An AHP Based Conceptual Design of an In-Pipe Inspection Micro Robot

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***Abstract-* The issue of low diameter pipe inspection microrobots is very important in microrobotic systems. This paper presents the results of a study on the various built or designed microrobots. This study includes comparing these in-pipe microrobots from dynamical efficiency, functionality, dynamical modeling and manufacturing points of view applying AHP method with the purpose of determining the best mechanisms in each field to assist the design of a novel microrobotic system with eliminating the existing problems. At the end a new design is suggested to fabricate.**

Key words – Microrobot, AHP, In-pipe moving mechanisms

I. Introduction

In microrobotic systems, the in-pipe inspection microrobots are an area of major importance. The in-pipe microrobots should be able to inspect the low diameter pipelines in dangerous and unavailable areas or in human body intestine for colonoscopy [4-7].

In this study various types of in-pipe microrobots up to year 2009 was collected and after eliminating the old and similar prototypes, 20 models is considered. First of all the effective parameters on the way of designing and manufacturing of an in-pipe inspection microrobot was identified. These parameters were categorized in four groups: dynamical efficiency, functionality, dynamical modeling and manufacturing. The purpose of this study is to compare the existed microrobots in case of each parameter and at last recognize the best characteristics in each group. The method which is employed for comparison and making decision about the best mechanism is AHP method in engineering design [21]. The trend of the study was in the way that first for each of the dynamical efficiency, functionality, dynamical modeling and manufacturing, the related criteria was specified. By the aid of criterion matrix in AHP method the weights of each criteria was calculated. Then using the pairwise comparison matrix [22], the 20 models were compared with each other in the case of each special criteria and the value of each model was evaluated. At the end with respect to criteria weights and models' values in the case of each criterion, the final value of models in each four groups was evaluated. And the results were detailed.

The paper is organized as follows. Section II is dedicated to a brief explanation of the 20 selected microrobots. Section III will present our studies on dynamical efficiency, functionality, dynamical modeling and manufacturing, section IV presents a conceptual design of an in-pipe inspection microrobot and finally section V will go on through.

II. The Studied Microrobots

Various types of microrobots taken into consideration in this study are categorized in 8 part with respect to their actuator types. A brief description about each one is given as below.

A. Dielectric

The studied microrobot in this field was presented by Choi et al.[1], which mimicked annelid animals like the earth worm. The new design soft actuator called ANTLA, is based on polymer dielectrics. As shown in Fig. 1, it has muscle like characteristics capable of performing motions such as forward, backward and controllable compliance[1].

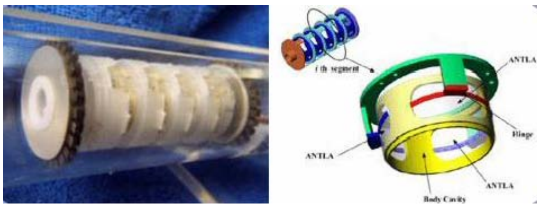


Fig. 1. Design by Choi et al.[1].

B. IPMC

In this field Kim et al. proposed a ciliary type 8-legged micro robot, with cast film based IPMC actuators, which can be operated in aqueous surroundings like inside of human body[2]. Walking principle of this micro robot is as shown in Fig. 2.

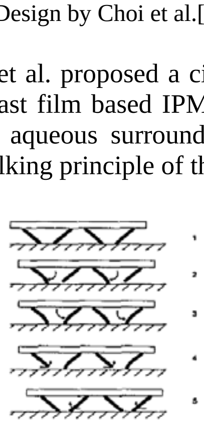


Fig. 2. Walking principle of Kim et al. micro robot[2].

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. 3, all 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 undulatory locomotion[1].

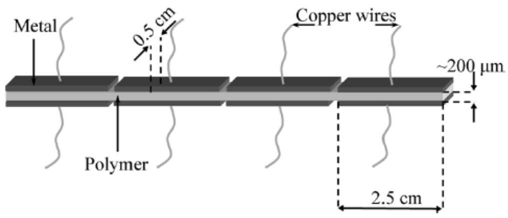


Fig. 3. Schematic IPMC worm presented by Kim et al.[1].

C. Electromagnetic

Lu et al.[4] presented a bristle-based inchworm mobile robot using a short stroke electromagnetic linear actuator. This tubular type electromagnetic linear actuator is installed inside the robot body. The stator of the actuator is attached the main body of the robot and the translator of the actuator acts as the movable unit of the robot that can make the robot extend or contract. The front leg or fin is attached to the main body while the rear one sticks to the movable unit. The main body and movable unit of the robot are joined by using a sealed bellows, as shown in Fig. 4, and the bristle legs are designed so that it can operate both on plane surfaces and in liquid[4].

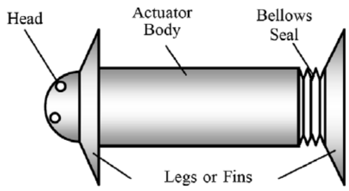


Fig. 4. Schematic structure of the Lu et al. inchworm robot[4].

The second micro robot in this domain is presented by Ma and Ya[5]. This wireless powered earthworm-like microrobot which has multi segment squirm mechanism,as shown in Fig. 5, is designed and manufactured driven by dc motors[5].

(a) (b)

Fig. 5. (a) A driving segment and (b) Microrobot as a whole[5].

Another one is a capsule-type microrobot proposed by Park et al.[6]. This microrobot has synchronized multiple legs that are actuated by a linear actuator, which can be composed of micro motor and lead screw, and two mobile cylinders inside of 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.6.

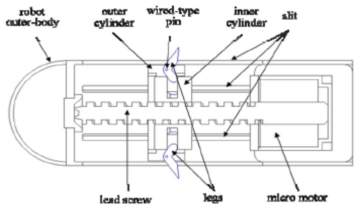


Fig. 6. Concept design of microrobot[6].

D’Attanasio et al.[7] have introduced a teleoperated mobile microrobot incorporating a type of electromagnetic micro motor. This one cubic centimeter microrobot used two micro motors to actuate the two wheels of the microrobot[7]. The schematic view of this microrobot is given in Fig. 7.

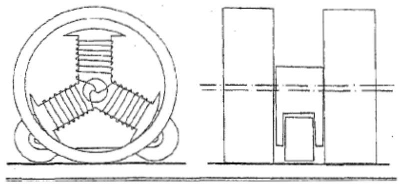


Fig. 7. Schematic view of 1-cubic-cm microrobot[7]

The last studied microrobot in this field was presented by Suzumori et al.[8]. As shown in Fig. 8, this microrobot utilize a novel micro mechanism called a planetary wheel mechanism. This mechanism is driven by a micro electromagnetic motor with a micro planetary reduction gear.

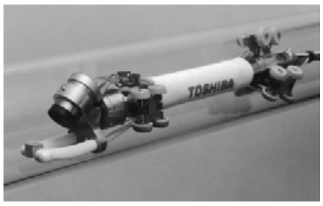


Fig. 8. Micro inspection robot carrying a recovered object in a 1-in pipe[8].

D. Phase-change actuator

Kato et al.[9] proposed an inchworm type in-pipe mobile microrobot driven by three gas-liquid phase change actuators. The actuator is made of welded stainless steel bellows and also the operating fluid (perfluorocarbon) and a heater are enclosed in it[9]. By applying or removing heat, the modules stretch and release respectively and also with frictional bulging brakes, the microrobot moves.

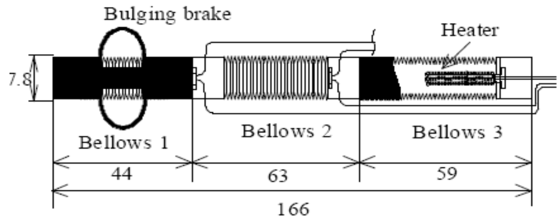


Fig. 9. Schematic view of Kato et al. microrobot[9].

E. Piezoelectric actuator

In this field three microrobots were considered. One of them is presented in Guozheng et al.[10]. This miniature multi-joint piezo-driving squirming robot, is composed of three linear piezo-driving cells and one head, as shown in Fig. 11. Through the sequentially deformations of these piezo elements, the microrobot slide a miniature displacement.

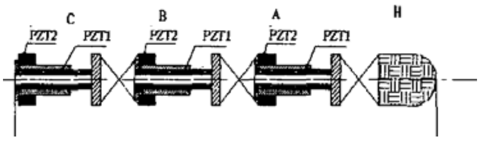


Fig. 10. The structure of the microrobot[10].

The other one in this field is Nishikawa et al.[11] in-pipe micro locomotive system. This system is composed of an outside host and a microrobot. The outside host supplies energy and transmits commands to the robot by using microwaves. The locomotive mechanism, as shown in Fig. 11, using a piezoelectric bimorph actuator moves according to inertia drive method[11].

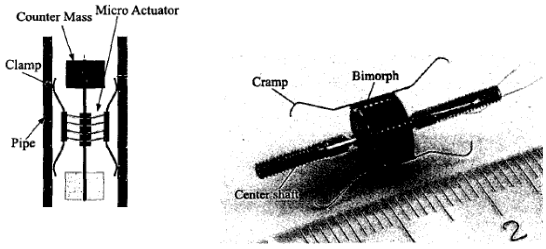


Fig. 11. Developed locomotive mechanism using multi-layered PZT Bimorph actuator.

The last studied microrobot in this field was in Hyunjun park et al.[12]. 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 a 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 by the housing element. Both sides of the shaft of TULA are fixed by shaft holder made of rubber within the robot body. As this moving element synchronized with the legs moves forward and backward, fore and rear legs push the wall of pipe. Thus, it obtains driving force to move[12].

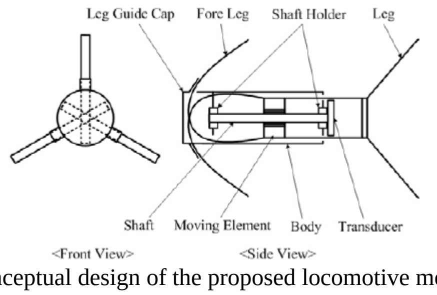


Fig. 12. Conceptual design of the proposed locomotive mechanism in Hyunjun park et al. [12].

F. *Pneumatic actuator*

In this field three microrobots were studied. These microrobots are actuated by air feeding systems, miniature valves and also suction cups. Carrozza et al.[13] 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 colonwall.

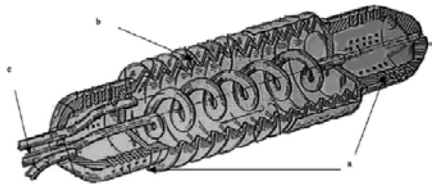


Fig.13. Pneumatic lay-out of the microrobot: (a) cylindrical clamper with suction holes and hemispherical tips; (b) rubber bellow; (c) service pipes[13].

Another microrobot in this field was a microrobotic endoscopic system suggested by Dario et al.[14]. The propulsion system based on inchworm principle, is composed of three modules. 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.

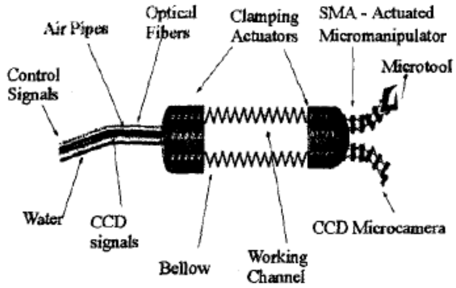


Fig. 14. Scheme of Dario et al. microrobot[14].

The last studied microrobot in this field was Lim et al. inch-worm like microrobot[15]. The mechanism uses only one pneumatic insufflation line to reduce the stiffness of the pneumatic lines and the friction force between pneumatic lines and the pipe wall. By drilling micro holes among the rear clamp, the elongation module, and the front clamp, the timing of the airflow among the chambers can be controlled. With one cycle operation of insufflation and stopping insufflation to the rear clamp, the inchworm-like locomotion of the robot is accomplished. The insufflating air is controlled with an on/off pneumatic valve.

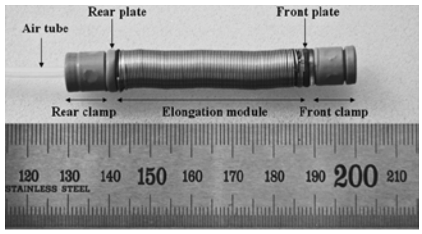


Fig. 15. Inchworm prototype microrobot[15].

G. *SMA actuator*

Although the studied pneumatic driven microrobots have a SMA-microvalve in their structures, in this part the SMA directly driven microrobots are studied. In this field Chang-jun et al.[16] designed a resilient-rigid coupling SMA (RRSA) driving micro-wheeled-robot, Fig. 16. The advantage of RRSA is to enlarge the displacement output apparently compared with ordinary SMA 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].

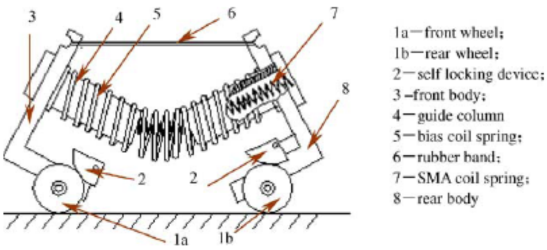


Fig. 16. Schematic diagram of the micro-wheeled-robot[16].

The other proposed microrobot in this field is Kim et al.[17] microrobot. This prototype was developed with two-way linear actuators using a pair of SMA springs and four clampers, as shown in Fig. 17. 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.

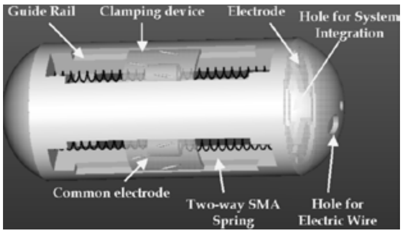


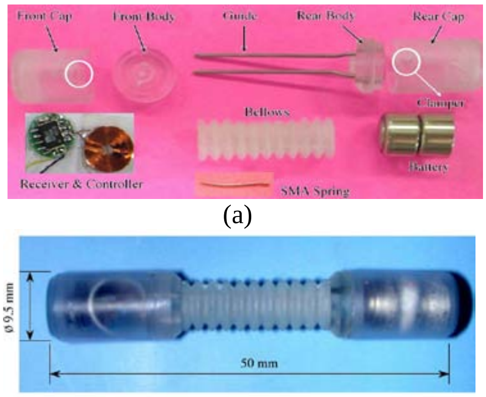
Fig. 17. Kim et al. microrobot[17].

Menciassi et al.[18] designed an artificial earthworm with four modules which can be driven independently according to undulatory locomotion of living earthworms. Each Module, as shown in Fig. 18, is actuated by one or more SMA 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. 18. (a) Earthworm module, (b) The artificial earthworm[18].

Kim et al.[19] also proposed another SMA-driven microrobot, using only one SMA spring actuator and one silicone bellow, as shown in Fig. 19. The SMA actuator and bellow play a role in contraction and extension of an earthworm muscle respectively, and results in microrobot locomotion.



(a)

(b)

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

The last studied microrobot in this field was Liu et al.[20] SMA actuated microrobot. As shown in Fig. 20, this microrobot has two kinds of SMA actuators. One for crawling part and the other for contracting part. The SMA spring will contract when subjected to 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 SMA spring is not subjected to 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].

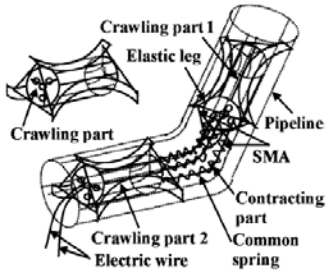


Fig. 20. Liu et al. proposed microrobot[20].

III. Comparison Tables

In this section the final results of the study was summarized in four tables. Each table is specified to one of the four groups. Due to the numbers of effective parameter in case of each group, the tables have 4 or 5 columns. The score of the models regarding each effective parameter (results from pairwise comparison matrix) multiplying the weight of the criteria (results from the criterion matrix) was given in the related column. The sum of the scores of effective parameters for each prototype results the final score of the specific prototype, which is given in the last column of each table.

A. *Dynamical efficiency*

In the field of dynamical efficiency the following criteria are considered. The speed, force generation and energy consumption of the microrobots. The results from the pairwise comparison matrix show the pneumatic models [20] generally have higher speeds and also higher generative force. In the environments where do not have any limitation about wireless microrobots, the pneumatic models work best. The next valuable groups in the tables are the micromotor [7] and SMA [14] actuated microrobots. The micromotor actuated microrobots have low energy consumption with medium force generation and also appropriate speed; and SMA actuated microrobots have low energy consumption. Despite the lower speed than micromotor actuated microrobots the SMA actuated robots have large amount of generative force.

The combination results of criterion matrix and pairwise comparison matrix are summarized in Fig.21. In this chart the higher the value of a prototype, the more dynamical efficient the prototype is. It is deduced from Fig. 21, after pneumatic prototypes, the SMA and micromotors actuated microrobots are the most dynamical efficient micro robots, respectively. The dielectric and piezoelectric actuated models because of high energy consumption are the lowest dynamical efficient microrobots, respectively.

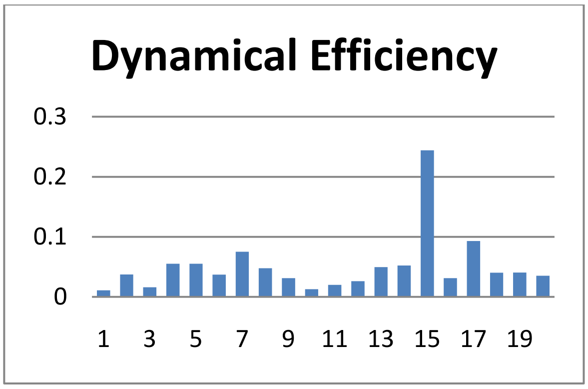


Fig. 21. Dynamical efficiency score chart

B. *Functionality*

Functionality is related to all one expects from an in-pipe microrobotic system. The microrobots are usually used in low diameter and out of reach pipelines. Therefore, it should be a system with low energy consumption thus can be supplied with the micro scale batteries. This microrobotic system also should have the appropriate speed and proper dimension for locomotion in low diameter pipelines. As a result the speed, the ability of working wireless and dimensions are considered as the criteria for judgment about functionality.

The results of the pairwise comparison matrix show that the prototypes with SMA actuators are the best choice for this purpose. At the second position the magnetic actuated microrobots are considered. Fig. 22. represents the combined results of the criterion and comparison pairwise matrixes.

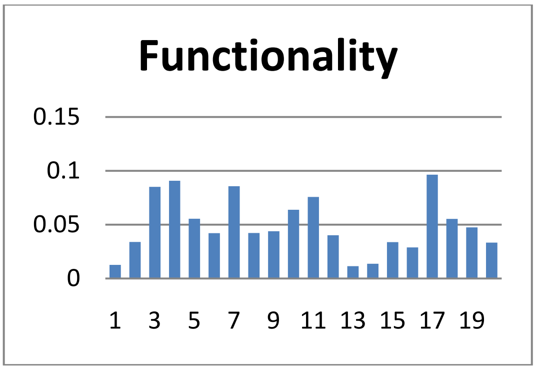


Fig. 22. Functionality score chart

C. *Manufacturing*

In the field of manufacturing the following criteria are considered; the complexity of assembling the required actuator to the system, number of modules, dimension and complexity of fabrication of clamping mechanism. According to 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. The results of the study on this field are given in Fig. 23. The higher the value of the model is, the easier the manufacturing process will be.

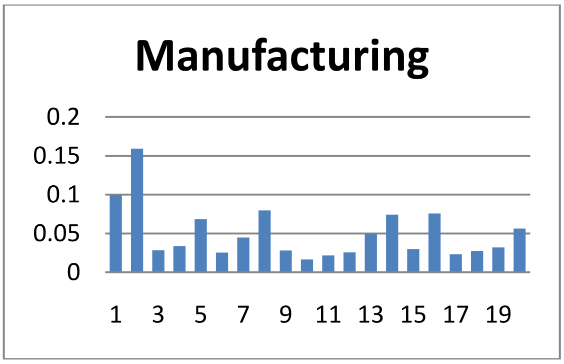


Fig. 23. Manufacturing score chart

D. *Dynamical modeling*

In the field of dynamical modeling, the contact area of the microrobot with the environment, 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. The results are given in Fig. 24.

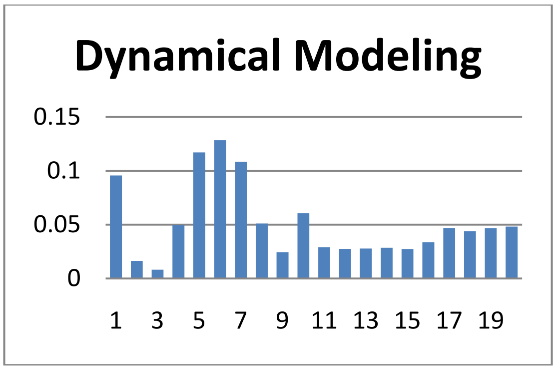


Fig. 24. Dynamical modeling score chart

IV. CONCEPTUAL DESIGN

According to the results concluded from the study, a conceptual design of an in-pipe inspection microrobot has been done. As shown in Fig. 25, the designed microrobot consists of three modules. One for motion and the other two one for clamping. The locomotion module consists of two springs; an SMA spring and a passive spring. In general state, the passive spring is at rest. The front clampers are in touch with the pipe and the rear ones are free. As soon as the current flows through the SMA wire, it contracts, the rear body move forward and the rear clampers, stick to the pipe wall. As the current cuts off, front clampers release and the passive spring forces the microrobot forward. This cycle repeat in each locomotion pace. The clamper part consists from two layer; an adhesive pad [23] bonded to an IPMC layer. Under the influence of an electric potential, the IPMC deflects. This deflection changes the adhesive pad angle relative to the pipe wall. As a result the adhesion force, which is pertained to this angle, changes and the clampers stick or release.

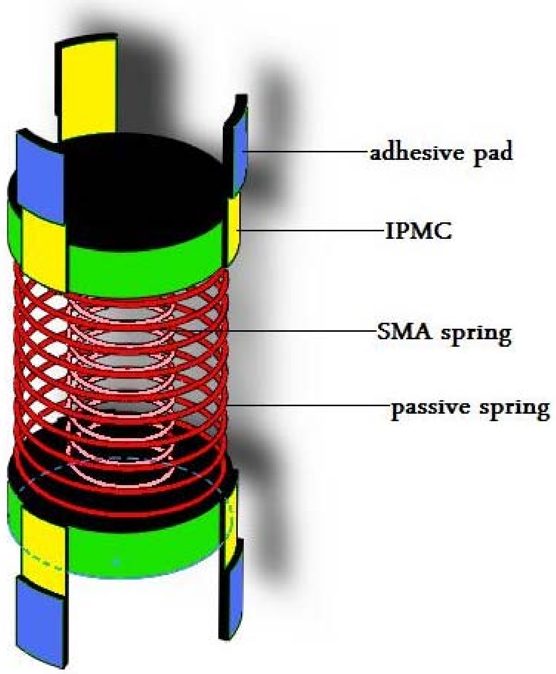


Fig. 23. Schematic diagram of the designed microrobot

V. CONCLUSION

In this paper, the effective parameters on the way of designing and manufacturing of an in-pipe inspection microrobot are studied and also a conceptual design of an in-pipe inspection microrobot has done. The effective parameters are categorized in 4 fields. By the aid of AHP method in engineering design the 20 more popular selected microrobots are compared and the results are presented. In the case of dynamical efficiency, [15], [17] and [7], in the case of functionality [17] and [4], in the case of manufacturing [2] and [1] and in the case of dynamical modeling [6] and [5] respectively were the best prototypes.

Our future work will be deriving the dominant equations on the presented microrobot and in the second stage fabrication of a novel one.

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