Imperialist Competitive Algorithm Optimised Adaptive Neuro Fuzzy Controller for Hybrid Force Position Control of an Industrial Robot Manipulator: A Comparative Study

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ABSTRACT

Due to the nonlinear nature of the dynamics of a robot manipulator, controlling the robot meticulously is a challenging issue for control engineers. The key purpose of this paper is to provide an accurate intelligent method for refining the functionality of orthodox PID controller in the problem of force/position control of a robot manipulator with unspecified robot dynamics during external disturbances. A grouping of imperialist competitive algorithm (ICA) and adaptive neuro fuzzy logic is applied for the tuning of PID parameters. This, therefore, forms an intelligent structure, adaptive neuro fuzzy inference system with proportional derivative plus integral (ANFISPD + I) controller, which is more precise in definite and indefinite circumstances. To show the efficiency of the proposed method, this algorithm is applied to solve constrained dynamic force/position control problem of PUMA robot manipulator. The simulated results are compared to those achieved from other evolutionary techniques such as Genetic Algorithm (GA) and Particle Swarm Optimisation (PSO). The simulation results exhibit that ICA-based ANFISPD + I outperforms the other evolutionary techniques.

Highlights

- An ICA-ANFISPD + I-based hybrid force/position controller has been proposed.
- Easy to implement.
- Works well in the case of disturbances.
- Actuator Dynamics has been considered.
- External disturbances have been considered.
- Robot dynamics are unknown.

1. Introduction

Various researchers have contributed to implementations of the modified conservative PD control scheme which only requires the joint position measurement as input. Two types
of observers may be used in the above instance: the observers developed a recognised model and the observers developed an unidentified model. In the primary cases one has the information regarding the dynamics of a robot manipulator to a little scope. It was presumed that dynamics of robot manipulator was obtainable, if the adaptive observer [1] lacks knowledge of the parameters.

The observer is based on an unknown model means that no accurate learning of the robot is essential. Broadly acknowledged observers based on unknown models were presented in [2], which could approximate the velocity component from the actual output. To achieve the global asymptotic stability by integrating integral actions or computed feed forward, a PD control was proposed in [3]. A hybrid observer RBF neural network-based controller was offered in [4] which can not only approximate the joint velocities but also compensate the gravity and friction.

In many industrial applications, it is desired for the robot manipulator to exert a prescribed force normal to a given surface, while following a prescribed motion trajectory tangential to the surface. A Modified Hybrid Control scheme was presented in [5] which accomplished an accurate position and force control for a robot manipulator in joint space by specifying the desired compliance in Cartesian space. A neural network-based adaptive control scheme for hybrid force/position control for rigid robot manipulators is presented in [6]. Based on the decomposed robot dynamics into force, position and redundant joint subspaces, a neural network-based controller is proposed to learn the parametric uncertainties, existing in the dynamical model of the robot manipulator. A novel neuro-adaptive force/position tracking controller for a robotic manipulator, in compliant contact with a surface under non-parametric uncertainties, is proposed in [7] which assumes structural uncertainties to characterise the compliance and surface friction models, as well as the robot dynamic model.

The problem of the configuration-dependent dynamics of the manipulator in constrained motion was dealt in [8] with the implementation of a hybrid force/velocity control for contour tracking tasks of unknown objects performed by industrial robot manipulators. An augmented hybrid impedance force/position control scheme is developed and presented in [9] for a redundant robot manipulator. The outer loop controller improves transient performance, while the inner loop controller consists of a Cartesian-level potential difference controller, a redundancy resolution scheme at the acceleration level and a joint-space inverse dynamic controller. A hybrid adaptive fuzzy control approach-based position/force control of robot manipulators is proposed in [10] to solve the overwhelming complexity of the deburring process and imprecise knowledge about robot manipulators. A fuzzy neural network-based position/force control, which enables the controller to deal efficiently with force sensor signals, was presented in [11], which includes noise and/or unknown vibrations caused by the working tool, to search the direction of the constraint surface of an unknown object.

There are many theoretical and practical hurdles, which are still unachievable, because of unspecified robot manipulator dynamics and environmental complexities. Standard approaches are appropriate when one has the precise mathematical modelling of all the fundamental and vital parameters that are available. On the other hand, most of the time one has to work in real environment where the dynamic model and external environmental variables are unidentified [12]. Conventional controllers, such as PD and PI alone, do not perform well in the case of removing steady state error and enhancing the transient response.
Recently, for achieving high robustness opposed to noise and to unravel the nonlinear control snag, some of the hybrid intelligent type fuzzy proportional integral derivative (FPID) controller techniques have been combined with conventional techniques and presented in [13–18], which illustrates the improved steady state and transient response.

Optimisation provides the possibility to easily handle redundant mechanisms, to assign the degrees of freedom of the robot to multiple and possibly concurrent tasks, to enforce hard constraints corresponding to physical limitations, etc., to name just a few. Optimisation is used in numerous schemes for generalised inverse kinematics, linear and non-linear control, direct and inverse optimal control, trajectory optimisation, planning, etc., with already impressive achievements. There are many optimisation algorithms and numerous ways to formulate a robotic problem.

In the present paper, an ICA-based optimised hybrid force/position control approach is proposed for trajectory control of robot manipulator, which works well in the absence of anonymous dynamics of a robot manipulator in a constraint environment. The constraint has been taken in joint space by restricting the manipulator to move in the Z direction. The proposed ICA-ANFISPD + I force/position controller follows the trajectory exceptionally smoothly with bare minimum error.

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Section 2 establishes the actuator dynamic model for the n degrees of freedom (DOF) robot manipulator. The force/position control followed by ICA optimisation technique has been discussed in Section 3. Section 4 presents controller performance criteria used to statistically demonstrate the validity of ANFISPD + I controller with discussed optimisation techniques. Simulation outcomes to reveal the efficiency of the controller with various optimisation techniques are discussed in Section 5, followed by conclusions in Section 6.

2. Dynamics of Robot Manipulator

First, the traditional dynamic model of an n DOF robot manipulator is presumed to be in the subsequent form [19]

\[ M(q)\ddot{q} + V_m(q, \dot{q})\dot{q} + G(q) + F(\dot{q}) = \tau \]  

(1)

where \( M(q) \in R^{nxn} \) represents the inertia matrix, \( V_m(q, \dot{q}) \in R^{nxn} \) represents the centripetal-Coriolis matrix, \( G(q) \in R^n \) represents the gravity effects, \( F(\dot{q}) \in R^n \) denotes the friction effects, \( \tau(t) \in R^n \) signifies the torque input control vector and \( q(t), \dot{q}(t), \ddot{q}(t) \in R^n \) signify link position, velocity and acceleration, respectively. The actuator dynamics for a robot manipulator may be written as [19]

\[ M'(q)\ddot{q} + V'_m(q, \dot{q})\dot{q} + G'(q) + F'(\dot{q}) = K'v \]  

(2)

where

\[ M'(q) = (J_M + R^2 M); V'_m(q, \dot{q}) = (B_M + R^2 V_m); \]

\[ G'(q) = R^2 G; F'(\dot{q}) = (RF_M + R^2 F); \]

\[ K_M = \begin{bmatrix} \frac{K_{Mi}}{R_{d1}} & 0 \\ 0 & \frac{K_{Mi}}{R_{d1}} \end{bmatrix}; R = \begin{bmatrix} r_i & 0 \\ 0 & r_i \end{bmatrix}; \]
\[
B = \begin{bmatrix}
(B_{Mi} + \frac{K_{bi}K_{Mi}}{R_{ai}}) & 0 \\
0 & (B_{Mi} + \frac{K_{bi}K_{Mi}}{R_{ai}})
\end{bmatrix};
\]

\[
K' = RK_{Mi}; J_M = \begin{bmatrix}
J_{Mi} & 0 \\
0 & J_{Mi}
\end{bmatrix};
\]

where \( v \in \mathbb{R}^n \) is the control input motor voltage, \( q_M = \text{vec}(q_{Mi}) \in \mathbb{R}^n \) with \( q_{Mi} \) is the \( i \)th rotor angle, \( J_M \) is the motor inertia, \( B_{Mi} \) is the rotor damping constant, \( F_{M} \) is the actuator friction, \( R_{ai} \) is the armature resistance, \( K_{Mi} \) is a torque constant, \( K_{bi} \) is a back emf constant and \( J_{Mi} \) is the motor inertia of the \( i \)th motor. \( r_i \) is the gear ratio of the coupling.

or
\[
q_i = r_i q_{Mi}; q = Rq_M
\]

where \( r_i \) is a constant less than 1 if \( q_i \) is revolute, else unit of m/rad if \( q_i \) is prismatic.

After including nonlinear unmodelled disturbances, Equation (2) can be rewritten as

\[
M'(q)\ddot{q} + V'_m(q, \dot{q}) + G'(q) + F'(\dot{q}) + \tau_d = K'v
\]

\[
M'(q)\ddot{q} + N'(q, \dot{q}) + \tau_d = K'v = \tau'
\]

3. Intelligent ANFISPD + I Force/Position Controller Design

An optimised hybrid ANFISPD + I force/position controller, applied to six DOF PUMA robot arm, has been shown in Figure 1. The controller applied has two inputs and a single output (TISO) structure. The inputs used are position error (\( e \)) and velocity error (\( \dot{e} \)). The integral error (\( e_i \)) has been used simply to perform orthodox integral action.

3.1. Force/Position Control

The dynamic model of an \( n \) DOF robot manipulator with environmental contact on a prescribed surface is presumed to be in the subsequent form [19]

\[
M'(q)\ddot{q} + V'_m(q, \dot{q}) + G'(q) + F'(\dot{q}) + \tau_d = \tau' + J^T(q)\lambda
\]

where \( q(t) \in \mathbb{R}^n \), \( J(q) \) is a Jacobian matrix associated with the contact surface geometry, and \( \lambda \) is a vector of contact forces exerted normal to the surface described to the surface. The constraint surface for robot manipulator is considered in the \( Z \) direction in joint space. The Jacobian matrix is

\[
J(q) = \frac{\partial Z}{\partial q}
\]

The constraint equation reduces the number of degree of freedom to

\[
n_1 = n - m
\]

To find the constraint motion along the \( Z \) direction, the reduced order dynamics for robot manipulator is

\[
M'(q_1)L(q_1)\ddot{q}_1 + V'_m(q_1, \dot{q}_1)\dot{q}_1 + F'(\dot{q}_1) + G'(q_1) + \tau_d = \tau' + J^T(q_1)\lambda
\]
Figure 1. Complete block diagram for intelligent ANFISPD + I hybrid force/position controller.

where \( q_1(t) \in \mathbb{R}^{n_1} \), \( L(q_1) \) is an extended Jacobian matrix given by

\[
L(q_1) = \begin{bmatrix} \ln_1 \\ \frac{\partial Z}{\partial q_1} \end{bmatrix}
\]

(11)

The reduced order dynamics describing the motion in the plane of constraint surface is

\[
\ddot{M}q_1 + \dot{V}_1 \dot{q}_1 + \ddot{F} + \ddot{G} + \ddot{\tau}_d = \ddot{\tau}
\]

(12)

where

\[
\ddot{M} = L^T M'(q_1) L; \quad \dot{V}_1 = V_1(q_1, \dot{q}_1); L^T = L^T(V'_m L + M'(q_1) \dot{L}); \\
\ddot{F} = L^T F'; \quad \ddot{G} = L^T G'; \quad \ddot{\tau}_d = L^T \tau_d; \quad \ddot{\tau} = L^T \tau'
\]

As

\[
J(q_1) L(q_1) = 0
\]

(13)

The suppositions and the necessary properties of the model given in Equation (6) utilised in the proposed controller development are given as

Property 1: The inertia matrix \( \ddot{M}(q_1) \) is positive definite symmetric and bounded above and below.

Property 2: The matrix \( (\ddot{M}(q_1) - 2\ddot{V}_1(q_1, \dot{q}_1)) \) is skew symmetric.

Property 3: \( \| \ddot{F}(\dot{q}_1) \| = a + b \| \dot{q}_1 \| \) for some unknown positive constants \( a, b \).

Property 4: \( \| \ddot{\tau}_d \| \leq c \) for some unknown positive constants \( c \).
The joint space constraint by restricting the manipulator to move in the $Z$ direction is given.

$$Z = 0 = -d_4 c_{23} + a_3 s_{23} + a_2 s_2$$  \hspace{1cm} (14)

$$\theta_2 = a \tan 2(\pm \sqrt{a^2 + b^2 - c^2}, c) - a \tan 2(b, a)$$  \hspace{1cm} (15)

$$a = a_3 s_3 - d_4 c_3$$
$$b = a_2 + a_3 c_3 + d_4 s_3$$
$$c = Z = 0$$  \hspace{1cm} (16)

$$\theta_2 = a \tan 2(\pm \sqrt{(a_3 s_3 - d_4 c_3)^2 + (a_2 + a_3 c_3 + d_4 s_3)^2 - (0)^2}, 0)$$
$$- a \tan 2((a_2 + a_3 c_3 + d_4 s_3), (a_3 s_3 - d_4 c_3))$$  \hspace{1cm} (17)

The Jacobian is

$$J(q) = \frac{\partial Z}{\partial q} = \begin{bmatrix}
0 & (d_4 s_{23} + a_3 c_{23} + a_2 c_2) & (d_4 s_{23} + a_3 c_{23}) & 0 & 0 & 0
\end{bmatrix}$$  \hspace{1cm} (18)

3.2. ANFISPD + I Force/Position Controller

It combines the learning capabilities of neural networks with the processing power of fuzzy logic. Jang [20] proposed and explained the use of ANFIS for solving a fuzzy inference system under consideration having two inputs ($x$ and $y$) and one output $z$, which contains the rule base of two fuzzy if–then rules as

Rule 1: If $x$ is $A_1$ and $y$ is $B_1$, then $f_1 = p_1 x + q_1 y + r_1$
Rule 2: If $x$ is $A_2$ and $y$ is $B_2$, then $f_2 = p_2 x + q_2 y + r_2$

During the training of the network, the input is propagated layer by layer in forward direction, while the error is propagated in backward direction. In layer 1, the membership function is applied on premise parameters. To show the firing strength, layer 2 multiplies the incoming signals. Layer 3 calculates the firing strength of the signals received and forwards it to layer 4, which calculates an adaptive output for giving them as input to the layer 5, which computes the overall output.

The procedural equations used at different layers are given in the flowchart, as shown in Figure 2. Then the output of the hybrid ANFISPD + I force/position controller is, therefore,

$$u(t) = [L_i^5 + K_i \int_0^t e_m(t) dt] * K_u$$  \hspace{1cm} (19)

Here $L_i^5$ is the output ANFISPD controller.

$$\bar{\tau} = u(t) - J^T(q)[\lambda_d + K_f \lambda]$$  \hspace{1cm} (20)

3.3. Objective Function

The scalar valued $L^2$ norm, for an entire error curve, is used as a performance index to match the performance of all controllers. The root mean square (RMS) average of the trajectory
errors, measured by the $L^2$ norm measures, is given by \[ (21) \]

where $t_0, t_f \in R^+$ represents the first and last values of times, respectively. The RMS error value are 0.0125, 0.0159 and 0.0255 in the case of ICA-ANFISPD + I, PSO-ANFISPD + I and GA-ANFISPD + I controllers, respectively. A lesser $L^2(e)$ value shows that, the controller is
performing better because of the lesser tracking error, which is for the ICA-ANFISPDL + I in this case.

A brief overview of ICA is discussed in the next section.

3.4. Imperialist Competitive Algorithm (ICA)

Imperialist competitive algorithm (ICA), a new population-based stochastic search algorithm inspired by imperialistic competition, was originally proposed by Atashpaz Garighari and Lucas [22,23]. In ICA, the countries can be viewed as population individuals and divided into two groups based on their power, i.e. colonies and imperialists. Also, one empire is formed by one imperialist with its colonies. Furthermore, two operators called assimilation and revolution and one strategy called imperialistic competition are the main building blocks that are employed in ICA.

The main framework of ICA consists of eight steps: generating the initial empire, assimilation, revolution, exchanging positions of the imperialist and a colony, total power of an empire, imperialistic competition, eliminating the powerless empires and convergence. We describe the steps in detail in the following subsections.

Imperialism is the standpoint of developing power and control by a government to further increase its own territory. A country may rule others out by either direct control or less obvious means such as a control of markets for goods or raw materials which is the so-called neocolonialism [24]. Imperialist Competitive Algorithm (ICA) is a new global heuristic and initiative search that utilises imperialism and imperialistic contest process as an origin of inspiration. The hierarchical steps of ICA are as follows:

1. Select some random points on the function and initialise the empires.

   To begin the ICA, initial population is randomly created and then objective function for all solutions is computed. The most powerful countries (Nimp) are selected as imperialists and the remaining Ncol of the population are colonies that should be assigned to the imperialist. The colonies distribute among the imperialists with respect to their power.

2. Move the colonies towards their relevant imperialist.

   After all colonies among imperialists are distributed and the initial empires are created, the assimilation policy should be executed. According to this policy, all the colonies move and get closer to their relevant imperialist based on various socio-political axes (e.g. the culture, language and economic policy).

3. If there is a colony in an empire which is dominating its relevant imperialist, exchange the positions of that colony and the imperialist.

   Revolution is a powerful strategy that increases the power exploration of the algorithm and helps in escaping from local minimums. This strategy is similar to the mutation process in GA to create diversification in solutions. The probability of revolution in ICA illustrates the percentage of colonies that randomly change their position. After applying revolution, numbers of colonies may reach to a better position (i.e. lower cost) in comparison with their imperialist. In such cases, the colony in each empire moves to the position of that imperialist. This process avoids the optimisation process getting stuck at locally optimal values.
(4) Compute the total cost of all empires (related to the power of both imperialist and its colonies).

The total power of an empire is defined as summation of imperialist power and a percentage of the mean power of its colonies.

(5) Pick the weakest colony from the weakest empire and give it to the stronger empire.

Imperialistic competition is a key process in ICA framework in which all empires attempt to take over the possession of colonies from other empires and also control them. This event causes to reduce the power of weaker empires, while powerful empires tend to increase their powers. This strategy is formulated by choosing the poorest colony of the poorest empire and making a competition among all empires to possess these colonies.

(6) Eliminate the powerless empires.

When powerless empires lose all their colonies, they will collapse in the imperialistic competition and their colonies are consequently divided among other empires.

(7) If there is more than one empire, go to 2, if not stopped.

The ICA is stopped when there is just one empire and all colonies are under the control of that empire.

The implementation procedure is shown in Figure 3.

In this paper, the applied methodology chooses the best values for these deterministic coefficients by utilising the Imperialist Competitive Algorithm (ICA). This algorithm optimises the $18 (K_{P(6X1)}, K_{D(6X1)}, K_{I(6X1)})$ PID parameters in order to determine the appropriate values for them. In the ICA algorithm, the root mean square error is used to calculate the minimum cost function for each decade. The ICA is initialised by 50 initial countries, and 8 initial imperialist countries, 100 iterations and the revolution rate is equal to 0.3.

The effectiveness of the proposed controller ANFISPD + I force position controller is evaluated using performance criteria discussed in the next session (Table 1).
Table 1. Performance metrics and their formulas.

| Metrics | Formulas |
|---------|----------|
| NMSE    | \( \frac{1}{T^n} \sum_{i=1}^{n} (q_{di} - q_{pi})^2 \) |
| MAPE    | \( \frac{\sum_{i=1}^{n} |q_{di} - q_{pi}|}{q_{di}} \times 100\% \) |

\( q_{di} \) and \( q_{pi} \) are the desired and predicted joint angle values.

Table 2. PID gain parameters.

| Sr. No. | ICA-ANFISPD + I | PSO-ANFISPD + I | GA-ANFISPD + I |
|---------|----------------|----------------|----------------|
|         | \( K_P \) | \( K_D \) | \( K_I \) | \( K_P \) | \( K_D \) | \( K_I \) | \( K_P \) | \( K_D \) | \( K_I \) |
| 1.      | 2.04 | 0.78 | 0.10 | 7.16 | 4.46 | 0.76 | 9.44 | 30.00 | 1.82 |
| 2.      | 0.98 | 2.78 | 0.10 | 2.62 | 13.26 | 0.29 | 30.00 | 30.00 | 2.81 |
| 3.      | 4.57 | 1.77 | 0.10 | 6.44 | 1.93 | 0.68 | 6.68 | 30.00 | 0.80 |
| 4.      | 4.81 | 0.26 | 0.10 | 8.83 | 3.31 | 1.28 | 9.84 | 30.00 | 2.64 |
| 5.      | 7.31 | 0.77 | 1.59 | 12.22 | 4.98 | 1.75 | 30.00 | 30.00 | 2.35 |
| 6.      | 5.59 | 0.93 | 0.92 | 8.47 | 3.55 | 1.82 | 29.91 | 30.00 | 7.82 |

4. Controller Performance Criteria

The performance of discussed hybrid force/position controller has been evaluated statically using

1. Normalised Mean Square Error (NMSE)
2. Mean Absolute Percentage Error (MAPE)

Table 2 shows these performance indices and their expressions to measure the deviation between the actual and predicted values. The smaller the values of NMSE and MAPE, the closer are the predicted values to the actual values.

5. Simulations and Results

For showing the efficiency of the suggested ICA-ANFISPD + I controller over PSO-ANFISFPD + I, and GA-ANFISPD + I controller, the simulation has been performed for a six DOF PUMA robot manipulator using MATLAB 2012b by considering the PUMA-560 robot manipulator dynamics from [24]. The friction term and the gravity term and external disturbances taken are as follows:

\[
G = \begin{bmatrix}
0 \\
-37.196 \cos(t^2) - 8.445 \sin(t^2 + t^3) + 1.023 \sin(t^2)
\end{bmatrix}
\begin{bmatrix}
0.248 \cos(t^2 + t^3) \cos(t^4) \sin(t^5) + \sin(t^2 + t^3)
0.028 \sin(t^2 - t^3) \sin(t^4) \sin(t^5)
0.028[\cos(t^2 - t^3) \sin(t^5)] + [\sin(t^2 - t^3) \cos(t^4 - t^5)]
\end{bmatrix}
\]
\[ \tau_{dc} = \begin{bmatrix} q \sin(3t) + \dot{q} & 0.5q \sin(2qt^2) + 1.2qt^2 & 1.2q \sin(t^3) + 0.8qt^3 & 0 & 0 & 0 \end{bmatrix}^T \]
\[ \tau_{dd} = \begin{bmatrix} 0.2\dot{q} \sin(t) & 0.1\dot{q} \sin(t^2) & 0.1\dot{q} \sin(t^3) & 0 & 0 & 0 \end{bmatrix}^T \]
\[ F_c = \begin{bmatrix} 10 & 5 & 2 & 0 & 0 \end{bmatrix}^T \]
\[
F_d = \begin{bmatrix}
2 \times \text{Random Waveform Generated of } (\pi \times t) \text{ Sample Size} \\
2 \times \text{Random Waveform Generated of } (\pi \times t) \text{ Sample Size} \\
2 \times \text{Random Waveform Generated of } (\pi \times t) \text{ Sample Size} \\
2 \times \text{Random Waveform Generated of } (\pi \times t) \text{ Sample Size} \\
2 \times \text{Random Waveform Generated of } (\pi \times t) \text{ Sample Size} \\
2 \times \text{Random Waveform Generated of } (\pi \times t) \text{ Sample Size}
\end{bmatrix}
\]

where \( \tau_d = \tau_{dc} + \tau_{dd} \); \( F = F_c + F_d \).

The actuator parameters are
\[ K_{bi} = K_{Mi} = [0.189 \ 0.219 \ 0.202 \ 0.075 \ 0.066 \ 0.066] \]
\[ L_a^{-1} = 1000; \ R_{ai} = [2.1 \ 2.1 \ 2.1 \ 6.7 \ 6.7 \ 6.7] \]

Gear Ratio = [62.61 \ 107.36 \ 53.69 \ 76.01 \ 71.91 \ 76.73]

The desired force is \( \lambda_d = 20 \text{ nt} \).

The PID gain parameters, calculated with the help of various optimisation techniques, are given in Table 2.

The lower bound and upper bound values are 0.1 and 30, respectively, for the optimisation process in all cases.

To test the feasibility of the proposed controller tuned with ICA, PSO as well as GA optimisation techniques, the following four cases have been considered to study the simulation results:

1. **C (Complete Dynamics):** In this, we developed all the controllers based on Equation (12), which represents the complete dynamical system including actuator dynamics.

2. **WF (Dynamics without friction):** In this, we developed all the controllers based on Equation (12), which represents the complete dynamical system including actuator dynamics. The only difference with the first case is that friction term is absent.

3. **WG (Dynamics without gravity):** In this, we have designed the controllers based on a modified version of Equation (12), which lacks gravity term in it only.

4. **WTAU (Dynamics without external disturbances):** In this case, controllers are developed on a modified dynamic model based on Equation (12). The only difference from the first case is the absence of external disturbances.

The simulation experiments were conducted for 5s, 10s and 15s to study the performance of the proposed ICA-ANFISPD + I controller with PSO-ANFISPD + I and GA-ANFISPD + I controllers. The two desired trajectories taken are: (1) \( \sin(t) \) (2) \( 0.15\cos((\pi/2)t) \), for which the whole data have been recorded. Dissimilar trajectories and dissimilar robot parameters have been employed to get 18 observations. The performance of all the
The ANFISPD + I controller with ICA, PSO and GA optimisation techniques can be checked through their output responses also, which are shown in Figures 4–8. The controller tuned with ICA optimisation technique is able to deal with the continuous and discontinuous frictions, gravity and other external disturbances, while successfully following the desired trajectory with minimum errors.

The NMSE and MAPE values of path errors for joint angles, q1 to q6 except q2, are calculated for each experiment, but due to space limitation, results are discussed for 10 s only, as given in Tables 3–7.

Tables 3–7 show that the performance index of the ANFISPD + I controller is better with the ICA optimisation technique rather than PSO and GA optimisation techniques. The force tracking error response of ANFISPD + I controller with various optimisation techniques mentioned above is shown in Figures 9–11.
In Figure 9, the force error signal is settled down to zero after 0.028 s and the maximum and minimum overshoot is 0.0295 pu and $-0.015$ pu, whereas in Figure 10, it is 0.39 and $-0.04$, respectively. The maximum and minimum overshoot in Figure 11 is 0.39 pu and $-0.04$, respectively. The settling time in the case of all three controllers is 0.028, 0.053 and 0.089 s approximately. The mean square errors of joint force error signal are $3.87e-08$, $4.95e-05$ and $0.0423$ for ICA-ANFISPD + I, PSO-ANFISPD + I and GA-ANFISPD + I controller,
Table 4. Performance Index for q1 (10 s).

| Controller        | MAPE | NMSE |
|-------------------|------|------|
|                   | C    | WF   | WG   | WTAU | C    | WF   | WG   | WTAU |
| GA-ANFISPD + I    | 1.21E-06 | 1.20E-06 | 1.29E-06 | 1.72E-05 | 1.98E-07 | 1.91E-07 | 1.98E-07 | 1.19E-07 |
| PSO-ANFISPD + I   | 1.21E-06 | 1.22E-06 | 1.31E-06 | 1.75E-05 | 1.59E-05 | 1.62E-05 | 1.34E-06 |
| ICA-ANFISPD + I   | 1.21E-06 | 1.22E-06 | 1.31E-06 | 1.75E-05 | 1.59E-05 | 1.62E-05 | 1.34E-06 |

Table 5. Performance Index for q3 (10 s).

| Controller        | NMSE | MAPE |
|-------------------|------|------|
|                   | C    | WF   | WG   | WTAU | C    | WF   | WG   | WTAU |
| GA-ANFISPD + I    | 1.45E-06 | 1.45E-06 | 3.27E-06 | 1.75E-06 | 1.98E-07 | 1.91E-07 | 1.98E-07 | 1.19E-07 |
| PSO-ANFISPD + I   | 1.45E-06 | 1.45E-06 | 3.27E-06 | 1.75E-06 | 1.98E-07 | 1.91E-07 | 1.98E-07 | 1.19E-07 |
| ICA-ANFISPD + I   | 1.45E-06 | 1.45E-06 | 3.27E-06 | 1.75E-06 | 1.98E-07 | 1.91E-07 | 1.98E-07 | 1.19E-07 |

Table 6. Performance Index for q4 (10 s).

| Controller        | NMSE | MAPE |
|-------------------|------|------|
|                   | C    | WF   | WG   | WTAU | C    | WF   | WG   | WTAU |
| GA-ANFISPD + I    | 2.46E-06 | 2.46E-06 | 2.45E-06 | 2.32E-05 | 2.34E-05 | 2.40E-07 | 2.30E-07 | 2.36E-07 |
| PSO-ANFISPD + I   | 2.46E-06 | 2.46E-06 | 2.45E-06 | 2.32E-07 | 2.34E-05 | 2.40E-07 | 2.30E-07 | 2.36E-07 |
| ICA-ANFISPD + I   | 2.46E-06 | 2.46E-06 | 2.45E-06 | 2.32E-07 | 2.34E-05 | 2.40E-07 | 2.30E-07 | 2.36E-07 |

Table 7. Performance Index for q5 (10 s).

| Controller        | NMSE | MAPE |
|-------------------|------|------|
|                   | C    | WF   | WG   | WTAU | C    | WF   | WG   | WTAU |
| GA-ANFISPD + I    | 2.81E-06 | 2.80E-06 | 2.71E-06 | 2.30E-07 | 1.44E-06 | 1.44E-06 | 1.50E-06 |
| PSO-ANFISPD + I   | 2.83E-06 | 2.84E-06 | 2.76E-06 | 2.33E-07 | 1.39E-05 | 1.39E-05 | 1.38E-05 |
| ICA-ANFISPD + I   | 2.87E-06 | 2.87E-06 | 2.78E-06 | 2.46E-07 | 2.85E-05 | 2.87E-05 | 2.90E-05 |

Figure 9. ICA-based ANFISPD + I controller joint force error.

respectively. The fitness values found after optimisation process are 0.0125, 0.0159 and 0.0255 for ICA-ANFISPD + I, PSO-ANFISPD + I and GA-ANFISPD + I controller, respectively (Table 8).

Table 8. Performance Index for q6 (10 s).

| Controller        | NMSE | MAPE |
|-------------------|------|------|
|                   | C    | WF   | WG   | WTAU | C    | WF   | WG   | WTAU |
| GA-ANFISPD + I    | 3.52E-06 | 3.52E-06 | 3.52E-06 | 2.51E-05 | 3.87E-05 | 3.79E-05 |
| PSO-ANFISPD + I   | 3.50E-06 | 3.51E-06 | 3.51E-06 | 2.58E-06 | 2.52E-05 | 2.49E-05 |
| ICA-ANFISPD + I   | 3.58E-06 | 3.57E-06 | 3.57E-06 | 2.48E-06 | 1.10E-06 | 1.41E-05 | 1.41E-05 |
6. Conclusions

A hybrid ICA-ANFISPD + I force/position controller has been proposed for the trajectory control of a robot manipulator arm with unspecified robot dynamics. Various optimisation techniques have been applied to estimate the unknown parameters of the said controller. The fitness value for the proposed hybrid ICA-ANFISPD + I force/position controller is minimum. In order to know the controller performance, it was subjected to different tests with or without external disturbances in real constraint environment. The system performance of PUMA 560 robot manipulator has been investigated extensively through simulation outcomes for trajectory control and the force exerted by the manipulator on the surface. It has been demonstrated, via simulations, that the proposed model yields good results for handling uncertain dynamics while following the desired trajectory.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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