PD Type of Fuzzy Controller for a New 3DOF Fully Decoupled Translational Manipulator

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ABSTRACT
This paper deals with the controller design of a new fully decoupled 3DOF translational manipulator with fixed orientation of the end-effector. The proposed manipulator has several useful characteristics over its competitive counterpart such as Delta and Tsai in terms of workspace to size ratio, speed, rigidity and accuracy. The decoupled feature affects the selection of actuators size and power as well as affects the positioning accuracy of the moving platform. PD type of fuzzy controller is chosen to achieve a desired tracking performance. PD controller is widely accepted in industry due to its easiness of implementation. Fuzzy controller suits complex and nonlinear systems and has the ability to achieve zero steady state error. The proposed manipulator is tested for tracking quintic polynomial and another trajectory that composed of three sinusoidal waveform combined with different frequencies in addition to the payload variation. Moreover, the new manipulator is tested for pick and place application. Simulation results are based on Co-simulation between MS-ADAMS and Matlab. The nonlinear model is exported from MS-ADAMS to capture the dynamics of the manipulator while Matlab is used to implement the controller algorithm. The whole results show the efficiency of PD type of fuzzy controller in tracking desired trajectory even under payload variation.

Keywords—Parallel robot, 3DOF translational manipulator, decoupled motions, PD type fuzzy controller, robust control.

I. INTRODUCTION
Parallel manipulators in the recent decades seen a progress in their development due to its advantages over serial manipulator such as higher stiffness, higher accuracy, and lower inertia. This advantages empower them to be a reasonable choices for a wide range of applications. Parallel manipulators ordinarily comprise of a moving platform that is associated with a fixed base by at least two kinematic chains. However, it has a complex forward kinematics, small workspace, complicated structures, and a high manufacturing cost [1]. The limited DOF manipulators exhibit the advantages of parallel robots in addition to the total cost reduction for manufacturing and operations [2]. In many industrial applications such as pick and place, welding and painting, it is required to move the end-effector without changing its orientation. A lot of spatial 3DOF parallel manipulators like Delta and Tsai have been designed for the applications that required fixed orientation of the end-effector. However, they did not achieve the translational decoupling between actuators. Several types of architectures have been proposed to achieve fully decoupled translational motions with different theoretical approaches, some of these designs are 3CRR manipulator [3], [4]. Another type of decoupled translational manipulator called Tripteroton is presented in detail in many works [5], [6], [7]. Hence, many researchers try to solve the proposed problem of coupling motion with different structures as the Quadruperton [8] and Panopteron[9]. Although studies have recognized the kinematic translational decoupling, all the studies reviewed so far, however, they proposed quite complex structure for the decoupled translational manipulator. The proposed manipulator possesses unique characteristics such as decoupled translational motions, high workspace/size ratio, high accuracy and high speed. The proposed design surpasses in high payload/weight ratio. The key design feature is the use of parallelograms which maintain the orientation of the end-effector fixed. The proposed manipulator has several useful characteristics over its competitive counterpart such as Delta and Tsai. They provide a kinematic linearity between input and output movements. Moreover, this manipulator introduces a amplification factor between input and output motions.

One of the main concerns in manipulator applications is to introduce an efficient control strategy to realize its benefits. Traditional control schemes based on classical PD controllers and computed torque control have been successfully implemented [10]. These controllers considered widely accepted in industry due to its easiness of implementation and tuning. However, they cannot always ensure a good performance in regulation and trajectory tracking applications. Classical PD controller can not guarantees zero steady state error. Besides most of these types of control topologies are sensitive to uncertainties, measurements noise, disturbance inputs and unmodeled dynamics [11]. In order to accomplish a satisfactory controller results’, an intelligent controller can be combined with classical PD controller, particularly PD type of fuzzy controller. A fuzzy logic controller provides an alternative to these conventional control scheme specially for complex nonlinear systems. The control action in fuzzy logic controllers can be expressed with simple “if-then” rules. They can cover a much wider range of operating conditions than classical controllers and can operate with noise and disturbances. The stability analysis of a control system having a PD type of fuzzy controller, which has two inputs and a single output has been introduced previously in [12]. This hybrid scheme, PD type of fuzzy controller, reduces the steady state error significantly and shows a robust performance during payload variation and
different trajectory tracking.

This paper organized as follows: The description of the new 3DOF translational manipulator is presented in Section II. The kinematic analysis is discussed in Section III. Trajectory Planning is discussed in Section IV. PD type fuzzy controller is proposed in Section V, while the simulation results are analyzed in Section VII. Finally, some concluding remarks and future work are given in Section VIII.

II. DESCRIPTION OF THE NEW 3DOF DECOUPLED TRANSLATIONAL MANIPULATOR

The structure of the proposed new 3DOF decoupled translational manipulator is based on parallelogram mechanism. That consists of a pantograph mechanism with two types of parallelogram as shown in Fig. 1. One type of the parallelogram is acting on planes parallel to the pantograph plane with all joints have horizontal axes. It is responsible for fixing the orientation of the end-effector in the plane of the pantograph. The other type of the parallelograms is acting on planes perpendicular to the pantograph plane and is responsible for fixing the orientation of the end-effector in plane perpendicular to that of the pantograph. The joint with vertical axis at B is attached to horizontal link at end E is the end-effector that moves pure translational motions without changing the orientation according to the independent motions of the linear actuators acting on the three sliders. The new 3DOF decoupled translational manipulator has three input points, two of them are at A for the actuator \( y_a \) and \( z_a \), and the third point B for the actuator \( x_a \) and one output point E. These input points linearly control the displacement of output point E. Figure 2 shows the CAD model of the proposed manipulator.

III. KINEMATIC ANALYSIS

In order to analyze the kinematics of the new 3DOF translational manipulator, a fixed global reference system \( O-xyz \) is assigned as shown in Fig. 1. The following generalized coordinates \( E = (q_x, q_y, q_z) \) can be chosen to describe the pose of proposed manipulator.

A. Forward kinematic analysis

The purpose of the forward kinematics issue is to find the position of the moving platform \( q_x q_y q_z \) as a function of the actuated variables \( x_a y_a z_a \). In parallel manipulator the forward kinematics is much more complex due to the existence of the closed chains. This complexity yields in many parallel robots architecture have no closed form solutions. The proposed manipulator has straight forward kinematics relationships. The mechanical system in Fig. 3 has three input variables; two of them \( y_a \) and \( z_a \) are located at points A and the other one \( x_a \) at point B. The following two vector-loop closure equations can be written as follows:

\[
\vec{OE} = \vec{OA} + \vec{AD} + \vec{DE},
\]

\[
\vec{OE} = \vec{OB} + \vec{BF} + \vec{FE},
\]

where \( O \) is the origin of the fixed coordinate system O-xyz. The axes \( x, y, \) and \( z \) coincide with the actuation axes of the three translational actuators. The position vector of the end-effector and the vector of the linear actuated joint variables are \( E = [q_x, q_y, q_z]^T \) and \( p = [x_a, y_a, z_a]^T \) respectively. Since the end-effector of the proposed manipulator has only translational motions in Cartesian frame, the rotation matrix becomes identity. Let \( AC = BC = DF = a \) and \( CD = BF = FE = b \) as design constraints. Loop equation (1) is used to obtain the following set constraint equations

\[
q_x = (\cos \theta_1 + \cos \theta_2)(a + b) \cos \phi,
\]

\[
q_y = y_a = (\sin \theta_1 + \sin \theta_2)(a + b),
\]

\[
q_z = z_a = -(\cos \theta_1 + \cos \theta_2)(a + b) \sin \phi,
\]
Similarly, three additional equations can be derived from loop equation (2)
\[ q_x - x_a = (\cos \theta_1 + \cos \theta_2)b \cos \phi, \]  
\[ q_y = (\sin \theta_1 + \sin \theta_2)b, \]  
\[ q_z = -(\cos \theta_1 + \cos \theta_2)b \sin \phi. \]  
Dividing (3) by (6) to get the relation between the input actuator \( x_a \) and the output displacement \( q_x \) along \( x \)-axis
\[ q_x = M_x x_a, \]  
where \( M_x = 1 + \frac{b}{2} \) is the magnification factor of the input variable \( x_a \). Similarly, from (4) and (7) and from (5) and (8), one gets the relationships between \( y_a \) and \( q_y \) and between \( z_a \) and \( q_z \) respectively.
\[ q_y = M_y y_a, \quad q_z = M_z z_a, \]  
where \( M_y = M_z = \frac{b}{a} \) are the magnification factors of the input variables \( y_a \) and \( z_a \) respectively. The relations (9) and (10) illustrate the linearity between the input and output displacements as well as the decoupling of the translational motions.

IV. PD TYPE OF FUZZY CONTROLLER

Fuzzy logic controller (FLC) is a very popular technique which is quite suitable for industrial applications of parallel robots. A fuzzy logic (FL) system consists of four parts: knowledge base, fuzzier, fuzzy inference engine working on fuzzy rules, and defuzzier. Linguistic rules express the relationship between input variables. It is not possible to design a controller which operates professionally at any different condition without retuning. It may bring the system out of stability because the controller cannot track all the changes in the operating states. In PD type of fuzzy controller, the controller combines the simplicity of the conventional PD controller and the robustness of fuzzy logic controller. The final step in FLC is defuzzification that is required to determine the "crisp output", resolves the applicable rules into a single output value. The two inputs are; the error which is represent as \( e \), the derivative of the error \( \Delta e \), this error represent the difference between the instantaneous system actual output and the desired output [13]. The scaling gains, \( K_P \) and \( K_D \) in FLC behave as PD controller while the gain \( K_u \) assists in improving the overall performance of the controller where \( u \) is the control signal. The most important advantage of using scaling factors is that we can design a PI, PD and PID type of fuzzy controllers. In this case the gained experience in tuning conventional PD controllers, for example, is used in tuning the PD type of fuzzy controllers. The chosen fuzzy rules are based on heuristics and experience that gained from the previous knowledge of the model and the defuzzification method is calculated based on centroid method. Table I represents the matrix of rules to cover all possible combinations of fuzzy subsets for two input variables PD type of fuzzy controller [14]. Each input and the output consists of seven triangular membership functions: negative big 'NB', negative medium 'NM', negative small 'NS', zero 'ZO', positive small 'PS', positive medium 'PM', positive big 'PB', this gives a total of 49 rules. The universe of discourse for the inputs \( e \) and \( \Delta e \) and for the output \( u \) is normalized for both inputs and output \( \in [-1 : 1] \). The control surface of PD like system is shown in Fig. 4. The architecture of PD type fuzzy controller is shown in Fig. 5.

V. TRAJECTORY PLANNING

A motion planning for parallel manipulators is considered in which the path 'position, velocity, acceleration, etc' is determined with respect to its kinematic constraints only. The cubic-polynomial planning is commonly used in robotics context for trajectory tracking validation. However, in speed profile, the jerk is discontinuous. The discontinuity of jerk may lead to vibration that deteriorates manipulator performance. Therefore, jerk continuity is desirable to improve control performance of a manipulator. In [15], a fifth-order 'quintic' polynomial to plan a given path is proposed in which the trajectory is given as:
\[ \lambda(t) = a_1 t^5 + a_2 t^4 + a_3 t^3 + a_4 t^2 + a_5 t + a_6, \]
This results in a quadratic function of jerk, which is continuous and second-order differentiable:
\[ \ddot{x} = 60 a_1 t^2 + 24 a_2 t + 6 a_3. \]
Fig. 6: The motion of the new 3DOF translational manipulator on the three orthogonal axes

Fig. 7: The actuator motion in $x$, $y$ and $z$ of the proposed manipulator under quintic polynomial trajectory.

Fig. 8: The actuator forces $f_x$, $f_y$ and $f_z$ of the proposed manipulator under quintic polynomial trajectory.

Fig. 9: The tracking error $e_x$, $e_y$ and $e_z$ of the proposed manipulator under the quintic polynomial trajectory.

Bounded jerk limits and actuator torque limits will be used to accomplish a time planning and path parametrized by a quintic polynomial [16]. Two different type trajectories were used to validate the controller robustness; first, quintic polynomial and secondly three sinusoidal waveform with different frequencies are combined together with maximum frequency $3 \text{ rad/sec}$.

VI. SIMULATION VERIFICATIONS

A. ADAMS Dynamic Modeling Software

The parallel manipulator is highly nonlinear complex model and obtaining a dynamic model is not an easy task in general, besides obtaining dynamic model not guarantees accu-
namic analysis. Based on the dynamic analysis and the payload manipulation, the manipulator is simulated using MS-ADAMS software for dynamic analysis. For control purpose, the new 3DOF decoupled translational manipulator is simulated using MS-ADAMS software for dynamic analysis. Based on the dynamic analysis and the payload requirements, the bearing and actuators are selected. The virtual prototype was developed in MSC-ADAMS environment. Figure 6 shows ADAMS simulation for the three fully decoupled 3DOF translational motion of the design. Thereafter, the model exported to ADAMS, the next step is to activate the co-simulation environment between ADAMS and Matlab. Co-simulation between these two softwares facilitate building a virtual environment for validating different control schemes. This environment is built by activating the control modules ‘Adams/Controls’ from the ‘plug-in manager’ in ADAMS. The input force in ADAMS is supplied from MATLAB as a variable depending on the control architecture and the dynamic model of the system.

B. ADAMS/Matlab Co-Simulation Results

The PD type of fuzzy controller is applied to the proposed manipulator. The motion in task space is a three-dimensional vector consisting of the three position components \( E = [q_x, q_y, q_z] \); therefore, the tracking error is defined as \( e_x, e_y, e_z \). Three PD type of fuzzy controller are used one controller for each actuator. The output of the controller is defined by a three-dimensional wrench in the joint space \([f_x f_y f_z]\). The initial conditions of the actuators’ positions are \( x_0 = 100mm, y_0 = 50mm, z_0 = 0mm \). The desired trajectory of the moving platform, first, is generated by quintic polynomial functions. The time of simulation is considered to be 5sec, and the gains are chosen by trial and error as: \( k_p = 2, 1.5, 2, k_d = 0.01, 0.01, 0.02 \) and \( k_u = 500, 550, 100 \). Figures 7a, 7b and 7c show the motion at the three axes while Figs. 8a, 8b and 8c show the actuator forces \( f_x f_y f_z \). The error during three axis motions are described by Figs. 9a, 9b and 9c for actuator x, y and z respectively. The PD type fuzzy controller has a high tracking ability with no overshoot and very small steady state error. Afterward, the new 3DOF translational manipulator is tested for tracking a trajectory composed of three sinusoidal waveform of frequencies 1.5[rad/sec], 1.5[rad/sec] and 3[rad/sec]. The scaling gains remains with no change. The new 3DOF decoupled transna-
payload variation. This controller shows a robust performance controller is applied under two different trajectories and during relying on the performance of the controller. PD type of fuzzy control is carried out on the co-simulation environment which assists is received from Matlab/Simulink. The numerical simulation exported from MSC-ADAMS software and the control signal with constant orientation of the end-effector. The kinematic for a new 3DOF fully decoupled translational manipulator show a feasibility of analytically manipulator can work with satisfied performance when payload varied from noload case to 1.4 kg with a very small tracking error as shown in Fig. 10. The control effort under the second trajectory is shown for the three actuators in Figs. 12a, 12b and 12c and the error in motion is shown in Figs. 13a, 13b and 13c for actuator x, y and z respectively. PD type of fuzzy controller assist on achieving very small steady state error with no overshoots even at payload variation which is strongly required for robot applications’ to work with no overshoots and fast settling time. Then, the proposed manipulator is tested for pick and place application, in Figs. 11a and 11b the motions in x and y axis respectively are shown with no overshoot and error smaller than 0.7mm. The conceptual design of 3DOF fully decoupled translational manipulator show a feasibility of this design for high speed trajectory tracking and pick and place. This proposed manipulator is intended to be used in high speed applications with a high accurate positing ability. The total results approve the feasibility of this new 3DOF translational manipulator and assure its efficiency with PD type fuzzy control, on tracking high speed different trajectories accurately and during pick and place.

VII. CONCLUSIONS

In this paper, A PD type of fuzzy controller is investigated for a new 3DOF fully decoupled translational manipulator with constant orientation of the end-effector. The kinematic analysis shows a fully decoupled translation motions in the three orthogonal axes x, y, and z. The dynamic model is exported from MSC-ADAMS software and the control signal is received from Matlab/Simulink. The numerical simulation is carried out on the co-simulation environment which assist relying on the performance of the controller. PD type of fuzzy controller is applied under two different trajectories and during payload variation. This controller shows a robust performance during tracking quintic polynomial and second trajectory that composed of three sinusoidal waveform combined with different frequencies. The simulation results show a satisfactory performance in terms of overshoots, settling time and steady state error.

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