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Design and Modeling of a Novel Flexible Surgical Instrument Applicable in Minimally Invasive Surgery

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Abstract

Some of laparoscopic surgeries maneuvers, suturing for instance, require precise and dexterous movements. These surgeries are difficult to perform, as they require using rigid instruments. So, multi degrees of freedom hand held instruments have been developed to increase movement dexterity. In this paper, design and modeling of a novel surgical hand held flexible instrument is presented. This instrument consists of three main components, which are wrist mechanism, cable and back end mechanism, and end effector mechanism. The proposed surgical instrument has 5DOF with 8 mm diameter and has bending range of -90 to +90 degrees in horizontal and vertical directions. The designed instrument is wire actuated using steel cables. In order to control the flexible instrument, a servo system is constructed. Main advantages of this surgical instrument are its low weight and the ability of providing sufficient degrees of freedom for movement in complex spaces. Kinematic analysis of the designed instrument results in relative orientation and position of the end effector to the handle. The proposed instrument can improve the issue of lack of dexterity in the complicated spaces concerning minimally invasive surgeries.

Keywords: Laparoscopic Surgeries, Snake-Like Instruments, Flexible Instruments.

INTRODUCTION

Laparoscopic minimally invasive surgery (LMIS) is the surgical operation of the chest, abdomen, spine and pelvis done through small incisions (ports) of 5 to 10 mm diameter with the help of specialized instruments and endoscopes. Unlike an open surgery in which large areas of a patient's body have to be cut off, laparoscopic surgery requires only small incisions [1,2].

MIS has marvelous characteristic of reducing patient's burden. Reduction of trauma, risk of inflammation, disfigurement and patient pain, which will result in shorter immobilization (about 24 hours), and hospitalization with earlier return to work and lower cost are other advantages of laparoscopic surgeries. However, this type of surgery requires increased skill on the surgeon behalf, which is a result of limited degrees of freedom (DOFs) concerning surgical instruments used in laparoscopic surgery [3-5].

In spite of all these advantages, minimally invasive surgeries suffer from few negative limitations such as less tool placement flexibility compared to open surgeries. Non-intuitive effects on the tip movements caused by insertion point such as movement insertion and velocity scaling are the other important limitations. Since MIS instruments are rigid or only limitedly flexible, some anatomical regions are not accessible. Most current laparoscopic tools have rigid shafts, which make it difficult to approach the worksite through small incisions [6,7].

Additionally, the length and structure of most of endoscopic instruments reduce the surgeon's ability to feeling forces exerted by tissues and organs on the end effector [8]. In conclusion, lack of dexterity and sensitivity of endoscopic tools are major impediments to development of minimally invasive surgery [9].

In order to solve the mentioned problems, robotic manipulators with multi degrees of freedom at their tip have been reported as an alternative to conventional instruments [10-13]. Application of flexible surgical tool manipulators is attracting more attention from the research community. For example, Dario et al. [14] presented a 1DOF planar SMA actuated flexible device for knee arthroscopy. Recently, Reynaerts et al. [15] presented a 2DOF, 5 mm diameter wire actuated flexible tool using super elastic NiTi tube with flexure joints. After that, Guthart and Salisbury [16] developed a flexible robot with a discrete backbone and wire actuation. A few years later Cooper et al. [17] presented a wire actuated multi-DOFs flexible instrument. Recent works in this field presented miniaturized linkage designs for flexible robots [18], wire actuated robots [19] and flexible units with miniature gear motors embedded inside the links [20]. One of the most commonly used instruments in MIS is the gripper, which is used for moving tissues away from the operation field, or to stretching it [21]. The proposed surgical instrument has 5DOF with 8 mm diameter. This instrument is wire actuated using steel cables with the aim of size reduction.

In this paper, the process of designing a hand held instrument with additional degrees of freedom at the instrument tip is presented. The surgeons will be able to use this instrument when additional dexterity is required. They can use it while standing at the operating table during specific phases of surgery. The instrument can be used easily and rapidly, since it does not require complex set up procedures. Its main advantages are its low weight and small size due to the use of a cable mechanism.

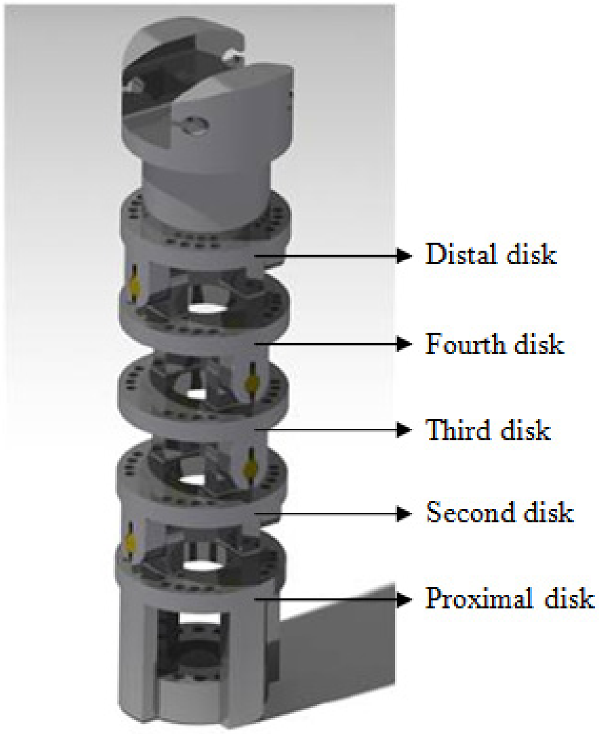

Figure (1). Designed wrist mechanism includes multiplicity disks with pivot joints.

MATERIALS and METHODS

The proposed minimal invasive surgical instrument consists of three main components, which are wrist mechanism that provides pitch and yaw rotation between the tool's shaft and end effector, cable and back end mechanism and finally the end effector mechanism. The actuation cables are used for manipulation and controlling of the disks, and finally control the movement of the wrist mechanism and end effector for gripping the biologic tissue. Along with multi degrees of freedom of the snake-like proposed instrument, its small size and the ability to bend in the range of -90 to +90 degrees in both vertical and horizontal directions are of high importance. The instrument's workspace can even be increased with the help of more elements in the wrist without any further complications such as the need for more motors. Due to the ability of the rotatable gripper, the instrument can be used for maneuvers in small workspaces with low dexterity such as suturing.

Wrist mechanism

The wrist mechanism, Figure (1), is consisted of multiple disks stacked in series, which is designed by CATIA V5R19. The proximal disk is coupled to the instrument's shaft and the distal disk is coupled to end effector support member. Each disk is configured to rotate in one degree of freedom in pitch or in yaw with respect to each neighboring disk. In addition to that, each disk is pivotable relative to its adjacent disk by a pivot joint. Second disk and distal disk are pivotable relative to their adjacent disks around a pitch axis, which is nonparallel to the shaft axis. The third disk and the fourth disk are pivotable relative to their adjacent disks around a second axis, which is nonparallel to the shaft axis and nonparallel to the pitch axis. Therefore, wrist provides 4 degrees of freedom for surgical instrument.

In order to have a total rotation of 90 degrees in yaw direction, two consecutive segments of the third disk and the fourth disk have to rotate, i.e., a rotation of about 45 degrees between the second disk and the third disk and the additional rotation of 45 degrees between the third disk and the fourth disk will provide the desired direction (Figure (2-A)).

A combination of 45 degrees of rotation in pitch direction between proximal disk and the second disk and 45 degrees of rotation in pitch direction between the fourth disk and the distal disk will provide the same results of 90 degrees in pitch direction (Figure (2-B)). Another combination of pitch and yaw bending can be achieved via rotation of the disks in both pitch and yaw directions. The addition of more disks makes a larger workspace possible. The central lumen of 3 mm diameter serves as a conduit for end effector actuator cables and also house fluid conduits or electrical conductors.

Cable and back end mechanism

As explained before, the wrist segment consists of five disks driven by cables with a diameter of half a millimeter. In order to lower the forces on each cable, sixteen cables are used. Eight of these cables, i.e., distal cables, connect to the fifth disk, which is placed at the end

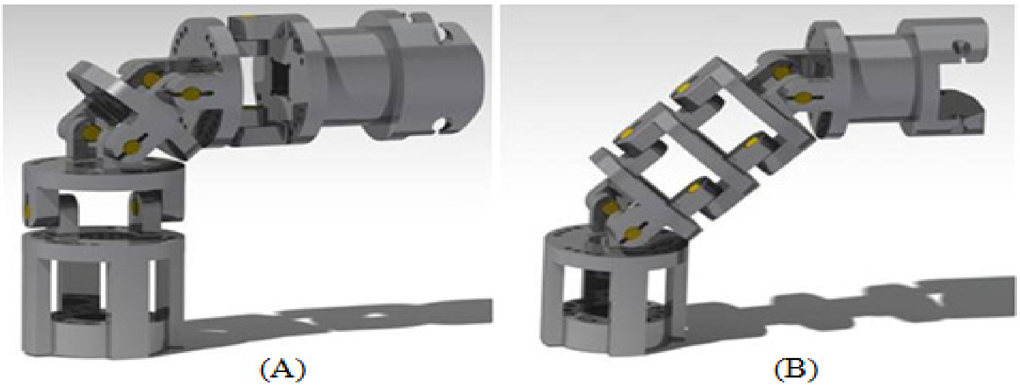

Figure (2). (A) Total yaw in wrist is 90 degrees, (B) Total pitch in wrist is 90 degrees.

of the wrist. The other eight, i.e., medial cables, connect to the third disk, which is placed in the middle. All of the cables are connected to the actuator disk via 16 holes. The main job of these cables is to manipulate and control the movement of the wrist elements. Figure (3) shows the actuator mechanism in the back end of the mechanism. Considering cable tension in the state of maximum displacement of wrist elements and the orientation of the actuator disk are necessary in hole configuration.

The actuator plate is moved with the help of two linkage systems, which are coupled to the plate via ball and socket joints. As the links move in the same or opposite directions, pitch or yaw rotations can be resulted, respectively (Figure (4)). Different combinations of these two types of movements can result in different desired orientation of the disk actuator. In order to overcome cable entanglement, due to the axial degree of freedom and rotation in that direction, a bearing is placed between the actuator plate and cable actuator disk.

End effector mechanism

In the particular application of minimally invasive surgeries, the term "end effector" refers to a working distal part that is moved by means of the wrist member for a medical function. There are different types of end effector; some of which have a single working member such as a scalpel, a blade or an electrode and the others have a pair of working members such as forceps, gripers or scissors. In the designed instrument, the opening and closing motions of the gripper are wire driven.

Using the first element of the wrist as a base, the grip support is assumed on the distal end of the mechanism. This support is consisted of two working members, called jaws. With the help of pivot pins, the jaws are connected to the support so that the grip movement is made possible. The closing and opening states of the gripper are shown in Figure (5).

A two-part actuator is placed inside the jaws. One part is connected to the jaws via pins passing through a

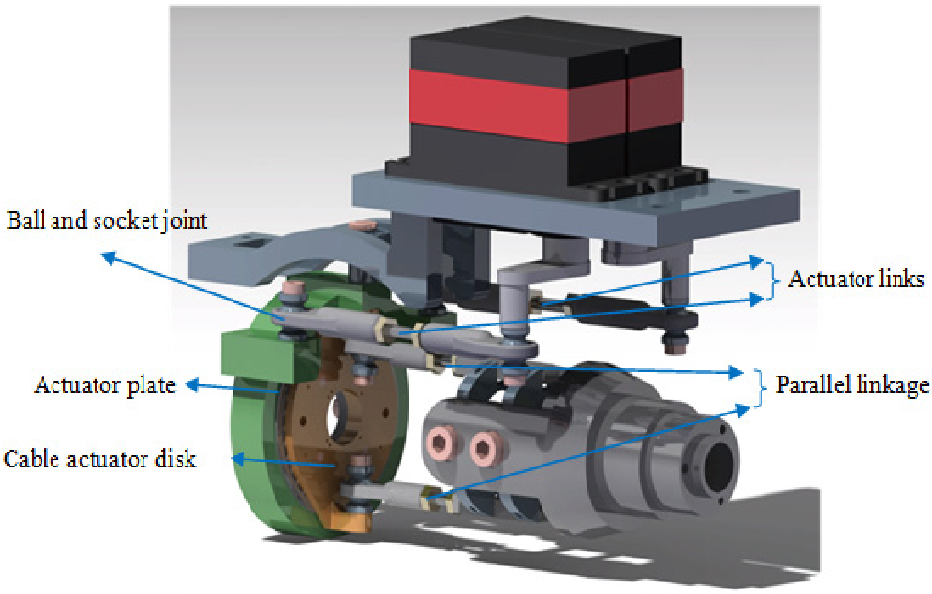

Figure (3). Designed actuator mechanism where the actuator cables are manipulated.

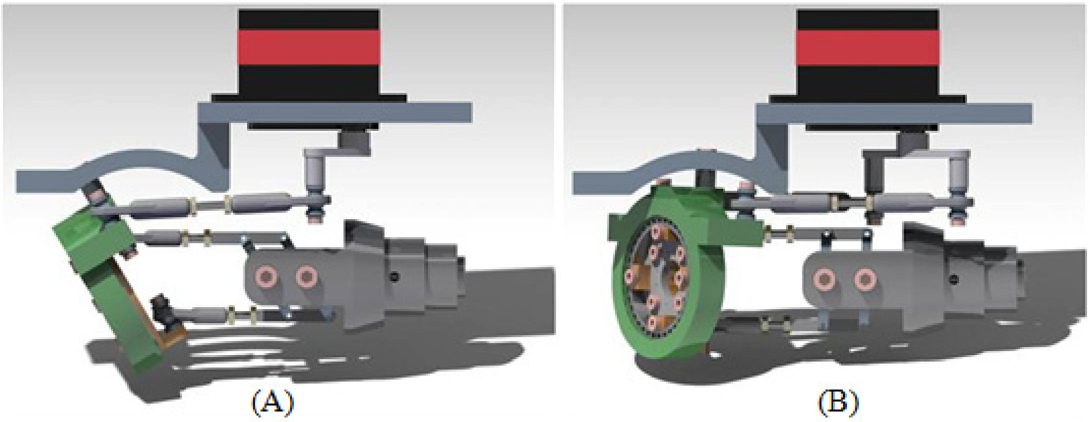

Figure (4). (A) Pitch rotation of actuator plate, (B) Yaw rotation of actuator plate.

pair of slots and reaching the jaws on the side. As these parts move relative to each other, the pins go up and down along the slots and the opening or closing actions take place. In other words, as the closing segment is pulled relative to the opening segment with the help of an actuation cable, the closing action is made possible and vice versa. Passing through the shaft, these two actuation cables are attached to a sliding part at the end. The sliding part moves on a rail and transforms the rotational movement of the handle into the linear movement of the opening and closing actuation cables. The whole range of motion of these cables is achieved with a rotation of about 40 degrees of the handle (Figure (6)).
In order to have a better understanding of the feasibility of the proposed structure a prototype was made out of Plexiglass, which is shown in Figure (7). This prototype has 20 mm diameter and 40 cm length.

Instrument Kinematics

The designed instrument is comprised of five DOF, four of which are made by revolute joints between the disks and the other one is due to the rotational degree of freedom in the shaft. Figure (8) shows the orientation of the frames on the disks and the shaft. In this schematic, the z-axis of each frame was aligned with the axis of rotation and it was positioned at the center of the mechanism. Denavit-Hartenberg (D-H) parameters were assigned to the mechanism joints in order to specify the position and orientation of the instrument [22] (Table (1)).

Considering this parameter setup, Equation (1) that follows was used to calculate the transformation matrices (T) between each of the frames. In this matrix, the angular motions of the joints were denoted as θ_i, the relative position as p_x, p_y and p_z, the link angles as α_{i-1}, and the sine and cosine functions as 's' and 'c', respectively [23]. In these parameters, i indicates the joint number.

$$(1)\quad {}^{i-1}_{\ \ i}T = \begin{bmatrix} c\theta_i & -s\theta_i & 0 & p_x \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & p_y \\ s\theta_i s\alpha_{i-1} & c\theta_i s\alpha_{i-1} & c\alpha_{i-1} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Forward kinematics maps joint configuration defined by its degree of freedom (θ_1, θ_2, θ_3) to the end effector's

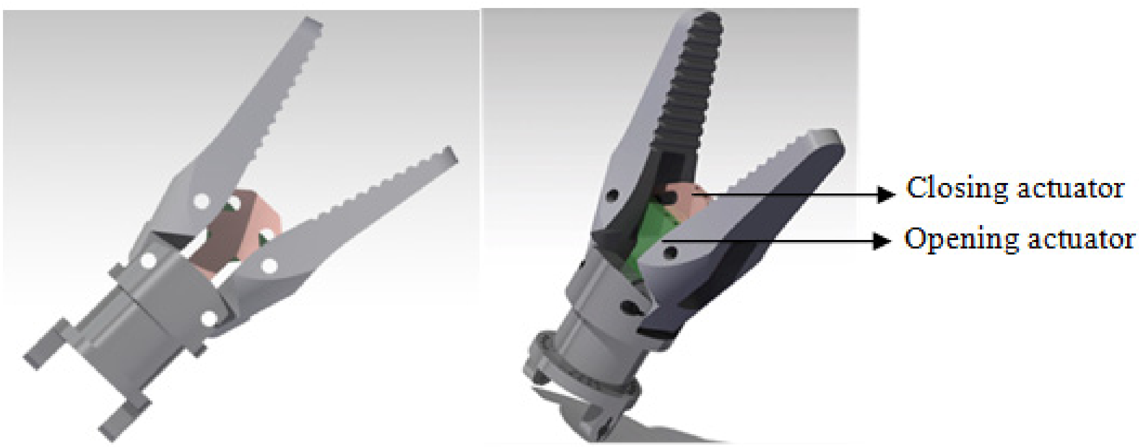

Figure (5). The designed end effector is used for gripping the tissue.

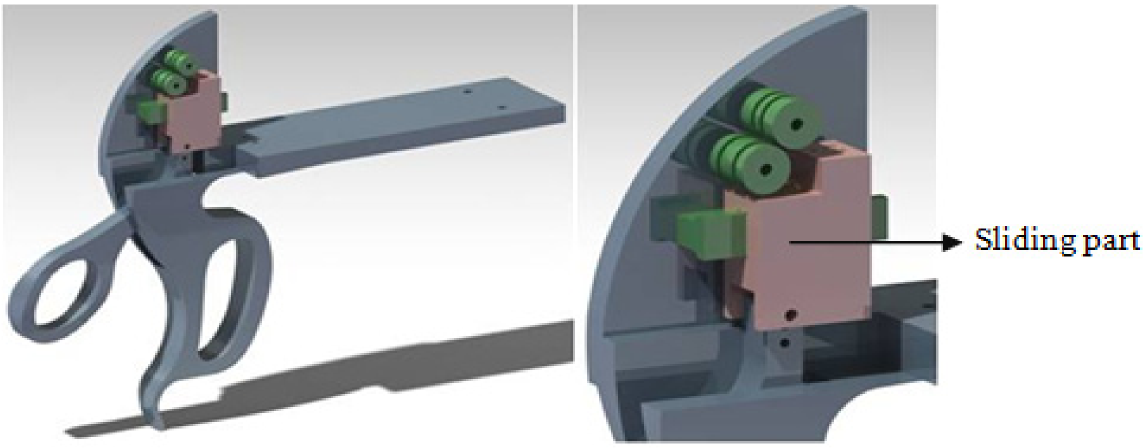

Figure (6). Change of handle rotational movement to the linear displacement in gripper cables.

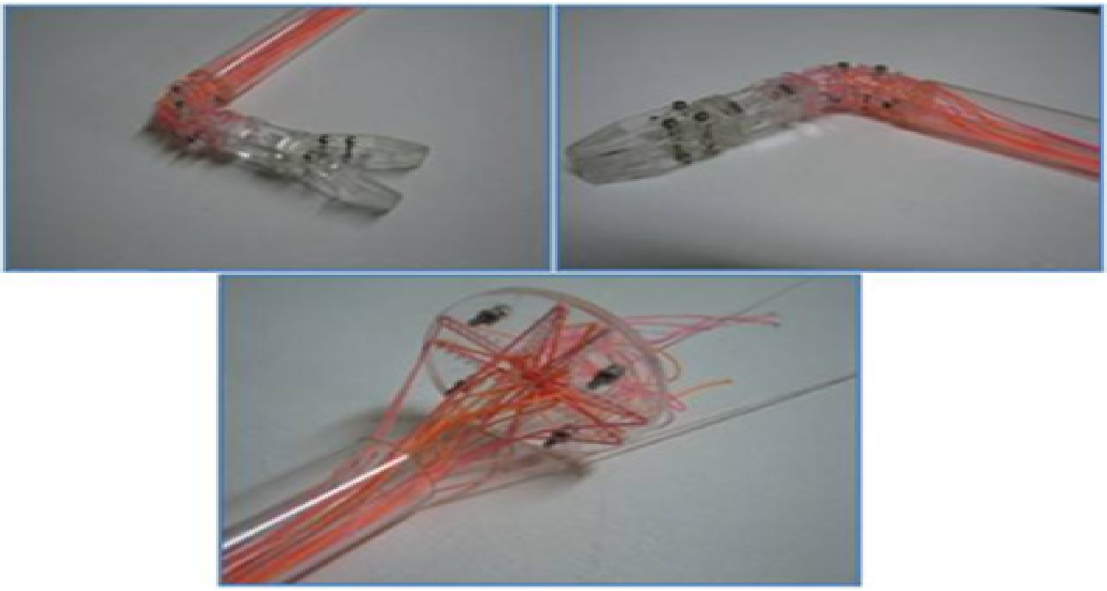

Figure (7). Photograph showing whole configuration of the designed flexible instrument.

position and orientation. Using the joint parameters and transformation matrices, the homogeneous transformation matrix Equation (2), which relates the end effector of instrument to the frame at the base point, was found by multiplication of every individual link's transform matrix.

$$ {}^{0}_{5}T = {}^{0}_{1}T\; {}^{1}_{2}T\; {}^{2}_{3}T\; {}^{3}_{4}T\; {}^{4}_{5}T \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2) $$

Table (1). Serial Instrument D-H Parameters to specify the position and orientation of it.

q_i	d_i	a_{i-1}	a_{i-1}	i
q_1	0	0	0	1
q_2	0	0	π/2	2
q_3	0	L	π/2	3
q_3	0	L	0	4
q_2	0	L	-π/2	5

The final matrix is used for calculating the resulted position and orientation of the end effector in laparoscopic surgery for reaching to a certain tissue and grasping it.

Drive Units

The instrument's movement is controlled with the help of two servomotors and one interface. These servomotors control the actuator plate's motion. A DC motor is then used in order to rotate the shaft. Opening and closing motions of the gripper are manual and wire driven.

These servomotors use error-sensing feedback to control mechanical position with signals. In other words, with the help of changing the system's velocity they manage to control its position. Input position is compared to the actual position of the mechanical system, which is measured by a potentiometer at the output. Any difference between these two values (the error signal) is

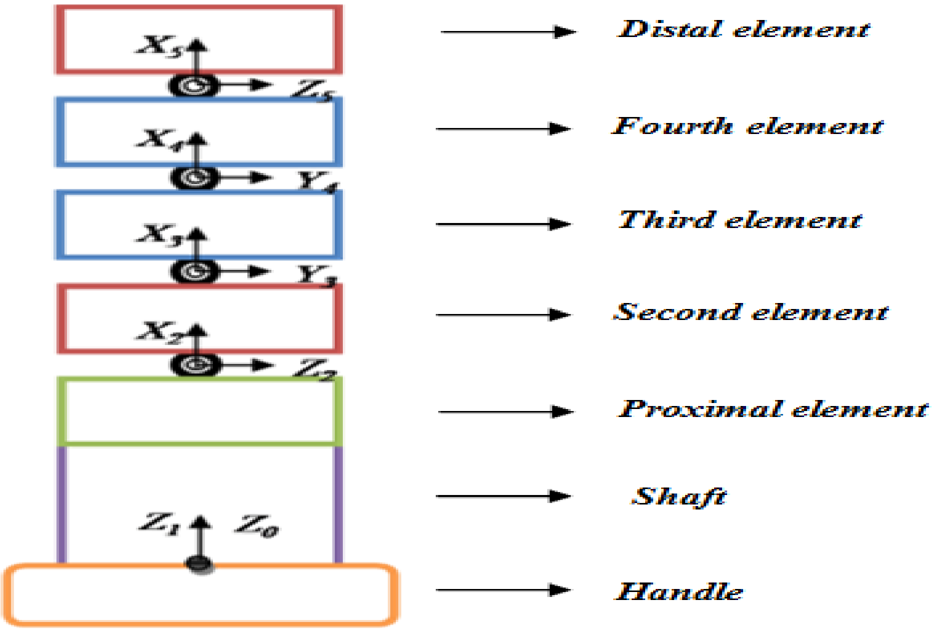

Figure (8). Schematic of placing frames on the disks and instrument shaft.

then amplified and used in order to drive the system in the direction necessary to reduce or eliminate the error.

Workspace Analysis

In general, any conventional laparoscopic surgery is done via 4DOF motions (Çavuşoğlu et al., 2001), which contains two rotations (up/down and left/right) about two axes placed on the incision surface, one translation (in/out) along the axis perpendicular to the incision surface, and finally one axial rotation. Recently, some instruments have improved workspace dexterity with the aid of one additional degree of freedom, put in the wrist [24].

The proposed instrument with 4DOF in the wrist and one DOF in the shaft was simulated by MATLAB 7.4 and the results were compared to the simulation of the conventional instrument with one DOF in the wrist and one DOF in the shaft. The objective of comparing these simulations is to determine whether the workspace covered by the instrument is sufficient for MIS surgery or not.

RESULTS and DISCUSSION

According to the structure of the elements, rotation of about 33 degrees is needed in cable actuator disk for providing rotation of about 90 degrees in the wrist elements. In order to control the developed multi DOFs snake-like instrument, a servo system is constructed. Three motors transmit the driving power to the instrument. Two of them are used in order to actuate the actuator plate motion and the other one is for the rotation of the shaft. Kinematics of the mechanism is derived via using the homogeneous transformation matrix; after which the position and orientation of the instrument end effector are determined. Based on the parameters such as mass, material and geometry, the motion of the designed instrument and conventional instrument are simulated and a workspace analysis is performed.

Figure (9) shows three-dimensional position of the end effector in the designed instrument with respect to time, i.e., the workspace of the instrument. It illustrates that the range of movement in designed surgical instrument is approximately 200x400x400 mm. Similarly, the graph in Figure (10) shows that the workspace is 100x10x400 mm for any conventional instrument during normal operation.

Therefore, comparing the range of movement in these instruments indicates that the designed surgical instrument can reach a larger workspace. These graphs show that the mechanical structure of the designed instrument is acceptable in the surgical environment and has sufficient workspace to provide necessary space during laparoscopic surgeries.

CONCLUSION

This paper proposes design and modeling of a novel flexible surgical instrument, which can improve dexterity issues in minimally invasive surgeries. This novel surgical hand held instrument has great effectiveness and potential, which makes it adequate for use in any surgeon while standing at the operating table. Its main advantages are its low weight and small size due to the use of cable driven mechanism.

The goal behind this work is to give the surgeon the possibility of orienting the tip directly in a more natural way. Work is underway to construct the designed surgical instrument and to prepare it for clinical tests. For future works, the size and weight of this instrument can be easily reduced further.

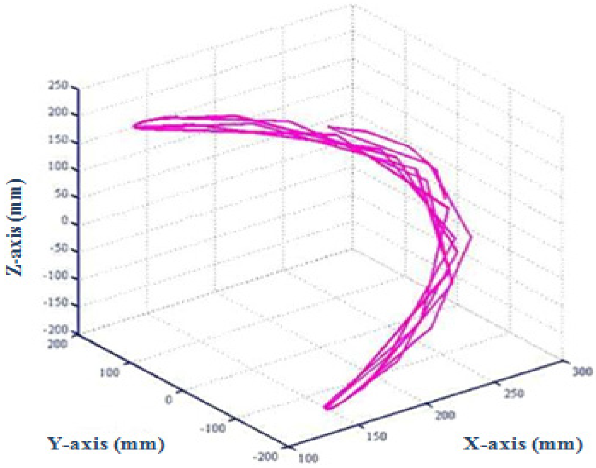

Figure (9). Three-dimensional position of the designed surgical instrument with respect to time.

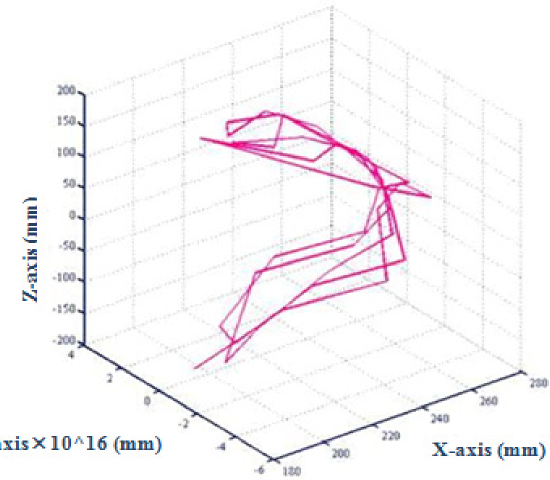

Figure (10). Three-dimensional position of the conventional instrument with respect to time.

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