Smart Actuators for Colonoscope Actuation

Mohamed E. Rabie
Egyptian Armed Forces, Military Technical College

Abstract

In recent years, much has been studied on the colonoscope because it is a very important tool for diagnosing colon cancer, which is the second leading cause of cancer in the developed countries. Colonoscopy is one of the most technically demanding endoscopic examinations in the modern health service. This is a procedure often painful for the patient and complex for the surgeon. The conventional process involves manual insertion and manoeuvring of the colonoscope by the surgeon, which may lead to some problems like intestine perforation that might occur when the colon wall is punctured due to the colonscope being forcibly pushed by the surgeon to ease its penetration through difficult corners. Therefore, it is important to redesign conventional wired colonoscope devices to facilitate their safe insertion and navigation into the bowel. This project is concerned with the development of electromagnetic actuators, which can produce uniformly distributed magnetic field capable of generating high magnetic thrust forces. In this activity, different actuators have been investigated for the purpose of colonoscope actuation through difficult corners of the colon, which would improve its penetration problems and reduce the intestine perforation problems.

ANSYS, finite element analysis, FEA, software has been utilised to design the electromagnetic circuits of the actuators which incorporate magnetic and non-magnetic materials that could generate the magnetic force required for the navigation and actuation of the colonoscope. The mechanical design of these actuators was then carried out using Solidworks CAD software.

Keywords: endoscopic; electromagnetic actuators; magnetic thrust forces; actuation; navigation

1- Introduction and Background

In modern medical life, colonoscopy is an important medical procedure for detecting various diseases such as colorectal polyps' colon and rectum cancer. According to the National Cancer Institute [1], cancers of the colon are the fourth most commonly diagnosed cancers. However, most colon cancers can be cured if detected at their early stages. Colonoscopy allows surgeons to look inside the large intestine that starts from the rectum to the small intestine. This procedure is used to look for early signs of colon or rectum cancer. It can detect colon disease of the entire colon, including the large intestine which other solutions are not available, with the highest accuracy. Moreover, colonoscopy is the only method that can operate within the colon so that surgeons can undertake treatment of the colon. On the other hand, this procedure is very difficult because the complex structure and size of the colon limits the insertion of the wired colonoscope.

New high performance actuator materials are capable of converting the electrical energy to any form of energy like the magnetic energy or vice versa and are required for a wide range of current applications such as mini- and microrobots, adaptive structures, prosthetic devices, pumps, valves, heel-strike generators, and strain sensors. Most of these materials excel in some measures of performance (as actuation pressure or strain), however they are unsatisfactory in others such as (efficiency, fast response).

Therefore, it is important to solve this problem by automating the colonoscopy by using suitable actuators for actuation and guidance the colonoscope into the bowel. In this work, we aim to develop smart actuator to assist the wired colonoscope insertion and self-actuation into the bowel. Electromagnetic actuators were designed for this purpose that the electromagnetic actuators have an electrical and a magnetic circuit, which are built together. Although different materials can be used in both the electric and magnetic circuit, it is common to talk about copper for the electric circuit and iron for the magnetic circuit.

Conventional Colonoscope

The conventional colonoscope is a flexible, snake-like medical instrument to diagnose the colon. Generally, it consists of a high-resolution mini-camera, an air/water channel, fibre optic bundles for illumination, a suction/biopsy channel and tendon knobs to steer the end of the scope as shown in figure (1).

It consists of three main sections:

1- *The umbilical cord, which* attaches the scope to the light source.
2- *The control unit, which* houses the angulation knob and valves which control the flipping of the distal end and air/water channel respectively.
3- *The insertion tube, which* is the portion that is introduced into the patient's colon via the anus. Moreover, it carries two extra items: biopsy channel, which allows miniature surgical tool to pass through and control wires that are fixed to the angulation knob to enable flipping the distal end of the scope.

Drawbacks of conventional colonoscopy

Although colonoscopy was developed nearly 40 years ago, colonoscopy is still a skill, which requires motivation, determination and dexterity. It has benefited humankind in many ways, however, there are still weaknesses that should and could be avoided by using recent technologies, which are encountered:

- Unpleasant for the patients because of its long duration and its accompanied pain.
- Needs high level of expertise and long training time for the colonoscopists.
- Tedious and cumbersome procedure (boring).
- Difficulty in manoeuvring at manual insertion.
- Formation of an unintended loop.

Automation of colonoscopy

The previous problems may be solved by automating the colonoscopy which achieving some advantages:

- It removes the need for experience and skills of the colonoscopists.
- It reduces the training time of the colonoscopists to learn treatments for abnormalities found on the intestinal walls, without the need to perfect the manual skills required to use a conventional colonoscope.
- Reduction of trauma and discomfort of patients.
- Automatic locomotion of the colonoscope inside the colon.
- It can reduce the costs since one surgeon can do many operations, since only diagnosis will be required.
- Reduction of postoperative and hospitalization.

The skills of the surgeons will no longer be the dependent factor with automation. Moreover, computers, leading to be faster, more precise and consistent than the human being, will control movements of the colonoscope. The endoscopist is still the person who decides every move of the machine and to take over when there are uncertainties or in case of an emergency, therefore he must be present at all times to guide the machine to do its work.

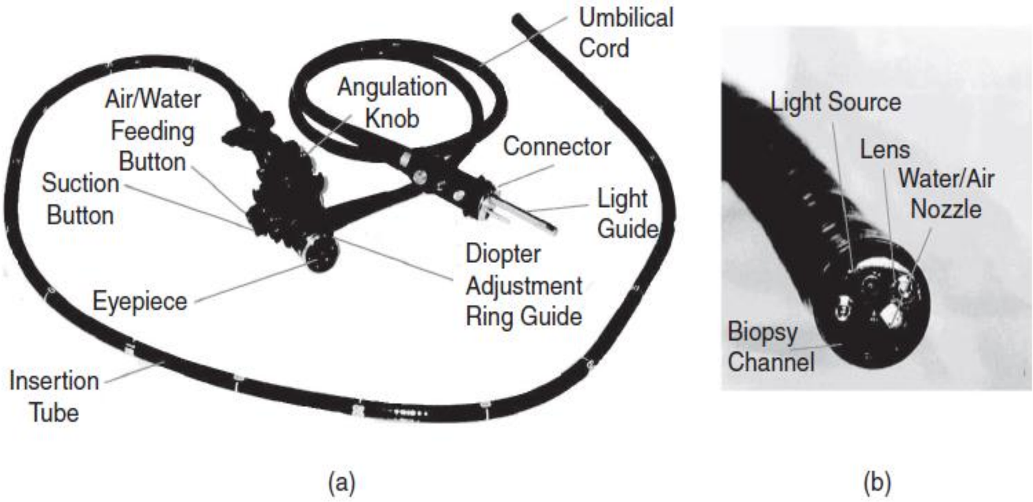

Figure 1. The (a) conventional colonoscope and (b) its distal end view displaying the arrangement of the CCD camera, air/water channel, fibre optic bundle and biopsy channel. The control wire is fixed internally onto the headpiece. [2]

2- Two-Dimensional Electromagnetic Actuator

On our activity, we were using electromagnetic actuator, which is depending on the idea of magnetism phenomenon. There were some works on using the electromagnetic idea for actuator, which was accompanied with satisfied results, we are rebuilding and reconstructing those ideas for getting better results for the output force and the magnetic flux density. Moreover, we designed the actuator with lower size than before for any type of colonoscopy' actuators, pneumatic, hydraulic and electromechanical since the outer diameter of the colonoscopy after building the actuators is 18mm and it is a great advantage of using electromagnetic idea that provides higher force. Many designs were done for getting the optimum values for the important parameters of getting optimum electromagnetic circuit like, the size and shape of actuator, the direction of supplied current, the diameter of the used wire, the types of used materials, the way of combination of actuator parts, the current density… Therefore, the 2D model was optimized and implemented the 3D model that is important to verify the results and hence manufacture the practical actuators. Electromagnetic finite element analysis software, ANSYS, was used during the whole work beside the Solidworks structural simulation. The first step of the 2D design is to calculate the magnetic field density of the gap between actuators. According to the magnitude of magnetic field density, parameters such as current density and the size of actuator could be optimized.

2.1. Analysis

It is based on the electromagnetic actuator which analysed as a 2D axi-symmetric design. It calculates the magnetic flux density and the force on the upper and lower irons which are the moving components of the actuator.

- In order to calculate the force generated by the solenoid design, the following equation, in general, can be used:

$$F = \mu \frac{\mathrm{dB}}{\mathrm{dX}} \qquad (6) \qquad [3]$$

- The magnetic field can be calculated by:

$$B = \mu_o \left(\frac{\mathrm{N}}{\mathrm{L}} \right) . I \qquad (8) \qquad [4]$$

Where: **B** is the magnetic flux density (T), $\mu_o = 4\pi * 10^{\wedge}(-7)$ H/m, **L** is the length of each magnet (m), **N/L** is the number of turns per unit length and **I** is the passing current (A).

As shown in equation (8), the magnetic flux density field is directly proportional to the applied current (I) and the number of turns per unit length (N/L) since the permeability is constant. In addition, it is shown; there is no dependence on the diameter of the solenoid or the shape of the solenoid itself. For two cylindrical magnets with radius R, and height h, with their magnetic dipole aligned, the force can be calculated approximately by,

$$\mathrm{F} = \left[\frac{{B_o}^2 A^2 (L^2+R^2)}{\pi \mu_o L^2}\right] * \left[\frac{1}{x^2} + \frac{1}{(x+2L)^2} - \frac{2}{(x+L)^2}\right] \ (\mathrm{N}) \quad (9) \qquad [5]$$

Where, ***B₀*** is the magnetic flux density that very close to each pole (T), ***A*** is the area of each pole (m^2), ***L*** is the length of each magnet (m), ***R*** is the radius of each magnet (m), and ***x*** is the separation between the two magnets (m).

- Now, the equation of magnetic force between two cylindrical with their magnetic dipole aligned could be obtained by combining the equations (8) and (9), which is,

$$\mathrm{F(x)} = \mu_o \frac{I^2 A^2 N^2 (L^2+R^2)}{n L^4} * \left[\frac{1}{x^2} + \frac{1}{(x+2L)^2} - \frac{2}{(x+L)^2}\right] \ (\mathrm{N}) \qquad (10)$$

It can be shown that the magnetic force between two solenoids is proportional to the square of the applied current, the number of turns per unit length and the area of each pole. On the other hand, it is inversely proportional to the quadratic of the separation between these two solenoids. Hence, when using the electromagnetic finite element analysis, (FEA), it can be found that the magnetic force increases while the length of the magnet and the area of the coil increase. Multiple designs were considered and tested using ANSYS simulation software.

2.1.1. Current density

As mentioned, it is important to verify the current density of the coil, so it can be calculated using the following equation [6]:

$$Js = \frac{n*i}{A} = 308*3/\,(0.525*0.34) = 5176 \text{ A/cm}^2.$$

2.2. Basic idea

The basic idea of working the electromagnetic actuator in this work for generating the advanced displacement, according to the design required, is mainly depending on the way of generating high magnetic flux density on the gap area between each pair of actuators which provides enough force between these actuators and there are two types of forces which are repulsive and attractive. These forces can be controlled by the direction of current inside the coil. It can be shown that the force generated in the air gap within the path of a magnetic field is inversely proportional to the square of the width of the air gap and directly proportional to the cross-sectional area of the air gap. Therefore, the last design sought to minimise the air gap width whilst still providing adequate actuator stroke length. Therefore, it is very important to take into consideration the advanced displacement, the speed of the colonoscopy and maximise the cross-sectional area of the air gap within reasonable limits until reaching the optimum magnetic flux density and hence the force generated by the path line passed through the air gap.

2.3. 2D Electromagnetic Actuation design

Figure (2) shows the 2D electromagnetic actuators, pair of actuators, each contains iron, coil and thin fin, which are designed for the actuation system of the colonoscopy, and are separated by small air gap. A1, A2, A3, A4, A5, A6, A7 and A8 are the cross section areas of the upper iron, the upper fin, the upper coil, the lower iron, the lower fin, the lower coil, the air gap and the tube of the colonoscopy, respectively, as shown in the figure. All these parts are axisymmetric around the Y-axis that will be cylinder on the real actuator. In addition, on the right, figure (3) shows the electromagnetic actuator after assigning the suitable materials which different colours indicate different materials by different permeability for each.

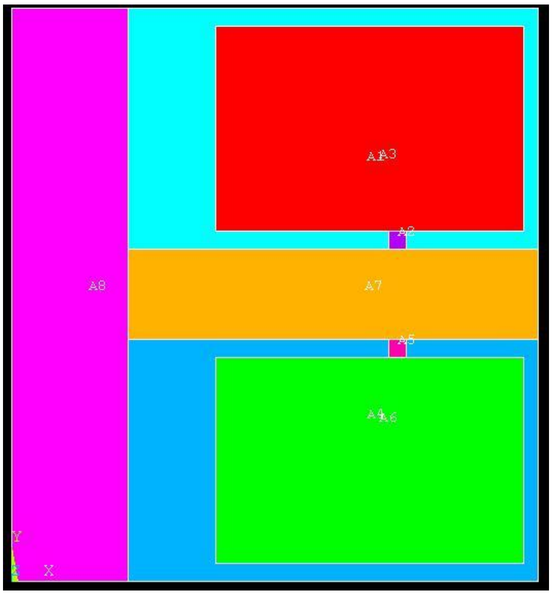

Figure 2 Basic design of actuation design

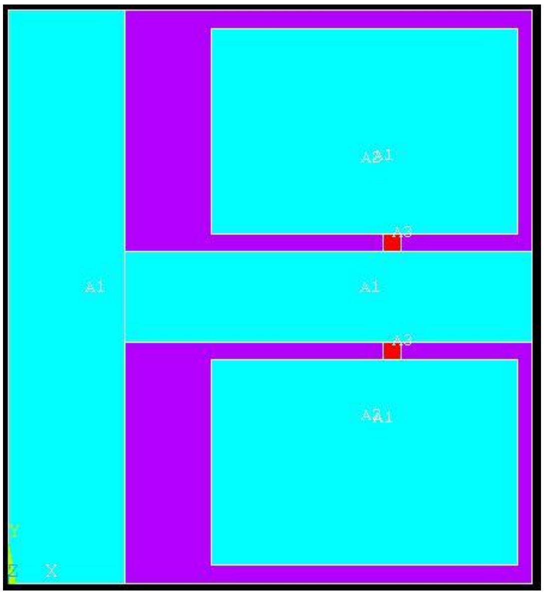

Figure 3 Basic design after assigning the materials

2.4. Obtaining the solution

After applying the loads which are classified into the current density and into the force boundary condition of the whole design that is applied for getting flux parallel field solution, we obtained the flux parallel as shown in figure (4). It is important to notice that, the flux lines are showed by this shape because of the different of materials' permeability since the material that has higher magnetic permeability, it allows more flux lines to pass through it. The iron has the highest permeability value 950 H/m, followed by the air gap 1 H/m and then the thin fin 0.1 H/m. The thin fin was used here in order to persuade the flux lines to pass through the air gap instead of going into the iron, as if it was not used, there was probability for the path lines not to pass through the air gap and hence there was no flux generated into it, so fin is used in the current work.

In order to measure the magnetic flux density on the air gap, three paths were used, path 1, path 2 and path 3, as shown in Fig. (5). Figures (6) and (7) show the graphical representations of total magnetic flux density of paths (1, 2), since the maximum of magnetic flux density for path 1 is 2.446 T however it was rapidly decayed after 10 % from its distance (1.5 mm) to 0.758 T which is remaining for 80 % of the distance. This value, 0.758 T, is satisfied for this design. On the other hand, as shown in Fig. (7), the maximum of magnetic flux density of path 2 is 0.847 T and the minimum is 0.657 T which has not high important weight for the design. Fig. (8) shows the graphical representation of the total magnetic flux density of the horizontal path, path 3, that its maximum magnetic flux density is around 0.7 T since it decreased for a very short distance and then rapidly increased to keep its maximum along the its distance 7 mm.

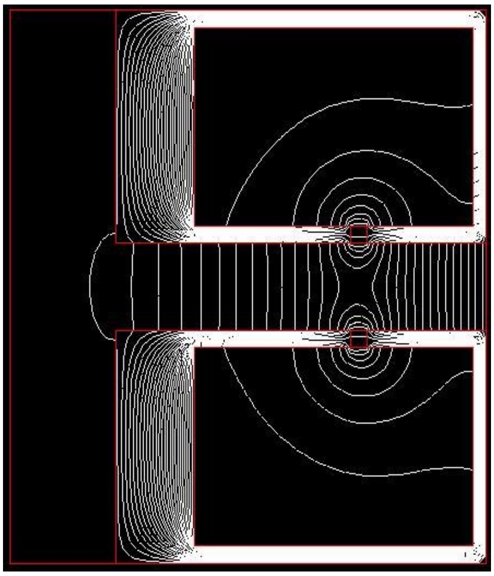

Figure 4 Flux lines pass through the air gap

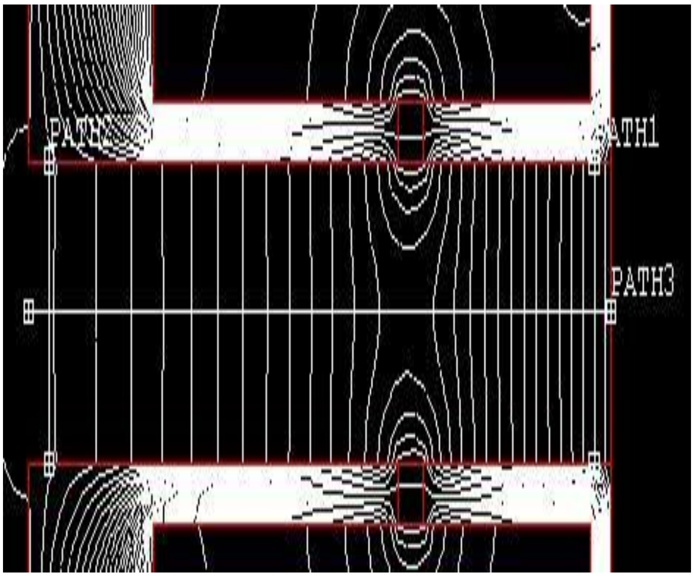

Figure 5 Paths

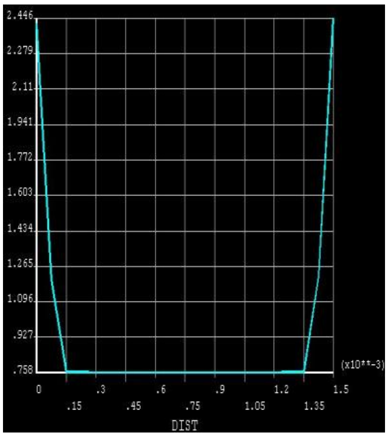

Figure 6 Magnetic flux density of path 1

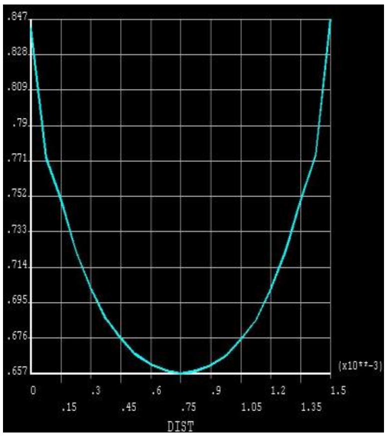

Figure 7 Magnetic flux density of path 2

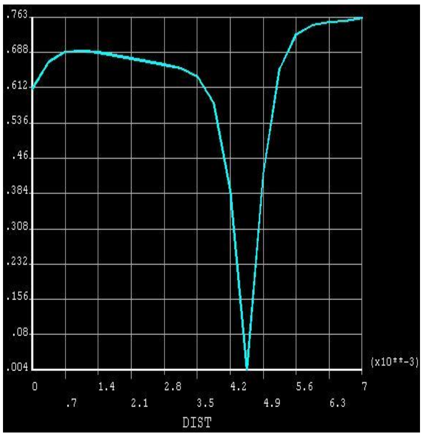

Figure 8 Magnetic flux density of Path 3

2.5. Summarize magnetic forces

In order to calculate the attractive or the repulsive forces generated on the air gap between the upper and lower actuators, there are two methods using for this purpose which are path method and component method and it was found that the force values (Y direction forces) are almost similar for the last two methods which verified that we followed the correct steps of measuring the force which is = 45.14 N as shown in tables (1) and (2). This same force which is equal to 45.14 N can be applied on the components while performing a workbench or Solidworks simulation which is showing in the next sections. It is shown from the tables that there was a small difference between the values of the force that were calculated by Virtual Work method and Maxwell Stress Tensor method, however we were used the value of Virtual Work method. Maxwell stress tensor method calculates forces based on the magnetic field on the surface surrounding the object. This method requires a finer mesh to reduce numerical error. The Virtual work method however determines the forces by calculating derivation of energy with respect to a virtual displacement. Generally, out of the two methods, Maxwell stress tensor method is less accurate for same mesh density.

3. Three-Dimensional Electromagnetic simulation

ANSYS Workbench software was used for achieving the 3D electromagnetic design of the actuator. Figure (9) shows the 3D Electromagnetic design which is a cylindrical shape around the colonoscopy tube as shown, since there are two actuators separated by the air gap, 1.5 mm. The total diameter of the design is 18 mm and the height is 9.5 mm. We used two actuators in order to compare them with those used on the 2D design, their total magnetic flux density, magnetic flux density on the air gap between the two actuators and force generated from the iron.

Table 1 Summary of forces of defining the iron as a component

```
__SUMMARY OF FORCES BY VIRTUAL WORK___
 Load Step Number:        1.
 Substep Number:          1.
 Time:              0.1000E+01
 Units of Force:          ( N )
 Component         Force-Y
  Upper iron      -0.45145E+02
  Lower iron       0.45811E+02
______
 SUMMARY OF FORCES BY MAXWELL STRESS TENSOR
 Units of Force:   ( N )
 Component         Force-Y
  Upper iron      -0.46529E+02
  Lower iron      0.46416E+02
Note: Maxwell forces are in the Global
Cartesian coordinate system.
Virtual work forces are in the element ESYS
coordinate system.
```

Table 2 Summary of forces of defining a surrounded closed path around the iron

```
__SUMMARY OF FORCE CALCULATIONS BY MAXWELL
STRESS TENSOR____
 Force in x-direction = -1.5432 N.

 Force in y-direction = -45.17732822 N.

 Parameter defined for force in X direction:
FX.

 Parameter defined for FORCE in Y direction:
FY.
```

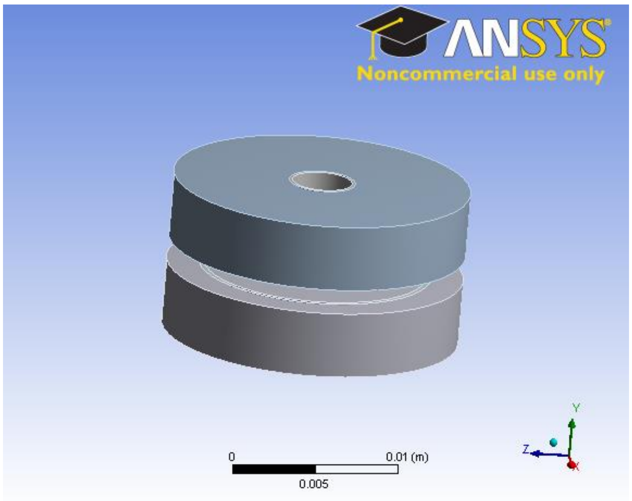

Figure 9 3D Electromagnetic design

The same steps were followed in order to get the solution for the workbench analysis like 2D ANSYS simulation, except the step of applying the current density since its terms should be applied individually:

- Current applied to the wire= 3A.
- Total number of turns= 308 turns.
- Area of the coil= 5.25 mm * 3.4 mm= 17.85 mm².

The current density that obtained from the 2D design was 5176 A/cm² which verified the value got here using the 3D ANSYS workbench as shown in figure (10). It is important to assign the current on the same direction for both actuators as shown in figures (10) and (11). After the solution was done, it is important to calculate the total magnetic flux density of the design.

Figure (12) showed the total magnetic flux density of the cross section of the actuators which has the maximum around 27 T and the minimum around 7.2 e-005 T. The important here is the maximum obtained at the endings of the area of the air gap which is 3.06 T and it decreased gradually till reaching the minimum at the middle of the gap between the actuators. In addition, when we compared this result with the one got from the 2D design, it was found almost the same as shown in figure (13). Also, there was around 3 T obtained at the area of the air gap between the actuators which verified the result of the 3D design which also ascertained that we followed the right steps for the design.

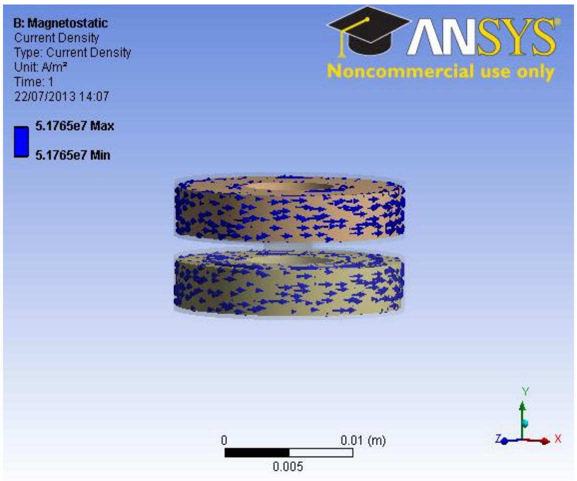

Figure 10 Current density on 2 actuators

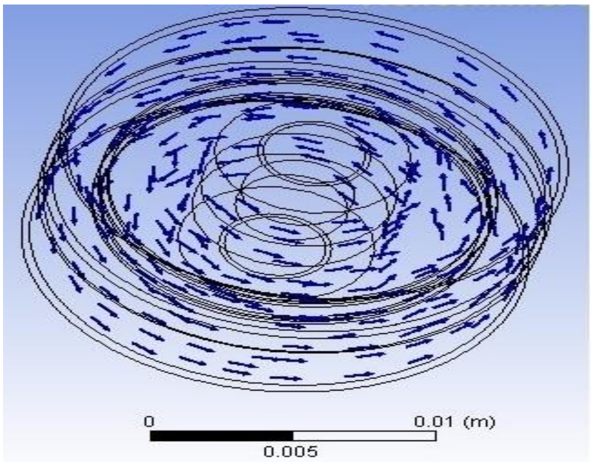

Figure 11 Current direction in the actuators

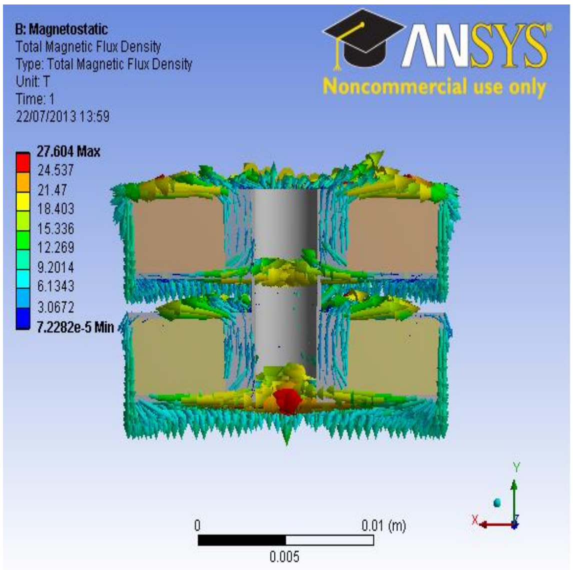

Figure 12 Total magnetic flux density

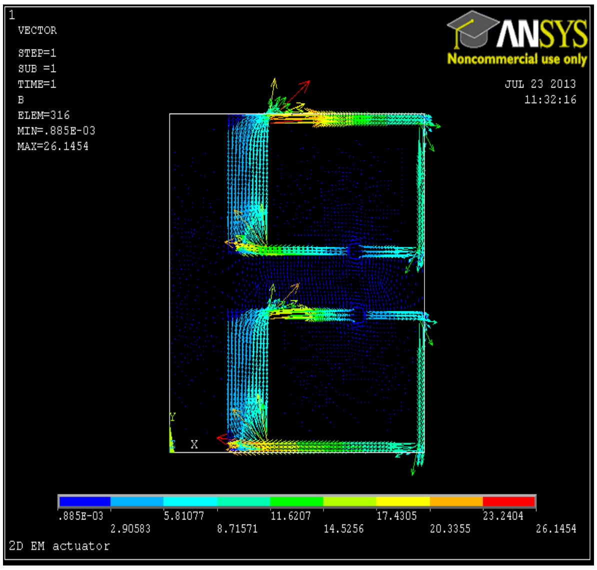

Figure 13 Total magnetic flux density of 2D design

4. Three-Dimensional Structural Assessment

Solidworks software was used for achieving the structural 3D design of the electromagnetic actuator. In this section, a mechanical prototype of the 3D structural actuator design and analysis process will be introduced with the same properties as done on the 2D design. Hence, after obtaining the maximum magnetic force generated by the actuator on last sections, we used this value to apply it in the air gap between each pair of actuators in order to measure and simulate the actuation process which is divided into attraction and extension processes that is done by Solidworks simulation.

Two-Actuators design

Figure (14) shows the 3D structural design which is cylindrical shape around the colonoscopy tube as shown, since there are two actuators separated by the air gap, 1.5 mm. The total diameter of the design is 18 mm and the height for each actuator is 4 mm. This design is a part from the whole design that should be applied along the tube which there are 120 actuators will be built along the tube which takes distance around 65.85 cm and they are separated by the air gap 1.5 mm.

In order to run the simulation, the proper materials should be assigned to the design which there are four different parts, the iron, the coil, the thin fin and the tube. We assigned Gray Cast Iron for the iron component, Copper for the coil and Silicon for both the thin fin and the tube. The next step is to apply the force which has the value of 45.14 N, hence the mesh is generated which is a solid mesh type. The force is applied between the two faces of the actuators between each pair as shown in figure (15). Firstly, there was 45.14 N applied for the attraction process and then applied -45.14 N for the expansion process. Figures 16 and 17 show the required processes from the actuators which describe the attraction and repulsion processes. The resultant displacement of these two actuators as shown in figure (18), which Y-axis is the resultant displacement and X-axis is the nodes along the surface of the actuator, is around 1.545 mm that showed a good representation for two actuators.

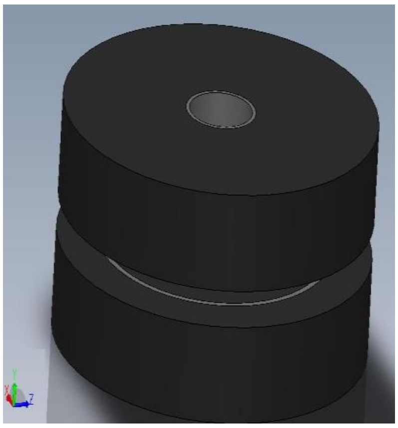

Figure 14 3D structural design

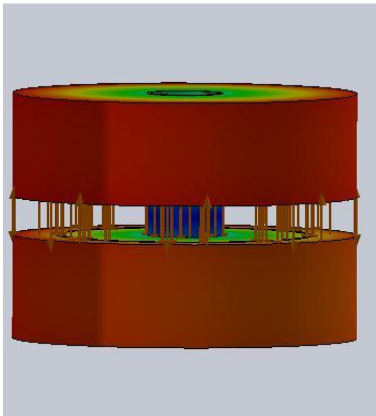

Figure 15 Applying the force

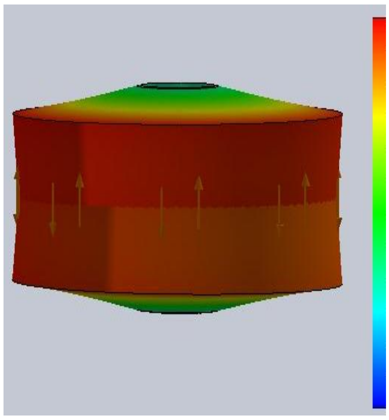

Figure 16 Attraction force applied

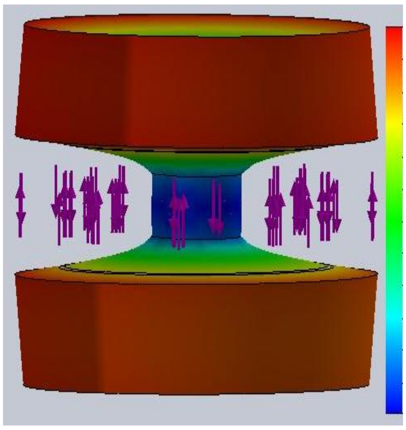

Figure 17 Repulsion force applied

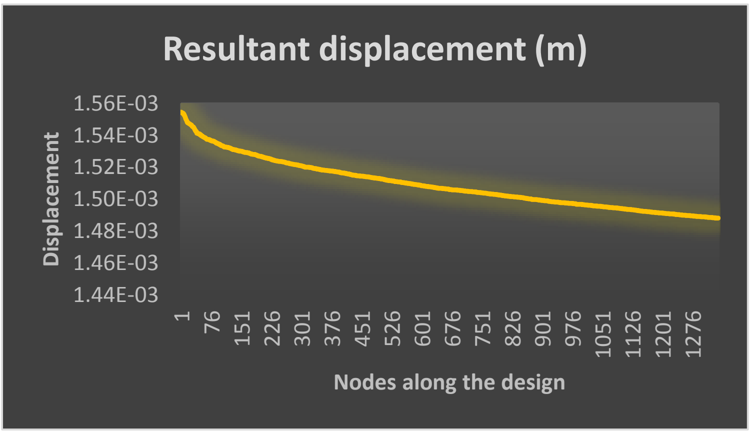

Figure 18 Resultant displacement of two actuators

4. Conclusion

The principle of working the electromagnetic actuators is mainly depending on the way of how to generate the magnetic flux density across the air gap between each pair of the actuators which provides enough force between them. According to the direction of the current on the designed coils, it is simple to control the type of the generated force which there are two forces, the attractive and the repulsive forces. The outcomes of the project were mostly achieved. A functioning electromagnetic actuator was designed and constructed which it was made from purely electromagnetic components. Specific conclusions were drawn based on the results presented in each design that constitute the main part of the present work.

A finite element model was created and simulations were performed for this design. We used ANSYS and ANSYS Workbench software for the electromagnetic simulation and Solidworks software for the mechanical structural assessment. There is merit for using the idea of the electromagnetism for designing our actuators because we could achieve the design with lower size, for example, after implementing the actuation design around the colonoscopy tube, the whole design of the colonoscopy device will be 18 mm in diameter which is beyond the limit of the conventional colonoscopy, 20 mm. Therefore, it is a great advantage to design an actuator with lower size rather than most of wired colonoscopy's actuators like pneumatic, hydraulic and electromechanical actuators.

Our future activity will essentially focus on the following aspects:

- We will seek to increase the advanced displacement, therefore we will increase the air gap area by increasing the separation between the actuators to be 2.5 mm instead of 1.5 mm. This will give a great opportunity for using lower number of actuators along the tube of the colonoscopy which it will not be heavier than the design of 1.5 mm air gap. However, there is an important consideration is the value of the magnetic flux distribution that will be expected to decrease.
- The next important challenge is to design a smart actuator using electroactive polymer (EAP) actuator. Electroactive polymers (EAPs) can generate strains that are as high as two orders of magnitude greater than the striction-limited, rigid, and fragile electroactive ceramics (EAC). Further, EAP materials are superior to shape memory alloys (SMAs) in higher response speed, lower density and greater resilience [7]. Electroactive polymers (EAPs) offer the promise of creating the flexible, low-mass actuators that can form the basic building blocks of the desired EAP actuator. Their main attractive features are relatively small density, compatibility with large deformations, and ease of manufacture and modification. Its actuator gives large displacements reaching levels of 200%-380%, since we will use the 3M VHB 4910 acrylic adhesive films which have exhibited up to 380% strain in area expansion at 5-6 kV when they are highly prestrained [8].

5. References

1- B. A. Miller, L. N. Kolonel, L. Bernstein, Jr., J. L. Young, G. M. Swanson, D. West, C. R. Key, J. M. Liff, C. S. Glover, and G. A. Alexander, ""Racial/ethnic patterns of cancer in the United States 1988–1992,"," in *National Cancer Institute, Bethesda, MD, N*, 1996.

2- IRWAN KASSIM, LOUIS PHEE, WAN S. NG, FENG GONG, PAOLO DARIO, and CHARLES A. MOSSE , "Locomotion Techniques for Robotic Colonoscopy,," *EEE ENGINEERING IN MEDICINE AND BIOLOGY* , pp. pp.49-56, May-Jun 2006,.

3- Nikunj shah, Rob Jamieson., Electromagnetic Linear Actuator., 2006.

4- "Magnetic field of a solenoid" Physics 232, Elementary Physics, 1997. [Online]. Available: http://www.pa.msu.edu/courses/1997spring/phy232/lectures/ampereslaw/solenoid.html . [Accessed 01 08 2013].

5- Vokoun D, Beleggia M, Heller L, Sittner P, "Magnetic interaction and forces between cylindrical permanent magnets," *Journal of Magnetism and Magnetic Materials,* vol. 321, pp. 3758-3763.

6- V. V. Trivedi, "Smart Actuator for Rehabilitation Training System," Dundee, United kingdom, Aug,2009.

7- R. k. a. J. P. J. Perline R., "Electrostriction of polymer dielectrics with compliant electrodes as a means of actuation," *Sensor Actuat. A,* vol. 64(1998), pp. 77-85, 1998.

8- M. R. S. S. a. H. P. Qibing Pei, "Multiple-degrees-of-freedom electroelastomer roll actuators," *SMART MATERIALS AND STRUCTURES*, no. SRI International, 333 Ravenswood Avenue,Menlo Park, CA 94025, USA, pp. 86-92, 16 September 2004.