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FUZZY LOGIC CONTROL IN ROBOT MANIPULATORS: A COMPARATIVE ANALYSIS WITH BOOLEAN LOGIC

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Abstract. *Robot manipulators encounter significant control challenges stemming from nonlinear dynamics, parametric uncertainties, and external disturbances. While Boolean logic-based controllers operate through precise binary thresholds, fuzzy logic control utilizes linguistic rules and graded membership to emulate human decision-making. This paper examines both control paradigms, detailing theoretical foundations and practical implementation for a 2-DOF manipulator. Quantitative comparisons reveal fuzzy logic's superior adaptability in trajectory tracking and disturbance rejection, while Boolean methods maintain advantages in computational efficiency. The study concludes with controlled selection guidelines based on application-specific requirements.*

Keywords: *Fuzzy logic, Boolean control, Robot manipulator, PID controller, Nonlinear dynamics, Membership functions, Adaptive control, Trajectory tracking.*

НЕЧЕТКОЕ ЛОГИЧЕСКОЕ УПРАВЛЕНИЕ В РОБОТОТЕХНИЧЕСКИХ МАНИПУЛЯТОРАХ: СРАВНИТЕЛЬНЫЙ АНАЛИЗ НА ОСНОВЕ ЛОГИКИ

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Аннотация. *Роботизированные манипуляторы сталкиваются со значительными проблемами управления, связанными с нелинейной динамикой, параметрическими неопределенностями и внешними возмущениями. В то время как контроллеры, основанные на булевой логике, работают через точные двоичные пороги, нечеткое логическое управление использует лингвистические правила и градуированную принадлежность для имитации человеческого принятия решений. В данной работе рассматриваются обе парадигмы управления, подробно описываются теоретические основы и практическая реализация 2-DOF манипулятора. Количественные сравнения показывают превосходную адаптивность нечеткой логики в отслеживании траекторий и отклонении возмущений, в то время как методы Буля сохраняют преимущества в эффективности вычислений. Исследование завершается руководством по контролируемому отбору, основанным на специфических требованиях к применению.*

Ключевые слова: *Нечеткая логика, Булево управление, Робот-манипулятор, PID-контроллер, Нелинейная динамика, Функции принадлежности, Адаптивное управление, Траектория отслеживания.*

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ROBOTLASHTIRILGAN MANIPULYATORLARDA NORAVSHAN MANTIQIY BOSHQARUV: MANTIQQA ASOSLANGAN QIYOSIY TAHLIL

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Annotatsiya. *Robotlashtirilgan manipulyatorlar nochiziqli dinamika, parametrik noaniqliklar va tashqi ta'sirlar bilan bog'liq bo'lgan sezilarli boshqaruv muammolariga duch keladi. Bul mantiq asosidagi kontrollerlar aniq ikkilik chegaralar orqali ishlasa, noaniq mantiqiy boshqaruv inson qarorlarini imitatsiya qilish uchun lingvistik qoidalar va darajalangan tegishlilikdan foydalanadi. Ushbu ishda boshqaruvning ikkala paradigmasi ko'rib chiqiladi, 2-DOF manipulyatorining nazariy asoslari va amaliyotda qo'llanilishi batafsil tavsiflanadi. Miqdoriy taqqoslashlar noaniq mantiqning trayektoriyalarni kuzatish va og'ishlarni chetlashtirishda ajoyib moslashuvchanligini ko'rsatadi, Bul usullari esa hisoblash samaradorligi bo'yicha ustunliklarni saqlab qoladi. Tadqiqot o'ziga xos qo'llash talablariga asoslangan nazoratli tanlash bo'yicha qo'llanma bilan yakunlanadi.*

Kalit so'zlar: *Noaniq mantiq, Mantiqiy boshqaruv, Robot manipulyator, PID kontroller, Nochiziqli dinamika, Tegishlilik funksiyalari, Moslashuvchan boshqaruv, Kuzatuv trayektoriyasi.*

Introduction. Robot manipulators demand robust control strategies to address inherent nonlinear dynamics, parameter uncertainties, and environmental disturbances. Traditional Boolean logic-based controllers function through binary true/false conditions, requiring precise system modeling and exhibiting limitations in handling ambiguous scenarios. In contrast, fuzzy logic control, introduced by Zadeh, employs gradual set membership and linguistic rules to manage imprecision. This paper analyzes both control philosophies, examines their theoretical distinctions, implements a 2-DOF manipulator case study, and evaluates performance against Boolean-based PID control. Comparative assessment provides insight into selecting appropriate control methodologies in robotic applications.

Materials and methods. The theoretical framework of robot manipulator dynamics, Boolean logic control, and fuzzy logic fundamentals is outlined in this section. A practical implementation for a 2-DOF manipulator is included, featuring control modules, trajectory planning, and disturbance modeling.

Robot manipulator dynamics. The dynamic behavior of an n-link manipulator follows the equation:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + \tau_d = \tau$$

where q represents joint angles, M the inertia matrix, C Coriolis and centrifugal forces, G gravitational effects, τ_d external disturbances, and τ the control torque input.

For a 2-DOF planar manipulator, the dynamics are explicitly given by:

$$M(q) = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix},\ C(q,\dot{q}) = \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix},\ G(q) = \begin{bmatrix} g_1 \\ g_2 \end{bmatrix}$$

where: $m_{11} = I_1 + I_2 + m_1 l_{c1}^2 + m_2(l_1^2 + l_{c2}^2 + 2l_1 l_{c2}\cos q_2;$

$m_{12} = I_2 + m_2(l_{c2}^2 + l_1 l_{c2}\cos q_2);$

$m_{21} = m_{12};$

$m_{22} = I_{22} m_2 l_{c2}^2;$

$c_{11} = -m_2 l_1 l_{c2}\dot{q}_2 \sin q_2;$

$c_{12} = -m_2 l_1 l_{c2}(\dot{q}_1 + \dot{q}_2)\sin q_2;$

$c_{21} = m_2 l_1 l_{c2}\dot{q}_1 \sin q_2;$

$c_{22} = 0;$

$g_1 = (m_1 l_{c1} + m_2 l_1) g \cos q_1 + m_2 l_{c2} g \cos(q_1 + q_2);$

$g_2 = m_2 l_{c2} g \cos(q_1 + q_2).$

with m_i, l_i, l_{ci}, and I_i denoting the mass, link length, center-of-mass distance, and moment of inertia of link i, respectively.

Boolean logic control principles. Boolean logic controllers operate on binary principles where conditions are either true (1) or false (0). The Boolean-PID controller for joint i is defined by:

$$\tau_i = \begin{cases} \tau_{max} \\ K_p e_i + K_i \int e_i\,dt + K_d \dot{e}_i; \\ -\tau_{max} \end{cases}$$

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$if \quad e_i > \epsilon_i$
$if \quad |e_i| \le \epsilon_i.$
$if \quad e_i < -\epsilon_i$

where $e_i = q_{d,i} - q_i$ is the position error, ϵ_i is the error threshold (e.g., 0.3 rad), and τ_{max} the maximum torque. This discontinuous action causes chattering near $|e_i| = \epsilon_i$.

Fuzzy logic fundamentals. Fuzzy logic control processes imprecise information through three core stages:

1. **Fuzzification**: Maps crisp inputs to fuzzy sets via membership functions. For input x (e.g., error), a triangular membership function is:

$$\mu_{\text{trimf}}(x; a, b, c) = \max\left(\min\left(\frac{x-a}{b-a}, \frac{c-x}{c-b}\right), 0\right).$$

where a, b, c define the triangle's vertices.

2. **Rule Inference**: Applies IF-THEN rules of the form:

$$R_k: IF\ e\ is\ A_k\ AND\ \ is\ B_k\ THEN\ \tau\ is\ C_k;$$

where A_k, B_k, C_k are fuzzy sets. The firing strength for rule k is:

$$w_k = \mu A_k(e) \star \mu B_k(\dot{e}).$$

with $\star$ being a t-norm (e.g., minimum).

3. **Defuzzification**: Converts fuzzy output to crisp value. Using centroid method:

$$\tau = \frac{\sum_{k=1}^{N} w_k \cdot z_k}{\sum_{k=1}^{N} w_k}.$$

where z_k is the centroid of C_k.

Practical implementation. The control architecture consists of the following modules:

Trajectory planner: Generates reference trajectory $q_d(t)$ using cubic polynomials:

$$q_d(t) = a_0 + a_1 t + a_2 t^2 a_3 t^3.$$

with coefficients satisfying boundary conditions.

Disturbance model: Impulse disturbance at $t = t_d$:

$$\tau_d t = A_d \delta(t - t_d).$$

where $\delta(\cdot)$ is the Dirac delta function.

Adaptive payload: Time-varying payload mass:

$$m_p(t) = \overline{m}_p[1 + \eta \sin(\omega t)].$$

with η=0.5 modeling ±50% variation.

Fuzzy inference system:

Inputs: $e = q_d - q$, $\dot{e} = \dot{q}_d - \dot{q}$;

Output: τ.

Rule matrix for joint 1:

Table 1.

Fuzzy inference rule matrix for Joint 1

$e \backslash \dot{e}$	NB	NM	Z	PM	PB
NB	PB	PB	PM	PS	Z
NM	PB	PM	PS	Z	NS
Z	PM	PS	Z	NS	NM
PM	PS	Z	NS	NM	NB
PB	Z	NS	NM	NB	NB

Numerical integration. Dynamics solved via Runge-Kutta 4th order:

$$k_1 = f(t, y);$$
$$k_2 = f\left(t + \frac{h}{2}, y + \frac{h}{2}k_1\right);$$
$$k_3 = f\left(t + \frac{h}{2}, y + \frac{h}{2}k_2\right);$$
$$k_4 = f(t + h, y + hk_3);$$
$$y_{n+1} = y_n + \frac{h}{6}(k_1 + 2k_2 + 2k_3 + k_4).$$

with step h=0.001 s.

To better visualize the conceptual difference between Boolean and Fuzzy logic, the following diagram illustrates their output response across a normalized input range from -1.0 to +1.0. Boolean logic shows abrupt changes between binary states, while fuzzy logic provides a smooth, continuous output:

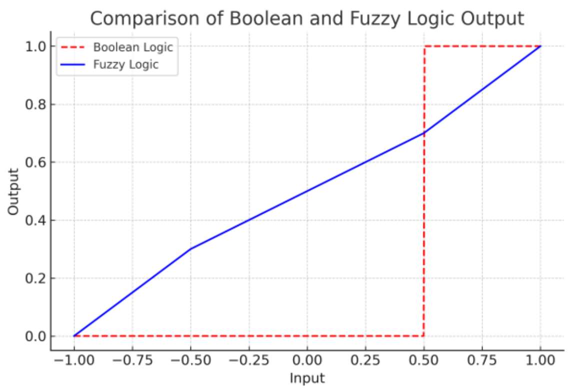

Fig.1. Output Response of Boolean vs Fuzzy Logic.

Results and discussion. The output comparison between Boolean and Fuzzy logic controllers highlights significant distinctions. Boolean control exhibits discontinuous, abrupt torque transitions, while fuzzy control ensures smooth, continuous output signals. This smoothness translates into better trajectory tracking and lower mechanical stress.

Fuzzy logic strengths. Fuzzy logic excels in handling sensor noise and model uncertainties through graded membership functions, eliminating

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control chattering observed in Boolean systems near thresholds. Its heuristic rules enable autonomous adaptation to dynamic changes like payload variations, reducing maintenance interventions. Continuous output transitions provide smoother motion profiles, critical in precision applications. The methodology requires no explicit dynamic model, accelerating implementation for complex systems.

Boolean logic advantages. Boolean-based systems offer superior computational efficiency with execution times approximately 90% faster than fuzzy inference, advantageous for high-speed applications. Their discrete state-space structure permits exhaustive formal verification through model checking techniques, crucial for safety-critical systems. The binary decision framework simplifies debugging and certification processes.

Performance Trade-offs. The fundamental differences manifest in control surfaces:

- Boolean-PID: Discontinuous surface $\tau(e,\dot{e})$ with step transitions

Fuzzy Logic: Continuous surface defined by $\tau = \mathcal{F}(e,\dot{e})$ where

$$\mathcal{F}(e,\dot{e}) = \frac{\sum_k w_k(e,\dot{e}) z_k}{\sum_k w_k(e,\dot{e})};$$

exhibits smooth nonlinear mapping.

Conclusion. Fuzzy logic control demonstrates superior performance for robot manipulators operating under uncertain conditions, significantly outperforming Boolean-based methods in trajectory tracking accuracy and disturbance rejection. Its linguistic rule structure provides intuitive design flexibility and adaptability to dynamic changes without re-parameterization. Boolean logic remains preferable for deterministic applications requiring minimal computational latency and formal verifiability. Future advancements should focus on neuro-fuzzy hybridization for automated rule optimization and FPGA implementations to address computational constraints. Controller selection should prioritize uncertainty tolerance versus processing speed requirements based on specific application demands.

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