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Performance assessment of in-pipe inspection microrobots by FAHP method

M. Ghandehari*, M. Omidvari, R. Nadafi

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Abstract Since the issue of low diameter in-pipe inspection microrobots is particularly important in microrobotics field, in this paper, the results of a study on the various built or designed microrobots are presented. The objective of our paper is the prioritizing of in-pipe microrobots because that is an important tool in medical and industrial applications. This study , which includes 7 types of in-pipe microrobots such as Dielectric, Ionic Polymeric Metal Composite, Electromagnetic, Phase-change actuator, Piezoelectric actuator, Pneumatic actuator and Shape Memory Alloy actuator compares with some criteria such as the consuming power, response time, efficiency, dynamical modeling, producing force and manufacturing. These criteria are provided by specialists in standard organizations. In here, Fuzzy Analytic Hierarchy Process method is used for the best mechanisms determination in each field and weight of each criteria and their importance is determined. This study assists the design of a novel microrobotic system based on Fuzzy Analytic Hierarchy Process method with the design criteria consideration.

Keyword: Microrobot, Fuzzy Analytic Hierarchy Process, In-Pipe Microrobot.

1 Introduction

In microrobotic systems, the in-pipe inspection microrobots are an area of major importance. The importance and necessity of this study are to identify priority mechanisms of in-pipe microrobots for medical applications such as endoscopy, colonoscopy, and industry such as inspection of narrow pipelines, etc. The in-pipe microrobots should be able to inspect the low diameter pipelines in dangerous and unavailable areas such as narrow nuzzles or in the human body's intestine for the colonoscopy [4-7]. In this paper, the mission of in-pipe microrobot is the inspection of the narrow nuzzles. Always in power plants, the risers, which are very narrow, hot and inaccessible, need to check in operation. Likewise, aircraft fuel tubes that are narrow and inaccessible should be checked. Therefore, the main task of in-pipe microrobots in this paper is an inspection of the narrow tubes. The payload is a camera which captures and saves the image of the tube. After making operation, the user loads the pictures and defective

* **Corresponding Author. (✉)**
E-mail: Nasrin.ghandehari@gmail.com (M. Ghandehari)

M. Ghandehari
Science and Research Branch, Islamic Azad University, Tehran, Iran

M. Omidvari
Industrial and Mechanical Enginering Faculty, Qazvin Islamic Azad University, Iran

R. Nadafi
Space Science and Technology Institute, Amirkabir University of Technology, Iran

areas are determined.

In this article, for the purpose stated above, various types of in-pipe microrobots up to now were collected and after eliminating the old and similar prototypes, all in-pipe microrobots are categorized in 7 types based on: Ionic Polymeric Metal Composite (IPMC), electromagnetic, phase-change actuator, piezoelectric actuator, Pneumatic actuator and Shape Memory Alloy (SMA) microactuator. The criteria of this paper are the consuming power, response time, efficiency, dynamical modeling, producing force and manufacturing that hierarchy of this case is presented in Fig.1.

Power consumption and efficiency are two key parameters in every system. Each designer tries to select elements which have lower consuming power with high efficiency, thus we consider those as criteria. Similarly, the response time refers to the microactuator of microrobot and affects the forwarding speed. Due to the time limitation, we consider response time as the next criteria. Control engineer deals with the dynamical modeling and producing force. In-pipe microrobots need to be controlled thorough the path, then microrobots must have the simple dynamical model and higher producing force. Finally, it is clear that each designed microrobots should be fabricable then the manufacturing is considered to be one of the criteria.

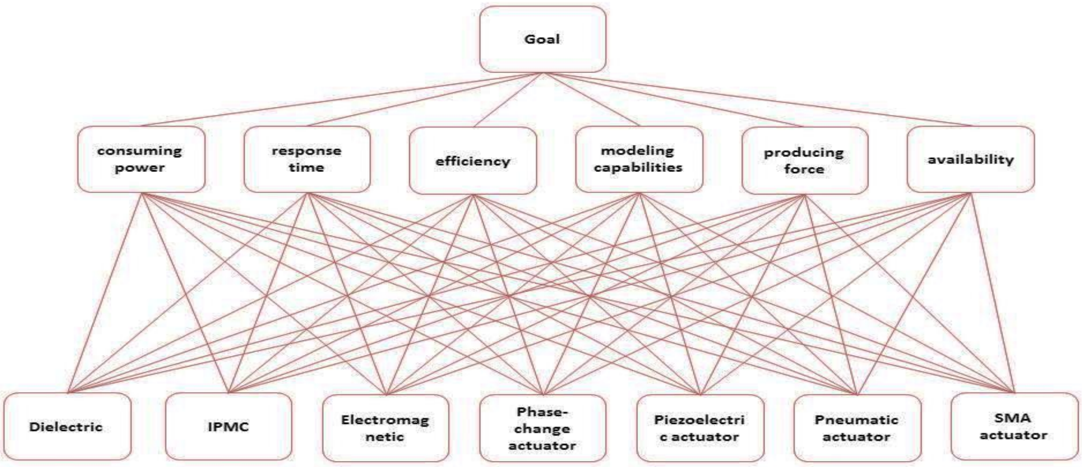


Fig. 1 Hierarchy of the problem

The paper is organized as follows. Section 2 is dedicated to a brief explanation of the 7 selected microrobots. Section 3 will present our studies on consuming power, response time, efficiency, modeling capability, producing force and manufacturing and section 4 will describe the research methodology in detail. Eventually, section 5 and 6 will present the results and conclusion of our research.

2 The studied microrobots (alternatives)

Various types of microrobots, taken into consideration in this study, are categorized in 7 parts with respect to their actuator types. A brief description of each one is given below.

A. *Dielectric actuator*

The studied microrobot in this field, which is presented in [1], was mimicked annelid animals that it likes the earthworm. The new design soft actuator called ANTLA is based on the polymer dielectrics. As shown in Fig.2, it has muscle like characteristics with the capability of performing motions such as forward, backward and controllable compliance [1].

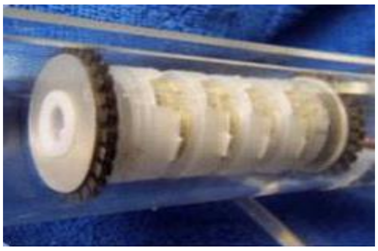


Fig. 2 Design by Choi et al. [1].

B. *Ionic Polymeric Metal Composite actuator*

In this field, Kim et al. proposed a ciliary type 8 Ionic Polymeric Metal Composite actuators, which can be operated in aqueous surroundings like inside of the human body [2]. Walking principle of this microrobot is shown in Fig. 3.

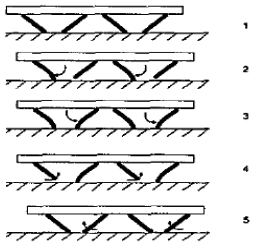


Fig. 3 Walking principle of Kim et al. micro robot [2].

Using a similar actuator Arena et al. presents an innovative wormlike robot which is totally made of IPMCs, and each actuator has to carry its own weight. As shown in Fig.4, all of the actuators are connected together without using any other additional part, thereby constituting the robot structure itself. Worm locomotion is performed by bending the actuators sequentially from “tail” to “head,” imitating the traveling wave observed in real-world non-adulatory locomotion [1].

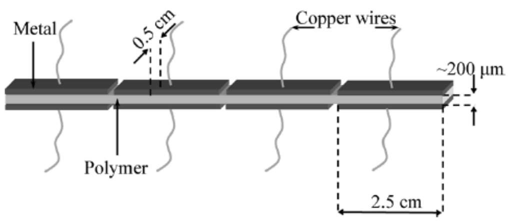


Fig. 4 Schematic Ionic Polymeric Metal Composite worm presented in Kim et al. [2].

C. Electromagnetic actuator

Lu et al. presented a bristle-based inchworm mobile robot using a short stroke electromagnetic linear actuator. The main body and movable unit of the robot are joined by using a sealed bellows, as shown in Fig. 5 and the bristle legs are designed so that it can operate both on plane surfaces and also in liquid [6].

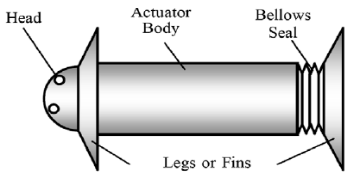


Fig. 5 Schematic structure of the Lu et al. inchworm robot [6].

The second main group of these microrobot types is presented by Ma and Ya [7]. This wireless powered earthworm-like microrobot which has a multi segment squirm mechanism (shown in Fig. 6) is designed and manufactured driven by dc motors [7].

(a) **(b)**

Fig. 6 (a) A driving segment and (b) Microrobot as a whole [7].

Another one is a capsule-type microrobot proposed by Park et al. [8]. This microrobot has synchronized multiple legs actuated by a linear actuator which can be composed of micromotor and lead screw, and two mobile cylinders inside the capsule. By the kinematic relation between the legs and the mobile cylinders, the microrobot can move forward in the gastro-intestine. The concept design of the microrobot is shown in Fig.7.

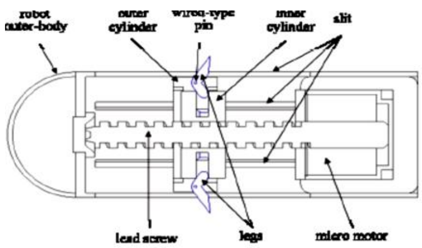


Fig.7 Concept design of microrobot [8].

D’Attanasio et al. [9] have introduced a tele-operated mobile microrobot incorporating a type of electromagnetic micro motor. This one cubic centimeter microrobot used two micromotors to actuate the two wheels of the microrobot [9]. The schematic view of this microrobot is given in Fig.8.

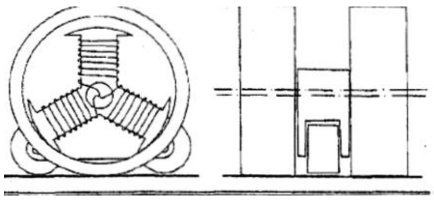


Fig. 8 Schematic view of a microrobot [9]

The best studied microrobot in this field was presented by Suzumori et al. [13]. As shown in Fig. 9, this microrobot utilizes a novel micro mechanism called a planetary wheel mechanism for robot drive and micro electromagnetic motor with a micro planetary reduction gear to drive the planetary wheel mechanism.

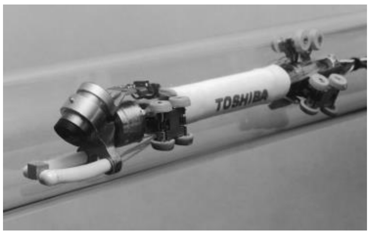


Fig. 9 Micro inspection robot carrying a recovered object in pipe [13].

D. Phase-change actuator

Kato et al. [11] proposed an inchworm type in-pipe mobile microrobot driven by three gas-liquid phase change actuators (Fig. 10). The actuator is made of welded stainless steel bellows and also the operating fluid and a heater are enclosed in it [11]. By applying or removing heat, the modules stretch and release, respectively, and also the microrobot moves with the frictional bulging brakes.

Fig. 10 A photograph of the fabricated microrobot by Kato [11].

E. Piezoelectric actuator

In this field, three microrobots were considered. One of them is presented in Guozheng et al. [12]. This miniature multi-joint piezo-driving squirming robot is composed of three linear piezo-driving cells and one head as shown in Fig. 11. The microrobot move a miniature displacement through the sequentially deformations of these piezo-elements.

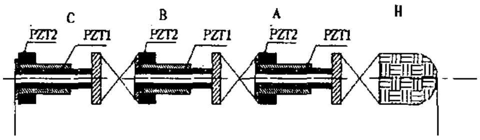


Fig. 11 The structure of the microrobot [12].

The other one in this field is Nishikawa et al. [13] in which in-pipe micro locomotive system is presented. This system is composed of an outside host and a microrobot. The outside host supplies energy and transmits the commands to the robot by using microwaves. The locomotive mechanism shown in Fig. 12, using a piezoelectric bimorph actuator, moves according to inertia drive method [13].

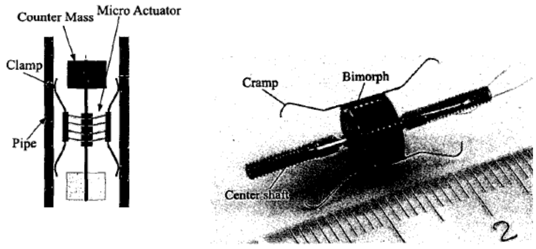


Fig. 12 Developed locomotive mechanism using multi-layered PZT bimorph actuator [13].

The latest studied microrobot in this field was in Hyunjun park et al (Fig.13) [8]. A Tiny Ultrasonic Linear Actuator (TULA) was employed in this microrobot. TULA is composed of piezoelectric ceramics, elastic material, a housing element to fix piezoelectric ceramics and a shaft to guide a moving element. The shaft guiding moving element is fixed in a copper plate of the elastic material that bonded on ring-shaped piezoelectric ceramics. The unified copper plate and piezoelectric ceramics are also combined with the housing element. Both sides of the shaft of TULA are fixed by shaft holder made of rubber within the robot body. The moving element installed with legs is disposed in the robot body.

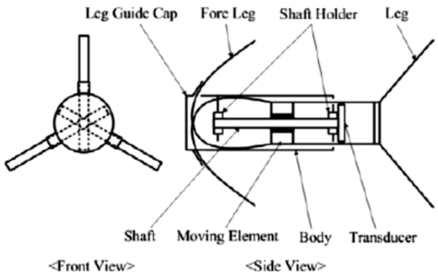


Fig. 13 Conceptual design of the proposed locomotive mechanism [8].

F. *Pneumatic actuator*

In this field, three microrobots were studied. These microrobots are actuated by air feeding systems, miniature valves and also suction cups (Fig.14). Carrozza et al. [15] proposed a miniature microrobot propelled by three pneumatic actuators. One of these actuators is extensor which elongates to provide longitudinal motion, and the two others are clampers, which provide traction to the minirobot by adhering to the colon wall.

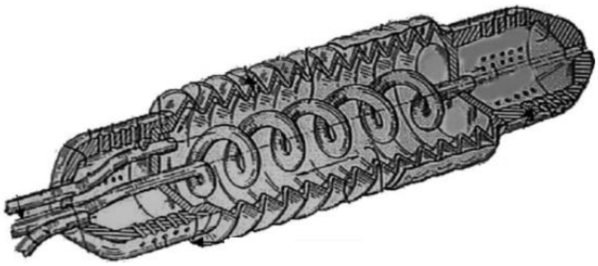


Fig. 14 Pneumatic lay-out of the microrobot: (a) cylindrical clamper with suction holes and hemispherical tips; (b) rubber bellow; (c) service pipes [15].

Another microrobot in this field was a microrobotic endoscopic system suggested by Dario et al. [4]. The propulsion system based on inchworm principle is composed of three modules (Fig.15). Two modules which were located at two ends of the device have the primary role of providing traction to the microrobot by appropriately clamping the walls of the intestine. A third module whose role is to extend the microrobot is located between the two clampings.

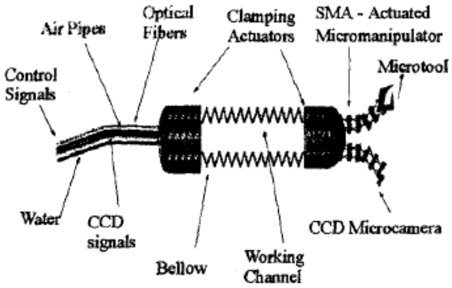


Fig. 15 Scheme of Dario et al. microrobot [4].

The last studied microrobot in this field was Lim et al. inch-worm like microrobot (Fig.16). The mechanism uses only one pneumatic insufflations line to reduce the stiffness of the pneumatic lines and the friction force between pneumatic lines and the pipe wall. By drilling microholes among the rear clamp, the elongation module, and the front-clamp, the timing of the airflow among the chambers can be controlled. The inchworm-like locomotion that is the rear clamping expansion of the elongation module and the front clamping is realized in sequence as the air insufflates to the rear clamp. With one cycle operation of insufflations and stopping insufflations to the rear clamp, the inchworm-like locomotion of the robot is accomplished. The insufflating air is controlled with an on/off pneumatic valve.

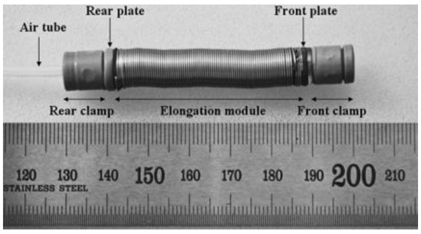


Fig. 16 Inchworm prototype microrobot [14].

G. Shape Memory Alloy actuator

Despite the studied pneumatic driven microrobots have a Shape Memory Alloy actuator in their structures, in this part, the Shape Memory Alloy directly driven microrobots are studied. In this field, Chang-Jun et al. [16] designed a resilient-rigid coupling Shape Memory Alloy (RRSA) driving micro-wheeled-robot (Fig.17). The advantage of RRSA is to enlarge the displacement output apparently compared with the ordinary Shape Memory Alloy linear actuators. Instead of following the traditional motion mechanism of legged-structure, the motion of the micro-robot is implemented by the wheel rotating mechanism which consists of rolling structures and a type of self-locking device [16].

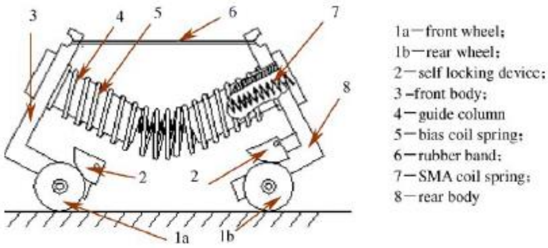


Fig. 17 Schematic diagram of the micro-wheeled-robot [16].

Another proposed microrobot in this field is Kim et al. [17] microrobot. This prototype was developed with two-way linear actuators using a pair of Shape Memory Alloy springs and four clampers as shown in Fig. 18. To drive the mechanism, the clamper slides forward when a front linear actuator is contracted. After the clamper finished sliding forward, the clamper clamps the contact surface and the body moves forward during the contraction of the rear linear actuator. Finally, the clamper releases the contact surface and slides forward as the front linear actuator is contracting.

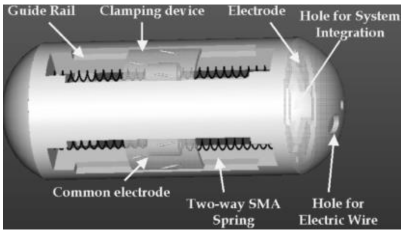
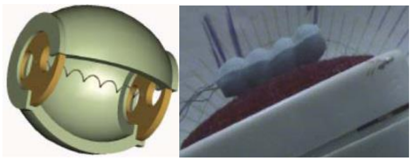


Fig. 18 Kim et al. microrobot [17].

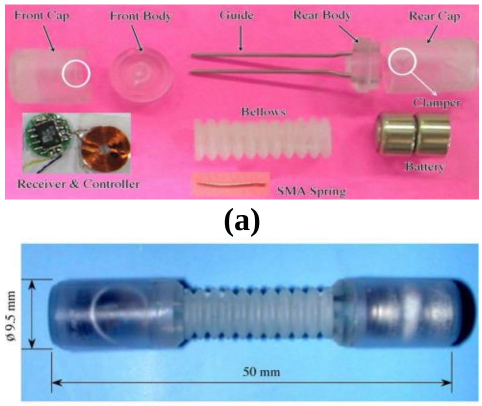
Menciassi et al. [18] designed an artificial earthworm with four modules which can be driven independently according to non-adulatory locomotion of living earthworms. Each module shown in Fig. 19 is actuated by one or more Shape Memory Alloy springs. The robot is covered by a shaped silicone material which can be used as a platform to insert tiny legs for obtaining differential friction conditions [18].



(a) (b)

Fig. 19 (a) Earthworm module, (b) The artificial earthworm [18].

Kim et al. [19] also proposed another Shape Memory Alloy microrobot using only one Shape Memory Alloy spring actuator and one silicone bellow is shown in Fig. 20. The Shape Memory Alloy actuator and the bellow play a role in contraction and extension of an earthworm muscle, respectively, and results in the microrobot locomotion.



(b)

Fig. 20 (a) Components of locomotive robot; and (b) assembled locomotive robot [19].

The latest studied microrobot in this field was Liu et al. [20] Shape Memory Alloy actuated microrobot. As shown in Fig. 21, this microrobot has two kinds of Shape Memory Alloy actuators. One is for crawling part and the other one is for the contracting part. The Shape Memory Alloy spring will contract when subjected to an electric current. In consequence, the contact force between the common leaf spring (an elastic leg) of the crawling part and the pipeline is only the friction caused by the gravity of the crawling part. If the Shape Memory Alloy spring is not subjected to an electric current, the common leaf spring will exert force on the pipeline with its elasticity. This is actuating principle of the crawling part. The same theory applies to the actuating principle of the contracting part [20].

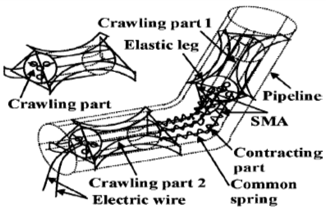


Fig. 21 Liu et al. proposed microrobot [20].

3. The studied parameter (criterias)

In this section, the effective parameters such as the consuming power, response time, efficiency, dynamical modeling, producing force and manufacturing, for each prototype are described. These parameters are obtained from interviews with specialists in standard organizations.

A. Consuming Power

Nowadays, the energy saving is very important in the robotics field. Therefore, the consuming power is a prominent parameter in the evolution of microrobots. In this paper, we have studied the category of microrobots based on this parameter.

B. Response Time

The “response time” of a microrobot is the time that a microrobot requires to do one cycle of its movement. The lower response time causes the microrobot speed is increased. Thus the response time is studied in this paper as a key parameter.

C. Efficiency

The efficiency of a microrobot is constituted of speed and energy consumption. The literature survey shows the pneumatic models generally have higher speeds and also higher generative force. In the environments, where there is no limitation about wireless microrobots, the pneumatic models work the best. The next valuable groups are the micromotor and Shape Memory Alloy actuated microrobots. The micromotor actuated microrobots have low energy consumption with the medium force generation and also appropriate speed; and Shape Memory Alloy actuated microrobots have low energy consumption. Despite having the lower speed than micromotor actuated microrobots, the Shape Memory Alloy actuated robots have large amount of generative force. However, the dielectric and piezoelectric actuated microrobots have high energy consumption and thus they are the lowest dynamical efficient microrobots.

D. Manufacturing

In the field of manufacturing, the complexity of assembling the required actuator to the system, number of modules, dimensions and complexity of fabrication of clamping mechanism are considered to be the criteria. According to the complexity of joining the modules in micro scale, the number of these features is important. Dimension is another important factor because it could change the manufacturing process from microfabrication to easy macro ones.

E. Modeling capabilities

In the field of modeling capabilities, the contact area of the microrobot with the environment, the number of modules, actuator type and the existence of flexible elements are considered. The weights of the above parameters are specified to obtain the prototypes which can be modeled preferably simpler and more accurate.

F. Producing force

In the field of producing force, the amount of produced force by microrobot’s actuator is considered. According to what mentioned before, all microrobots in this paper are categorized based on the type of their actuator therefore, microrobots which have potent actuators are better choices to carry out the same loads.

4. Methodology

In this paper, the Analytic Hierarchy Process method is used in Fuzzy mode for prioritizing and ranking the criteria for designing the in-pipe microrobot. Readers can refer to [21-33] for more details. Overall, each of the Analytic Hierarchy Process problem deals with three general levels; first level: general goal of the problem, second level: criteria of the evaluation and third level: alternatives (possible choices). The total ratio of the weight is calculated for each alternative with respect to the main goal. The alternative that has the greatest weight should be chosen as the best alternative. Many studies have been performed from different aspects and finally to be ultimate to the Fuzzy Analytic Hierarchy Process method. Fuzzy Analytic Hierarchy Process was developed to avoid the functional hazards that solve the problems of an equivocal hierarchical. In this method, based on the answers given to the questions by decision makers, triangular fuzzy numbers are replaced for vague data and for a particular level of the hierarchy, paired comparisons matrix is formed. In the fuzzy logic approach, for each paired comparison, an intersection point is found, and then the membership value is equal to its weight. After defining the criteria, a questionnaire is made up until the levels of criteria are determined. To assess the questions of people, only the respective descriptive variable was chosen. So, after weighing the importance of the criteria through a questionnaire, the following options of scale (Table 1) are set and they include triangular fuzzy numbers (TFNs) which are converted to be generalized in the calculation and analysis of the results.

Table1 TFNs and reciprocal TFNs for FAHP levels of importance

Intensity Of Importance	Definition	TFN	Reciprocal TFN
1	Equal Importance	(1,1,1)	(1,1,1)
2	Intermediate Values	(1/2,3/4,1)	(1,4/3,2)
3	Moderate Importance	(2/3 , 1 , 3/2)	(2/3 , 1 , 3/2)
4	Intermediate Values	(1 , 3/2 , 2)	(1/2 , 2/3 , 1)
5	Strong Importance	(3/2 , 2 , 5/2)	(2/5 , 1/2 , 2/3)
6	Intermediate Values	(2 , 5/2 , 3)	(1/3 , 2/5 , 1/2)
7	Very Strong Importance	(5/2 , 3 , 7/2)	(2/7 , 1/3 , 2/5)
8	Intermediate Values	(3 , 7/2 , 4)	(1/4 , 2/7 , 1/3)
9	Extreme Importance	(7/2 , 4 , 9/2)	(2/9 , 1/4 , 2/7)

In here, we use triangular fuzzy numbers shown as $\mathbf{N} = (a_1 \quad b_1 \quad c_1)$. So the mathematical operations by two triangular fuzzy numbers $\mathbf{N} = (a_1 \quad b_1 \quad c_1)$ and $\mathbf{M} = (a_2 \quad b_2 \quad c_2)$ are as follows:

$$\mathrm{N} + \mathrm{M} = (a_1 + a_2 \quad b_1 + b_2 \quad c_1 + c_2) \tag{1}$$

$$\mathrm{N} - \mathrm{M} = (a_1 - c_2 \quad b_1 - b_2 \quad c_1 - a_2) \tag{2}$$

Inversion, division and multiplication of two triangular fuzzy numbers will not be a triangular fuzzy number, but it would be somewhat different; because the differences are usually small and the mathematical calculations will also be easier. With this assumption we have:

$$\mathrm{N}^{-1} = \left(\frac{1}{c_1} \quad \frac{1}{b_1} \quad \frac{1}{a_1}\right) \tag{3}$$

$$\frac{\mathrm{N}}{\mathrm{M}} = \left(\frac{a_1}{c_2} \quad \frac{b_1}{b_2} \quad \frac{c_1}{a_2}\right) \tag{4}$$

$$\mathrm{N} \times \mathrm{M} = (a_1 \times a_2 \quad b_1 \times b_2 \quad c_1 \times c_2) \tag{5}$$

Multiplying a constant number by a triangular fuzzy number will give a triangular fuzzy number:

$$\mathrm{k} \times \mathrm{M} = (ka_1 \quad kb_1 \quad kc_1) \tag{6}$$

In this paper, it is used from the extended analysis method of Chang's for developing the analytic hierarchy process into fuzzy space. This method is based on the arithmetic average of the experts' ideas; Saati normalized the method by using triangular fuzzy numbers. The implementation steps of the method are as follows [33]:

Step1: The structure of decision hierarchy is drawn by using objective criteria levels and option that is named "hierarchical tree".

Step2: Forming paired-judgment matrix from agreement matrixes with the decision tree and by using experts' opinions in terms of triangular fuzzy numbers and in the form of the matrix below (Fuzzy judgment matrix).

$$A = \begin{bmatrix} (1\ 1\ 1) & \begin{Bmatrix} \tilde{a}_{121} \\ \tilde{a}_{122} \\ \vdots \\ \tilde{a}_{121\mathrm{P}12} \end{Bmatrix} & \cdots & \cdots & \begin{Bmatrix} \tilde{a}_{1n1} \\ \tilde{a}_{1n2} \\ \vdots \\ \tilde{a}_{1\mathrm{nP1n}} \end{Bmatrix} \\ \begin{Bmatrix} \tilde{a}_{211} \\ \tilde{a}_{212} \\ \vdots \\ \tilde{a}_{21\mathrm{P}21} \end{Bmatrix} & (1\ 1\ 1) & \cdots & \cdots & \begin{Bmatrix} \tilde{a}_{2n1} \\ \tilde{a}_{2n2} \\ \vdots \\ \tilde{a}_{2\mathrm{nP2n}} \end{Bmatrix} \\ \vdots & & & & \vdots \\ \vdots & & & & \vdots \\ \vdots & & & & \vdots \\ \begin{Bmatrix} \tilde{a}_{n11} \\ \tilde{a}_{n12} \\ \vdots \\ \tilde{a}_{\mathrm{n1Pn1}} \end{Bmatrix} & \begin{Bmatrix} \tilde{a}_{n11} \\ \tilde{a}_{n12} \\ \vdots \\ \tilde{a}_{\mathrm{n2Pn2}} \end{Bmatrix} & \cdots & \cdots & (1\ 1\ 1) \end{bmatrix} \tag{7}$$

That Pij is the number of participants giving opinions for i rather than j priority.

Step3: Calculate the arithmetic mean of the opinions of decision makers' to achieve the following matrix:

$$\widetilde{\mathrm{A}} = \begin{bmatrix} (1\ 1\ 1) & \widetilde{\mathrm{a}_{12}} & \widetilde{\mathrm{a}_{1n}} \\ \widetilde{\mathrm{a}_{21}} & (1\ 1\ 1) & \widetilde{\mathrm{a}_{2n}} \\ \vdots & \vdots & \vdots \\ \widetilde{\mathrm{a}_{n1}} & \widetilde{\mathrm{a}_{n2}} & (1\ 1\ 1) \end{bmatrix} \tag{8}$$

$$\widetilde{\mathrm{a}_{\mathrm{IJ}}} = \frac{\sum_{\mathrm{k}=1}^{\mathrm{P}_{IJ}} \tilde{a}_{\mathrm{IJk}}}{\mathrm{P}_{IJ}} \qquad \mathrm{I}, \mathrm{J} = 1,2, \dots, \mathrm{n} \tag{9}$$

Step4: In this step, calculate the sum of elements in rows.

$$\widetilde{\mathrm{s}_{\mathrm{I}}} = \sum_{\mathrm{J}=1}^{\mathrm{n}} \widetilde{\mathrm{a}_{\mathrm{IJ}}} \qquad \mathrm{I} = 1,2, \dots, \mathrm{n} \tag{10}$$

Step5: This step is the normalization that normalizes the sum of rows. If $\widetilde{\mathbf{s}_{\mathrm{I}}} = (l_I \quad m_I \quad u_I)$ it will be calculated as:

$$\widetilde{\mathrm{M}_{\mathrm{I}}} = \left(\frac{l_{\mathrm{I}}}{\sum_{\mathrm{I}=1}^{\mathrm{n}} u_{\mathrm{I}}} \quad \frac{m_{\mathrm{I}}}{\sum_{\mathrm{I}=1}^{\mathrm{n}} m_{\mathrm{I}}} \quad \frac{u_{\mathrm{I}}}{\sum_{\mathrm{I}=1}^{\mathrm{n}} l_{\mathrm{I}}} \right) \tag{11}$$

Step6: Now calculate the degree of greatness probability of each $\mathrm{M_I}$ to other $\mathrm{M_I}$ is calculated and called $\mathrm{d}(\mathrm{A}_I)$. That will be:

$$\mathrm{d}(\mathrm{A}_I) = \mathrm{Min\ V}(\mathrm{M_I} \geq \mathrm{M_K}) \quad K = 1,2, \dots, n \qquad K \neq I \tag{12}$$

$$V(M_I \geq M_K) = hgt(M_I \cap M_K) = \begin{cases} 1 & \text{if} \quad m_2 \geq m_1 \\ 0 & \text{if} \quad l_2 \geq u_1 \\ \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & \text{otherwise} \end{cases} \quad (13)$$

Thus, the matrix of weight vectors is obtained as follows:

$$W = (d(A_1) \quad d(A_2) \quad \cdots \quad d(A_n))^T \quad (14)$$

Step7: Final step for obtaining the normalized weights is Normalization, through normalizing the weight vectors.

$$\bar{W} = \left[\frac{d(A_1)}{\sum_{i=1}^{n} d(A_I)} \quad \frac{d(A_2)}{\sum_{i=1}^{n} d(A_I)} \quad \cdots \quad \frac{d(A_n)}{\sum_{i=1}^{n} d(A_I)}\right] \quad (15)$$

The weights that are calculated through above method are certain and indisputable. We implement this method in MATLAB software, which the results are presented in the next section.

5. Results

As mentioned before, using Analytic Hierarchy Process method makes it possible to minimize the subjective judgments of the experts. It is efficient in presenting a model for the performance assessment. This is efficient because of the possibility of comparing and evaluating different criteria and selecting the optimal criterion regarding the given criteria. Since it is a logical method to compare the alternatives and select the optimal alternative with respect to all of the effective features, Analytic Hierarchy Process provides a suitable framework to participate in the decision-making process. Similarly, due to the flexibility, low cost, quick access to result, Analytic Hierarchy Process method is suitable for solving such problems. However, this method is simple and applicable; it includes some disadvantages such as the possibility of making mistakes by the experts in determining the weights and the problems of standardizing their subjective measurement units. Using fuzzy logic in this paper, we can achieve more precise results. To consider 5 criteria, and also hierarchy of the problem that defined in Table 1, the results of Fuzzy Analytic Hierarchy Process are presented in Tables 2 and 3 for 7 micro robots.

As can be seen in Table 2, the consuming power to weight 0.0011 has the least importance and response time with weight 0.3653 has the most importance. According to Table 3, maximum consuming power is also related to micro robot with Ionic Polymeric Metal Composite actuator and the minimum consuming power is related to micro robot with Dielectric actuator, maximum response time is related to micro robot with Piezoelectric actuator and minimum response time is related to micro robot with Shape Memory Alloy actuator, maximum efficiency is related to micro robot with Ionic Polymeric Metal Composite actuator and minimum efficiency is related to micro robot with Dielectric actuator, maximum modeling capabilities is related to micro robot with Pneumatic actuator and minimum modeling capabilities is related to micro robot with Ionic Polymeric Metal Composite and Dielectric actuator, maximum producing force is related to micro robot with Pneumatic actuator and minimum consuming power is related to micro robot with Piezoelectric actuator, and finally maximum manufacturing is related to micro robot with Piezoelectric actuator and minimum consuming power is related to micro robot with Phase-change actuator. Comparison chart of micro robots based on the criteria of performance assessment is presented in Fig.22.

Table 2 The weight of criteria for performance assessment of an in-Pipe inspection micro robots

Criteria	Consuming power	Response time	Efficiency	Dynamical modeling	Producing force	Manufacturing
Weight	0.0011	0.3653	0.0263	0.0572	0.2857	0.2645

Table 3 Comparison of micro robots with criterias of performance assessment

Criteria / Alternative	**Consuming power**	**Response time**	**Efficiency**	**Dynamical modeling**	**Producing force**	**Manufacturing**
Dielectric actuator	0.0014	0.1550	0.0028	0.0055	0.0488	0.1004
Ionic Polymeric Metal Composite actuator	0.9876	0.0925	0.3748	0.0055	0.0994	0.2145
Electromagnetic actuator	0.0016	0.2248	0.0193	0.0806	0.1648	0.1090
Phase-change actuator	0.0019	0.0911	0.0754	0.1512	0.1429	0.0012
Piezoelectric actuator	0.0023	0.3864	0.1861	0.0892	0.0483	0.2163
Pneumatic actuator	0.0028	0.0374	0.0761	0.4743	0.2762	0.1756
Shape Memory Alloy actuator	0.0024	0.0128	0.2656	0.1939	0.2196	0.1831

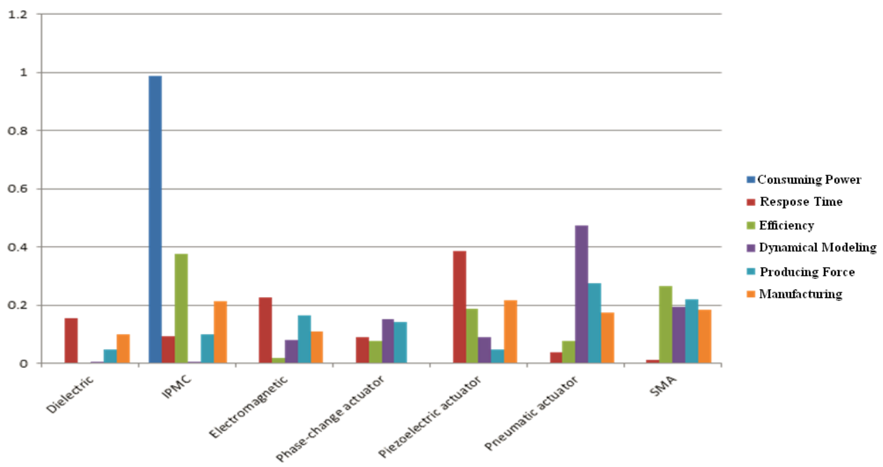


Fig. 22 Comparison chart of micro robots based on criterias of performance assessment

6. Discussion and conclusion

In this article, the effective factors on the way of designing and manufacturing of an in-pipe inspection microrobot are studied. These parameters are categorized in 6 fields. By the aid of Fuzzy Analytic Hierarchy Process method in engineering design, the more popular in-pipe microrobots are compared and the results are presented in 7 main groups as mentioned before. As we saw in the previous section, according to Tables 2 and 3, in terms of consuming power criteria, the most suitable type is micro robot with Ionic Polymeric Metal Composite actuator;

in terms of response time criteria, the most suitable type is micro robot with Piezoelectric actuator, in terms of efficiency criteria, the most suitable type is micro robot with Ionic Polymeric Metal Composite actuator; in terms of dynamical modeling criteria, the most suitable type is micro robot with Pneumatic actuator; in terms of producing force criteria, the most suitable type is micro robot with Pneumatic actuator; and finally in terms of manufacturing criteria, the most suitable type is micro robot with Piezoelectric actuator.

The innovation of this study is the AHP method using, which has many applications in research and articles. Due to the uncertainties in decision making, FUZZY logic was used to implement this technique.

The results of this research are very effective in selecting the mechanism of the micro-robot with the desired characteristics and performance. Because, according to research, we know that with regard to future developments and significant advances in nanotechnology and advances in the field of microsensors and computing, we are witnessing the emergence and application of nano and microrobots in various sciences including medical sciences.

References

1. R Choi, S. M Ryew, K. M Jung, H. M Kim, J. W Jeon, J. D Nam, R. Maeda, and M. Tanie, (2002). Micro robot actuated by soft actuators based on dielectric elastomer, Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems, 1730-1735.
2. B Kim, J Ryu, Y Jeong, Y Tak, B Kim, JO Park, (2003). A ciliary based 8 legged walking micro robot using cast IPMC actuators. International IEEE Conference on Robotics and Automation (ICRA '03).
3. Paolo Arena, Claudia miniature pressure regulator for a miniature robot for colonoscopy, (2003). Sensors And Actuators A 105, 119–131.
4. P. Dario, M.C. Carrozza, L. Lencioni, B. Magnani, S. D'attanasio, (1997). A micro robotic system for colonoscopy, Proc. IEEE Int. Conf. on Robotics And Automation, 1567-1572.
5. Hyunjun Park, Byungkyu Kim, Jong-Oh Park , Seok-Jin Yoon , (2006). A crawling based locomotive mechanism using a tiny ultrasonic linear actuator (TULA), 39th Int. Symposium On Bonomo, Luigi Fortuna, MattiaFrasca, Salvatore Graziani. Design and control of an ipmc wormlike robot, IEEE transactions on systems, man, and cybernetics—part b: cybernetics, 36 (5).
6. Haiwei Lu, Jianguo Zhu, Zhiwei Lin, YouguangGuo, (2009). An inchworm mobile robot using electromagnetic linear actuator, Mechatronics.
7. Guanying Ma andGuozheng Yan, (2007). Wireless powered microrobot for gastrointestinal detection, Proc. IEEE Int. Conf. Mechatronics and Automation, 1085- 1089.
8. Hyunjun Park, Sungjin Park, Euisung Yoon, Byungkyu Kim, Jongoh Park, andSukho Park, (2007). Paddling Based Microrobot For Capsule Endoscopes, IEEE Int. Conf. Robotics and Automation, 3377–3382.
9. S. D'attanasio,R. Lazzarini, C. Stefanini, M.C. Carrozza, P.Dario, (1997). A One Cubic Centimeter Mobile Microrobot With a Steering Control, Proc. IEEE, 1318-1324.
10. Koichi Suzumori, ToyomiMiyagawa, Masanobu Kimura, and Yukihisa Hasegawa, (1999). Micro Inspection Robot For 1-In Pipes IEEE/ASMETransactions On Mechatronics, 4 (3), 286-292.
11. Shigeo Kato, Takayuki Naito, Manabu Ono and Shinichi Matsuda, (2003). An Inchworm Type In-Pipe Mobile Microrobot Driven ByThree Gas-Liquid Phase-Change Actuators, proceedings of the annual meeting- american society for precision engineering, 295-298.
12. Yan Guozheng, Lu Qiuhong, Ding Guoqing, Yan Detian, (2002). The Prototype of A Piezoelectric Medical Microrobot, IEEE International Symposium on Micromechatronicsand Human Science,73-77.
13. Hideaki Nishikawa, TakanariSasaya, Takayuki Shibata, Takashi Kaneko, Naoki Mitumoto, ShinichirouKawakita and Nobuaki Kawahara, (1999). In-Pipe Wireless Micro Locomotive System, IEEE International Symposium on Micromechatronicsand Human Science, pp. 141-147.
14. Jinwan Lim, Hyunjun Park, Jaemin An, Yeh-Sun Hong, Byungkyu Kim, Byung-Ju Yi, (2008). One Pneumatic Line Based Inchworm-Like Micro Robot For Half-Inch Pipe Inspection, Mechatronics 18, 315–322.
15. Maria Chiara Carrozza, Alberto Arena, Dino Accoto, Arianna Menciassi, Paolo Dario, (2008). A Sma-Actuated Robotics, 85-90.

16. Qin Chang-Jun, Ma Pei-Sun, Yao Qin, (2004). A Prototype Micro-Wheeled-Robot Using SMA Actuator, Sensors And Actuators A 113, 94–99
17. Byungkyu Kim, Sunghak Lee, Jong Heong Park, Jong-Oh Park, (2005). Design and Fabrication of a LocomotiveMechanism for Capsule-Type Endoscopes UsingShape Memory Alloys (SMAs), IEEE/ASME Transactions On Mechatronics, 10(1) 77-56.
18. A. Menciassi, S. Gorini, G. Pernorio, P. Dario, (2004). A Sma Actuated Artificial Earthworm. International IEEE Conference on Robotics and Automation (ICRA '04).
19. Byungkyu Kim, Moon Gu Lee, Young Pyo Lee, Yongin Kim, Geunho Lee, (2006). An Earthworm-Like Micro Robot Using Shape Memory Alloy Actuator, Sensors And Actuators A 125, 429–437.
20. Fang-Hu Liu,Pei-Sun Ma, Jian-Ping Chen,Jie Zhu, And Qin Yao, (2002). Locomotion Characteristics of an SMA-Actuated Micro Robot Simulating a Medicinal Leech In a Pipeline, Journal Of Robotic Systems, 245-253.
21. EvangelosTriantaphyllou , Stuart H. Mann, (1995). Using The Analytic Hierarchy Process For Decision MakingIn Engineering Applications: Some Challenges, Int. Journal of Industrial Engineering: Applications And Practice, 2 (1), 35-44.
22. E. Triantaphyllou, B. Shu, S. Nieto Sanchez, and T. Ray, (1998). Multi-Criteria Decision Making: An Operations Research Approach, Encyclopedia of Electrical And Electronics Engineering, (J.G. Webster, D.), John Wiley & Sons, New York, Ny, 15, 175-186.
23. Chen, Q., and Triantaphyllou, E., (2001). Estimating Data for Multi-criteria Decision Making Problems: Optimization techniques, in: Pardalos, P.M., and Floudas, C., (Eds.), Encyclopedia of Optimization, 2, Kluwer, Boston, MA, 27–36.
24. European Green City Index, Assessing the environmental impact of Europe's major cities, A research project conducted by the Economist Intelligence Unit, sponsored by Siemens, Munich, Germany, 2009.
25. Kaya,T., Kahraman,C., (2011). An integrated fuzzy AHP–ELECTRE methodology for environmental impact assessment, Elsevier B.V., 38, 8553-8562.
26. Krishnendu Shaw and else, (2012). Supplier selection using fuzzy AHP and fuzzy multi-objective linear programming for developing low carbon supply chain, Expert Systems with Applications, 39, 8182-8192.
27. Lu Li a, Zhi-Hua Shia, Wei Yinb, Dun Zhua, Sai Leung Ngc, Chong-Fa Caia, A-Lin Lei, (2009). A fuzzy analytic hierarchy process (FAHP) approach to eco-environmental vulnerability assessment for the danjiangkou reservoir area, China, Ecological Modelling, 220, 3439–3447.
28. Mau-Crimins,T., de steiguer,J.E., Dennis,D., (2005). AHP as a means for improving public participation: a pre–post experiment with university students, Elsevier B.V., 7, 501-514.
29. Mei-Fang Chen a, Gwo-Hshiung Tzeng b,c, Cherng G. Ding, (2008). Combining fuzzy AHP with MDS in identifying the preference similarity of alternatives, Applied Soft Computing, 8, 110–117.
30. Monitto M., Pappalardo P., Tolio T., (2002). A new Fuzzy AHP method for the Evaluation of Automated, Journal CIRP Annals - Manufacturing Technology, 51 (1), 395–398.
31. X. Liu and L. Jiang, (2012). A novel vertical handoff algorithm based on fuzzy logic in aid of grey prediction theory in wireless heterogeneous networks, Journal of Shanghai Jiaotong University (Science), 17, 25-30.
32. Zheng,G.,Zhu,N.,Tian,Zh.,Chen,Y., Sun, B., (2012). Application of a trapezoidal fuzzy AHP method for work safety evaluation and early warning rating of hot and humid environments, Safety Science , 50, 228-239.
33. Omidvari, M.,Ghandehari,M., (2014). Urban environmental management performance assessment by fuzzy analytical hierarchy processing (FAHP), Journal of Environmental Accounting and Management. 2(1), 31-41.