

TEXNOLOGIK JARAYONLARNI BOSHQARISHNING NEYRON TARMOQLARGA ASOSLANGAN ADAPTIV MODELLARI VA ALGORITMLARINI ISHLAB CHIQISH

O'roqova Shahzoda Tojimurodovna

Temiz shahar 20- sonli maktab

shahzodatojimurodovna@gmail.com

ANNOTATSIYA

Maqolada nolinear, ko'p o'zgaruvchili va vaqt bo'yicha xususiyatlari o'zgarib turadigan texnologik jarayonlarni boshqarishda neyron tarmoqlarga asoslangan adaptiv modellar va algoritmlardan foydalanish masalalari ko'rib chiqiladi. Tadqiqotda feed-forward neural network, NARX, recurrent neural network, LSTM, GRU hamda physics-informed neural network modellarining texnologik jarayonlarni identifikatsiyalash va prognozlashdagi imkoniyatlari tahlil qilindi. Neyron modelni model predictive control bilan integratsiyalash, model xatosini real vaqt rejimida kuzatish, parametrlar driftini aniqlash va event-triggered online learning asosida modelni yangilash tamoyillari ishlab chiqildi. Adaptiv boshqaruv arxitekturasida sensor ma'lumotlarini filtrlash, holatlarni baholash, neyron prediktor, cheklovli optimallashtirish, xavfsizlik nazorati va rezerv boshqaruvchidan foydalanish nazarda tutiladi. Tahlil shuni ko'rsatadiki, neyron tarmoqning yuqori prognoz aniqligi o'z-o'zidan samarali boshqaruvni kafolatlamaydi; yopiq kontur barqarorligi, hisoblash vaqti, constraintlarni bajarish va operating regiondan tashqaridagi noaniqliklar ham birgalikda nazorat qilinishi zarur.

Kalit so'zlar: neyron tarmoq, adaptiv boshqaruv, texnologik jarayon, model predictive control, RNN, LSTM, NARX, PINN, online learning, system identification.

АННОТАЦИЯ

В статье рассматриваются адаптивные модели и алгоритмы управления нелинейными, многомерными и нестационарными технологическими процессами на основе нейронных сетей. Анализируются возможности feed-forward neural

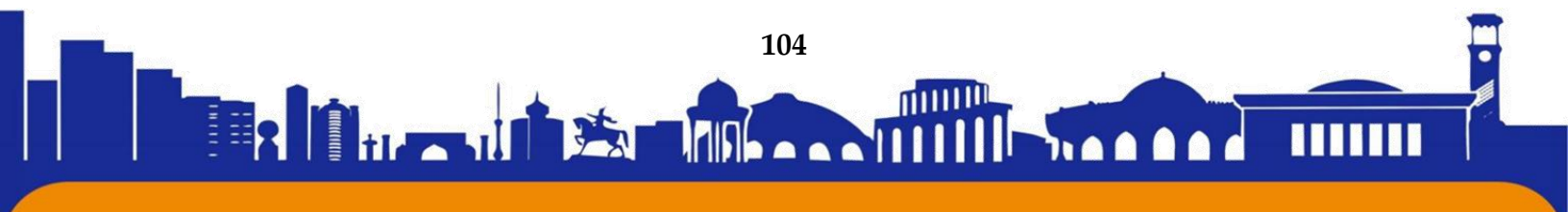
network, NARX, recurrent neural network, LSTM, GRU и physics-informed neural network для идентификации и прогнозирования динамики технологических объектов. Разработаны принципы интеграции нейронной модели с model predictive control, мониторинга ошибки модели в реальном времени, выявления дрейфа параметров и адаптации модели на основе event-triggered online learning. Предложенная архитектура включает фильтрацию сенсорных данных, оценивание состояния, нейронный предиктор, оптимизацию с ограничениями, контроль безопасности и резервный регулятор. Показано, что высокая точность нейросетевого прогноза сама по себе не гарантирует эффективное управление: необходимо совместно учитывать устойчивость замкнутого контура, вычислительные ограничения, выполнение технологических ограничений и неопределённость за пределами обучающей области.

Ключевые слова: нейронная сеть, адаптивное управление, технологический процесс, model predictive control, RNN, LSTM, NARX, PINN, online learning, идентификация систем.

ABSTRACT

This article examines neural-network-based adaptive models and algorithms for controlling nonlinear, multivariable, and time-varying technological processes. Feed-forward neural networks, NARX, recurrent neural networks, LSTM, GRU, and physics-informed neural networks are analyzed as models for process identification and prediction. The study develops principles for integrating neural predictors with model predictive control, monitoring model error in real time, detecting parameter drift, and updating the model through event-triggered online learning. The proposed architecture combines sensor-data filtering, state estimation, a neural predictor, constrained optimization, safety supervision, and a fallback controller. The analysis shows that high neural-network prediction accuracy alone does not guarantee effective control; closed-loop stability, computational feasibility, constraint satisfaction, and uncertainty outside the training region must also be considered simultaneously.

Keywords: neural network, adaptive control, technological process, model predictive control, RNN, LSTM, NARX, PINN, online learning, system identification.



KIRISH

Zamonaviy texnologik ishlab chiqarish jarayonlarining muhim xususiyati ularning nolinearlighi, ko'p parametrlilik ekanligi va ish rejimining vaqt bo'yicha o'zgarib turishidir. Kimyo, neft-kimyo, metallurgiya, issiqlik energetikasi, oziq-ovqat ishlab chiqarish va uzluksiz texnologik liniyalarda boshqariladigan obyekt parametrlari xomashyo tarkibi, jihoz holati, tashqi muhit, ishlab chiqarish yuklamasi va texnologik rejimga qarab o'zgaradi.

An'anaviy PID yoki lokal chiziqli regulatorlar nominal ish nuqtasida samarali bo'lishi mumkin. Biroq obyekt parametrlari o'zgarganda dastlab tanlangan regulator koeffitsientlari optimal bo'lmay qoladi. Ayniqsa, bir nechta kirish va chiqish parametrlariga ega jarayonlarda o'zaro bog'lanishlar kuchli bo'lsa, klassik regulatorlarni sozlash murakkablashadi.

Neyron tarmoqlar bunday sharoitda texnologik obyektning analitik modelini to'liq qurmasdan turib, kirish va chiqish signallari o'rtasidagi nolinear munosabatlarni ma'lumotlardan o'rganish imkonini beradi. Feed-forward neural network qisqa xotirali yoki statik munosabatlar uchun, recurrent neural network va LSTM/GRU esa vaqt bo'yicha kechikish hamda dinamik bog'lanishlarni ifodalash uchun qulaydir.

Model predictive control texnologik jarayonlarni optimal boshqarishning kuchli vositalaridan biri hisoblanadi. MPC kelajakdagi jarayon holatini model yordamida prognozlaydi, ma'lum vaqt oralig'i uchun boshqaruv ketma-ketligini optimallashtiradi va faqat birinchi boshqaruv ta'sirini obyektga uzatadi. Keyingi vaqt qadamida yangi o'lchov asosida optimallashtirish takrorlanadi.

Neyron tarmoq bilan MPCni birlashtirish, ayniqsa fizik model yaratish qiyin bo'lgan nolinear jarayonlarda istiqbolli hisoblanadi. Biroq neyron modelning ishlashi uning o'qitilgan ma'lumotlar diapazoniga bog'liq. Jarayon yangi rejimga o'tganda prediction error oshishi va controller noto'g'ri qaror qabul qilishi mumkin.

Shu sabab adaptiv boshqaruvning asosiy vazifasi neyron modelni faqat bir marta o'qitish emas, balki uning ishonchliligini doimiy kuzatish, model va real obyekt o'rtasidagi

tafovutni aniqlash va zarur hollarda model parametrlarini xavfsiz ravishda yangilashdan iborat.

Ushbu maqolaning maqsadi texnologik jarayonlarni boshqarish uchun neyron tarmoqqa asoslangan adaptiv model va algoritm arxitekturasini ishlab chiqish, turli neyron modellarni qiyoslash hamda model identifikatsiyasi, online adaptation va MPCni yagona boshqaruv sikliga birlashtirishdan iborat.

METODOLOGIYA VA ADABIYOTLAR TAHLILI

Tadqiqot tizimli va qiyosiy-analitik yondashuv asosida olib borildi. Neyron tarmoqlarning texnologik jarayonlarni identifikatsiyalash va boshqarishdagi o'rni, model predictive control, data-driven MPC, adaptive control va physics-informed neural networks bo'yicha ilmiy ishlar umumlashtirildi.

Ren va hammualliflar neural network modelling for MPC yo'nalishida FNN, RNN, GRU, LSTM va encoder-decoder arxitekturalarini tahlil qilgan. Ushbu modellar nolinear kimyoviy jarayonlarda prediction model sifatida qo'llanishi mumkin, ammo training sifati va closed-loop performance alohida baholanishi lozim.

Morato va Felix data-driven MPC bo'yicha adaptiv boshqaruv, reinforcement learning va trajectory-based usullar rivojlanayotganini ta'kidlaydi. Mazkur yondashuvlarning umumiy jihat - jarayon modeli haqida to'liq analitik ma'lumot bo'lmagan holatda ma'lumotlar asosida boshqaruv qarorini shakllantirishdir.

Physics-informed neural network yondashuvida neyron tarmoqning yo'qotish funksiyasiga fizik model tenglamalarining residuali kiritiladi. Natijada model faqat ma'lumotdagi statistik bog'lanishni emas, texnologik jarayonning fizik qonuniyatlarini ham hisobga oladi.

Taklif qilinayotgan adaptiv model umumiy ko'rinishda $y(k+1)=f\theta[y(k), y(k-1), \dots, u(k), u(k-1), d(k)]$ shaklida ifodalanadi. Bu yerda y jarayon chiqishi, u boshqaruv ta'siri, d tashqi buzilishlar, θ esa neyron tarmoq parametrlari hisoblanadi.

MPC optimallashtirish mezonini setpoint tracking xatosi, control effort va constraint violation penaltylarni birlashtiradi. Shu sabab controllerning maqsadi faqat setpointga tez

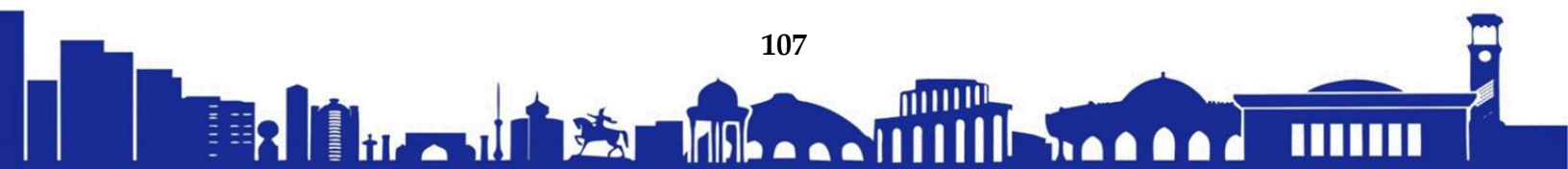
yetish emas, balki boshqaruv harakatini silliq va texnologik xavfsizlik talablariga mos saqlashdir.

Adaptiv mexanizmida neyron model har bir vaqt qadamida majburiy qayta o'qitilmaydi. Prediction residual belgilangan chegaradan ohsa yoki model confidence ko'rsatkichi pasaysa, online update ishga tushadi. Ushbu tamoyil event-triggered adaptation sifatida qaraladi.

NATIJALAR

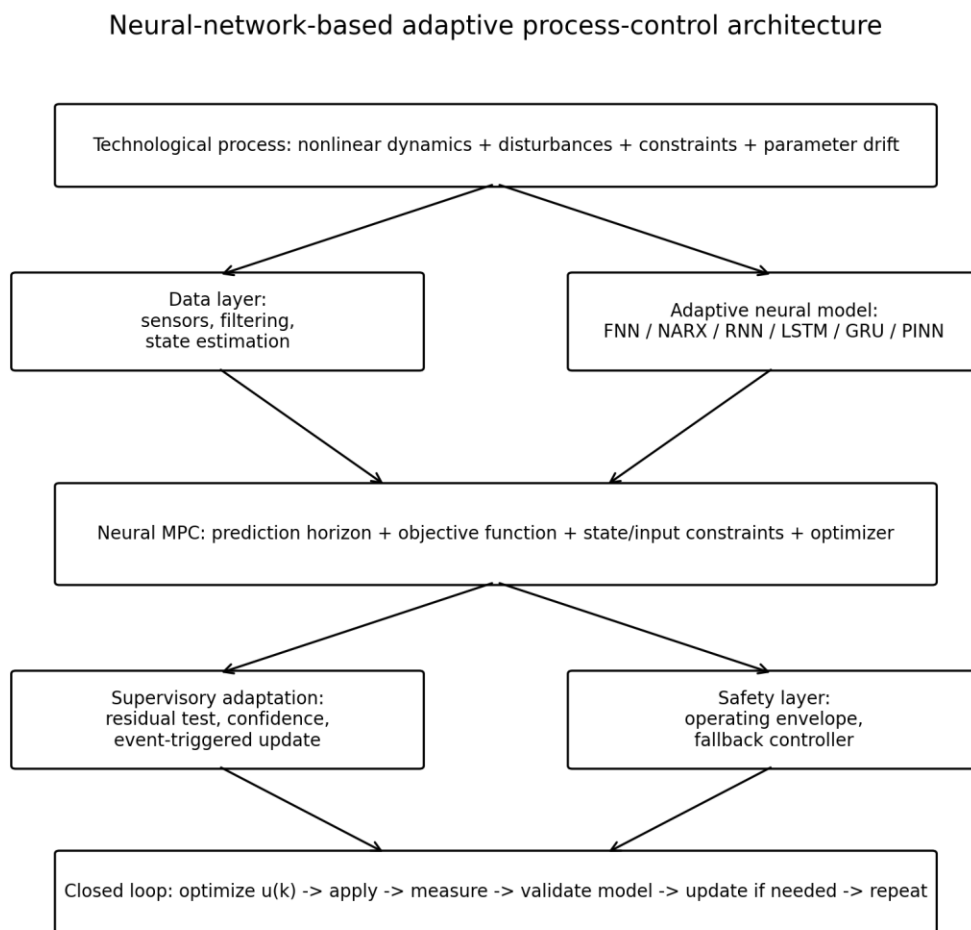
Tahlil natijasida texnologik jarayonlarni neyron tarmoq asosida adaptiv boshqarish uchun uch pog'onali arxitektura shakllantirildi. Birinchi pog'ona sensor va ma'lumotlarni qayta ishlash qatlami bo'lib, bunda signal filtrlash, anomal o'lchovlarni aniqlash va jarayon holatini shakllantirish bajariladi. Ikkinchi pog'ona neyron prediktor, uchinchi pog'ona esa MPC va supervisory adaptation blokidan iborat.

Model turi	Afzalligi	Vaqt xotirasi	Online moslashuv	Hisoblash yuklamasi	Qo'llash holati
FNN/MLP	Oddiy va tez approksimatsiya	Laglar tashqaridan	Oson	Past-o'rta	Tez dinamika
NARX	Input-output history aniq	Ha	Yaxshi	O'rta	Sanoat identifikatsiyasi
RNN	Ichki dinamik state	Ha	Mumkin	O'rta	Nolinear dinamik obyekt
LSTM/GRU	Uzoq bog'lanishni ushlaydi	Kuchli	Mumkin	O'rta-yuqori	Kechikishli jarayon



PINN	Fizik constraintni kiritadi	Modelga bog‘liq	Mumkin	Treningda yuqori	Ma’lumot cheklangan holat
------	-----------------------------	-----------------	--------	------------------	---------------------------

1-jadval. Texnologik jarayon boshqaruvida neyron model arxitekturalarining qiyosiy xususiyatlari.



1-rasm. Neyron tarmoqqa asoslangan adaptiv texnologik jarayon boshqaruvining integratsiyalashgan arxitekturası.

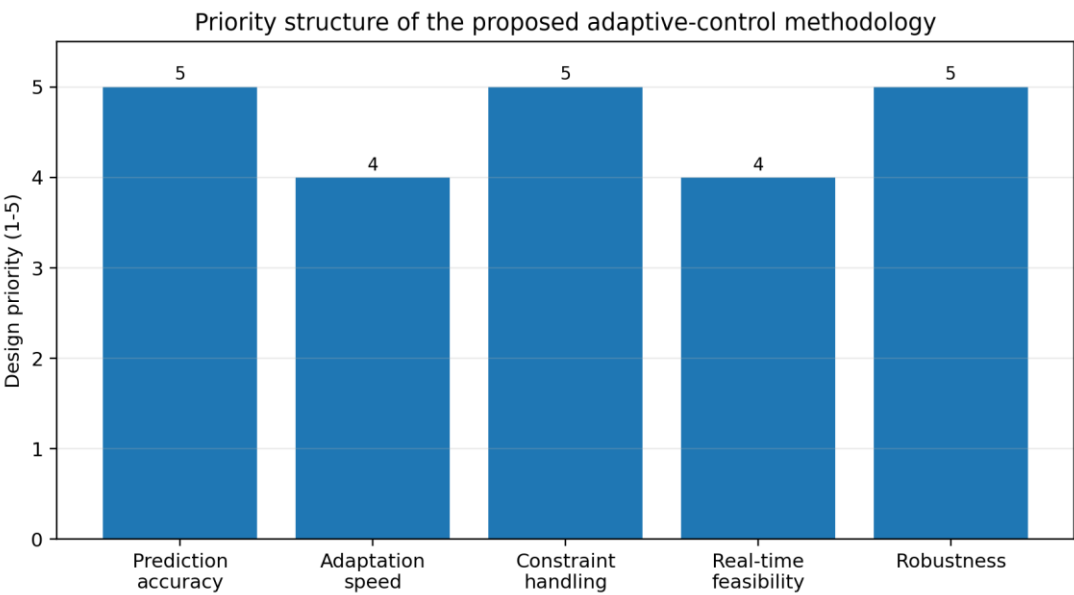
Taklif etilgan arxitekturada supervisory layer model xatosi, sensor anomaliyasi va operating regionni nazorat qiladi. Prediction residual normal diapazonda bo‘lsa, neyron prediktor faqat inference rejimida ishlaydi. Residual barqaror ravishda oshganda learning rate, training window va regularization cheklovlari bilan online update faollashtiriladi.



MPC cost funksiyasi setpoint tracking xatosi, control effort va constraint violation penaltydan iborat bo‘lishi mumkin. Shu sabab neyron modelga asoslangan controllerning maqsadi faqat setpointga tez yetib borish emas, actuator harakatini silliq saqlash va texnologik cheklovlardan chiqmaslikdir.

Bosqich	Kirish	Hisoblash	Chiqish	Xavf	Himoya mexanizmi
Data validation	Sensor stream	Filter va anomaly check	Clean state	Bad sensor	Quality flag
Neural prediction	y,u,d history	RNN/NARX/PIN N inference	Predicted states	Model drift	Residual monitor
Adaptation trigger	Prediction residual	Threshold/confidence logic	Update/no update	Overfitting	Dead-band
MPC optimization	NN model + constraints	Finite-horizon optimization	$u^*(k...k+N)$	Infeasible solve	Soft constraint/fallback
Control action	First optimal move	Actuator saturation	$u(k)$	Unsafe extrapolation	Operating envelope
Learning log	Closed-loop data	Windowed training	Updated θ	Forgetting	Bounded update

2-jadval. Neural adaptive MPC algoritmining tavsiya etiladigan bosqichlari.



1-diagramma. Taklif etilgan adaptiv boshqaruv metodologiyasida dizayn prioritetlari. Bu diagramma tajriba statistikasi emas, metodik ustuvorlikni koʻrsatadi.

Indikator	Mazmuni	Yaxshi natija	Boshqaruvdagi roli	Izoh
RMSE	Prognoz xatosi	Past	Neural model aniqligi	Offline va closed-loop alohida baholanadi
IAE	Integral absolute error	Past	Tracking sifati	Uzoq davom etuvchi xatoni koʻrsatadi
Overshoot	Ortiqcha oshish	Past	Dinamik sifat	Xavfsizlik limitlari bilan bogʻliq
Constraint violations	Cheklov buzilishi	0	Xavfsizlik	Hard/soft constraint farqlanadi

Solver time	Hisoblash vaqti	Sample timedan kichik	Real-time feasibility	Warm-start muhim
Prediction residual	Model-real tafovuti	Barqaror	Drift detection	Adaptation trigger

3-jadval. Adaptiv boshqaruv tizimini baholash indikatorlari.

MUHOKAMA

Neyron tarmoqlar asosidagi adaptiv boshqaruvning asosiy afzalligi analitik modeli murakkab bo'lgan texnologik obyektlarni ma'lumotlar asosida ifodalash imkoniyatidir. Bu ayniqsa nolinear, ko'p o'zgaruvchili va vaqt bo'yicha parametrlari o'zgaruvchi jarayonlarda muhim.

Biroq prediction accuracy va control performance bir xil tushuncha emas. Neural model offline datasetda yuqori aniqlik ko'rsatishi mumkin, biroq yopiq konturda controller bilan ishlaganda kichik model xatosi ham boshqaruv harakatlari orqali kuchayishi mumkin.

Shu sabab neural modelni baholashda faqat validation loss emas, closed-loop RMSE, IAE, overshoot, constraint violation va real-time solver time ham kuzatilishi kerak.

Neyron modelning yana bir xavfi training distributiondan tashqariga chiqishdir. Model faqat ma'lum operating regionda o'qitilgan bo'lsa, undan tashqaridagi extrapolation ishonchsiz bo'lishi mumkin. Bunday vaziyatda operating envelope va fallback controller alohida ahamiyat kasb etadi.

Online learning ham ehtiyotkorlik bilan qo'llanishi kerak. Juda katta learning rate modelning disturbance yoki sensor shovqiniga ortiqcha moslashishiga olib keladi. Juda kichik learning rate esa haqiqiy model driftni kech qoplaydi. Event-triggered adaptation ushbu kompromissni boshqarish imkonini beradi.

RNN va LSTM modellari vaqtli jarayonlarni yaxshi tasvirlasa-da, online MPC ichida ularning hisoblash narxi yuqori bo'lishi mumkin. Shu sabab architecture complexity sample time bilan muvofiqlashtirilishi zarur. Ayrim jarayonlarda ixcham NARX yoki MLP model amaliy jihatdan foydaliroq bo'lishi mumkin.

PINN yondashuvi data-driven va first-principles modellar orasidagi kompromisdir. Fizik constraintlar model extrapolationini yaxshilashi mumkin, biroq murakkab differensial tenglamalar uchun training xarajati sezilarli oshadi.

Sanoat joriy etishda interpretability va operator ishonchi ham muhim. Neural controller tavsiya qilgan control actionning sababini operatorga tushuntirish qiyin bo'lsa, uning safety-critical jarayonda qabul qilinishi cheklanadi. Shu bois confidence measure, alarm va fallback logic muhandislik talabi sifatida qaralishi kerak.

Safety instrumented system, hard interlock va actuator limits neural controllerni almashtirmaydi. Adaptiv neyron controller normal operating envelope ichida performance optimization vazifasini bajarishi, mustaqil xavfsizlik qatlamlari esa saqlanib qolishi kerak.

Kelgusidagi amaliy tadqiqot real kimyo, neft-kimyo, metallurgiya yoki energetika obyektida neural soft sensor, adaptive NN-MPC, uncertainty quantification va event-triggered adaptationni bir tizimda baholashga qaratilishi maqsadga muvofiq.

XULOSA

Neyron tarmoqlarga asoslangan adaptiv modellar texnologik jarayonlarning nolinearligi, parametr drift va murakkab o'zaro bog'lanishlarini ma'lumotdan o'rganish imkonini beradi. Ularni MPC bilan birlashtirish prognoz, optimallashtirish va constraint boshqaruvini yagona yopiq konturga birlashtiradi.

FNN va NARX nisbatan yengil real-time model sifatida, RNN/LSTM/GRU vaqtli dinamika uchun, PINN esa data va fizik qonunlarni birlashtirish uchun mos. Model tanlovi prediction accuracy bilan birga hisoblash va stability talablari asosida bajarilishi kerak.

Adaptiv algoritmnining eng muhim elementi online trainingning o'zi emas, model xatosini ishonchli aniqlash va qachon moslashish kerakligini belgilashdir. Trigger-based adaptation, bounded updates va fallback controller sanoat xavfsizligi uchun muhim.

Amaliy joriy etishda neural predictor-MPC tizimi sensor quality monitoring, uncertainty margin, hard safety constraints, operator supervision va validated fallback bilan birgalikda loyihalanishi kerak.

Shundagina neyron tarmoq texnologik jarayonlarni boshqarishda tajriba vositasidan ishonchli engineering komponentiga aylanishi mumkin.

FOYDALANILGAN ADABIYOTLAR (APA 7)

1. Ren, Y. M., Alhajeri, M. S., Luo, J., Chen, S., Abdullah, F., Wu, Z., & Christofides, P. D. (2022). A tutorial review of neural network modeling approaches for model predictive control. *Computers & Chemical Engineering*, 165, 107956. <https://doi.org/10.1016/j.compchemeng.2022.107956>
2. Morato, M. M., & Felix, M. S. (2024). Data science and model predictive control: A survey of recent advances on data-driven MPC algorithms. *Journal of Process Control*, 144, 103327.
3. Xu, Q., Dong, J., Peng, K., & Yang, X. (2024). A novel method of neural network model predictive control integrated process monitoring and applications to hot rolling process. *Expert Systems with Applications*, 237, 121682.
4. Model Predictive Control using Physics Informed Neural Networks for Process Systems. (2024). *IFAC-PapersOnLine*, 58(14), 775-780.
5. Al Bannoud, M., da Silva, C. A. M., & Martins, T. D. (2024). Applications of metaheuristic optimization algorithms in model predictive control for chemical engineering processes: A systematic review. *Annual Reviews in Control*, 58, 100973.
6. Turan, E. M., & Jäschke, J. (2024). Closed-loop training of static output feedback neural network controllers for large systems: A distillation case study. *Journal of Process Control*, 143, 103302.
7. Sancı, M. E., & Günel, G. Ö. (2024). Neural network based adaptive inverse optimal control for non-affine nonlinear systems. *Neural Processing Letters*, 56, 46.
8. Panzer, M., & Gronau, N. (2024). Designing an adaptive and deep learning based control framework for modular production systems. *Journal of Intelligent Manufacturing*, 35, 4113-4136.
9. Narendra, K. S., & Parthasarathy, K. (1990). Identification and control of dynamical systems using neural networks. *IEEE Transactions on Neural Networks*, 1(1), 4-27.
10. Åström, K. J., & Wittenmark, B. (2008). *Adaptive Control* (2nd ed.). Dover Publications.

11. Haykin, S. (2009). Neural Networks and Learning Machines (3rd ed.). Pearson.
12. Goodfellow, I., Bengio, Y., & Courville, A. (2016). Deep Learning. MIT Press.
13. Rawlings, J. B., Mayne, D. Q., & Diehl, M. (2017). Model Predictive Control: Theory, Computation, and Design (2nd ed.). Nob Hill Publishing.
14. Camacho, E. F., & Bordons, C. (2007). Model Predictive Control (2nd ed.). Springer.
15. Ljung, L. (1999). System Identification: Theory for the User (2nd ed.). Prentice Hall.