

Fusion of Fuzzy Logic and PD Control for a Five-Fingered Smart Prosthetic Hand

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Abstract—A hybrid of soft control technique of adaptive neuro-fuzzy inference system (ANFIS) and fuzzy logic (FL) and hard control technique of proportional-derivative (PD) for a five-fingered, smart prosthetic hand is presented. The ANFIS is used for inverse kinematics and FL is used for tuning the PD parameters with two input layers (error and error change) using 7 triangular membership functions and 49 fuzzy logic rules. Simulation results with FL-tuned PD controller exhibit superior performance compared to the PD and PID control alone.

Index Terms—Prosthetic Hand, Fuzzy Logic, PD Control, Adaptive Neuro-Fuzzy Inference System, Hybrid Control

I. INTRODUCTION

During the recent wars in Afghanistan and Iraq, “at least 251,102 people have been killed and 532,715 people have been seriously wounded” [1]. Further, in the United States, the Amputee Coalition of America (ACA) [2] reports that there are approximately 1.9 million people living with limb loss, due to combat operations (such as conflicts, wars etc.), and non-combat operations such as accidents, or birth defects. According to a study of the 1996 National Health Interview Survey (NHIS) published by Vital and Health Statistics [3], it is estimated that one out of every 200 people in the U.S. has had an amputation. In other words, about one in every 2,000 new born babies will have limb deficiency and over 3,000 people lose a limb every week in America. By the year 2050, the projected number of Americans living with limb amputation will become 3.6 million [4]. In the past several decades, prosthetic hands have been developed by various researchers in the field [5]–[9], but reproducing the human hand in all its various functions, appearance, visibility, and weight is still a challenging task [5].

Hard computing/control (HC) techniques are used at lower levels for accuracy, precision, stability and robustness. HC comprises proportional-derivative (PD) control [10], proportional-integral-derivative (PID) control [11], [12], optimal control [12]–[15], adaptive control [16]–[19] etc. with specific applications to prosthetic devices. However, our previous works [10]–[12], [20] for a smart prosthetic hand showed that PID controller resulted in overshooting and oscillation.

Soft computing (SC) or computational intelligence (CI) [21] is an emerging field based on synergy and seamless integration of neural networks (NN), fuzzy logic (FL) and optimization methods, such as genetic algorithms (GA), particle swarm (PS) [10], [22], [23], tabu search (TS) [23] and so on. The methodology based on SC can be used, in particular with FL, at upper levels of the overall mission where human involvement and decision making is of primary importance, whereas the HC can be used at lower levels for accuracy, precision, stability and robustness. Hence, we present the integration of SC and HC to solve problems that cannot be solved satisfactorily by using either HC or SC methodology alone with specific applications to prosthetics.

In this paper, we first consider briefly trajectory planning and kinematics problems associated with a five-fingered prosthetic hand. Then, adaptive neuro-fuzzy inference system (ANFIS) is used to solve inverse kinematics problem for three-link fingers (index, middle, ring, and little). Next, the dynamics of the hand is derived and feedback linearization technique is used to obtain *linear* tracking error dynamics. Then we propose the fuzzy logic-based PD (hybrid) controller, which uses fuzzy logic with 7 triangular membership functions in each input/output layer and 49 logic rules to tune PD gain parameters. The resulting overall hybrid system incorporating both soft and hard control techniques is simulated with practical data for the hand and found the performance to be superior to PD or PID alone. Finally, we provide conclusions and future work.

II. MODELING

A. Trajectory Planning and Kinematics

The trajectory planning using cubic polynomial was discussed in our previous work [10], [11], [14], [18], [19], [24] for a two-fingered (thumb and index finger) smart prosthetic hand.

Kinematics is the study of geometry in motion and is restricted to a natural geometrical description of motion by

the manners, including positions, orientations, and their derivatives (velocities and accelerations) [25], [26]. Forward and inverse kinematics of articulated systems study the analytical relationship between the angular positions of joints and the positions and orientations of the fingertips. A desired trajectory is usually specified in *Cartesian* space and the trajectory controller is easily performed in the *joint* space. Therefore, conversion of Cartesian trajectory planning to the joint space [26] is necessary. Using inverse kinematics, the joint angular positions of each finger need to be obtained from the known fingertip positions. Then the angular velocities and angular accelerations of joints can be obtained from the linear and angular velocities and accelerations of fingertips by differential kinematics. The inverse and differential kinematics of two-link thumb and three-link fingers were discussed in our previous publications [10], [11], [14], [18], [19], [24] for a two-fingered (thumb and index finger) smart prosthetic hand.

For five fingers shown in Figure 1, X^G , Y^G , and Z^G are

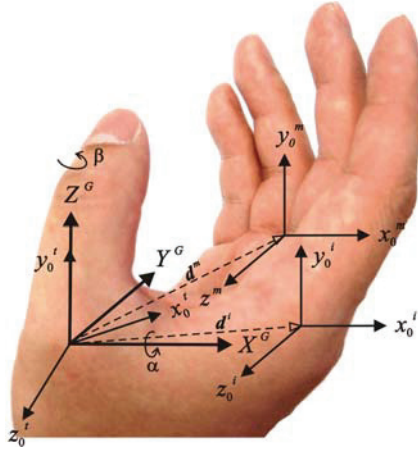


Fig. 1. Relationship between Global Coordinate and Local Coordinates: Local coordinate x^t - y^t - z^t of thumb can be reached by rotating through angles α and β to X^G and Y^G of global coordinate, subsequently. Local coordinate x^i - y^i - z^i of index finger can be obtained by rotating through angle α to X^G and then translating a vector $\mathbf{d}^i$ of the global coordinate.

the three axes of global coordinate. Local coordinate x^t - y^t - z^t of thumb can be reached by rotating through angles α and β to X^G and Y^G of the global coordinate, subsequently. Local coordinate x^i - y^i - z^i of index finger can be obtained by rotating through angle α to X^G and then translating a vector $\mathbf{d}^i$ of the global coordinate; similarly, the local coordinate x^j - y^j - z^j of middle finger ($j = m$), ring finger ($j = r$), and little finger ($j = l$) can be obtained by rotating through angle α to X^G and then translating the vector $\mathbf{d}^j$ ($j = m, r$ and l) of the global coordinate.

B. Adaptive Neuro-Fuzzy Inference System (ANFIS)

The inverse kinematics problems can be solved by using adaptive neuro-fuzzy inference system (ANFIS) method [27] where the input of fuzzy-neuro system is the Cartesian space and the output is the joint space. ANFIS is a fuzzy inference system implemented in the framework of adaptive

networks which provides the best optimization algorithm to find parameters in order to fit the data. ANFIS includes *premise parameters*, that defines membership functions, and *consequent parameters*, that defines the coefficients of each output equation. ANFIS tunes the membership function and identifies the coefficients by the backpropagation gradient descent and least-squares methods, respectively. ANFIS uses a hybrid learning algorithm to identify parameters of Sugeno-type fuzzy inference systems for fuzzy modeling procedures to learn information about a data set in order to compute the membership function and track the given input/output data. Figure 2 (a) shows a two input first-order Sugeno fuzzy model with two rules and Figure 2 (b) depicts the equivalent ANFIS structure for all the computation below. Sugeno-type fuzzy

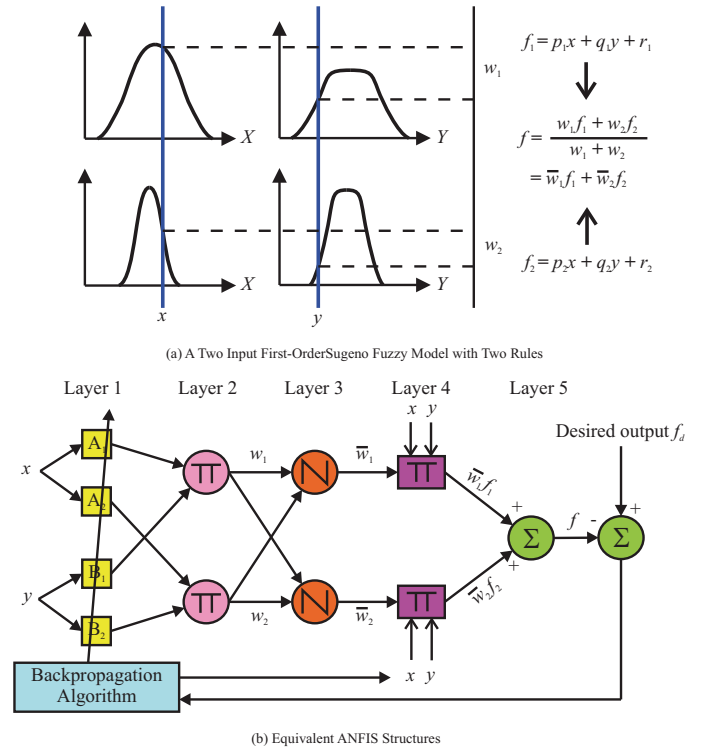


Fig. 2. ANFIS Architecture: (a) A Two Input First-Order Sugeno Fuzzy Model with Two Rules (b) Equivalent ANFIS Structure [27]. The inverse kinematics problems are solved by using adaptive neuro-fuzzy inference system (ANFIS) method where the input of fuzzy-neuro system is the Cartesian space and the output is the joint space. ANFIS is a fuzzy inference system implemented in the framework of adaptive networks which provides the best optimization algorithm to find parameters in order to fit the data.

system has the following **Rule Base** [27]–[31].

If x is A_1 and y is B_1 , then $f_1 = p_1x + q_1y + r_1$.

If x is A_2 and y is B_2 , then $f_2 = p_2x + q_2y + r_2$.

Here, x and y are inputs to constitute the premise parameters A_1, A_2, B_1 , and B_2 (Layer 1 in Figure 2 (b)). p_i, q_i , and r_i ($i = 1, 2$) are the consequent parameters. We evaluate the rules by choosing *product* Π for T-Norm (Layers 2 and 3) which results in

$$w_i = \mu_{A_i}(x) \mu_{B_i}(y), \quad i = 1, 2. \quad (1)$$

Here, $\mu_{A_i}(x)$ and $\mu_{B_i}(y)$ are designed fuzzy membership functions. Now after leaving the arguments (Layer 4), we get the output $f(x, y)$ by **Rule Consequences**.

$$f(x, y) = \frac{w_1(x, y)f_1(x, y) + w_2(x, y)f_2(x, y)}{w_1(x, y) + w_2(x, y)}. \quad (2)$$

f (Layer 5) can be written as

$$\begin{aligned} f &= \frac{w_1 f_1 + w_2 f_2}{w_1 + w_2} \\ &= \bar{w}_1 f_1 + \bar{w}_2 f_2, \end{aligned} \quad (3)$$

where

$$\bar{w}_1 = \frac{w_1}{w_1 + w_2}, \quad \bar{w}_2 = \frac{w_2}{w_1 + w_2}. \quad (4)$$

C. Dynamics of Hand

The dynamic equations of hand motion are derived via Lagrangian approach using kinetic energy and potential energy as [17], [24]–[26], [32]

$$\frac{d}{dt} \left(\frac{\partial \mathcal{L}}{\partial \dot{\mathbf{q}}} \right) - \frac{\partial \mathcal{L}}{\partial \mathbf{q}} = \boldsymbol{\tau}, \quad (5)$$

where $\mathcal{L}$ is the Lagrangian; $\dot{\mathbf{q}}$ and $\mathbf{q}$ represent the angular velocities and angle vectors of joints, respectively; $\boldsymbol{\tau}$ is the given torque vector at joints. The Lagrangian $\mathcal{L}$ can be expressed as

$$\mathcal{L} = T - V, \quad (6)$$

where T and V denote kinetic and potential energies, respectively. Substituting (6) into (5), dynamic equations of thumb can be obtained as below.

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{G}(\mathbf{q}) = \boldsymbol{\tau}, \quad (7)$$

where $\mathbf{M}(\mathbf{q})$ is the inertia matrix; $\mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})$ is the Coriolis/centripetal vector and $\mathbf{G}(\mathbf{q})$ is the gravity vector. (7) can be also written as

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{N}(\mathbf{q}, \dot{\mathbf{q}}) = \boldsymbol{\tau}, \quad (8)$$

where $\mathbf{N}(\mathbf{q}, \dot{\mathbf{q}}) = \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{G}(\mathbf{q})$ represents nonlinear terms. The dynamic relations for the two-link thumb and the remaining three-link fingers are quite lengthy and omitted here due to lack of space [24], [33], [34].

III. CONTROL TECHNIQUES

A. Feedback Linearization

The nonlinear dynamics represented by (8) is to be converted into a linear state-variable system using feedback linearization technique [17]. Alternative state-space equations of the dynamics can be obtained by defining the position/velocity state $\mathbf{x}(t)$ of the joints as

$$\mathbf{x}(t) = [\mathbf{q}'(t) \quad \dot{\mathbf{q}}'(t)]'. \quad (9)$$

Let us repeat the dynamical model and rewrite (8) as

$$\frac{d}{dt} \dot{\mathbf{q}}(t) = -\mathbf{M}^{-1}(\mathbf{q}(t)) [\mathbf{N}(\mathbf{q}(t), \dot{\mathbf{q}}(t)) - \boldsymbol{\tau}(t)]. \quad (10)$$

Thus, from (9) and (10), we can derive a linear system in *Brunovsky canonical form* as

$$\dot{\mathbf{x}}(t) = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \mathbf{x}(t) + \begin{bmatrix} \mathbf{0} \\ \mathbf{I} \end{bmatrix} \mathbf{u}(t) \quad (11)$$

with its control input vector given by

$$\mathbf{u}(t) = -\mathbf{M}^{-1}(\mathbf{q}(t)) [\mathbf{N}(\mathbf{q}(t), \dot{\mathbf{q}}(t)) - \boldsymbol{\tau}(t)]. \quad (12)$$

Let us suppose the prosthetic hand is required to track the desired trajectory $\mathbf{q}_d(t)$ described under path generation or tracking. Then, the tracking error $\mathbf{e}(t)$ is defined as

$$\mathbf{e}(t) = \mathbf{q}_d(t) - \mathbf{q}(t). \quad (13)$$

Here, $\mathbf{q}_d(t)$ is the *desired* angle vector of joints and can be obtained by trajectory planning [10], [11], [14], [18], [24]; $\mathbf{q}(t)$ is the *actual* angle vector of joints. Differentiating (13) twice, to get

$$\dot{\mathbf{e}}(t) = \dot{\mathbf{q}}_d(t) - \dot{\mathbf{q}}(t), \quad \ddot{\mathbf{e}}(t) = \ddot{\mathbf{q}}_d(t) - \ddot{\mathbf{q}}(t). \quad (14)$$

Substituting (10) into (14) yields

$$\ddot{\mathbf{e}}(t) = \ddot{\mathbf{q}}_d(t) + \mathbf{M}^{-1}(\mathbf{q}(t)) [\mathbf{N}(\mathbf{q}(t), \dot{\mathbf{q}}(t)) - \boldsymbol{\tau}(t)] \quad (15)$$

from which the control function can be defined as

$$\mathbf{u}(t) = \ddot{\mathbf{q}}_d(t) + \mathbf{M}^{-1}(\mathbf{q}(t)) [\mathbf{N}(\mathbf{q}(t), \dot{\mathbf{q}}(t)) - \boldsymbol{\tau}(t)]. \quad (16)$$

This is often called the *feedback linearization* control law, which can also be inverted to express it as

$$\boldsymbol{\tau}(t) = \mathbf{M}(\mathbf{q}(t)) [\ddot{\mathbf{q}}_d(t) - \mathbf{u}(t)] + \mathbf{N}(\mathbf{q}(t), \dot{\mathbf{q}}(t)). \quad (17)$$

Using the relations (14) and (16), and defining state vector $\mathbf{x}(t) = [\mathbf{e}'(t) \quad \dot{\mathbf{e}}'(t)]'$, the *tracking error dynamics* can be written as

$$\dot{\mathbf{x}}(t) = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \mathbf{x}(t) + \begin{bmatrix} \mathbf{0} \\ \mathbf{I} \end{bmatrix} \mathbf{u}(t). \quad (18)$$

Note that this is in the form of a *linear* system such as

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t). \quad (19)$$

B. Fuzzy Logic-Based PD Hybrid Control

Figure 3 shows the block diagram of the hybrid fuzzy logic-based PD controller for the presented five-fingered prosthetic hand with control signal as

$$\mathbf{u}(t) = -\mathbf{K}_P(t)\mathbf{e}(t) - \mathbf{K}_D(t)\dot{\mathbf{e}}(t) \quad (20)$$

with the proportional $\mathbf{K}_P(t)$ and derivative $\mathbf{K}_D(t)$ diagonal gain matrices with time varying. We then rewrite (17) as

$$\begin{aligned} \boldsymbol{\tau}(t) &= \mathbf{M}(\mathbf{q}(t)) [\ddot{\mathbf{q}}_d(t) + \mathbf{K}_P(t)\mathbf{e}(t) + \mathbf{K}_D(t)\dot{\mathbf{e}}(t)] + \\ &\quad \mathbf{N}(\mathbf{q}(t), \dot{\mathbf{q}}(t)). \end{aligned} \quad (21)$$

Then we use mamdani fuzzy inference system to tune the time-varying parameters $\mathbf{K}_P(t)$ and $\mathbf{K}_D(t)$ of PD controller. Figure 4 shows the structural characteristics of proposed fuzzy inference system, which includes two inputs (error $\mathbf{e}$ and error change $\dot{\mathbf{e}}$) on the left and one output ($\mathbf{K}_P$) on the right. Each input or output layer contains seven triangular membership

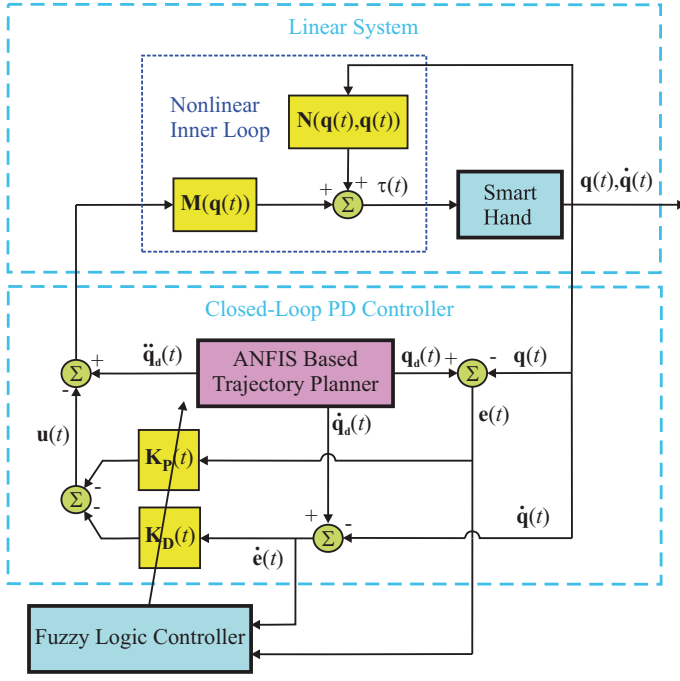


Fig. 3. Block Diagram of the Presented Hybrid Fuzzy Logic-Based Proportional-Derivative (PD) Controller for a Five-Fingered Prosthetic Hand: Errors and error changes are calculated by actual and desired angles, which are based on adaptive neuro-fuzzy inference system (ANFIS) trajectory planner. Then fuzzy logic controller tunes all parameters of closed-loop PD control so that the required torque of the prosthetic hand nonlinear system is computed by control input.

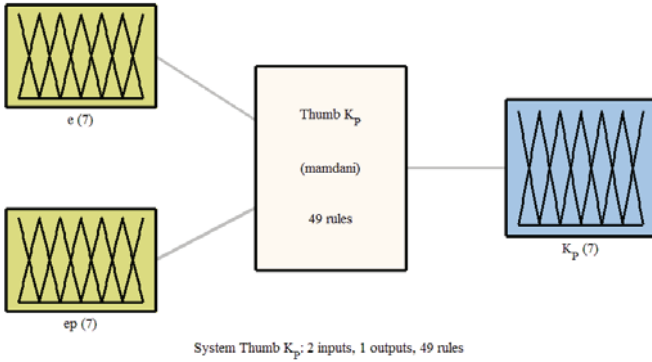


Fig. 4. The Structural Characteristics of Proposed Fuzzy Inference System: Two inputs (error e and error change $\dot{e}$) on the left and one output (tuned K_p) on the right with 49 logic rules

functions as shown in Figure 5 and 49 logic rules as listed in Table I. After using 49 logic rules, the output surface K_p of fuzzy inference system is generated as shown in Figure 6. Similarly, K_d can be computed by the same way.

IV. SIMULATION RESULTS AND DISCUSSION

Figure 7 shows that a five-fingered prosthetic hand with 14 DOFs is reaching a rectangular rod in order to grasp the object. When thumb and the other four fingers are performing extension/flexion movements, the workspace of fingertips is restricted to the maximum angles of joints. Referring to inverse

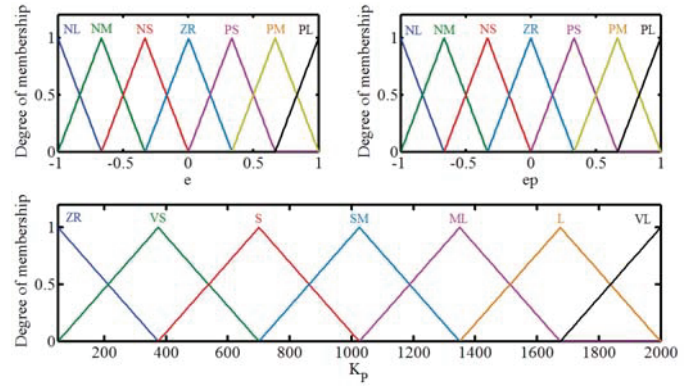


Fig. 5. All Membership Functions: Each of Two Inputs (Upper Panel) and One Output (Lower Panel) Uses 7 Triangular Membership Functions

TABLE I
A COMPLETE FUZZY LOGIC RULE BASE

$\dot{e} \setminus e$	NL	NM	NS	ZR	PS	PM	PL
NL	ZR	ZR	ZR	ZR	VS	S	SM
NM	ZR	ZR	ZR	VS	S	SM	ML
NS	ZR	ZR	VS	S	SM	ML	L
ZR	ZR	VS	S	SM	ML	L	VL
PS	VS	S	SM	ML	L	VL	VL
PM	S	SM	ML	L	VL	VL	VL
PL	SM	ML	L	VL	VL	VL	VL

N: negative; P: positive; ZR: zero; L: large; M: medium; S: small; V: very

kinematics, the first and second joint angles of the thumb fingertip are constrained in the ranges of $[0,90]$ and $[-80,0]$ (degrees). The first, second, and third joint angles of the other four fingers are constrained in the ranges of $[0,90]$, $[0,110]$ and $[0,80]$ (degrees), respectively [35].

Next, we present simulations with PD and PID controllers and fuzzy inference system tuned PD controller for the 14 DOFs five-fingered smart prosthetic hand. The parameters of the two-link thumb/three-link fingers [36] were related to desired trajectory. All parameters of the smart prosthetic hand selected for the simulations are given in Table II and the

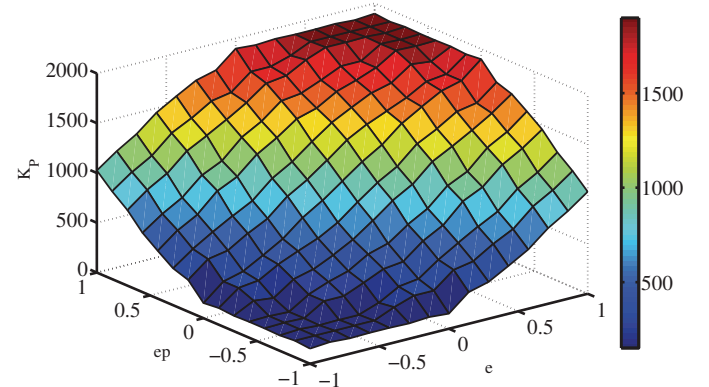


Fig. 6. The Output Surface of Fuzzy Inference System with Two Inputs and 49 Logic Rules

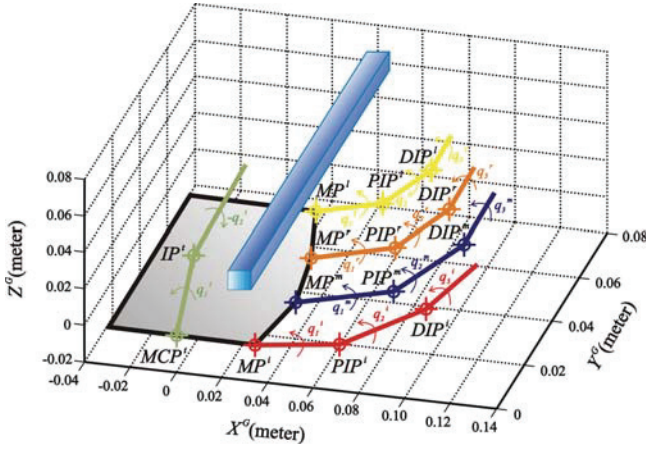


Fig. 7. Five-Fingered Prosthetic Hand Grasping a Rectangular Object

side length and length of the target rectangular rod are 0.010 and 0.100 (m), respectively. The relating parameters between the global coordinate and the local coordinates are defined in Table III. Moreover, in this work, we assumed that each link

TABLE II
PARAMETER SELECTION OF THE SMART HAND

Parameters	Values
Thumb	
Time (t_0, t_f)*	0, 20 (sec)
Desired Initial Position (X_0^t, Y_0^t)**	0.035, 0.060 (m)
Desired Final Position (X_f^t, Y_f^t)**	0.0495, 0.060 (m)
Desired Initial Velocity ($\dot{X}_0^t, \dot{Y}_0^t$)*	0, 0 (m/s)
Desired Final Velocity ($\dot{X}_f^t, \dot{Y}_f^t$)*	0, 0 (m/s)
Length (L_1^t, L_2^t)	0.040, 0.040 (m)
Mass (m_1^t, m_2^t)	0.043, 0.031 (kg)
Index Finger	
Desired Initial Position (X_0^i, Y_0^i)**	0.065, 0.080 (m)
Desired Final Position (X_f^i, Y_f^i)**	0.010, 0.060 (m)
Length (L_1^i, L_2^i, L_3^i)	0.040, 0.040, 0.030 (m)
Mass (m_1^i, m_2^i, m_3^i)	0.045, 0.025, 0.017 (kg)
Middle Finger	
Desired Initial Position (X_0^m, Y_0^m)**	0.065, 0.080 (m)
Desired Final Position (X_f^m, Y_f^m)**	0.005, 0.060 (m)
Length (L_1^m, L_2^m, L_3^m)	0.044, 0.044, 0.033 (m)
Mass (m_1^m, m_2^m, m_3^m)	0.050, 0.028, 0.017 (kg)
Ring Finger	
Desired Initial Position (X_0^r, Y_0^r)**	0.065, 0.080 (m)
Desired Final Position (X_f^r, Y_f^r)**	0.010, 0.060 (m)
Length (L_1^r, L_2^r, L_3^r)	0.040, 0.040, 0.030 (m)
Mass (m_1^r, m_2^r, m_3^r)	0.041, 0.023, 0.014 (kg)
Little Finger	
Desired Initial Position (X_0^l, Y_0^l)**	0.055, 0.080 (m)
Desired Final Position (X_f^l, Y_f^l)**	0.020, 0.060 (m)
Length (L_1^l, L_2^l, L_3^l)	0.036, 0.036, 0.027 (m)
Mass (m_1^l, m_2^l, m_3^l)	0.041, 0.023, 0.014 (kg)

*All fingers use same parameters

**All parameters are in local coordinates

of all fingers is a circular cylinder with the radius (R) 0.010 (m), so the inertia I_{zzk}^j of each link k of all fingers j ($= t, i,$

TABLE III
PARAMETER SELECTION OF CONVERSION BETWEEN GLOBAL AND LOCAL COORDINATES

Parameters	Values
Rotating α	90 (deg)
Rotating β	45 (deg)
Translating d^i	(0.035, 0, 0) (m)
Translating d^m	(0.040, 0, -0.020) (m)
Translating d^r	(0.035, 0, -0.040) (m)
Translating d^l	(0.025, 0, -0.060) (m)

m, r and l) can be calculated as

$$I_{zzk}^j = \frac{1}{4}m_k^j R^2 + \frac{1}{3}m_k^j L_k^j{}^2. \quad (22)$$

All initial actual angles are zero and the diagonal coefficients, K_P , K_I and K_D , for the PD or PID controller alone are arbitrarily chosen as 100. From the derived dynamic and control models, after the parameters (K_P and K_D) are selected, the control signal u and torque τ can be calculated.

Figure 8 shows tracking errors (e_1^t and e_2^t on the left

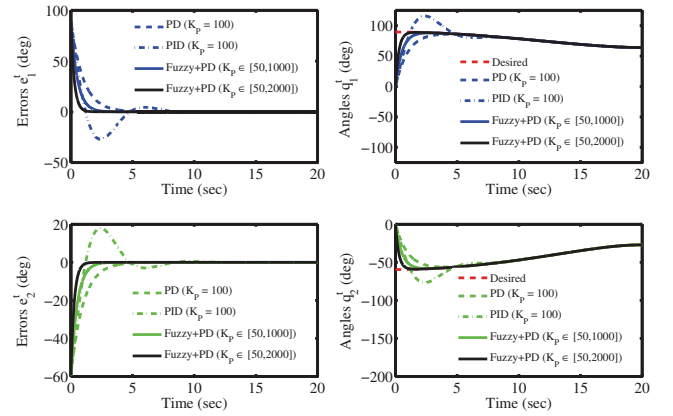


Fig. 8. Tracking Errors (Left) and Desired/Actual Angles (Right) of Joints 1 (Upper) and 2 (Lower) for Two-Link Thumb Using PD (Dash Line), PID (Dot Line) and Fuzzy Logic Based PD (Solid Line) Controllers

column) and desired/actual angles (q_1^t and q_2^t on the right column) of joints 1 (the top row) and 2 (the bottom row) for two-link thumb using PD (dash line), PID (dot line) and fuzzy logic based PD (solid line) controllers. The tracking errors for PD control are convergent within 5 seconds without overshooting, but PID control acts longer (approximate 10 seconds) with overshooting and oscillation. The proposed hybrid fuzzy logic PD control using parameters $K_P \in [50, 1000]$ and $K_D \in [50, 500]$ provides faster convergence than both PD and PID controllers. To further study whether the parameter range influences tracking errors, we found that the larger parameter range, the faster convergent speed after altering $K_P \in [50, 2000]$ without additional computational time. We also used fuzzy logic controller with two inputs (error and error rate) and one output (control signal), but the control system could not obtain convergent tracking errors (data not shown). These data suggest that fusion of soft computing (SC) and

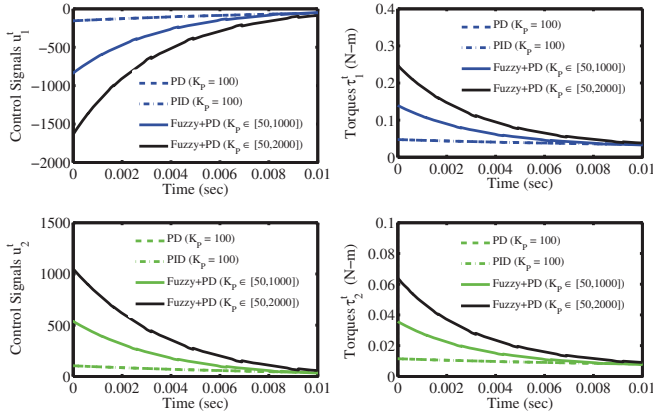


Fig. 9. Control Signals (Left) and Actuated Torques (Right) of Joints 1 (Upper) and 2 (Lower) for Two-Link Thumb Using PD (Dash Line), PID (Dot Line) and Fuzzy Logic Based PD (Solid Line) Controllers in 0.01 Second

hard control (HC) is superior to either HC or SC methodology alone.

The time-variant computed control signals (u_1^t and u_2^t) and torques (τ_1^t and τ_2^t) for two-link thumb within the first 0.01 second are shown in Figure 9, suggesting that the presented hybrid fuzzy logic PD controller requires more power (torque) than PD and PID controllers in order to obtain faster convergent tracking errors.

Similarly, Figures 10, 12, 14 and 16 show tracking errors and desired/actual angles for all remaining three-link fingers. Figures 11, 13, 15 and 17 show control signals and torques for the mapping three-link fingers.

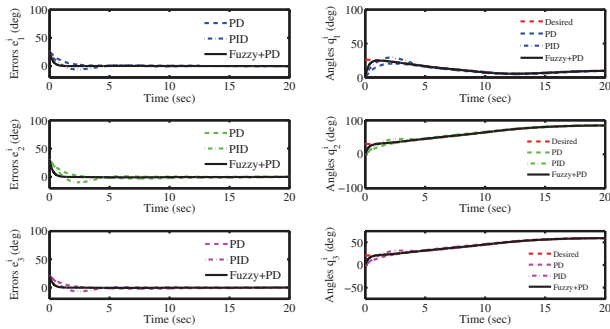


Fig. 10. Tracking Errors (Left) and Desired/Actual Angles (Right) of Joints 1 (Top), 2 (Middle) and 3 (Bottom) for Three-Link Index Finger Using PD (Dash Line), PID (Dot Line) and Fuzzy Logic Based PD (Solid Line) Controllers

V. CONCLUSIONS AND FUTURE WORK

For a five-fingered smart prosthetic hand, a hybrid control technique involving soft control with adaptive neuro-fuzzy inference system (ANFIS) and fuzzy logic (FL) and hard control with proportional-derivative (PD) was presented. The ANFIS is used for inverse kinematics and FL is used for tuning the PD parameters with two input layers (error and

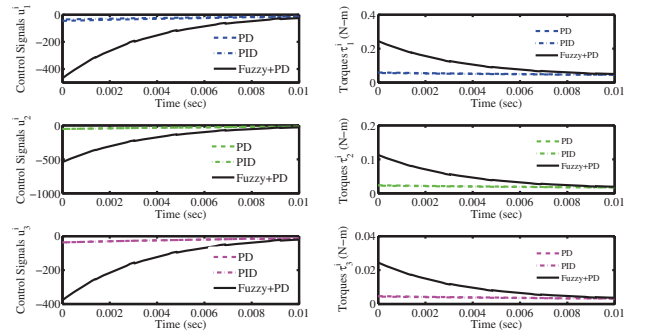


Fig. 11. Control Signals (Left) and Actuated Torques (Right) of Joints 1 (Top), 2 (Middle) and 3 (Bottom) for Three-Link Index Finger Using PD (Dash Line), PID (Dot Line) and Fuzzy Logic Based PD (Solid Line) Controllers in 0.01 Second

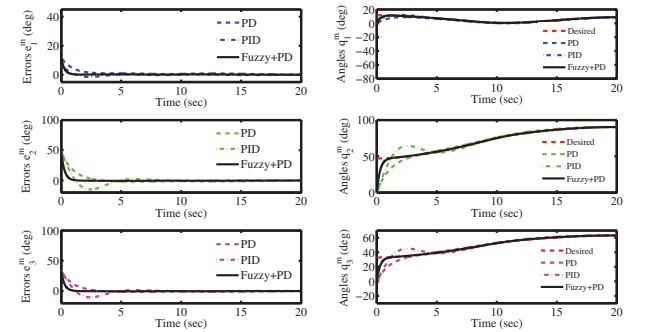


Fig. 12. Tracking Errors (Left) and Desired/Actual Angles (Right) of Joints 1 (Top), 2 (Middle) and 3 (Bottom) for Three-Link Middle Finger Using PD (Dash Line), PID (Dot Line) and Fuzzy Logic Based PD (Solid Line) Controllers

error change) using 7 triangular membership functions and 49 fuzzy logic rules. Simulation results with FL-tuned PD (hybrid) controller showed superior performance compared to the PD and PID control alone. Work is underway to extend this methodology to a real-time implementation on the prototype of a prosthetic hand.

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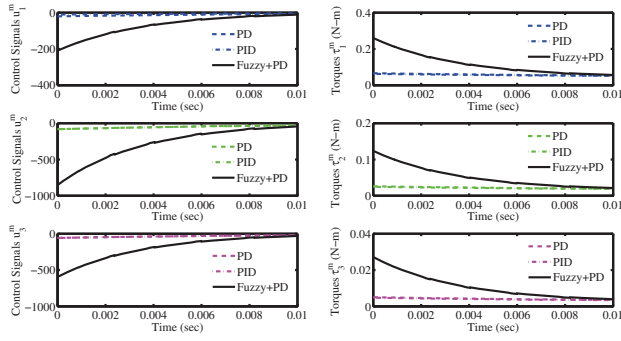


Fig. 13. Control Signals (Left) and Actuated Torques (Right) of Joints 1 (Top), 2 (Middle) and 3 (Bottom) for Three-Link Middle Finger Using PD (Dash Line), PID (Dot Line) and Fuzzy Logic Based PD (Solid Line) Controllers in 0.01 Second

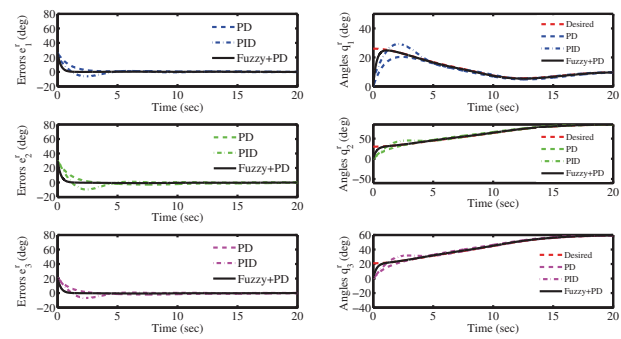


Fig. 14. Tracking Errors (Left) and Desired/Actual Angles (Right) of Joints 1 (Top), 2 (Middle) and 3 (Bottom) for Three-Link Ring Finger Using PD (Dash Line), PID (Dot Line) and Fuzzy Logic Based PD (Solid Line) Controllers

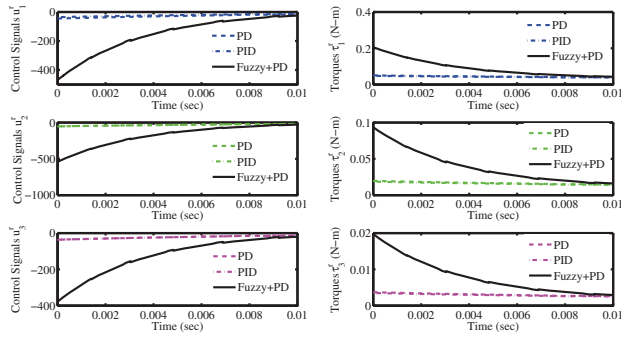


Fig. 15. Control Signals (Left) and Actuated Torques (Right) of Joints 1 (Top), 2 (Middle) and 3 (Bottom) for Three-Link Ring Finger Using PD (Dash Line), PID (Dot Line) and Fuzzy Logic Based PD (Solid Line) Controllers in 0.01 Second

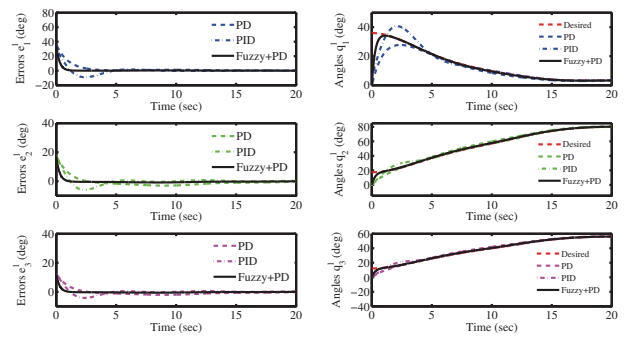


Fig. 16. Tracking Errors (Left) and Desired/Actual Angles (Right) of Joints 1 (Top), 2 (Middle) and 3 (Bottom) for Three-Link Little Finger Using PD (Dash Line), PID (Dot Line) and Fuzzy Logic Based PD (Solid Line) Controllers

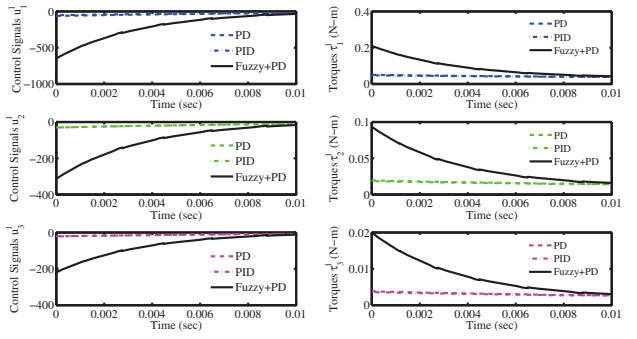


Fig. 17. Control Signals (Left) and Actuated Torques (Right) of Joints 1 (Top), 2 (Middle) and 3 (Bottom) for Three-Link Little Finger Using PD (Dash Line), PID (Dot Line) and Fuzzy Logic Based PD (Solid Line) Controllers in 0.01 Second

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