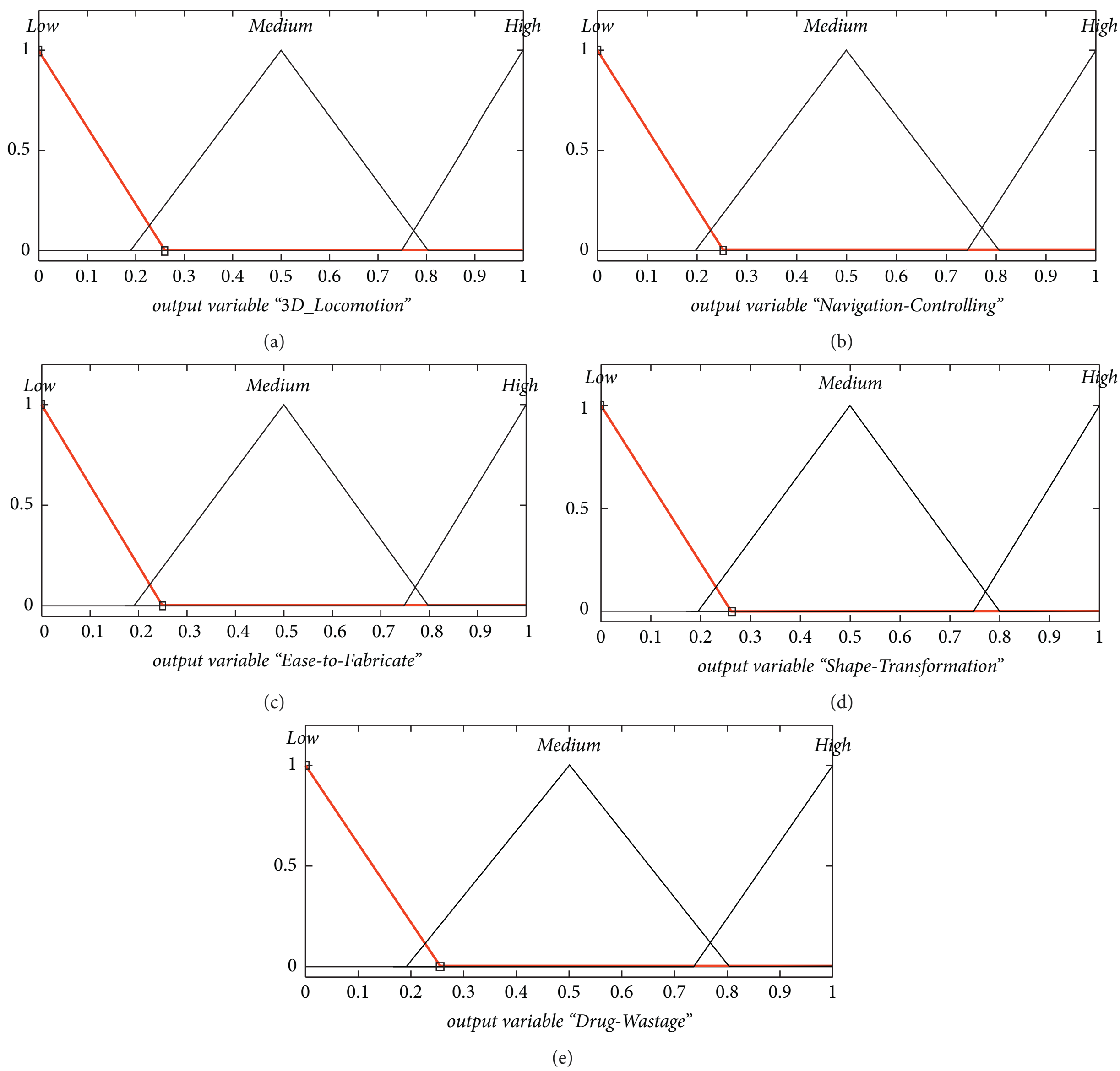

FIGURE 6: Membership functions for output. (a) 3D locomotion. (b) Navigation controlling. (c) Ease to fabricate. (d) Shape transformation. (e) Drug wastage.

(10) Relative closeness to the ideal solution is analyzed using the following formula:

$$\mathbf{P_i} = \frac{\mathbf{S_i^-}}{\mathbf{S_i^+} + \mathbf{S_i^-}}. \tag{3}$$

3. Fuzzy TOPSIS for Microrobots

In this work, microrobots including MEMS based piezo-electric microrobots, electro-magnetic microrobot, and hydro-gel microrobot are analyzed on the basis of 3D locomotion, navigation controlling, ease of fabrication, shape transformation, and drug wastage. Initially, the attributes and criteria are defined. For all three attributes, the criteria are defined based on a scientific research article. The selected information from the articles is analyzed to predict the possible attribute and criteria. The alternative which is the microrobots is numbered as R1, R2, and R3: R1 for piezo-electric microrobots, R2 for electro-magnetic microrobot, and R3 for hydro-gel microrobot. Attributes include 3D locomotion (A1), navigation controlling (A2), ease to fabricate (A3), shape transformation (A4), and seat drug wastage (A5). In terms of a fuzzy logic system, the attributes are converted into linguistic terms using the basic fuzzy triangular based system as shown in Figure 8. Linguistic terms including VS, S, M, L, and VL are taken.

Fuzzy numbers associated with the linguistic terms are shown in Table 2.

On the basis of the fuzzy ranges, the literature review is carried out to analyze the effect of parameters alongside the attributed weights designed. Table 3 shows the attribute weights designed based on literature review and fuzzy TOPSIS system.

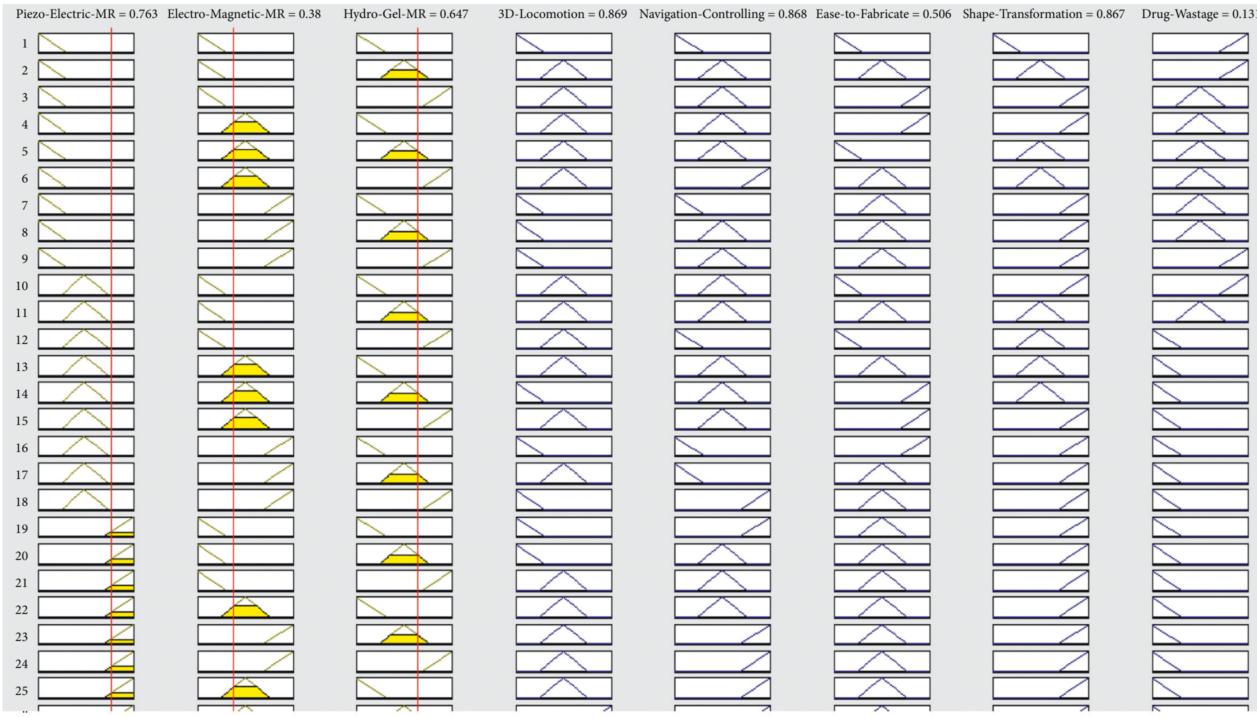

Figure 7: Rule viewer for the fuzzy analysis.

Table 1: Error between simulated and MAMDANI model calculated values.

	Simulated	Calculated	Error
3D locomotion	0.870	0.865	0.57
Navigation controlling	0.868	0.864	0.46
Ease of fabrication	0.506	0.51	0.78
Shape transformation	0.868	0.87	0.22
Drug wastage	0.131	0.135	0.5

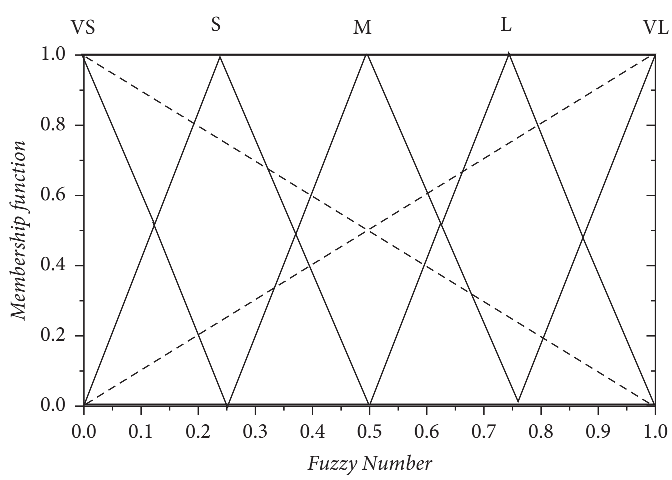

Figure 8: Linguistic terms for fuzzy logic number conversion.

Positive and negative ideal solutions are calculated which predict the best MEMS based microrobot for drug delivery. The negative ideal alternative shows the least suitable MEMS based microrobot for drug delivery application.

4. Results and Discussion

The decision matrix and the weighted standardized decision matrix (V_{ij}) are calculated for this work which is shown in Table 4.

Table 2: Linguistic terms and their ranges.

Linguistic Term	Range	Average
VS	0,0,0.3	0.1
S	0,0.3,0.5	0.26
M	0.3,0.5,0.7	0.5
L	0.5,0.7,1	0.7
VL	0.7,0.7,1	0.8

Table 3: Attributed weights for microrobots.

Criteria	Attributed weights (Wj)		
	Piezo-electric microrobots	Electro-magnetic microrobot	Hydro-gel microrobot
3D locomotion	9	8	7
Navigation controlling	7	7	8
Ease to fabrication	9	9	6
Shape transformation	7	6	6
No drug wastage	7	7	6

Table 4: Weighted standardized decision matrix (Vij) for all microrobots.

Criteria	Weighted standardized decision matrix (Vij)		
	Piezo-electric microrobots	Electro-magnetic microrobot	Hydro-gel microrobot
3D locomotion	0.13	0.114	0.1
Navigation controlling	0.055	0.055	0.063
Folding and unfolding based on temperature	0.147	0.22	0.147
Shape transformation	0.256	0.23	0.22
No drug wastage	0.272	0.25	0.23

The ideal solution and negative ideal solution are now calculated by using the formula stated below, and the ideal solution means the most suitable microrobot with the best parameters. The ideal solution is calculated using the following as shown in equation (1).

A negative ideal solution means the microrobots which is most unsuitable for use in drug delivery application and is not suitable for all the decision criteria. The negative ideal solution is calculated using the formula as shown in equation (2).

Relative closeness to the ideal solution is calculated using the formula as given in equation (3).

Table 5 shows the ideal solution and its closeness to the result. The ideal solution in this work is considered the best MEMS microrobot for drug delivery applications.

Piezo-electric and electro-magnetic microrobots show better results in terms of different factors including locomotion, navigation, shape transformation, and drug wastage. However, a piezo-electrically driven microrobot can be more beneficial in terms of other robots. This is due to the fact that the net flow in such microrobots is high which results in more accurate delivery of drug towards the sample. Similarly, thinner these types of microrobots can easily move towards thinner veins like arteries and capillaries due to their better navigation and travelling speed. This makes piezo-electric microrobots an excellent choice for use in bio-medical applications. Similarly, it provides better micropositioning and manipulation along with higher resolution, low cost, ease to fabricate, and small size suitable to be inserted in the human body for various different bio-medical applications.

Table 6 shows the benchmark table with respect to the literature review. It described the comparison between the fuzzy TOPSIS method used in various different fields using microrobots. These fields include its application in industrial arc welding, military industry, and overall multiple applications. Methods used include fuzzy TOPSIS, fuzzy AHP, and TOPSIS entropy method which are categorized as different multicriteria decision-making techniques for TOPSIS analysis.

As seen in all other applications of MEMS based microrobots, the basic parameters including its cost, availability, speed, accuracy, repeatability, ease of fabrication, capacity, and consumption have been analyzed for microrobots used in various different industries as shown in Table 6. This work however helps to provide multicriteria decision-making in predicting the best MEMs based microrobot for bio-medical application (drug delivery) for the basic parameters. Piezo-electric and electro-magnetic microrobots are considered the most suitable option for use as microrobot for drug delivery applications owing to their better shape transformation and movement.

TOPSIS provides the solution as a single ideal solution based on the decision-maker's proposed criteria and alternatives. Other multicriteria decision-making techniques including VIKOR, AHP, and BWM can be used in order to analyze and simulate the selection of microrobot. However, TOPSIS and VIKOR are considered the most suitable type of MCDM due to their work in the selection of alternatives in the existence of contradictions, number of alternative

Table 5: Closeness to the ideal solution for the microrobot.

Parameters	Piezo-electric microrobot	Electro-magnetic microrobot	Hydro-gel microrobot
$\mathbf{S_i^+}$	0.035	0.05	0.078
$\mathbf{S_i^-}$	0.088	0.10	0.034
$\mathbf{S_i^+ + S_i^-}$	0.123	0.15	0.112
$\mathbf{S_i^- / S_i^+ + S_i^-}$	0.71	0.66	0.329

Table 6: Benchmark table.

	Application	Parameters	Method	Remarks
Chu [27]	Multiple applications	Cost, load capacity, man–machine interface, availability of diagnostic software	Fuzzy TOPSIS method	Analysis of objective and subjective attribute
Chodha [28]	Industrial arc welding	Mechanical weight, repeatability, payload capacity, maximum reach, average power consumption	TOPSIS-entropy technique	Entropy weights method used for assigning attributes
Simion [29]	Military industry	High speed, accuracy, large arm reach, reduced dimensions of the robot's body, and arm, high flexibility, and reduced cost	MCDM (AHP method)	Industrial robots with different technical specifications
This work	Bio-medical applications	3D locomotion, stationary controlling, navigation controlling, shape transformation, drug wastage, ease of fabrication	Fuzzy TOPSIS method	Predicting the best robot for drug delivery application

processes and criteria, agility through the process of decision-making, computational complexity, adequacy in supporting a group decision, and addition or removal of a criterion [30].

The main contribution of this work includes providing a multicriteria decision-making method to predict the most suitable and sustainable type of microrobot from biomedical applications mainly drug delivery. This will help to improve the quality of drug delivery with better efficiency by using the proposed microrobot.

5. Conclusion

Microrobots are becoming an essential part of use in biomedical and other applications. Microrobots are becoming more popular and useful for invasive surgery, drug delivery, and pumping fluid. However, the suitability of the robot to be used is an important issue while using microrobot for biomedical application. This work shows the application of various different micropumps for use in drug delivery application by analyzing the output parameters of microrobots. Piezo-electric microrobots, electro-magnetic microrobots, and hydrogel microrobots are analyzed in this work, and fuzzy rule based system significantly shows the effect of these microrobots on the 3D locomotion, navigation controlling, shape transformation, ease of fabrication, and drug wastage. The rule-based fuzzy system provided authentic structure for fuzzy set and uncertainty handling susceptibility generated by the formally used fuzzy system. Fuzzy TOPSIS study is carried out which shows that the piezo-electric microrobots have the best closeness to the ideal solution of 0.71 as compared to other microrobots for use in drug delivery. For the electro-magnetic micropump and hydrogel micropump, the closeness to the ideal solution is 0.66 and 0.329, respectively. The scientific reason includes better and enhanced movement of the drug in the narrow medium as well as excellent micropositioning. The implementation of these sensors on the basis of their parameters in other applications including electronics, optics, material science, and mechanical systems can be carried out in the future. In the future, the interval-type fuzzy type 3 can be implemented in order upper and lower bounds of the membership function ranges are not constant, but they are fuzzy sets. This will help reduce the uncertainty and noise in the resulting fuzzy rule based system because the dependence on linguistic values decreases. These simulation results may be useful for fabrication of microrobots for biomedical applications.

Data Availability

All data are included within the manuscript, and more detail can be made available upon request from the corresponding authors.

Conflicts of Interest

The authors declare no conflicts of interest.

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References

[1] A. K. Inkulu, M. V. A. R. Bahubalendruni, and A. Dara, “Challenges and opportunities in human robot collaboration context of Industry 4.0 - a state of the art review,” *Industrial Robot: The International Journal of Robotics Research and Application*, vol. 49, no. 2, pp. 226–239, 2021.

[2] V. G. Pratheep, T. Tamilarasi, K. Dhileephan et al., “Design and fabrication of multitasking transit robot,” *IOP Conference Series: Materials Science and Engineering*, vol. 1057, no. 1, Article ID 012034, 2021.

[3] A. K. Basu, A. Basu, S. Ghosh, and S. Bhattacharya, *Introduction to MEMS in Biology and Healthcare*, AIP Publishing LLC, Melville, NY, USA, 2021.

[4] R. Garcia-Ramirez and S. Hosseini, “History of bio-micro-electromechanical systems (BioMEMS),” in *BioMEMS*, pp. 1–20, Springer, Berlin, Germany, 2021.

[5] D. Wang, H. Xie, L. Thomas, and S. J. Koppal, “A miniature LiDAR with a detached MEMS scanner for micro-robotics,” *IEEE Sensors Journal*, vol. 21, no. 19, pp. 21941–21946, 2021.

[6] B. Sun, G. Wood, and S. J. S. Miyashita, “Milestones for autonomous in vivo microrobots in medical applications,” *Surgery*, vol. 169, no. 4, pp. 755–758, 2021.

[7] B. Ahmad, M. Gauthier, G. J. Laurent, and A. J. I. T. o. R. Bolopion, “Mobile microrobots for in vitro biomedical applications,” *Surveyor*, vol. 38, 2021.

[8] W. Chen, X. Fan, M. Sun, and H. J. M. Xie, “The cube-shaped hematite microrobot for biomedical application,” *Mechatronics*, vol. 74, Article ID 102498, 2021.

[9] D. Folio, *Magnetic Microrobotics for Biomedical Applications*, Université d’Orléans, Orléans, France, 2021.

[10] D. Zhang, “Perception and manipulation of microrobots via optical tweezer,” Thesis or Dissertation, Imperial College London, London, UK, 2021.

[11] A. Aghakhani, O. Yasa, P. Wrede, and M. Sitti, “Acoustically powered surface-slipping mobile microrobots,” *Proceedings of the National Academy of Sciences*, vol. 117, no. 7, pp. 3469–3477, 2020.

[12] Z. Lao, N. Xia, S. Wang, T. Xu, X. Wu, and L. J. M. Zhang, “Tethered and untethered 3D microactuators fabricated by two-photon polymerization: a review,” *Micromachines*, vol. 12, no. 4, p. 465, 2021.

[13] S. Pané, P. Wendel-Garcia, Y. Belce, X.-Z. Chen, and J. Puigmartí-Luis, “Powering and fabrication of small-scale robotics systems,” *Current Robotics Reports*, vol. 2, no. 4, pp. 427–440, 2021.

[14] J. Choi, J. Hwang, J.-y. Kim, and H. Choi, “Recent progress in magnetically actuated microrobots for targeted delivery of therapeutic agents,” *Advanced Healthcare Materials*, vol. 10, no. 6, Article ID 2001596, 2021.

[15] E. Doutel, F. J. Galindo-Rosales, and L. Campo-Deaño, “Hemodynamics challenges for the navigation of medical microbots for the treatment of CVDs,” *Materials*, vol. 14, no. 23, p. 7402, 2021.

[16] A. V. Singh, M. Ansari, M. Mahajan et al., “Sperm cell driven microrobots—emerging opportunities and challenges for biologically inspired robotic design,” *Micromachines*, vol. 11, no. 4, p. 448, 2020.

[17] S. Jeon, A. K. Hoshiar, K. Kim et al., “A magnetically controlled soft microrobot steering a guidewire in a three-dimensional phantom vascular network,” *Soft Robotics*, vol. 6, no. 1, pp. 54–68, 2019.

[18] L. Yang, L. J. A. R. O. C. Zhang, and A. Systems, “Motion control in magnetic microrobotics: from individual and multiple robots to swarms,” *Annual Review of Control, Robotics, and Autonomous Systems*, vol. 4, no. 1, pp. 509–534, 2021.

[19] L. E. Beaver, S. Das, and A. Malikopoulos, “A first-order approach to model simultaneous control of multiple microrobots,” 2021, https://arxiv.org/abs/2111.03232.

[20] L. S. Novelino, Q. Ze, S. Wu, G. H. Paulino, and R. Zhao, “Untethered control of functional origami microrobots with distributed actuation,” *Proceedings of the National Academy of Sciences*, vol. 117, no. 39, pp. 24096–24101, 2020.

[21] A. Flayyih Hussein, B. Ibraheem Jameel, and K. Karam Abd, “Comparative analysis of Fuzzy MCDM methods for material selection in biomedical application,” *Association of Arab Universities Journal of Engineering Sciences*, vol. 25, no. 2, pp. 137–148, 2018.

[22] O. Ehrenberg and G. Kósa, “Analysis of a novel piezoelectric micro-pump for drug delivery in a medical integrated micro system,” in *Proceedings of the 2012 4th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob)*, pp. 467–472, Rome, Italy, June 2012.

[23] S. Tasoglu, C. H. Yu, H. I. Gungordu, S. Guven, T. Vural, and U. Demirci, “Guided and magnetic self-assembly of tunable magnetoceptive gels,” *Nature Communications*, vol. 5, p. 4702, 2014.

[24] J. Giltinan, E. Diller, C. Mayda, and M. Sitti, “Three-dimensional robotic manipulation and transport of micro-scale objects by a magnetically driven capillary micro-gripper,” in *Proceedings of the 2014 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 2077–2082, IEEE, Hong Kong, China, May 2014.

[25] T. Xu, J. Yu, X. Yan, H. Choi, and L. Zhang, “Magnetic actuation based motion control for microrobots: an overview,” *Micromachines*, vol. 6, no. 9, pp. 1346–1364, 2015.

[26] W. Hu, K. S. Ishii, Q. Fan, and A. T. Ohta, “Hydrogel microrobots actuated by optically generated vapour bubbles,” *Lab on a Chip*, vol. 12, no. 19, p. 3821, 2012.

[27] T. C. Chu and Y. C. Lin, “A fuzzy TOPSIS method for robot selection,” *International Journal of Advanced Manufacturing Technology*, vol. 21, no. 4, pp. 284–290, 2003/02/01 2003.

[28] V. Chodha, R. Dubey, R. Kumar, S. Singh, and S. Kaur, “Selection of industrial arc welding robot with TOPSIS and Entropy MCDM techniques,” *Materials Today Proceedings*, vol. 50, pp. 709–715, 2022.

[29] M. Simion, L. Socaciu, O. Giurgiu, and S. M. Petrişor, “The selection of industrial robots for military industry using AHP method: a case study,” *Acta Technica Napocensis Series: Applied Mathematics, Mechanics, and Engineering*, vol. 61, no. 2, 2018.

[30] A. M. Ghaleb, H. Kaid, A. Alsamhan, S. H. Mian, and L. Hidri, “Assessment and comparison of various MCDM approaches in the selection of manufacturing process,” *Advances in Materials Science and Engineering*, vol. 2020, no. 1, 16 pages, Article ID 4039253, 2020.