New Fully Decoupled Manipulator with Three Translational Motion for Pick and Place Applications

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***Abstract*—A new three degree of freedom 3-DOF manipulator with fully decoupled translational motion is proposed in this paper. The conceptual design of the proposed manipulator is based on the pantograph mechanism which provide the decoupling motion. Parallelogram mechanisms are added to the pantograph to obtain the fixed orientation of the end-effector in XYZ directions. The proposed manipulator not only has the same characteristics of parallel manipulators as high stiffness, high accuracy and small power consumption, but also has large workspace compared to its volume as serial manipulators. Thus, the advantages of both parallel and serial manipulators are offered in the proposed manipulator. Moreover, it possess unique characteristic over decoupled parallel manipulator counterparts in terms of workspace to size ratio. Besides, this manipulator moves with high speed as the Pantopteron manipulator and many-times faster than the other decoupled parallel manipulators based on the magnification factor of the pantograph mechanism. The mobility, kinematic analysis and workspace of the proposed manipulator are studied in details. The simulation results are carried out using ADAMS software to validate the feasibility of the conceptual design.**

Keywords-decoupled mations; translational maniplatours; constant orientation; workspace; pick and place

I. INTRODUCTION

Parallel manipulators provide compact structure, high stiffness, and lower moving inertia, high load to weight ratio, high dynamic performance, and high accuracy [1]. So, it has attracted significant attention amongst researchers and industry in the past decade. As a result, many industrial parallel robots are developed as Delta robot and Tsai robot [2], [3]. These robots provide translational motion with constant orientation to cover a wide applications as pick-and-place, parallel kinematic machines, and medical devices. In contrast, parallel manipulators suffer from disadvantages such as the small workspace and coupling of kinematics and dynamics. Since, such kind of these robots needs a 3-DOF to position the end-effector in a specific location. This means one should control three actuators to produce just the motion of the end effector due to the coupling between the joints. This problem, predictably associated with nonlinearity, high coupled kinematics, singularities and a complex shaped workspace [4]. Hence, the decoupling motion between the robot actuators and positioning the end effector with fixed orientation are important issues for many industrial applications as pick and place operations. In order to solve this problem, in the last few years, a large family of decoupled 3-DOF translation parallel mechanism was developed to solve such kind problem. Gosselin and Kong [5] have presented their patent about simple 3-DOF translational parallel robot, with fully-decoupled input-output equations. Then, many researchers proposed series of decoupled 3-DOF translational parallel mechanisms, all covered by the above-mentioned patent [6]-[10]. A new family of decoupled motion called Tripteron was presented in details in many works [11]-[14]. Hence, many researchers try to solve the proposed problem of coupling motion with different structures as the Quadrupteron [15], Isoglide4 [16] and Pantopteron [17]. The mechanism of Quadrupteron or Isoglide4, which are very similar, consists of four identical leg with PRRU type attached to a common platform. These robots are a 4-DOF parallel mechanism capable of producing the Schönflies motions consist of three translations plus one rotation about a given fixed direction. Besides, the linear actuators are employed and the displacements of three of them are directly proportional to the translational displacements of the mobile platform along a given Cartesian axis. The Pantopteron manipulator is similar to the Tripteron Cartesian parallel manipulator, but due to the use of three pantograph linkages, an amplification of the actuator displacements is achieved. Therefore, equipped with the same actuators, the mobile platform of the Pantopteron moves many times faster than that of the Tripteron. This amplification is defined by the magnification factor of the pantograph linkages. This paper introduces new 3-DOF translational manipulator with fully decoupled motion based on pantograph mechanism [18]. The advantages of parallel and serial manipulator are offered in this manipulator. Besides, the proposed manipulator has a unique advantage in terms of workspace/size ratio and velocity compared to other decoupled parallel manipulators.

This paper is organized as follows: Section II introduces a mechanism description and mobility analysis of the proposed manipulator. Then, Section III represents kinematics analysis. Section IV presents the workspace determination. Then, the system simulation results are carried out by ADAMS software in Section V. Finally, the conclusions are presented in Section VI.

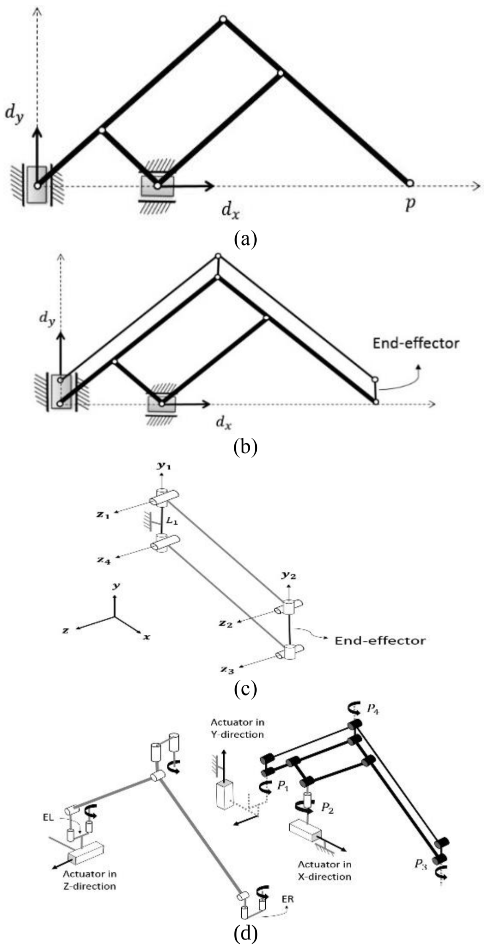

Figure 1. Kinematic description of the proposed manipulator.

II. Description and Mobility Analysis of the Manipulator

A. Description of the Architecture

The basic idea behind the proposed translational pantograph manipulator can be explained with the known 2D pantograph mechanism as shown in Fig. 1(a). When the horizontal slider moves certain distance horizontally, the extreme point P moves in the same direction the same distance multiplied by the magnification factor (a+b)/a. Similarly, when the vertical slider moves certain distance vertically, point P moves in the opposite direction the same distance multiplied by the magnification factor (b/a). Fig. 1(b) shows the known 2D pantograph with guiding mechanism. The extreme right vertical link represents the end-effector here as shown. The guiding mechanism which consists of two parallelograms forces the end-effector to move translational motion in 2D space without changing its orientation. The motion of this end-effector is controlled by the linear motions of the two horizontal and vertical sliders with the same rules used to control point P in Fig. 1(a). Then, to obtain fixed orientation in 3D space, the parallelogram mechanism with for universal joints was used to obtain fixed orientation as shown in Fig. 1(c). This mechanism consists of four revolute joints formed planar parallelogram in X-Y plane and another four revolute joints formed planar parallelogram in X-Z plane. The axes of the four revolute joints are parallel to each other and are orthogonal to those of the four revolute joints in the other parallelogram. This arrangement guarantees constant parallelism between axes y1 and y2 and axes z1 and z2. When the end-effector in this mechanism moves with respect to link 1, the end-effector achieve constant orientation in X-Y-Z directions [19]. Figure 1d shows the proposed manipulator after virtually dividing it into two parts by vertical plane for the sake of clarity. The steps to create the proposed manipulator begins with constructed the 2D pantograph with guiding mechanism shown in Figure with dark lines. Then, adding vertical joints which intersected with horizontal joints to produce universal joints. The three lowest points (P1; P2; P3) and the highest point (P4) of these linkages are attached to revolute joints having vertical axes as shown in Fig. 1(d). The middle lowest joint is attached directly to a horizontal slider acting in x-direction, while the remained two lowest joints and the highest joint form with other links and joints with light gray lines to produce two parallelograms with universal joints acting on planes perpendicular to the pantograph plane. The purpose of using parallelograms with universal joints is maintaining the end-effector link with constant orientation in 3D space and facilitate the motion of the proposed manipulator between the two planes XY and XZ. The Extreme Right (ER) horizontal link of the perpendicular-type parallelograms is the end-effector of the proposed manipulator. The Extreme Left (EL) horizontal link of the perpendicular-type parallelograms is fixed to a horizontal slider acting in z-direction relative to other vertical slider acting in y-direction relative to the ground. The magnification factors of the proposed manipulator in x- and y- directions are the same as the original 2D pantograph. The magnification factor in z-direction is the same as that of y-direction and equals b/a. Also the direction of the end-effector motion in z-direction is opposite to the motion direction of the slider acting along z axis. Fig. 2 shows the schematic diagram and CAD model of the proposed manipulator.

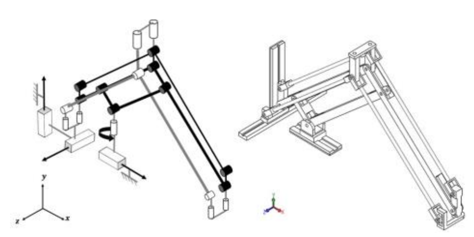

Figure 2. Schematic representation of the kinematic structure of the 3-DOF translational manipulator.

B. Mobility Analysis

Obtaining the number of degrees of freedom (DOF) is one of the most important issue for mechanism analysis, namely, the mobility of a mechanism. The general Grübler-Kutzbach (GK) criterion is considered as the most famous formula for mobility analysis. So, based on GK criterion, the mobility of the proposed of the manipulator can calculated as:

$$F = \lambda\,(n - j - 1) + \sum_{i=1}^{j} f_i = 6(21 - 25 - 1) + 25 = -5 \quad (1)$$

where λ represents the dimension of task space, n is the number of links, j is the number of joints, and fi indicates the degrees of freedom of joint i. The general GK criterion can only calculate the number of DOF of some mechanisms without obtaining the type of motion whether it is translational or rotational motion. Although the application of Grübler formula results in negative value which refers to non-moving structure, the movement of the system is a result of unique geometry similar to other parallel manipulators such as Delta and Tsai manipulators. The unique geometry here is that all the vertical axes of the joints are located in two parallel vertical planes. Thus, we analyze the system mobility using graphical approach. The structure of the proposed manipulator is constructed on parallelogram mechanism. The mechanism of the planar four-bar parallelogram consists of four bars connected end to end by revolute joints. Parallelogram mechanism structure enables the end-effector of the pantograph to maintain a fixed orientation with respect to an input link in 2D space. Then, the parallelogram mechanism with for universal joints was used to obtain fixed orientation in 3D space [19]. This arrangement of links and joints guarantees constant orientation for the proposed manipulator in X-Y-Z directions. Based on this concept, the mobility of the proposed manipulator can be calculated directly from the geometry of the mechanism. Since, the mobility of any spatial mechanism can be represent by six components, three translations in X, Y, Z directions and three rotations around X, Y, Z. So, the guiding planar pantograph in X-Y plan with two Parallelogram mechanisms can provide 2 DOF (translation on X and Y) with fixed orientation. Similarly to the planar pantograph described above, two parallelograms with universal joints are added in X-Z plane to fix the orientation of the end-effector while permitting translational motions in Z directions. As a result, the proposed pantograph manipulator has 3-DOF (three translations in X, Y, Z) with fixed orientation.

III. KINEMATIC ANALYSIS

The pantograph mechanism is characterized by linear relation between its input and output. This makes the direct and inverse kinematic is easier to implement for the proposed manipulator. Referring to the kinematic diagram in Fig. 3, the manipulator consists of 2 loops **OA'ADF** and **OBEF**.

A. Forward Kinematic Analysis

Based on a loop closure equations technique, the following two vector-loop equations can be written as follows:

$$\overrightarrow{OF} = \overrightarrow{OA} + \overrightarrow{A'A} + \overrightarrow{AD} + \overrightarrow{DF} \quad (2)$$

$$\overrightarrow{OF} = \overrightarrow{OB} + \overrightarrow{BE} + \overrightarrow{EF} \quad (3)$$

The position of the end effector with respect to the fixed frame can be described by a position vector q = [xe, ye, ze]^T as it possesses only a translational motion. Expressing the vector loop equations above in the fixed coordinate frame gives two sets of equations. The first loop **OA'ADF** gives:

$$x_e = (\cos\theta_1 + \cos\theta_2)(a+b)\cos\varphi \quad (4)$$

$$y_e - y_a = (\sin\theta_1 + \sin\theta_2)(a+b) \quad (5)$$

$$z_e - z_a = -(\cos\theta_1 + \cos\theta_2)(a+b)\,\sin\varphi \quad (6)$$

while the second loop; **OBEF** gives:

$$x_e - x_a = (\cos\theta_1 + \cos\theta_2) b \cos\varphi \quad (7)$$

$$y_e = (\sin\theta_1 + \sin\theta_2) b \quad (8)$$

$$z_e = -(\cos\theta_1 + \cos\theta_2) b \sin\varphi \quad (9)$$

where, φ is the angle of rotation around y in X-Z plane for the whole manipulator. While the angles Ψ , θ_1 and θ_2 are indicated geometrically in the schematic Fig. 3. By dividing equations (4) on (7) and obtaining the relation between the position of the end-effector and the input actuators in X-direction that can be simplified to be:

$$x_e = \frac{a+b}{a} x_a = M_x x_a \quad (10)$$

Similarly, from equations (5), (8) and equations (6) (9) the position of the end-effector in Y and Z directions can also simplified to:

$$y_e = \frac{-b}{a} y_a = M_y y_a, \quad z_e = \frac{-b}{a} z_a = M_z z_a \quad (11)$$

Since, forward kinematics is a mapping from joint coordinate space to space of end-effector positions. So, the relationship between the end effector movements [xe, ye, ze]^T and the actuators input [xa, ya, za]^T can be expressed in matrix form as follow:

$$\begin{pmatrix} x_e \\ y_e \\ z_e \end{pmatrix} = \begin{pmatrix} (a+b)/a & 0 & 0 \\ 0 & -b/a & 0 \\ 0 & 0 & -b/a \end{pmatrix} \begin{pmatrix} x_a \\ y_a \\ z_a \end{pmatrix} \quad (12)$$

where x_e, x_a are the position of the end effector and the actuator in x-direction respectively. The ratio (a+b/a) is the magnification factor M_x in x-direction. For the actuator in y direction y_e, y_a are the motion of the end effector and the motion of the actuator in y-direction respectively while the ratio (b/a) is the magnification factor M_y. The magnification factor in z-direction can be estimated as same as in y-direction. where z_e, z_a are the motion of the end effector and the motion of the of the actuator in z-direction respectively.

B. Inverse kinematic Analysis

The inverse kinematics problem is defined as finding the required values of the actuated joints that correspond to a desired position and orientation of the end effector. The solution of the inverse kinematic problem is a basic control algorithm in robotics. Therefore, the existence of multiple solutions to the inverse kinematics problem complicates the control algorithm. In contrast with the above system of independent equations can be inverted to give the trivial solution to the inverse kinematics of the proposed manipulator. Though, the inverse kinematic equations can be formed easily in matrix form as:

$$\begin{pmatrix} x_a \\ y_a \\ z_a \end{pmatrix} = \begin{pmatrix} a/(a+b) & 0 & 0 \\ 0 & -a/b & 0 \\ 0 & 0 & -a/b \end{pmatrix} \begin{pmatrix} x_e \\ y_e \\ z_e \end{pmatrix} \tag{13}$$

C. Velocity Analysis

In velocity kinematics, the Jacobian matrix J mapping the linear relation between the actuator velocity $\dot{\xi}$ and the end effector velocity $\dot{q}$ for a given configuration of the robot. For parallel manipulators, there are two Jacobian matrices:

$$J_\xi \dot{\xi} = J_q \dot{q} \tag{14}$$

where $\dot{\xi} = [\dot{x_a}, \dot{y_a}, \dot{z_a}]^{\mathrm{T}}$ is the vector of joint rates, while $\dot{q} = [\dot{x_e}, \dot{y_e}, \dot{z_e}]^{\mathrm{T}}$ is the vector of the end-effector velocities. So, the two Jacobian matrices can be represented as:

$$J_q = I_{(3\times3)}\,, \quad J_\xi = \begin{pmatrix} (a+b)/a & 0 & 0 \\ 0 & -b/a & 0 \\ 0 & 0 & -b/a \end{pmatrix} \tag{15}$$

where $J = J_\xi^{-1} J_q$. Then the Jacobian matrix of the proposed manipulator is:

$$J = \begin{pmatrix} a/(a+b) & 0 & 0 \\ 0 & -a/b & 0 \\ 0 & 0 & -a/b \end{pmatrix} \tag{16}$$

IV. WORKSPACE DETERMINATION

Compared with serial manipulators, parallel manipulators have relatively small workspace. Subsequently the workspace is one of the most imperative aspects to mirror its working capacity, and it is used to determine the shape and volume of the workspace for required applications. Since, the structure of the proposed manipulator is closed to that of serial manipulators, it has high workspace to size ratio comparable to that of serial manipulators. So, the proposed manipulator has large workspace compared with other decoupled manipulators. Then, according to Fig. 3:

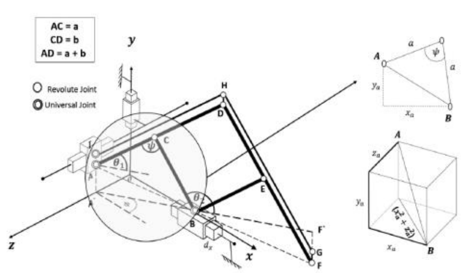

Figure 3. Schematic representation of the kinematic structure of the 3-DOF translational manipulator.

$$(\overline{AB})^2 = 2a^2(1-\cos\psi) \tag{17}$$

$$(\overline{AB})^2 = x_a^2 + y_a^2 \tag{18}$$

From equations (17) and (18) the workspace of the proposed manipulator in X-Y plane can be calculated as:

$$2a^2(1-\cos\psi) = x_a^2 + y_a^2 \tag{19}$$

The boundary of the workspace occurred at $\psi = \pi$. Since, the 2D pantograph workspace can be represented by ellipse in X-Y plan as shown in Fig. 4 that represent the 2D workspace divided to four quarters based on the motion modes of the actuators (± x and ± y). The workspace of the 2D pantograph with motion (+ x and − y) is found to be the right semi-ellipse having the following equation:

$$\frac{x_e^2}{(2aM_x)^2} + \frac{y_e^2}{(2aM_y)^2} = 1 \quad x_e > 0 \tag{20}$$

The motion of the manipulator in z can be concluded from Fig. 3 while:

$$(\overline{AB})^2 = 2a^2(1-\cos\psi) = x_a^2 + y_a^2 + z_a^2 \tag{21}$$

From equation (21), the equation of the total workspace for the proposed manipulator in X-Y-Z directions can be obtained as:

$$x_a^2 + y_a^2 + z_a^2 = 4a^2 \qquad x_e > 0 \tag{22}$$

The magnification factor in two axis are equal and less than the third axis this give the shape of oblate spheroid. Therefore the workspace of semi-ellipsoid can be described using equation (23) as shown in Fig. 5:

$$\frac{x_e^2}{(2aM_x)^2} + \frac{y_e^2}{(2aM_y)^2} + \frac{z_e^2}{(2aM_z)^2} = 1 \quad x_e > 0 \tag{23}$$

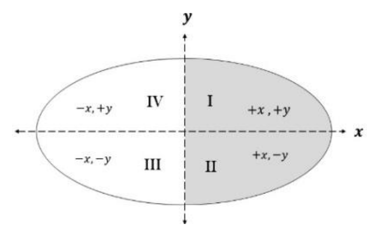

Figure 4. The workspace and motion modes of the 2D pantograph mechanism.

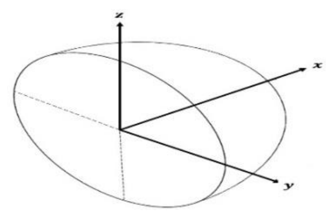

Figure 5. The total workspace of the proposed manipulator.

V. SIMULATION

In this section, ADAMS dynamic simulation software is used to validate the decoupling motion and constant orientation of the proposed manipulator using ADAMS software of the proposed manipulator. A 3D model for the manipulator is created using Solidworks software and then exported to ADAMS. The position and angular velocity of the end effector in X-Y-Z directions are shown in Fig. 6.

By analysis Fig. 6(a), it is easy to find that, when the actuator moved in x-direction, the end-effector moved along X-axis in the same direction with constant orientation and without any effect on the y and Z motion. Similarly, Fig. 6(b) shows the motion in the opposite direction of the end-effector along the Y-direction with constant orientation and without any coupling with X and Z motions. Finally, the motion curve in Z-direction indicate also the motion in the opposite

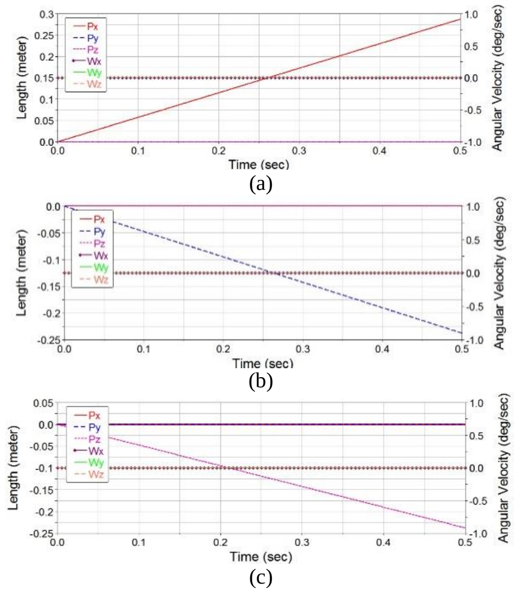

Figure 6. Simulation of the proposed manipulator using ADAMS software.

direction with the constant orientation and fully decoupled between the actuator's motions as shown in Fig. 6(c).

VI. CONCLUSIONS

In this paper, a virtual prototype of a new 3-DOF fully decoupled translational manipulator is presented. It can locate the end-effector in the desired position with constant orientation using only three translational actuators. Furthermore, the kinematic analysis shows a fully decoupled translation motion in the three orthogonal axes X, Y and Z that allow the end-effector to be controlled using a single actuator for each axis. Also, the relation between the input displacements of the actuators and the output displacements of the end-effector is linear. Finally, compared with the previously reported decoupled parallel manipulators as Isoglide4 or the Quadrupteron, the proposed manipulator faster than them by the magnification factor of the pantograph mechanism and the same speed as the Pantopteron. Besides, the proposed manipulator has large workspace. For future work claims, a typical 3 DOF spherical wrist can be added to form 6 DOF manipulator where the orientation of the end-effector here is independent on its position.

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