PID-like Fuzzy Logic Control Scheme for Control of a Planar Parallel (3PPR U-base) Manipulator

Yogesh Singh, M. Santhakumar

Abstract

The paper investigates the control of a three prismatic-prismatic-revolute (3 PPR) U-base planar parallel manipulator in the presence of parameter uncertainties and unknown disturbances. The 3PPR U-base planar parallel manipulator is a motion platform with singularity free workspace (bounded orientation angle $\theta_z \leq \pm 90^\circ$) and has manipulator legs located on the plane in association with a moving platform. Each leg has a prismatic-prismatic-revolute joint configuration in which one prismatic joint is active in each leg. To control the end-effector's mobility of the 3PPR U-base motion platform a proportional-integral-derivative (PID)-like fuzzy logic control scheme is introduced. To demonstrate the effectiveness of the proposed controller, experiments (on a in-house fabricated prototype of the proposed manipulator) with a desired characteristic trajectory are performed and its control performance is compared with an existing conventional PID controller. The results confirmed that the proposed controller has the capability to track the desired task space trajectory and gives a better robust control performance.

Keywords: Planar parallel manipulator, proportional-integral-derivative (PID) control, PID-like fuzzy logic control, task space trajectory control

1 Introduction

In comparison to the serial manipulators, parallel manipulators having few advantages such as higher stiffness, higher dynamic characteristics, higher positioning accuracy, lower inertia of moving parts and better accuracy [1]. However parallel manipulators undergo from some drawbacks including small workspace, complicated forward kinematics and coupled dynamics. As opposed to the spatial parallel manipulators, planar parallel manipulators have their motion restricted to a plane with the usage of prismatic and revolute joints. Planar parallel manipulators have a wider range of applications such as material handling and processing, fabrication, micro machining and the precise positioning devices due to their simplicity in joint and structural arrangements. It is well known that different configuration of 3-DOF planar parallel manipulators occur, such as 3RRR, 3RPR, 3RRP, 3RPP, 3PRR, 3PRP, 3PPR and combination of these joints (2PRP-PPR, etc.)[2, 3, 4, 5]. 3PPR U-base manipulator taken for the analysis because of its higher singularity free workspace and ease of control

Yogesh Singh
Discipline of Mechanical Engineering, Indian Institute of Technology Indore, Madhya Pradesh, E-mail:phd12110311@iiti.ac.in.

M.Santhakumar (Corresponding author)
Discipline of Mechanical Engineering, Indian Institute of Technology Indore, Madhya Pradesh, E-mail:santhakumar@iiti.ac.in.

over other planar parallel manipulators [3, 4]. In the case of planar parallel manipulator, most of the systems are restricted to only positioning applications (not utilised for other equally significant applications like trajectory tracking). Hence, there is a scope to develop an effective and an efficient motion control scheme for the parallel manipulators as a precise and accurate motion platform which can be utilise in industrial as well as surgical applications where the micro level precision is required. During the past few years, plenty of controllers such as PID (proportional-integral-derivative), SMC (sliding mode control), adaptive control, robust control etc. have been proposed and implemented for parallel manipulators[4, 5, 6, 7]. In the above mentioned controllers, the majority of control schemes are model based control and requires an exact mathematical model of the parallel manipulator system to enact better control performance. An exact mathematical modelling of any system (manipulator) is utterly rigorous due to its uncertainties in the system parameters which is highly nonlinear, coupled and belongs to time varying dynamical characteristics. In that condition, intelligent control schemes such as fuzzy logic control (FLC), neural network control and their hybrid combination has been successfully applied to robotic manipulators [8, 9, 10, 11, 12, 13]. However , these control schemes associated with complex designing methods and control structures. Combination of PI, PD, PID and FLC results in a dynamic fuzzy controller structure which gives better control performance and a simple control structure [9]. The main quality of the FLC is that, it can apply to the plants

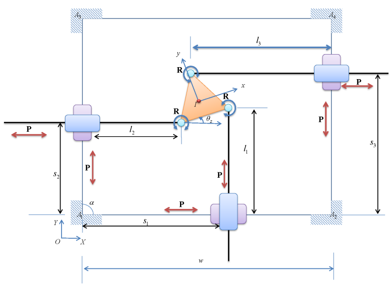

Figure 1: Frame diagram of the 3PPR U-base PPM

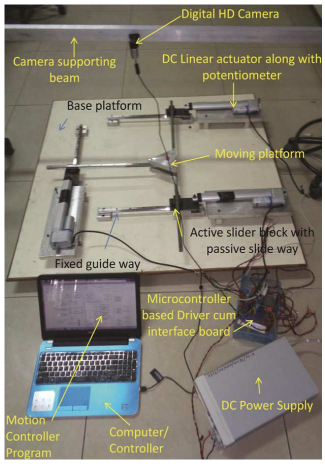

Figure 2: Experimental setup of the 3PPR U-base PPM

whose mathematical model is not well defined. For such plants, FLC can be executed to mimic human deductive thinking i.e. exhibit human-like thinking into an automated control system. To have an improvised control performance, a novel linear PID-like fuzzy logic control technique is designed and applied for the complex trajectory tracking control in task space of the 3PPR U-base PPM. The proposed control technique empowers, overcoming the difficulty due to parameter uncertainties, external disturbances and payload variations. The effectiveness of the proposed control technique is evaluated with trajectory tracking control problem of the 3PPR U-base PPM and validated through prototype real-time experimentation. Proposed control scheme shows better and robust control performance. Rest of the paper organised as follows, section 2, describes dynamic modeling of 3PPR U-base PPM. section 3, presents a proposed linear PID-like fuzzy logic controller design scheme. section 4, presented the performance analysis of the proposed control scheme. Finally conclusions are provided in section 5.

2 Dynamic modeling of a 3PPR U-base PPM

Figure 1 presented the schematic arrangement of the links, joints and frames of the 3PPR U-base PPM. It has three PPR legs which connect the base (fixed) platform to mobile platform (end-effector). 3PPR U-base PPM has three translation active joints (input) namely s_1, s_2 and s_3 which act as the joint-space variables. correspondingly position and orientation of the end-effector (x, y and θ_z) act as the task space variables. In the present paper dynamic modeling of the 3PPR U-base PPM is derived through Lagrangian-Euler method. Then the dynamic equation of motion of the manipulator can be expressed as follows:

$$M\left(s\right)\ddot{s}+C\left(s,\dot{s}\right)+F\left(\dot{s}\right)=\tau_s+\tau_{dis} \tag{1}$$

where, $M\left(s\right)$ is the inertia matrix. $s=[s_1 \quad s_2 \quad s_3]$ is the joint space variables. $C\left(s,\dot{s}\right)$ is the coriolis and centripetal effects of the manipulator. $F\left(\dot{s}\right)$ is the vector of the fictional effects of the manipulator. $\tau_s=[f_1 \quad f_2 \quad f_3]$ is the vector of the active prismatic joint forces of the manipulator. $\tau_{dis}=\tau_{edis}+\tau_{idis}$ is the disturbance vector due to both internal and external disturbances. τ_{edis} is the external disturbance vector due to payload variations and other effects. τ_{idis} is the internal disturbance vector due to system uncertainties, unmodeled dynamics and process noises.

3 Robust PID-like fuzzy logic control scheme

Fuzzy logic control (FLC) can deal with poorly understood processes and have an ability to approximate nonlinear system. FLC has an ability to cope with nonlinearities and uncertainty. To achieve the good control system performance, linear PI, PD or PID-like FLC introduced [9, 10, 11, 12, 13]. The proposed control scheme PID-like FLC elaborated and presented here. The FLC is a linguistic based controller that attempts to mimic the human thinking approach. The FLC uses experts knowledge to built a set of linguistic control rules and then convert it into an automatic control. The control structure of PID-like fuzzy controller is the combination of PI-like fuzzy control and PD-like fuzzy control as follows:

$$Z^n_{PID}=Z^n_{PI}+Z^n_{PD} \tag{2}$$

where, Z_{PI} is the velocity type PI control and Z_{PD} is the position type PD control and can be written as:

$$
\begin{aligned}
Z_{PI}^{n} &= Z_{PI}^{n-1} + \dot{z}_{PI}^{n} && (3)\\
\dot{z}_{PI}^{n} &= N_I e^n + N_P \dot{e}^n && (4)\\
Z_{PD}^{n} &= N_P e^n + N_D \dot{e}^n && (5)
\end{aligned}
$$

From equation (3) to (5), the PID-like fuzzy control law can be occurred as:

$$
Z_{PID}^{n} = Z_{PI}^{n-1} + (1 + T_i)\, e^n + (1 + T_i)\, \dot{e}^n \tag{6}
$$

where, N_P, N_I and N_D are proportional, integral and derivatives gain of the PID-like fuzzy controller. e^n is the fuzzy error variable at n^{th} instant between set point and actual output of the system. $\dot{e}^n$ is the derivative of the fuzzy error variable at n^{th} instant. T_i and T_d are the integral and derivative time constants respectively. Figure 3 shows the control structure of the PID-like fuzzy controller where, variables K_e and K_d are the input scaling factors for e and $\dot{e}$ respectively and K_1 , K_2 are the output scaling factor.

3.1 Fuzzification

Fuzzification is associated with the mapping between the range of values of input variables and corresponding universe of discourse. Error (e) and change in error $\dot{e}$ are the two fuzzy input variables and the control signal Z_{PID} is the output of the PID-like fuzzy controller. This control signal actuates the actuators of the robotic manipulator system to control its motion. There are seven different linguistic labels for e and $\dot{e}$ as follows: Negative Large (NL), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), Positive Large (PL). Similarly for the output variable Z_{PID}, the lingustic labels are as follows: Negative Large (NL), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), Positive Large (PL). The cross point level of 0.5 degree is considered for every two adjacent membership functions, as it results in faster rise time and less settling time. A triangular type membership functions are used for fuzzy sets NM, NS, Z, PS and PM. Mathematically triangular type membership function is given as:

$$
\mu_{\bullet}(x) = \begin{cases} 0 & x \le a_i \\ \dfrac{x - a_i}{b - a_i} & a_i \le x \le b_i \\ \dfrac{c_i - x}{c - b_i} & b_i \le x \le c_i \\ 0 & c_i \le x, \end{cases} \tag{7}
$$

where, $\bullet \in \{NM, NS, Z, PS, PM\}$, Trapezoidal membership functions are used for the fuzzy sets NL and PB. respectively. Here, x is the crisp variable which is being fuzzified and a_i, b_i and c_i are the breakpoints of the ith triangular or trapezoidal membership function of the input or output variable, x.

3.2 Rule Base Logic

For the optimum performance, control rules, membership functions and scaling factors are essential to be tuned perfectly. Fuzzy control rules are structured through the analyses of a controlled system. The rules are defined in such a manner that the deviation from a desired state can be amended and the control objective can be acquired [9]. The fuzzy control rules are justified through a closed loop trajectory in phase plane analysis. Based upon the heuristic knowledge a general robust rule base can be designed to produce PID type control characteristics. Table1 represents a general PID-like fuzzy control kind of rule base. The cell elucidated by the intersection of first row and first column represents a rule such as, "if e is NL and $\dot{e}$ is PL then Z_{PID} is Z". The main advantage of this rule base is, its good response within a short time without any prior knowledge of the system modeling.

Table 1: A general PID-like fuzzy control type rule base

$\dot{e} \setminus e$	NL	NM	NS	Z	PS	PM	PL
PL	Z	PS	PM	PL	PL	PL	PL
PM	NS	Z	PS	PM	PL	PL	PL
PS	NM	NS	Z	PS	PM	PL	PL
Z	NL	NM	NS	Z	PS	PM	PL
NS	NL	NL	NM	NS	Z	PS	PM
NM	NL	NL	NL	NM	NS	Z	PS
NL	NL	NL	NL	NL	NM	NS	Z

3.3 Defuzzification

Defuzzification process converts fuzzy terms to quantifiable result (crisp value) which is required to actuate the final control element. The crisp control action is required for controlling the motion and joint space variables of a manipulator. The Center of Area (COA) defuzzification technique is used here because it yields better steady-state performance [9]. The crisp output control action is defined as follows:

$$Z_{PID} = \frac{\int \mu_c(x) x dx}{\int \mu_c(x) dx} \tag{8}$$

where c denotes the fuzzy sets which are being clipped during defuzzification process.

Now, let us consider PID-like fuzzy control law which gives robust control performance against uncertainties in the model parameters and environmental disturbances. With this, a proposed robust control scheme can be presented as,

$$\tau_c = K_c Z_{PID} \tag{9}$$

where, K_c is the gain matrix of PID-like fuzzy controller and Z_{PID} is the centralized PID-like fuzzy control input vector. In this work, model uncertainty, unknown disturbance and time varying parameters compensated through PID-like fuzzy controller.

The following assumption and properties are considered to secure the asymptotic convergence of trajectory tracking response in overall closed-loop system:

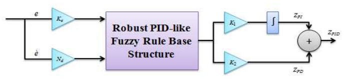

Figure 3: Control strucure: PID-like Fuzzy

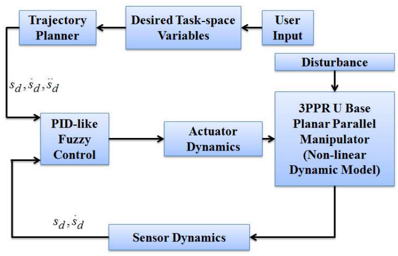

Figure 4: Linear PID-like fuzzy controller block diagram

Assumption 1: The PID-like fuzzy controller gain K_c is constant symmetric and positive definite (SPD) matrice by design, that is:

$$K_c = K_c^T > 0 \tag{10}$$

Property 1: The inertia matrix of the proposed manipulator system with respect to inertial frame is always positive definite, that is:

$$M(s) > 0, \forall\, s \,\epsilon\, \Re^n \tag{11}$$

Property 2: For the manipulator, the following property exists with respect to inertial reference (base) frame.

$$\xi^T(\dot{M}(s) - 2C(s,\dot{s}))\xi = 0,\ \forall\, \xi \,\epsilon\, \Re^n, s \,\epsilon\, \Re^n, \dot{s} \,\epsilon\, \Re^n \tag{12}$$

i.e. $\dot{M}(s) - 2C(s,\dot{s})$ is a skew-symmetric matrix.

4 Performance analysis

To prove the efficacy of the proposed control scheme, the performance analysis of the 3PPR U-base PPM is performed by real time experiments on a prototype of the 3PPR U-base PPM and compared with conventional PID control law.

4.1 Description of the Task

Effectiveness of the PID-like fuzzy logic controller validated by simulating the task of tracking a complex trajectory given by the user in terms of task-space along with the internal and external disturbance. As the parallel motion platforms are mainly used in moving a predefined trajectory, the path (complex trajectory) preferred to prove the effectiveness of the controller has been formed in such a way that, the results obtained would confirm the effective functioning of the planar parallel manipulator.

The path defined here consists of a vertical rise, a circular path with two different arcs followed by a ramp and a vertical drop and ending with a horizontal span thus reaching the starting point. The detailed time dependent task-space trajectory shown in Fig. 5(a).The initial velocity vector of the manipulator were set to zero and random values assigned.

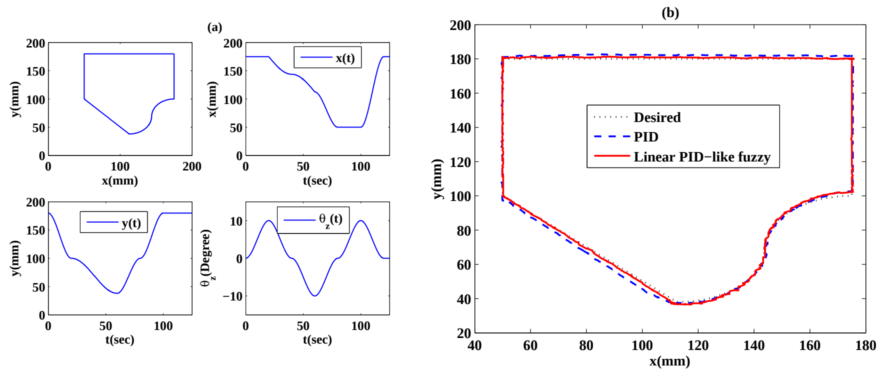

Figure 5: (a) Task-space trajectory (b) Task-space trajectories of the end-effector during complex trajectory tracking

4.2 Results and Discussions

The efficacy of the proposed controller is achieved from the numerical simulations and have been used as a reference for the real-time problems. Consideration of disturbances, parameter uncertainties and sensor noises have been included in the numerical model to ensure the usage of the proposed controller in real-time application without compromising either performance or effectiveness. To prove and validation of the proposed control scheme the same control scheme is used to real-time prototype experiment as shown in Fig. 2. to perform complex trajectory tracking operation. Comparison of the proposed control scheme is made with the conventional PID controller, given as follows:

$$\tau_c = N_P s + N_I \int s dt + N_D \frac{ds}{dt} \tag{13}$$

The results are obtained for the complex trajectory elucidated in Fig. 5(b), 6 and 7 and shows that proposed controller's performance are better and smooth as compared to conventional PID controller. The theoretical PID-like fuzzy logic controller gain values considered (for experiment purpose) as $K_c = 2I_3$,$K_1 = 2$,$K_2 = 3$,$K_e = 5I_3$,$N_P = 5$,$N_I = 0.01$,$N_D = 0.02$. Task-space and joint-space position errors are depicted in Fig. 6 and it can be observed that the proposed controller's performance is acceptable in terms of tracking errors. In the experimental results, oscillations are noticed in the task and joint-space errors which is in acceptable level. These oscillations can be easily removed by the application of high precise position sensor and suitable filtering technique which will increase the overall cost of the system. The norm of the joint position and task space errors depicted in Fig. 7, during the tracking trajectory for the clear understanding of the performance of the proposed control scheme used here. Fig.5(b), 6 and 7 shows that the proposed control scheme is in satisfactory level and tracking the trajectory with least errors.

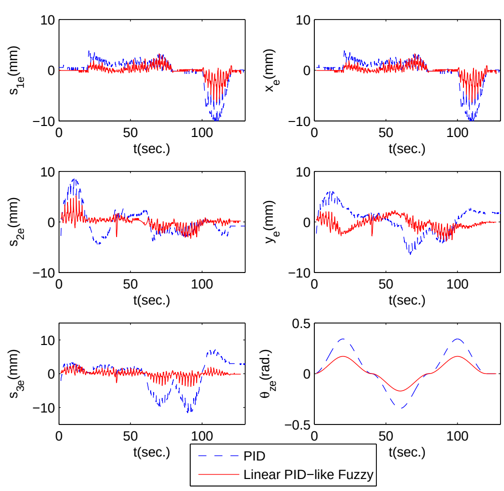

Figure 6: Linear time trajectories of the task joint-space and task-space position tracking errors

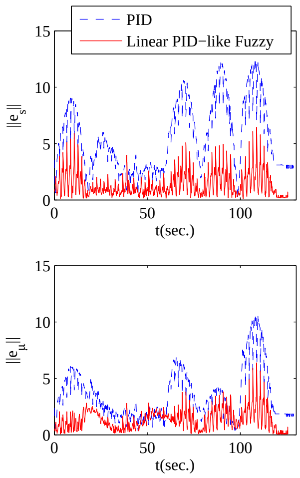

Figure 7: Time trajectories of the joint-space and task-space position tracking errors

5 Conclusion

In this paper, a robust linear PID-like fuzzy logic control scheme is designed and applied for a complex trajectory tracking in the task space control problem of the 3PPR U-base PPM (in house fabricated prototype). From the results, few of the points are observed and summarised as follows:

- Poor knowledge of the manipulator's model matrices like inertia, coriolis will be enough for designing and learning of the controller.
- Difficulties in tuning of controller gains are eliminated by using robust rule base structure of PID-like fuzzy controller.
- Linear PID-like fuzzy controller has the capability to work in the presence of disturbance and parameter uncertainty which has been proved in this paper, thus it is a robust controller.

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