Abstract: Wireless Capsule Endoscope (WCE) is a new diagnostic device that can be utilized for evaluating the whole digestive tract if effectively actuated. In this research, a new One Degree of Freedom (1DOF) actuation system based on a magnetic levitation concept is proposed for capsule endoscope navigation system. The proposed system, is used to move a permanent magnet inserted in WCE body by an arrangement of current controlled electromagnetic actuator placed on a 3DOF movable frame. The aim of this study is to design of a Proportional-Integral-Derivative (PID) controller to suspend the capsule and keep it at a demand test region. DC and AC magnetic field-based positioning systems using the Hall effect sensor and the coil sensor respectively are used to provide the controller by capsule position feedback. Improvement of the position feedback accuracy based on AC magnetic field using Discrete Fourier Transform (DFT) is presented. A realistic simulation design of the system is implemented using Matlab/Simulink environment to validate the PID controller. The navigation scheme is implemented practically utilizing Digital Signal Processor (DSP) to verify the effectiveness of the controller. Finally, simulation and experimental results of the capsule navigation system are presented to show the performance of the proposed controller.

1 Introduction

Wireless Capsule Endoscope (WCE) is a new monitoring technology utilized to examine the whole digestive tract of human body. However, there are still some critical challenges such as its passive movement and orientation which limit the possibility of its adoption as a commercial diagnosis tool in private clinics and hospitals. Although, much research works have been carried out by bio-engineers during the last decades in the methods of controlled actuation for capsule endoscope, however, the active mobility of this medical device is still in the developmental stages. Given Imaging in cooperation with Swain [1] presented a magnetically actuated WCE to evaluate the upper human GI tract. The medical device which, composes of a modified PillCam Colon with a permanent assembly, is navigated in the water-filled stomach by varying the position and orientation of an external large permanent magnet relative to the patient. Based on the proposed actuation method, all regions of stomach were tested, but, the control of the capsule movement was difficult task as the endoscopist only had the real-time pictures of the device’s camera stomach.

A new navigation system is proposed by Yim et al. [2] for a capsule endoscope. The group fabricated a model of a compliant capsule robot driven in the stomach based on medical procedures. The proposed actuation system consists of two permanent magnets inserted in both ends of a dummy capsule and an external permanent magnet connected across a motor. The force and torque of external permanent magnet are used to rotate the capsule. However, the force of the actuator was not controlled to navigate the dummy capsule in the free space of the stomach. Lien et al. [3] proposed a magnetic navigation system to enable endoscopists to manipulate capsule by means of moving their own hands as previously proposed by [4] [5]. They made a new capsule model provided by longer and shorter focal length lenses for visualization of far-end and close-up stomach wall. In the proposed actuation system, an external Magnetic Field Navigator (MFN) based on a permanent magnetic rotor is used to navigate the medical device inside a stomach. However, the proposed endoscopic capsule was not wireless, as it still needs to be connected to image data transfer and power cables.

A research group from Huazhong University of Science and Technology presented a robotic actuation system with multipermanent magnet for capsule manipulation in small intestine [6][7]. They made a capsule endoscope embedded in a magnetic shell. The actuation magnetic field of the proposed system is generated by external permanent magnets fixed in movable frame with a controlled servo unit. This enables applying a 5-DOF control system for the medical device. The proposed capsule manipulation system was successfully tested in an bowl phantom and an ex vivo porcine small intestine. However, the proposed steering system is not applicable as it is evaluated using blind capsule (without camera). The position feedback of the capsule is obtained from eyes which serve as the image visualization unit for the servo control unit. Moreover, the environment conditions of the human GI tract such as its Fluidic medium and the closed forms of the patient body are not taken into consideration in the performance evaluation of the proposed capsule guiding system. A new prototype of handheld magnetic actuator is fabricated by Sun et al. [8] for a spiral-type WCE. The proposed actuator mainly composes of an external permanent magnet attached to a step motor used to guide a dummy capsule provided by a cylindrical magnetic shell and a spiral. The rotational magnetic field produced by the handheld actuator can be used to move the spiral-type medical device. The ex-vivo experiments showed that, based on the control of the proposed magnetic actuator the endoscopic capsule can move forward or backward through the test region. However, the handheld actuator is not able to orient the capsule endoscope to the desired direction. In addition, the regulation control input supplied to the step motor is not determined based on the position feedback information of the capsule.

It is worth considering that using handheld magnetic generator to guide the capsule in the digestive tract includes some drawbacks such as high cost of these magnetic generator and exhibition a short-learning curve for the operator, moreover, the usage of such handheld devices would suffer from a limited lifetime due to the wear and tear of the magnetic coil.
systems during entire evaluation session for stomach is physically taxing for the operator. Moreover, obtaining full stomach evaluation would require more time and uncomfortable for the patient. Hence, developing a new capsule type would be beneficial. In 2019, a new magnetic capsule guidance system for evaluation the gastric cavity and small intestine in pediatric patients was proposed by Xie et al. [18]. The presented actuation system consists of capsule control system, a portable recorder and a capsule positioner. The capsule, which is made of biocompatible material, is provided by a magnet for movement purposes inside the body. In this control method, high-level controller is achieved by an operator. The control system is mainly composed of a magnetic head, a transnational rotary table, two monitors and a console. By regulating the magnetic head movement and generating a corresponding magnetic field, capsule movement can be controlled within the patient’s body. However, no control technique is employed to regulate the generated magnetic field used to actuate the capsule. In [19] a new autonomous control method for capsule endoscope is proposed in which, the operator acts as a high-level controller for steering and orienting the medical device inside the stomach. In the presented approach, the acquired photos by the capsule’s camera for human stomach is used as feedback information for planing to the desired path and maneuvers of the capsule. However, guiding efficiency of the capsule inside the stomach depends on the operator’s skills, which are difficult to achieve. Most of the proposed methods for actuating and controlling of the capsule endoscopes, the operator utilizes the captured images by the capsule as feedback information for determining the new desired position of the capsule. In other words, the operator acts as a high-level controller, while the low-level controller calculates the corresponding parameters values of the actuator required to navigate the capsule to the next location.

In this research, a new capsule navigation scheme based on magnetic levitation concept is presented for colon investigation. The aim of this work is to design and implement a One Degree of Freedom (1DOF) control system based on Proportional Integral Derivative (PID) controller technique to keep the endoscopic capsule at a demand test region. PID is the most common controller technique used in wide movement and industrial applications due to its simplicity, reliability and performance characteristics. It is worth considering that realization and tuning of the PID controller approach are also easy to implement as its gain parameters are relatively independent. The system feedback is based on capsule position information obtained from magnetic sensing unit, which is considered a promising measurement tool for the medical device position from outside the patient body. Initially, the Pulse Width Modulation (PWM) technique is adopted to sent the PID controller commands to the electromagnetic actuator due to its high driving efficiency and low power loss [20].

In this work, DC and AC magnetic fields are utilized to measure the capsule position feedback in the proposed actuation algorithm. Fixed point Digital Signal Processor (DSP) (TMS320F2812) is utilized to implement the controller system because of its precision data processing capability and high-speed, which empower fast real-time control of the calculation variables. However, despite the resolution advantages of DSP 12-bit conversion, the absolute accuracy of the Analog-to-Digital Conversion (ADC) is influenced by the inherent offset and gain errors. Therefore, calibration process for DSP’s ADC is recommended in order to increase the conversion accuracy [21].

The paper is organized as follows. Section 2 presents system configuration. In section 3, positioning and controller systems theory is introduced. Section 4 presents dynamic modelling of the proposed capsule control system. Actuation system strategy is stated in section 5. DC and AC positioning controller systems are introduced in Sections 6 and 7 respectively. An improved AC positioning controller scheme is presented in 8 followed by conclusion in section 9.
2 System configuration

The preliminary conceptual setup of the proposed 3DOF capsule navigation scheme is presented in Fig. 1(a). The introduced system mainly consists of a small permanent magnet with a length of \( L_d \) and radius of \( r_d \), a current controlled actuator with a length of \( L_c \) and base width and depth of \( W_c \) and \( D_c \) respectively, position detector, processor and movable frame. The NdFeB-based dipole is inserted in capsule and magnetized in the towards of its symmetrical axis in order to prevent rotation of the capsule camera during the examine journey of the digestive tract. An iron cored based coil is used as system actuator which placed on a 3DOF robotic frame manipulator. Two hall effect sensors (A1301) fixed in the poles of the electromagnetic coil are used in the position detection unit of the proposed control system.

The processor is based on IT TMS320F2812 DSP and is utilized to execute the proposed PID controller of the capsule actuation scheme. Finally, a 3DOF robot is adopted to actuate the floating embedded magnet though the bowel organ by placing the magnetic actuator anywhere above the patient in the vicinity of the endoscopic capsule.

3 Positioning and controller systems theory

In the proposed actuation system, two positioning approaches based on the Hall effect sensor and the coil sensor are adopted to measure the position of the capsule endoscope.

3.1 Positioning with DC magnetic field measurement

In the proposed actuation system, positioning of the WCE is based on using a 1-axis Hall effect sensor. It converts magnetic field, produced by an embedded magnet in the capsule, into electrical signals for processing by electronic circuits. Generally, the output voltage of the Hall effect devices can be quite small, even when a strong magnetic intensity is applied, therefore, they are manufactured with built-linear amplifiers and CMOS Class A output structure.

The voltage across the Hall effect sensor \( V_h \) attached to the coil, induced by the levitating magnet and the electromagnet currying current \( i(t) \), can be closely approximated as [22]:

\[
V_h(t) = \lambda i(t) + \frac{\varepsilon}{x^2(t)} + \rho,
\]

where \( \lambda, \varepsilon \) and \( \rho \) are coefficients with constant values that depend on the Hall effect sensor used, as well as the system geometry, and \( x \) is the axial distance between the floating magnet \( m \) and sensor.

Usually, \( \rho \) is quiescent output voltage \( (0.5V_{cc}) \), where \( V_{cc} = 5V \) is supply voltage to the Hall effect sensor chip, while \( \lambda \) and \( \varepsilon \) should be determined from measurement, as they depend not only on the sensor sensitivity, but also on where it is placed and the properties of the coil.

3.2 Positioning with AC magnetic field measurement

Coil sensors are one of the oldest and most well-known types of magnetic sensor. The response function of core coil sensors is easy to characterize by Faraday’s fundamental law of induction, as follows [23]:

\[
V_s = -N_s \frac{d\Phi}{dt},
\]

where \( V_s \) is the induced voltage \( (V) \), \( N_s \) is the number of coil turns, and \( \Phi \) is the magnetic flux passing through a coil. For control and measurement applications, a magnetic sensor with high sensitivity, adequate stability and reliability is needed in order to provide the control system by precise feedback information. Generally, the sensitivity of an air coil sensor is relatively low, so to improve the output response a ferromagnetic core with high permeability should be used. However, this enhancement is accompanied by the sacrifice of one of the most important advantages of the air-cored coil sensor which is the linearity. The core, even if made from highly permeable material, adds some nonlinear factors to the sensor transfer function. Furthermore, the resolution of the coil sensor also decreases by additional magnetic noise (e.g. Barkhausen noise). Moreover, the ferromagnetic core alters the distribution of the investigated magnetic field [23].

Therefore, in this study, an air-cored coil sensor will be employed for capsule positioning. To improve the sensitivity of the sensor an increase in the number of its turns can be adopted. However, this process will increase the resistance of the coil because the total length of wire increases, leading to additional resistance noise.

Following the scaling rules outlined, [24] [25], if the radius of the coil sensor \( r_s \) is maintained constant then the cross-sectional area of the wire must be decreased proportionally to \( N_s \) in order to improve the sensor output. However, the optimization process for coil sensor performance is not as easy [23]. In practice, the sensor must have enough windings with a reasonable wire gauge to ensure sufficient signal amplitude so that the performance is not affected by amplifier noise.

3.3 Controller technique

In this research, integer PID controller is utilized to execute the actuation algorithm of the proposed control system. The continuous time structure of the proposed PID controller is given by [26]:

\[
u(t) = K_pe(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt},
\]

where \( u(t) \) represents the output of the controller at time \( t \), \( e(t) \) denotes the error between the demand input and measured output while \( K_p, K_i \) and \( K_d \) represent the corresponding controller gains. This controller method is highly recommended for industry and accurate movement applications due to the simplicity of its principle and the ability to realized and tuned it as the gain coefficients of the controller are relatively independent.

4 System dynamics and modelling

A forces diagram of the proposed 1DOF actuation system is presented in Fig. 1(b). Based on the assumption that the origin of the coordinate system is placed in the center of the coil’s lower pole,
the magnetic force exerted by the coil on the embedded magnet is
govern by the following expression [27],
\[ \vec{F}(x(t), i(t)) = \frac{3\mu_0 \mu_r}{4\pi} \left\{ (\mu_c \vec{R})i_d + (\mu_d \vec{R})i_e + (\mu_c \vec{R})\vec{R} \right\} \]
\[ - \frac{5(\mu_c \vec{R})(\mu_d \vec{R})\vec{R}}{R^3} \]
where \( \mu_0 \) and \( \mu_r \) represent the air permeability \( \left( \frac{T \cdot m}{A} \right) \) and relative magnetic permeability of the coil core respectively, \( \mu_c \) and \( \mu_d \) denote magnetic moment vector of the coil and dipole \( (A \cdot m^2) \) respectively, \( \vec{R} \) denotes the distance vector from actuator to the dipole \( (m) \), and \( R \) represents the distance value between coil and the dipole \( (m) \).
\[ \mu_c = \mu_c(\hat{x} + \hat{y} + \hat{k}) \]
\[ \mu_d = \mu_d(\hat{x} + \hat{y} + \hat{k}) \]
where \( \mu_c = N i_A c \), \( N \), \( i \), and \( A_c \) are the turns number, current \( (A) \) and the cross-section area of the actuator \( (m^2) \) respectively, \( \mu_d = \frac{BV}{\mu_0} \), \( B \) is the intrinsic induction of the magnet \( (T) \) and \( V \) is the volume of the magnet \( (m^3) \). Under the assumption, the magnetization pole of the coil and the inserted dipole points to the \( x \)-direction, then based on (5) and (6) \( \mu_c = \mu_c \hat{x} \) and \( \mu_d = \mu_d \hat{x} \). Then, using (4), the attraction force at the levitated magnet placed at a distance \( x \) from the actuator, can be expressed by the following equation [28],[29]:
\[ F(x(t), i(t)) = K \frac{i(t)}{x(t)} \]
where \( K = \frac{3}{4\pi} \mu_r N A_c B V \) is a magnetic force constant depends on the physical parameters of the scheme \( \left( \frac{N A_c B V}{A} \right) \). The movement of the medical device in the magnetic field can be expressed by Newton’s second law.
\[ m \ddot{x}(t) = mg - K \frac{i(t)}{x(t)} \]
where \( m \) denotes the mass of the dipole \( (kg) \) and \( g \) represents the acceleration of the magnet due to gravity \( \left( \frac{m}{s^2} \right) \). For the purpose of a linear control scheme design, (8) is linearized by Taylor’s series expansion about operating values \( x_0 \) and \( i_0 \). Assume a perturbation about these equilibrium values \( (\dot{x}(t) = x_0 + \delta x(t), i(t) = i_0 + \delta i(t)) \), then the linearized model of the capsule dynamic about \( x_0 \) and \( i_0 \) can be represented by (9)
\[ \delta \ddot{x}(t) = - \left( \frac{K}{m x_0^2} \right) \delta i(t) + \left( \frac{4K i_0}{m x_0^2} \right) \delta x(t) \]
From Fig. 1(b), at equilibrium condition the resultant force on the floated magnet in the \( x \)-axis equals zero, which means the magnetic force on the dipole equals the gravitational force. Based on (8) and using operating values \( (x_0, i_0) \), the control input signal \( i_0 \) can be determined utilizing the following expression:
\[ i_0 = \frac{mg x_d}{K} \]
Taking the Laplace transform of (9), the transfer function of the system plant with the variation in current of the electromagnetic coil as the scheme input and the variation in suspended magnet location as the scheme output is;
\[ \frac{\delta X(s)}{\delta I(s)} = \frac{- \left( \frac{K}{m x_0^2} \right)}{s^2 - \left( \frac{4K i_0}{m x_0^2} \right)} \]
where \( \delta X(s) \) and \( \delta I(s) \) are the Laplace transform of \( \delta x(t) \) and \( \delta i(t) \) respectively. It is worth considering that the negative sign in the numerator of the transfer function denotes that there is an inverse relationship between the actuator current and the vertical magnet distance, with an increase in the actuator current \( \delta i(t) \), there will be a decrease in the inserted magnet distance \( \delta x(t) \) and vice versa. It is obvious from (11), that the system plant has two poles, one of which is in the right half of the \( s \)-plane at \( \sqrt{\frac{4Ki_0}{m x_0^2}} \), that makes the system unstable. Hence, a controller must be used to stabilize the system, in this research, a linear controller based on the PID technique is adopted to maintain the embedded magnet at the demand vertical distance.

In order to execute the proposed PID controller in state space, the model of the scheme dynamics should be formulated in state space form: let \( \delta X_{(n \times 1)} = \delta x(t) \) be the state vector of the scheme, \( \delta x(t) \) be the system output that should be controlled, and \( \delta U(t) \) be the vector of the control input, then the state space representation of the scheme can be described by (12) and (13).
\[ \dot{\delta X}(t) = A \delta X(t) + B \delta U(t) \]
\[ \delta Y(t) = C \delta X(t) + D \delta U(t) \]
where \( A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \), \( B = \begin{bmatrix} 0 \\ C1 \end{bmatrix} \), \( C = \begin{bmatrix} 1 & 0 \end{bmatrix} \), \( D = [0] \), \( C1 = \frac{4Ki_0}{m x_0^2} \) and \( C2 = - \frac{K}{m x_0^2} \).

5 Actuation system strategy

The navigation approach of the presented capsule control scheme comprises the following stages:

Stage 1: design and implementing a control system using an integer PID controller to actuate the floated dipole in one dimension within a region around the operating area and maintain it at a variable-x demand position relative to the actuator.

Stage 2: move the inserted dipole through the three dimensions simulated bowel by transferring the controlled actuator utilizing 3DOF robot navigator.

This research work focuses on achievement of stage 1. The idea of the introduced actuation scheme is easy to realize as it has been based on the concept of the magnetic levitation.

6 DC position feedback-based controller system [26]

In this section, controller design with position system based on DC magnetic field using Hall effect sensor will be simulated and then implemented in real-time to validate the proposed system.

6.1 Hall effect sensor calibration

The position of the suspended dipole was determined experimentally using two Hall effect sensors fixed on the lower and upper poles of the electromagnetic actuator. The lower sensor was calibrated experimentally utilizing a table of accurate position readings.
By maintaining the inserted dipole concentric with the magnetic sensor, the procedure of sensor calibration was achieved by dropping the embedded magnet from 15 mm (minimum operating distance) up to distance of 55 mm. The position reading of the sensor was amplified by a non-inverter amplifier to a level so that we could discriminate the dipole position signal from the sensor noise when the magnet was at the typical operating distance from the actuator coil.

The amplified position signal was then filtered to decrease unwanted noise signal and sampled utilizing the processor DSP’s ADC. In this study, a more reduction in the effect of the noise on the dipole position signal is achieved through calculation of an average of ten repeated sensor readings at each lowering step. The curve of experimental position data based on the sensor readings used to determine the vertical distance of the floated magnet is illustrated in Fig. 2(a). In order to decrease complexity of computational process in the DSP and support the execution speed of controller program, the formula used to determine dipole position \( x(t) \) based on the reading of DSP’s ADC \( V_p(t) \) was approximated by the following fourth-order expression utilizing the Matlab command "polyfit":

\[
x(t) = 0.003V_p^4(t) - 0.93V_p^3(t) + 3.476V_p^2(t) - 5.754V_p(t) + 3.58
\]

(14)

The validity of the above calibration expression to the magnet position values has a zero mean error with a standard deviation of \( \sigma = 0.32 \) mm. For the purposes of system simulation, the sensor reading \( V_p(t) \) can be formulated based on the magnet vertical distance \( x(t) \) as follows:

\[
V_p(t) = 3.2 \times 10^6x^4(t) - 5.1 \times 10^5x^3(t) + 2.96 \times 10^4x^2(t) - 769x(t) + 9.4
\]

(15)

In this study, the Hall effect sensor utilized to measure the dipole position was calibrated practically based on a precision positioning table. By keeping the magnet at a practical vertical distance 30 mm from the below actuator pole, the coil was excited by a step current of 0.5 A over the current range of 0-5 A with the step time of 30 s. Over the current range, the practical dipole position was measured based on (14) and then compared with its actual distance 30 mm to generate the position error which is shown in Fig. 2(b). It can be noted from the Fig. 2(b) that increasing the coil current increased the position error. The reason for this is that increasing coil current heats it hence varying the magnetic behaviour of the electromagnetic actuator.

### 6.2 Positioning algorithm

In this algorithm, the detection strategy of the magnet position is based on the idea that the magnetic sensor fixed on the lower coil’s pole senses the magnetic field for both the coil and the dipole, while the magnetic sensor placed in the upper coil’s pole measures the magnetic field of only the coil. The position signal of the magnet is determined by sending the sensors readings to the signal processing circuit for buffering, subtraction, amplification and finally filtering to reject interference and sensor noises. The processed signal is also passed to the DSP for sampling and PID controller implementation. This positioning method is still not an efficient as the sensors measurements influence by the problem of the DC actuation field cancellation. In addition, obtaining a precise position feedback requires a high degree of efficiency, not only in coil geometry design and manufacturing, but also in coil winding. Therefore, another positioning approach based on an AC magnetic field will be considered in this research.

### 6.3 Simulation design and results

In this study, the performance of the proposed actuation system is verified through simulation using the PID controller utilizing Matlab/Simulink environment. Based on the low capture rate on the medical device and bowel diameter, the PID controller is designed for the demand guidance response with rise time \( t_r \) and settling time \( t_s \) of 10 ms and 0.2 s respectively and maximum percent overshoot \( MP \) of 15%. To meet this, the dynamics of the capsule actuation system is modelled based on the values of the practical physical and magnetic parameters, which are stated in Table 1. In this research, the realistic of the simulation model for the proposed capsule actuation system is validated by using magnetic force constant \( K \), which is determined experimentally as follows. After placing the embedded magnet at distance \( x_o \) of the electromagnetic coil, the exciting current of the coil is slightly increased until the dipole just lifted off. Then, \( K \) can be determined by using (10) based on the measured parameters, \( x_o \), \( i_o \), \( m \), and \( g \). In addition, the position of the floated magnet is measured based on (14), instead of utilizing the theoretical expression of the Hall effect sensor output stated in (1).

Furthermore, two types of noise, measurement and process noises are also involved in the system model for realistic purposes. The measurement noise based on band-limited white noise with power of 25 \( \mu V \) is incorporated to compensate the position sensor error and A/D quantization error, while the process noise based on Gaussian noise with mean value of 0 V and variance of 0.24 mV is added to compensate the linearization influence of dynamics modelling and system perturbation.

To assess the performance of the PID controller, the system response was examined based on standard parameters of control criteria, which includes rise time, maximum percentage overshoot, settling time and steady state error. The Simulink model of the proposed actuation system is shown in Fig. 3, in which the position unit was utilized to calibrate the dipole vertical distance into its corresponding voltage value. This sensor output signal was then compared with the corresponding voltage value of the desired magnet position. Based on (10) and (12), the matrices elements of the state equation and the operation coil current were determined at \( x_o = 25 \) mm as follows:

- \( C_1 = 1569.6 \), \( C_2 = -69.7 \) and \( i_0 = 0.14 \) A.
- In control design of linearized systems, the trajectory of desired input should be initialized with value that is close to the equilibrium value. In this application, utilizing the initial magnet position and velocity \( x_i = 35 \) mm and \( V_{i0} = 0.26 \) respectively, under the demand magnet position \( x = 25 \) mm, which corresponds to step input \( V_s = 2.0275 \) V, the output of the controller based on gain parameters \( K_P = 1.2 \), \( K_I = 0.02 \) and \( K_D = 0.035 \) are presented in Fig. 4(a) and (b) respectively. The closed-loop pole zeros and states of the system are \( -0.0167 \) and \( -34.3 \) respectively. Regarding the system effort, Fig. 5(a) and (b) show the control input required to actuate the embedded magnet distance \( \delta x(t) \) and \( x(t) \) respectively.

It is obvious from the mini plot of Fig. 4(a) and (b), that the proposed PID control system succeeded to effectively guide the embedded magnet through the trajectory of the demand input with fast transient response, rise and settling time of 0.035 s and 0.35 s respectively. In this research, the controller gain parameters are tuned properly so that it can achieve a compromise between minimum control effort and the best control performance so that the output response as closed as possible to the desired input. Based on the mini figure of Fig. 5(a) and (b), the control effort of the proposed actuation scheme was reasonable: the initial and steady state value of the input signal was approximately 0.4 A and 0.14 A respectively. However, there was a fluctuation of approximately \( \pm 0.5 \) mm around the demand vertical distance and an maximum overshoot value of approximately 2.5 mm due to process and measurement added noises. It is worth considering that this small variance in the output response of the proposed capsule actuation system has no impact on the accuracy of the taken photographs as the capture rate of the capsule’s camera.

<table>
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</tr>
<tr>
<td>( D_c )</td>
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<tr>
<td>( r_d )</td>
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<td>( K )</td>
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<tr>
<td>( \mu )</td>
<td>42 ( \times 10^{-7} ) N.m/A</td>
</tr>
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</table>

### Table 1 Physical and magnetic parameters of the system
The preliminary experimental setup of the capsule navigation system is shown in Fig. 6. The block diagram in Fig. 7 shows the hardware stages of the proposed control scheme. It is mainly combined of a controller, a signal condition unit and a test bed stage. The controller is based on the fixed-point 32-bit DSP of 150 MHz maximum frequency with a 12-bit pipelined ADC module, which executes the PID controller calculation and supplies PWM command signal to the capsule actuator. The signal conditioner stage includes circuits of buffering, signal amplification, noise filtering and level regulation while the test bed composes of an electromagnetic coil, two Hall effect position sensors, and a current driver.

### 6.4 Controller implementation

#### 6.4.1 Hardware system design:

The position signal of the magnet with an initial position close to the equilibrium point \(X_0=[x_0, y_0]^T=[0, 0.025 m]^T\) by the Hall effect sensors. The position signal accuracy is increased by reducing the offset between the sensor readings as much as possible. The dipole position readings are sent to the signal processing stage for purposes of subtraction, level amplification and noise filtering and finally to the DSP’s on-chip A/D conversion for sampling. The accuracy of the signal conversion is increased by calibrating the DSP’s ADC in order to decrease the error conversion due to ingrained gain and offset errors of the processor. To further decrease the effect of the dipole position noise, an average filter is applied in the DSP on the sampled data. In the DSP, the measured magnet distance is compared with the demand vertical distance of \(x_d = 0.025 m\) to produce the error signal, which is sent to the PID controller. In the processor, the

### 6.4.2 Actuation algorithm implementation:

A simple PID controller is adopted to implement the 1D actuation algorithm for the capsule endoscope. The system operates by measuring the position signal of the capsule with an initial position close to the equilibrium point \(X_0=[x_0, y_0]^T=[0, 0.025 m]^T\) by the Hall effect sensors. The position signal accuracy is increased by reducing the offset between the sensor readings as much as possible. The dipole position readings are sent to the signal processing stage for purposes of subtraction, level amplification and noise filtering and finally to the DSP’s on-chip A/D conversion for sampling. The accuracy of the signal conversion is increased by calibrating the DSP’s ADC in order to decrease the error conversion due to ingrained gain and offset errors of the processor. To further decrease the effect of the dipole position noise, an average filter is applied in the DSP on the sampled data. In the DSP, the measured magnet distance is compared with the demand vertical distance of \(x_d = 0.025 m\) to produce the error signal, which is sent to the PID controller. In the processor, the
controller gains $K_p$, $K_i$ and $K_d$ are set to proper values so that it can investigate the required performance parameters stated in section 6.3. The controller command signal in the form of the PWM is calculated in the processor based on the error signal and the controller parameters. This PWM control signal, with a changing duty cycle, is utilized to regulate the electromagnetic actuator current through a current bridge circuit using a MOSFET transistor (IRL3334).

6.4.3 Experimental results: To verify the efficiency of the presented capsule navigation scheme and to validate the results of the Simulink model, the actuation scheme is practically implemented in real-time utilizing digital processor device based on the same conditions of the simulated model. Due to the high speed potential and acceleration of which the floated body is capable, it is required for a high sampling rate to be utilized within the actuation scheme in order to keep the floated object at desired position [32]. The sampling frequency of the actuator current is governed by the sampling of the DSP's ADC and the controller algorithm implementation time. On this basis, the sampling frequency of the ADC is set to the highest sampling rate of 25 MHz at which an average filter for the position signal is implemented in the DSP in order to decrease its fluctuation. Additionally, the controller algorithm was optimised in order to reduce the execution time. The experimental and simulation results were 70% compatible. The cause for this is because the real system is not modelled as it should as the dynamics of the system is linearized around the operating point to enable design a linear control system, furthermore, the static attraction force between the coil core and the dipole not being considered.

By applying a fine tuning for the gain parameter $K_p$, an improvement in the response of the scheme can be observed. Based on the PID gain parameters $K_p = 1.323$, $K_i = 0.022$, and $K_d = 0.434$, Fig. 8(a) and (b) illustrate the experimental displacement of the dipole generated by the actuator and the coil current respectively. The preliminary practical prototype of the suggested navigation system, as presented in Fig. 6, shows suspension of the dipole in the air with desired vertical distance of 25 mm and input signal of 0.16 A, as predicted. It can be seen from Fig. 8 that the controller enabled the magnet to track the desired step input trajectory efficiently. It can be seen from the mini figure of Fig. 5(b) and Fig. 8(b) that there is a very good convergence between the actuator current of the simulated and real control systems, which were at a steady state 0.14 A and 0.16 A respectively. This good match between the Simulink and experimental responses investigates the validity of the dynamics modelling and system simulation.

To verify the robustness of the PID control design, the performance of the navigation scheme is studied based on a square wave input signal with frequency of 2 Hz, a peak-to-peak amplitude of a 10 mm and an offset of 20 mm. The desired and actual magnet position and the applied actuator current based on gain parameters $K_p = 1.64$, $K_i = 0.1$, and $K_d = 0.65$ are presented in Fig. 9(a) and (b) respectively. It is clear from Fig. 9(a) that the controller succeeded to enable the embedded dipole to track the demand reference trajectory with an acceptable efficiency. The actuation scheme has a fast rise time $t_r$ of 0.12 s, and acceptable settling time $t_s$ of 0.4 s with a small system noise of ±0.8 mm. However, there is an overshoot of approximately 2.25 mm because of non-ideal loop response.

In this research, the response of the actuation system is optimised by the improvement of the position feedback of the actuation algorithm, which is discussed in the next section. Fig. 9(b), presents the value of the actuator current range which was at a steady state at about 0.09 – 0.37 A. Therefore, the robustness of the proposed control system is enough to successfully guide and stabilize the embedded magnet at desired region.

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**Fig. 6**: Experimental setup of the proposed 1DOF control system

**Fig. 7**: Block diagram of the hardware design for control system

**Fig. 8**: Real-time practical responses of the magnet position and control effort based on step input

**Fig. 9**: Real-time responses of the dipole vertical distance and coil signal under a square wave reference input
7 AC position feedback-based controller system

In the optimised control system, the dipole position can be obtained from the AC magnetic signal produced by the generating coil based on the coil sensor.

7.1 Coil sensor calibration

Because the coil sensor is placed outside the human body on the actuator pole, there is no limitation in its geometry and the number of turns parameters. Consequently, these parameters can be manipulated in the design of a high sensitivity coil sensor. In this research, the sensor was designed with a diameter of 40 mm and 50 turns with a 38 American wire gauge (AWG) copper wire.

As with the control system based on the DC position feedback, the system simulation is validated by using practical position information obtained from the calibrated coil sensor experimentally. Based on the same calibration procedure with using coherent detector for noise reduction purposes, Fig. 10(a) shows a vertical capsule position curve. To reduce the computational load of the algorithm implementation, the calculation process of the position was also, as in the DC positioning controller system, approximated by the following expression.

\[
x(t) = -0.4V_p^2(t) + 4.8V_p^4(t) - 22.3V_p^6(t) + 52.3V_p^8(t) - 60.8V_p^10(t) + 28.2
\]

For system simulation purposes, based on the capsule position, the position voltage signal can be expressed as follows:

\[
V_p(t) = 3.4 \times 10^6 x_4(t) - 4.83 \times 10^5 x_5(t) + 2.8 \times 10^4 x_6(t) - 743.5x_7(t) + 9.2
\]

To assess the positioning approach performance, again based on the same error measurement procedure mentioned previously, the magnet position was calculated using (16), and based on the actual position signal, the position error was calculated and is finally shown in Fig. 10(b). By comparing Fig. 2(b) with Fig. 10(b), it should be noted that, based on the coil sensor, there was a very important reduction in the position error achieved compared with the previous positioning method based on the Hall effect sensor. The reason for this is that the feedback position signal was determined from an AC magnetic field signal which was effectively discriminated from the DC magnetic actuation fields.

7.2 Simulation design and results

Using the gain parameters \(K_p = 0.576, K_i = 0.024\) and \(K_d = 0.0216\), Figs. 11(a) and (b) illustrate the time response for the states \(\delta x(t)\) and \(x(t)\) respectively. The control signal required for the capsule displacement \(\delta x(t)\) and \(x(t)\) are presented in Figs. 12(a) and (b) respectively. It can be seen from Fig. 11 that the controller effectively guided the inserted dipole through the demanded trajectory. By comparing the mini plot of Fig. 4 and Fig. 11, it should be noted that the system response based on the coil sensor retains a short settling time of approximately 0.25 s. In addition, the overshoot value is reduced from 33% to 25% and the position variation about the desired position is reduced to approximately of \(\pm 0.25\) mm. By comparing the mini figure of Fig. 5 and Fig. 12, the control signal of the system is decreased from 0.41 A to 0.33 A. The good response of the system is achieved since the controller is fed by more accurate position feedback due to the effective isolation of the position signal from the actuation signal.

7.3 Controller implementation

7.3.1 Hardware system design: The experimental setup and the hardware design block diagram of the AC positioning controller system are the same as those in the DC position positioning controller system; these were presented earlier in Fig. 6 and Fig. 7 respectively, except for the use of a coil sensor instead of the Hall effect sensors, and the attachment of a generating coil to the capsule for the localization purpose. Regarding the hardware design, the signal conditioner unit is modified to the following transmitter and receiver stages.

Position signal transmitter

The function of this stage is transmitting the capsule position signal based on the AC magnetic field. It is mainly composed of generating coil, which is a magnetic coil wound around the capsule body, a simple oscillator and amplifier to generate and amplify an AC signal respectively, and series LC resonant circuit to supply a high current AC signal to capsule coil. The excited capsule coil provides the controller by an accurate position information for capsule through detecting the AC magnetic field, which is decoupled from the DC actuation fields, by a suitable sensor.

Position signal receiver

In this section, an analog detector is designed to extract the AC capsule position signal and then send it to the controller in the digital
processor. The detector stage combined of LC, active PBF, LPF and regulator circuits.

7.3.2 Actuation algorithm implementation: The system operates by first exciting the generating coil by 100 kHz voltage signal and placing the capsule initially close to the operating position. The device position signal, which is mixed with unwanted noise, is measured by the coil sensor and then delivered to the processing circuit for filtering, amplification and rectification and finally sent to the A/D converter circuit in the DSP for sampling. Further reduction in the influence of the position noise is achieved by averaging the sampled signal in the DSP. The processed signal is then compared with the demand position signal (0.025 m), to produce an error signal that is sent to the PID controller. In the controller algorithm, the command signal is calculated based on the error signal and the gains $K_p$, $K_i$, and $K_d$. The control signal in PWM form with changing duty cycle is applied to the current driver circuit, which excites the electromagnetic coil by the required current to navigate the embedded dipole over the demand input trajectory.

7.3.3 Experimental results: Using the control gains $K_p = 0.78$, $K_i = 0.024$, and $K_d = 0.0216$, Figs. 13(a) and (b) present the capsule’s measured and demand positions and the coil current, respectively. Based on Fig. 13(a) and Fig. 11(a), it can be seen that there is good compatibility between the practical and simulation results. It is obvious that based on the optimization of the position feedback information, there are significant improvements in the performance of the control system is achieved. Comparing the mini plots of Fig. 13 with Fig. 8, the fall time $t_f$ of the magnet reduced from 1.1 s to 0.75 s, the maximum overshoot value reduced from 22.5% to 18%, and the fluctuation around the steady state position reduced from ±0.8 mm to ±0.6 mm. Again as mentioned before these overshoot and position fluctuation problems have little influence on the bowel and the capture rate of the capsule’s camera respectively [30] [31]. Regarding the input signal of the actuation scheme, the initial excitation current of the actuator decreased from approximately 0.64 A to 0.57 A while the steady state current value is still approximately 0.17 A. In the next section of this study, the controller system is developed through further improvements to the capsule position feedback in order to achieve more robust and accurate actuation system.

8 Improved AC position feedback-based controller system

The performance of the proposed PID controller based on coil sensor is improved by achieving the following procedures:

- Optimizing the response time of the actuation system and reducing AC interference by sending the controller command signals to the linear power transistor through a Digital to Analog Converter (DAC) instead of the PWM approach.
- Supporting the current driver circuit by using a high current gain power transistor TIP31C with a high current gain $h_{fe}$ of 25.
- Further noise reduction for the received position signal through digital filter based on a coherent detector.

9 Conclusion

In this research, a new capsule endoscope positioning and actuation systems for colon examination were proposed. The navigation system is based on current controlled magnetic levitation.

9.1 Position feedback sensing

Both DC and AC magnetic fields were used to obtain the position information of the capsule based on a Hall effect sensor and coil sensor respectively. An accurate position feedback can be obtained based on the Hall effect sensor as the position measurement depends only on the magnetic field of the inserted magnet, which was isolated by subtracting the sensor readings using a differential amplifier circuit. To further increase the accuracy of the feedback information,
9.2 Digital control

A PID controller was designed for capsule actuation. A realistic Simulink model based on experimental position measurements was executed to validate the presented controller. The performance of the simulated controller demonstrates its ability to effectively actuate the inserted dipole over the demand input trajectory, with a short settling time of 0.1 s, a low overshoot of 20% and a steady state position error of 2.25 mm.

To verify the effectiveness of the introduced control system, the controller was implemented practically using the DSP, where the position feedback based on the Hall effect sensors was adopted to generate PWM command signals, which were used to regulate the coil current. The experimental response of the proposed system has shown that the PID controller was able to successfully navigate the inserted dipole over the demand input trajectory with a settling time of 0.11 s, an overshoot of 25% and a steady state error of ±0.8 mm.

The proposed actuation system was optimised by improving the position feedback through the use of an AC magnetic signal to provide the position data based on the coil sensor. The practical response has shown that the optimised AC system, compared with the DC positioning based actuation system, has a shorter fall time, minimal overshoot value and steady state error.

To validate the robustness of the control system based on AC positioning actuation, the acting performance of the proposed control system is evaluated under square wave input. The real-time response has shown that the PID controller was able to successfully move the inserted dipole through the demand reference input. However, using the PWM technique to drive the coil of the optimised actuation system produces an AC interference effect on the coil sensor. Hence, the positioning scheme was improved by using the linear power amplifier to pass the controller command signals to the actuator.

10 References