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DESIGN PROCEDURES IN THE DEVELOPMENT OF AN ELECTROMAGNETIC MANIPULATOR

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Abstract

This paper addresses the conceptual design of and optimal dimensions for building a portable 3-DOF (Degree of Freedom) electromagnetic finger manipulator that can be used for many industrial applications. The overall design procedures are subdivided into the conceptual design, actuator design, configuration design, mechanical design, workspace design and the parametric design. The design procedures are developed based on a morphological chart, which combines the different functions used in the design. This chart allows us to select the best solution to satisfy our goals and objectives. We chose the electromagnetic actuation method to drive the manipulator. The manipulator workspace is 4 cm in the X and Z axes and the maximum swivelling angle in both axes is 30 degrees. The optimal dimensions of the electromagnetic coil are calculated. The magnetic force at 1 cm axial gap and 1 A excitation current is 8 N. This force can generate a 3 N force at the manipulator end-effector based on the manipulator dynamic model. The magnetic force versus the axial distance and versus the excitation current is calculated analytically and simulated using Finite element Methods.

Keywords: Mechatronics, Conceptual design, Design process, Robust design, Manipulator

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1 INTRODUCTION

The motivation behind this work lies in the design of a Multi-Degree of Freedom (M-DOF) electromagnetic finger manipulator that can be used for many industrial applications such as pick and place operations or machining operations. This paper addresses the conceptual design and optimal dimensions of a novel M-DOF finger manipulator for industrial applications such as pick-and-place operations and small material handling.

A pick-and-place operation can be defined as picking up a specific object and placing it in a desired position (Jones and Lozano-Perez, 1990). Pick-and-place operations are required in many industrial production operations such as assembly processes, inspecting, and classifying the products. These processes are described as costly and time-consuming processes (Huang, et al., 2004). One of the main factors, which might affect the accuracy of the M-DOF finger manipulators is the volume of the workspace. It is found that the accuracy is increased with the decreasing of the workspace volume (Ramadan et al., 2006). One of our objectives in this paper is to build a finger manipulator with large workspace volume which would still have accurate manipulation. Manipulating and material handling of a light object does not require the use of a robot of hundred kilograms (Huang, et al., 2004). Therefore, we aim to design a small and portable M-DOF finger manipulator that can be carried and used in different places.

Many M-DOF manipulators were designed in the literature (Carricato and Parenti-Castelli, 2003, Zeng, et al., 2011). A 3-DOF translational parallel mechanism named Delta robot was proposed by Clavel R. The parallelograms properties were used in this mechanism to improve the performance. This robot was considered the best choice for quick pick-and-place operations of light objects within a cylindrical workspace of around 5 to 1 diameter to height ratio (Clavel and Sogeva, 1990). Yeung and Mills (2004) proposed a Multi-Finger reconfigurable gripper for the purpose of Flexible Fixtureless Assembly (FFA) in order to overcome the problem of using the hardware fixtures which are commonly used in automotive industry. This technique can be used to grasp a sheet metal part from a part holder, locate the part in space precisely, and maintain the shape of the part without changing the tools or using the fixtures.

There are many constraints that should be taken into consideration in an ideal pick-and-place operation such as stability, which means that the object should stay stable and should not twist or slip in comparison with the gripper. Another important design consideration is the dynamic load. This parameter should be minimized as much as possible in order to reduce the deformation effect of the finger, which is usually used in the pick-and-place robots. The finger should be designed carefully and its material should be chosen from a light weight material. Many studies have been conducted to model and simulate the kinematic of the finger manipulators such as (Fattah et al., 1995), in which the authors used finite-element methods (FEM) to model the flexible links.

As mentioned before, this paper has been motivated by the increasing need for M-DOF manipulators which are capable of providing a precise force and motion control. The overall goal of the project is to design and optimize a portable 3-DOF finger manipulator. This goal will be accomplished by fulfilling the following research objectives (O):

- O1. To develop a finger manipulator that can produce a three Newton force at the end-effector in the x, y, and z directions.
- O2. To design a portable finger manipulator with a 4 cm^3 workspace.
- O3. To optimize the design in order to maximize the ratio between the workspace volume and the micromanipulator volume.
- O4. To optimize the design and development of the manipulator in order to maximize the ratio of the generated actuation force to the manipulator overall weight.

This paper is divided into four sections. In Section 2, design procedures are discussed. Section 3 describes the simulation and results. Finally, the paper is concluded in Section 4.

2 DESIGN PROCEDURES

This paper has been motivated by the increasing need for (M-DOF) manipulators which are capable of providing a precise force and motion control. The overall goal of the project is to design and optimize a portable M-DOF finger manipulator to be used in many industrial applications such as material handling and pick-and-place operations. Material handling and pick-and-place operations for small parts usually need a 3 Newton force at the end-effector. In addition, we will design the manipulator to have a 4 cm^3 workspace. To achieve these targets, the manipulator is designed based on the following specifications:

- The workspace volume should be maximized to enhance the material handling and pick-and-place operation.
- To develop a finger manipulator that can produce a three N force at the end-effector.
- To optimize the design dimensions in order to maximize the ratio of the generated force at the end-effector tip to the manipulator actuation force.

To create the initial design, a morphological chart will be used. The morphological chart (as shown in Table 1) outlines the different functions and several solution types within a design (Mansor et al., 2014). The morphological chart is helpful in generating new ideas and solutions. In this section, the design procedure will be discussed to choose the best solution in Table 1.

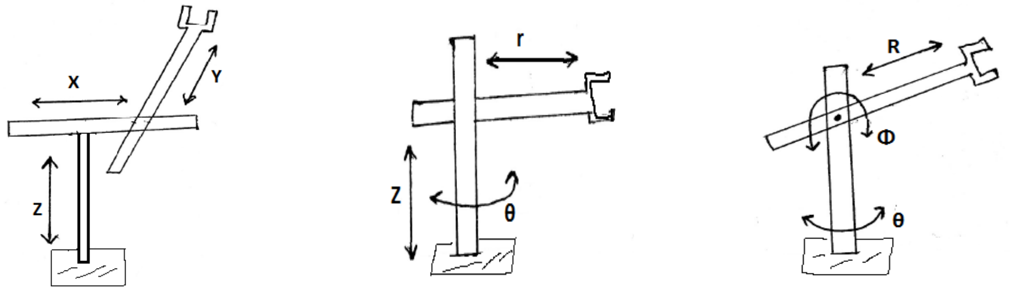
Table 1. Classification of the design elements using a Morphological Chart.

		Sub Solution				
Function		Option 1	Option 2	Option 3	Option 4	Option 5
	Actuator type	Motorized/ Electric	Hydraulic	Pneumatic	Piezoelectric	***Electromagnetic***
	Joint types	Revolute	slot	***Spherical***	Universal	Cylindrical
	DOF	Two	***Three***	Four	Five	Six
	X-axis motion	***Translation***	Rotation	Both		
	Y-axis motion	***Translation***	Rotation	Both		
	Z-axis motion	***Translation***	Rotation	Both		

Note: The bolded options were chosen for our design.

2.1 Conceptual Design

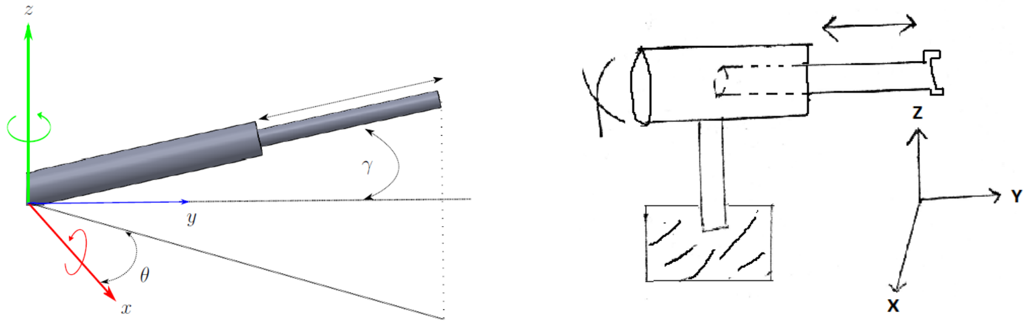
In most of the pick-and-place operations or material handling, the manipulator needs to move an object from one point to another point without changing the orientation of the moved object. Therefore no orientation movements are required. A manipulator with 3-DOF is enough to complete the job successfully (Option 2 in Table 1 for DOF function). The joint between any link pair can either be a prismatic (P) or a revolute (R). There are several joint configurations to build a 3-DOF such as three prismatic joints, three revolute joints, or any combination between them. PPP (Prismatic -Prismatic-Prismatic) configuration will not be suitable for our application due to the limited workspace and associated singularities problems for this configuration. In addition, building a PPP manipulator requires a large operating volume and we need to design a portable and small manipulator. The RRR (Revolute-Revolute-Revolute) configuration, on the other hand, is not suitable and not practical for pick-and-place operations due to singularities problems and hard kinematic modelling. The only design that would be useful for our application is a combination between prismatic and revolute joints. Based on the well-known three coordinate systems (Cartesian, cylindrical, and spherical), we can achieve 3-DOF movement using a Cartesian design (Figure 1.a), a cylindrical design (Figure 1.b), or a spherical design (Figure 1.c). The Cartesian design has three prismatic joints (PPP) and that will not be suitable based upon the above mentioned ideas. The cylindrical design has two prismatic joints and one revolute joint (RPP), while the spherical design has two revolute joints and one prismatic joint (RRP). To select the better design, we need to make a comparison between the two designs to find out which one can produce a larger force and cover a larger workspace. Regarding the actuation force at the end-effector, it depends on the selected actuator, so both designs are able to generate the same force if they have the same actuator type. The cylindrical design can reach all space around itself but not in the space above the manipulator itself, and this factor will limit the workspace. In addition, having more prismatic joints requires more linear actuators and that will increase the overall volume of the design. The spherical design, on the other hand, has larger workspace compared to the cylindrical design. Additionally, it has a smaller volume since it has less linear actuators. Compared with the layouts and specifications enumerated and discussed above, the spherical design (Figure 1.c) would be an ideal candidate for developing a 3-DOF manipulator. (In Figure 1, θ is the angle between the x axes and the manipulator needle, and φ is the angle between the z axes and the manipulator needle).



Cartesian design *Cylindrical design* *Spherical Design*

Figure 1. Different configuration for building a 3-DOF manipulator.

Our main target was to maximize the workspace and minimize the overall volume design. In order to improve our design, we can minimize the volume of the design by using a compound joint which contains two degrees of freedom such as spherical or universal joints instead of the two revolute joints. The design will have a finger mechanism which represents the R parameter in the spherical coordinate system (Figure 1.c). The finger mechanism consists of two rods and both are aligned and concentric along the y axis (Figure 2.a). Based on the above, a 3-DOF version of a spherical manipulator has been invented. As shown in (Figure 2.b), the manipulator is composed of a fixed base, a movable finger with two aligned and concentric rods, and a compound joint that allows the manipulator to rotate around the x and z axes. The small rod will move linearly in the y axis. Despite the fact that, the finger will rotate around the x and z axes, the end-effector will move linearly in the x, y, and z axes (Option 1 in Table 1 for movement functions). In Figure 2.a, the angle between the x axes and the manipulator needle is defined as θ. The angle between the xy plane and the micromanipulator needle is defined as γ.



Finger mechanism *Full manipulator design*

Figure 2. 3-DOF version of spherical manipulator.

2.2 Actuator Design

Different actuation methods can be used to drive the system. However, we need an actuation method that can produce the required force while at the same time does not increase the manipulator weight. Table 2 summarizes the advantages and disadvantages of the most common actuation methods used to drive manipulators.

Table 2. Summary of the advantages and disadvantages of the actuation methods.

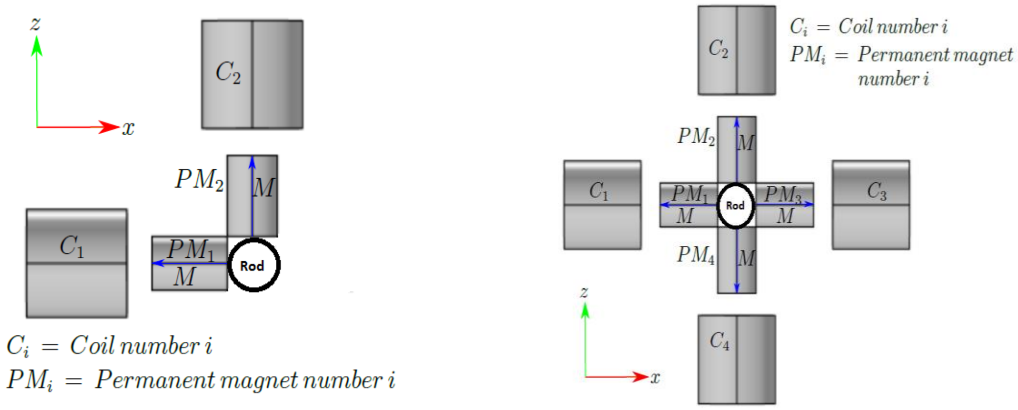
	Advantages	Disadvantages
Mechanical manipulators	High output force High output motion range	Low speed Backlash

		Friction
Motorized manipulators	High output force High output motion range	Low speed Backlash Friction Jumpy Movements
Hydraulic manipulators	High output force High travel range	Bulky design Temperature drift Slow response time
Pneumatic manipulators	High output force High travel range	Bulky design Fabrication is complex and costly
Piezoelectric manipulators	High actuation force High response time	Short travel range Nonlinearity and hysteresis Control and modelling is very complex
Electromagnetic manipulators	Contactless Frictionless Small in size High output force High travel range High response time Electric motor-free Low power consumption Wirelessly-controlled features	Workspace area is small Control and modelling is hard Drive unit is very large compared to the manipulator weight

As it can be seen from Table 2, the manipulators that are actuated by electromagnetic coils can be controlled wirelessly and that will eliminate the backlash associated with other types of actuation methods. In addition, using contactless and remotely controlled actuators will decrease the manipulator weight because of not using electric motors and gears that are connected to the manipulator joints and links. Due to the many advantages of the electromagnetic actuation compared to other types of actuation methods, electromagnetic actuation was used to drive our proposed finger manipulator (Option 5 in Table 1 for Actuator type function). However, we still need to address the shortcomings in the current designs such as: all the proposed electromagnetic manipulators so far suffer from the fact that they have a small workspace area and they require a large drive unit compared to other types of actuation methods. In addition, there are the difficulties in modelling and controlling the magnetic field and magnetic force.

2.3 Configuration Design

Configuration design deals with determining all of the features and how they are organized in the design. The main features that need to be determined are the electromagnetic coils and permanent magnets and the way in which they are organised in the design. Based on the movement of the mechanism, we need at least one actuator in the x and z axes in order to allow the finger to rotate around the x and z axes. A simple design will include one permanent magnet and electromagnetic coil pair in the x axis to rotate the finger rod around the z axis. Similarly, one permanent magnet and electromagnetic coil pair in the z axis are proposed to rotate the finger rod around the x axis as shown in Figure 3.a. The stability of the mechanism is the main problem with this design. Similarly, we can use two, three, or four pairs of permanent magnets and electromagnetic coils in each axis. Using three pairs will not be symmetric around the rod which might affect the manipulator stability, and also will complicate the total actuation magnetic force which will be applied to move the rod. If we use two or four pairs, we will overcome the previous problems. However, having four pairs will make the design bulky and our main goal was to decrease the manipulator overall volume. Hence, we use two pairs in each axis as shown in Figure 3.b. As a result, the drive unit consists of four electromagnetic coils aligned with four permanent magnets (two permanent magnets with a fixed gap between them in the x and z directions). In the y axis, we have a prismatic joint. Therefore, an axial electromagnetic coil located around the main rod to allow the smaller rod (which is a permanent magnetic material) to move in the y direction is enough to produce the required movement and force in the y axis (Figure 4).



(a) *One pair in each axis.*

(b) *Two pairs in each axis.*

Figure 3. Actuator configurations.

2.4 Mechanical Design

The proposed manipulator is a three DOF manipulator that moves along the x and z axes, and also moves linearly along the y axis. The manipulator consists of two concentric rods (which represent the finger mechanism). The main rod is connected to the permanent magnets using a four way connector. The design of the finger manipulator based on what was discussed in section 2.1 above needs to rotate around the x and z axes independently. Therefore the spherical joint will be the best option to allow these required motions (Option 3 in Table 1 for Joint type function). The spherical joint therefore will be used also to connect the main rod and the ground to allow the manipulator finger to rotate around the x and z axes. A simple CAD drawing with all of components of the proposed manipulator is shown in Figure 4.

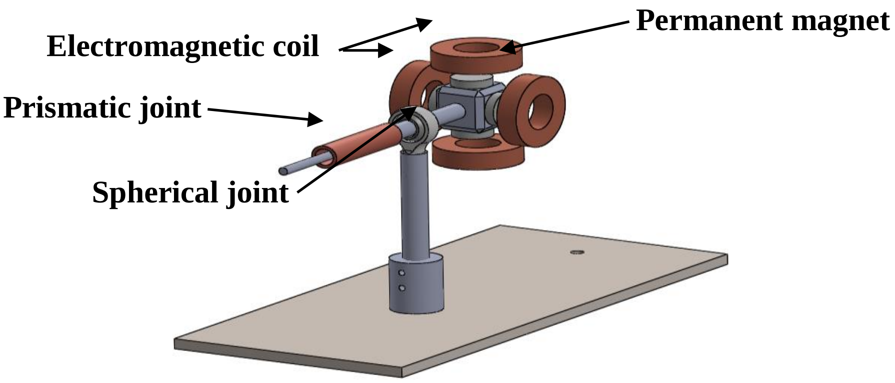


Figure 4. CAD drawing of the proposed manipulator.

2.5 Workspace Design

The workspace area of the manipulator can be found based on Figure 5.

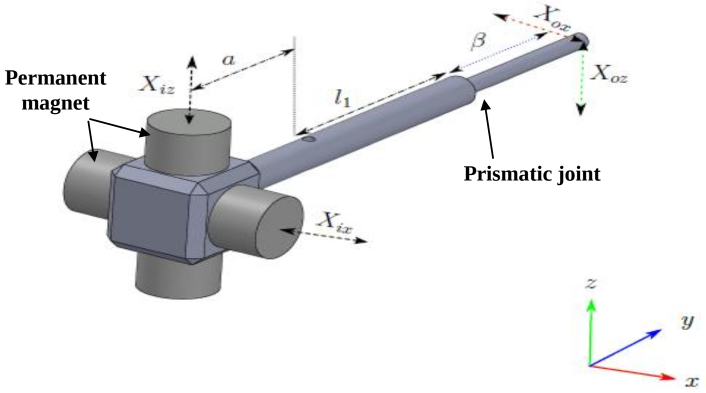


Figure 5. Three-dimensional workspace representation of the mechanism.

X_{ix} and X_{iz} are the permanent magnets movements in the x and z axes respectively. The workspace vector in the x, y, and z axes respectively is defined by [X_{ox}, β, X_{oz}]. β depends on the magnetic force between the electromagnetic coil and the permanent magnet in the y axis. The other workspace vector components can be found as follows (Equations (1) and (2)):

$$X_{ox} = X_{ix}(\frac{l_1+\beta}{a}) \tag{1}$$

$$X_{oz} = X_{iz}(\frac{l_1+\beta}{a}) \tag{2}$$

Where a is the distance between the center of the permanent magnets and the center of the spherical joint, and l_1 is the distance between the center of the spherical joint and the prismatic joint. If the micromanipulator end-effector moves 3 cm from the needle edge, and given that the maximum allowed movement of the permanent magnets in the x and z directions is 1 cm ($X_{iz} = X_{ix} = 1\ cm$). The micromanipulator end-effector can achieve up to 4 cm workspace in the x and z axes, if the dimensions of the mechanism are as follows: a = 2 cm, l_1 = 5 cm. 4 cm workspace is comparatively higher than the workspace values found in literature (Nakamura et al, 2000). This section presented the workspace analysis that is used to satisfy the stated objective of having a 4 cm workspace.

2.6 Parametric Design

The overall goal of parametric design is to find the optimal values for the design parameters in order to achieve the stated objectives. The main objective is to obtain a three N at the finger end-effector. In order to find the required actuation force to produce three N at the end-effector, we need to find the equation that describes the relationship between the input and output forces applied to the finger mechanism (Figure 6). The weight of the rod is low and therefore the force generated from the rod weight can be negligible. The finger mechanism is considered as a beam with one support (the spherical joint) and one actuation force in each of the x and z axes. There are also two generated forces at the end-effector, one in the x axis (F_{ox}) and one in the z axis (F_{oz}). Based on the Euler-Newton laws, the total torque around the spherical joint is equal to zero at the steady state. Therefore:

$$\mathrm{F_{ox}} = \mathrm{F_{ix}}(\frac{a}{\mathrm{l_1+\beta}}) \tag{3}$$

$$\mathrm{F_{oz}} = (\mathrm{F_{iz}} - 4\mathrm{F_m})(\frac{a}{\mathrm{l_1+\beta}}) \tag{4}$$

Solving these Equations (3) and (4) when ($\mathrm{F_{ox}} = \mathrm{F_{oz}} = 3$ N), the required actuation force on the x axis (F_{ix}) is 12 N, and the required actuation force on the z axis (F_{iz}) is 14.2 N (4 F_m =2.2 N, which is the weight of the permanent magnets). For design purposes and to make sure the actuator produces the required forces, we will find the best dimensions that can give higher values than the values found above. Therefore, the optimization process will be conducted to find the best dimensions that can give a 16 N in each axis, which means we need to generate 8 Newton between any permanent magnet and electromagnetic coil pairs. In order to generate this force, we need to find the magnetic force equation between a cylindrical permanent magnet and a thick electromagnetic coil.

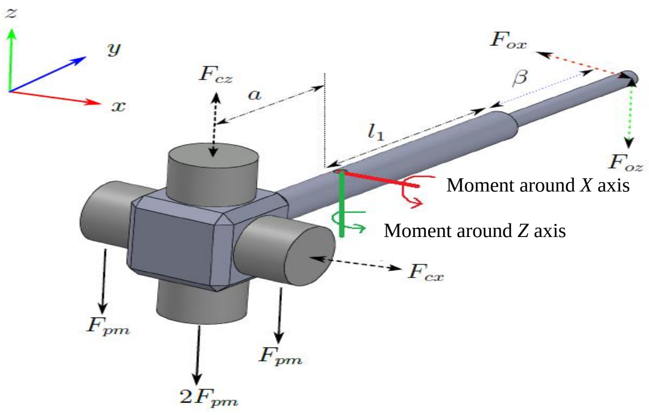


Figure 6. Free body diagram of the mechanism with all applied forces.

To find the dimensions for the actuator that can generate 8 Newton between any permanent magnet and electromagnetic coil pairs, we need to find the magnetic force formula between a cylindrical permanent magnet and a thick electromagnetic coil. In this paper, we use the "shell method," discussed in (Robertson et al., 2012). The magnetic force depends on many parameters, such as the dimensions of permanent magnet and electromagnetic force. We used a permanent magnet that is available commercially with a length and diameter of 2.54 cm. The coil is assumed to have 1600 Turns and the actuation current is 1 A. Based on the magnetic force formula with the given parameters, the dimensions of the electromagnetic coil that can generate 8 Newton are as follows: Inner radius: 1.52 cm, outer radius: 2.35 cm, and the length is 1.67 cm (more details about the optimization can be found in (Al Mashagbeh et al., 2016)).

3 SIMULATION

The workspace of the manipulator in the X and Z axes is shown in Figure 7. The maximum angle in the X and Z axes that the manipulator can achieve:

$$\sin(\theta) = \left(\frac{X_{ix}}{a}\right) = \left(\frac{X_{ox}}{l_1+\beta a}\right) = 0.5 \tag{5}$$

Solving for θ in Equation (5), (the maximum swivelling angle), the manipulator can rotate around the spherical joint in the X and Z axes by 30 degrees.

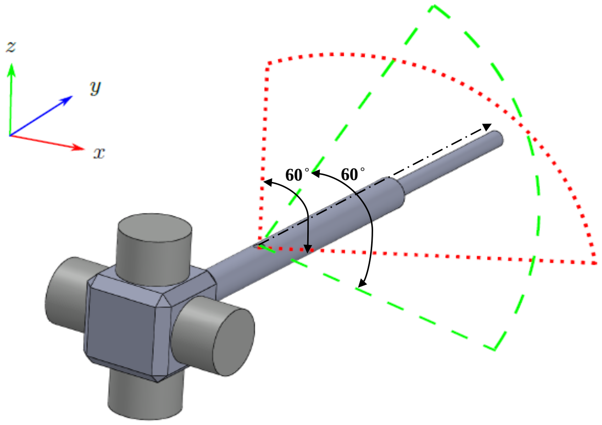


Figure 7. The workspace representation in the X and Z axes.

The variation of magnetic force with respect to the axial distance was simulated by using ANSYS software and calculated analytically. As shown in Figure 8, there is good matching between the analytical and FEM results. The axial distance represents the distance between the coil and the permanent magnet edges. The negative values of the axial distance mean that the permanent magnet is moving inside the coil. The maximum value of the magnetic force can be obtained when the axial distance is around (-0.8 cm). For the positive part the magnetic force decreases when the distance increases. Our optimization was conducted at 1 cm axial distance. It is expected that the manipulator will work around that distance so the magnetic force that we can obtain is 8 Newton, which will also satisfy our optimization to have 8 Newton in each axis. Because of the mechanical constraints, the permanent magnet is not designed to move inside the electromagnetic coil. Therefore, the range of the movement in Figure 8 is between 0 and 2 cm.

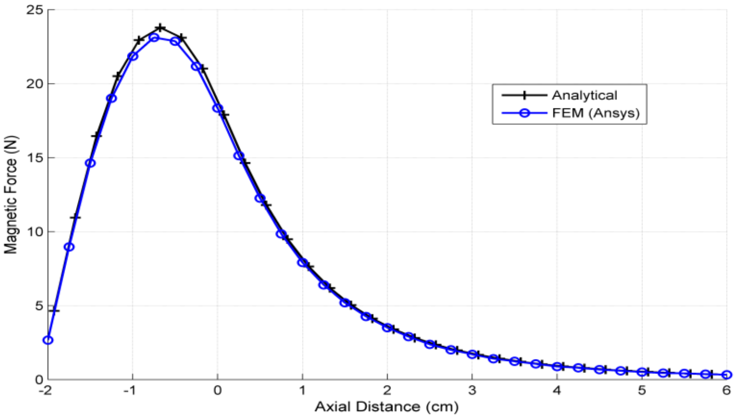


Figure 8. Magnetic force versus axial distance.

The magnetic force depends on the magnitude of the excitation current. The variation of the magnetic force with respect to the excitation current was studied and calculated analytically and by using FEM. As it is seen in Figure 9, a good matching was obtained between the FEM and analytical results. Generally the magnetic force is proportional to the coil current; hence we can generate more forces if we increase the excitation current. The current range is limited by the used American wire gauge (AWG).

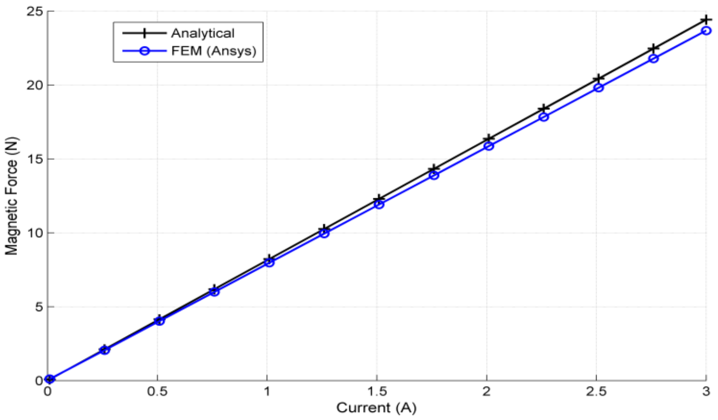


Figure 9. Magnetic force versus excitation current.

4 CONCLUSIONS

This paper addressed the design procedures of building a portable 3-DOF finger manipulator. The manipulator has many potential applications in industry such as pick-and-place operations and small material handling. The conceptual design, actuator design, configuration design, mechanical design, workspace design and the parametric design of a 3-DOF manipulator have been investigated in this paper. Based on the morphological chart which combines the different functions used in the design and their solutions, the design procedures were developed and the best solution was chosen to satisfy our goals. It was found that the electromagnetic actuation method was the best choice in our case due to its several advantages, such as its compact size, wirelessly-controlled features, and contact-free feature, which means no gears are required and friction problems are eliminated. The manipulator design was adapted from the spherical robot design. The manipulator consists of two concentric rods, which represent the finger mechanism. The main rod is connected to the permanent magnets using a four way connector. The manipulator workspace was calculated to be 4 cm in the X and Z axes and the maximum swivelling angle in both axes was 30 degrees. Given the dimensions of the commercially available permanent magnet, the optimal dimensions of the electromagnetic coil were found. The magnetic force at 1 cm axial gap and 1 A excitation current was 8 Newton. This force can generate a 3 Newton force at the manipulator end-effector based on the manipulator dynamic model. The magnetic force versus the axial distance and versus the excitation current was calculated analytically and simulated using FEM. The analytical results are in agreement with the FEM results. Future work will include fabricating and building the system to validate the simulation results with the experimental results.

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