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SANOAT KORXONALARIDA USKUNALAR HOLATINI SUN'IY INTELLEKT ORQALI BASHORATLASH

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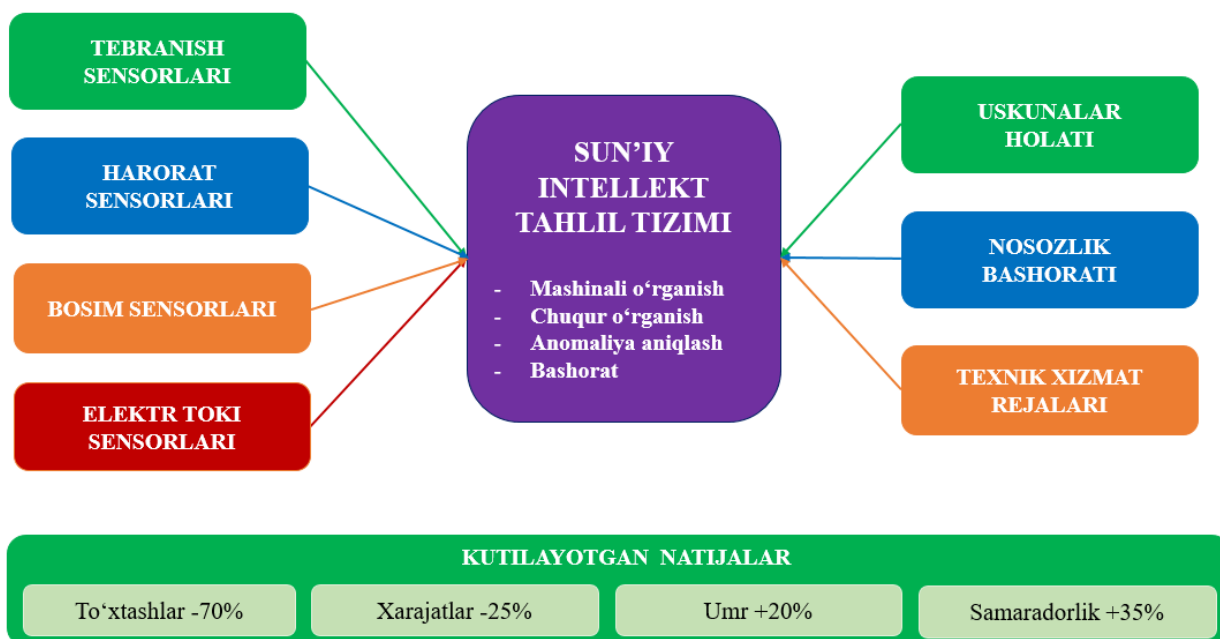
Abstract: This article examines predictive maintenance (PdM) systems for predicting equipment condition using artificial intelligence (AI) in industrial plants. The study utilizes theoretical analysis, a comparative study of international practices, and methods for evaluating the effectiveness of machine learning, deep learning, and signal processing algorithms in predicting equipment failures. The results demonstrate that AI-based PdM systems can significantly reduce unexpected downtime, optimize maintenance costs, and extend equipment service life. Using international experience as examples, the PdM methods of leading companies, such as Rolls-Royce, Caterpillar, ThyssenKrupp, and SKF, are analyzed and their results are presented. The key stages, technical requirements, and cost effectiveness of implementing AI-based PdM systems are substantiated.

Keywords: AI, PdM, predictive maintenance, equipment condition, failure prediction, remaining service life, vibration analysis, anomaly detection, machine learning, deep learning, signal processing, IoT, real-time monitoring, Industry 4.0.

KIRISH

Zamonaviy sanoat korxonalarida uskunalarning uzluksiz va samarali ishlashi ishlab chiqarish jarayonlarining barqarorligini ta'minlashda hal qiluvchi ahamiyat kasb etadi. Kutilmagan uskunar nosozliklari ishlab chiqarishning to'xtab qolishiga, katta moliyaviy yo'qotishlarga va xavfsizlik muammolariga olib kelishi mumkin. An'anaviy texnik xizmat yondashuvlari - reaktiv (buzilgandan keyin ta'mirlash) va profilaktik (belgilangan jadval bo'yicha ta'mirlash) - ko'pincha samarasiz bo'lib, ortiqcha xarajatlar yoki kutilmagan to'xtashlarga olib keladi. Sun'iy intellekt (SI) asosidagi bashoratli texnik xizmat (Predictive Maintenance - PdM) bu muammolarni hal qilishning eng samarali vositasiga aylandi.

O'zbekistonda sanoatni modernizatsiya qilish va ishlab chiqarish samaradorligini oshirish davlat siyosatining ustuvor yo'nalishi sifatida belgilangan. Bu sharoitda mahalliy korxonalarda SI asosidagi PdM tizimlarini joriy etish orqali uskunalarning ishonchligini oshirish va texnik xizmat xarajatlarini optimallashtirish alohida ahamiyat kasb etmoqda. Shu bois, ushbu maqolada sanoat korxonalarida uskunar holatini SI orqali bashoratlash bo'yicha zamonaviy yondashuvlar, xalqaro tajribalar va amaliy strategiyalar tahlil qilinadi. Jumladan, tebranish tahlili, harorat monitoring, akustik emissiya tahlili va ko'p sensorli diagnostika kabi usullar hamda Rolls-Royce, Caterpillar, ThyssenKrupp va SKF kabi yetakchi kompaniyalarning tajribalari ko'rib chiqiladi (1-rasm).



1-rasm. Sun'iy intellekt orqali uskunalar holatini bashoratlash tizimi

MAVZUGA OID ADABIYOTLAR SHARHI

Bashoratli texnik xizmat sohasida ko'plab olimlar tomonidan chuqur tadqiqotlar olib borilgan. R.Mobley o'z tadqiqotlarida bashoratli texnik xizmatning asosiy tamoyillari va texnologiyalarini ilmiy asoslab bergan. Uning fikricha, PdM tizimlari uskunalarining haqiqiy holatiga asoslanib texnik xizmat ko'rsatish imkonini beradi, bu esa ortiqcha yoki yetarli bo'lmagan texnik xizmatning oldini oladi.

T.Carvalho, F.Souares, R.Vita, R.Francisco mashinali o'rganish usullarining bashoratli texnik xizmatdagi qo'llanilishi bo'yicha keng ko'lamli adabiyotlar tahlilini amalga oshirganlar. Ularning tadqiqotlariga ko'ra, Random Forest, Support Vector Machine, Neural Networks va Deep Learning algoritmlar PdM vazifalarida eng ko'p qo'llaniladigan usullar hisoblanadi. Ular sensor ma'lumotlarini qayta ishlash va nosozliklarni bashorat qilishda chuqur o'rganish algoritmlarining yuqori samaradorligini ta'kidlaganlar.

Y.Ran, X.Zhou, P.Lin, Y.Wen, R.Deng tomonidan olib borilgan tadqiqotda PdM tizimlarining arxitekturasini, maqsadlari va yondashuvlari atroflicha tahlil qilingan. Ularga ko'ra, zamonaviy PdM tizimlari IoT, bulutli hisoblash va SI texnologiyalarining integratsiyasiga asoslanadi. Tadqiqotlar shuni ko'rsatadiki, SI asosidagi PdM tizimlari an'anaviy usullarga nisbatan nosozliklarni bashorat qilishda 30-50% yuqori aniqlikka erishadi.

Lei, Li, Guo va boshqalar (2018) uskunalar salomatligini prognozlash bo'yicha keng ko'lamli tadqiqot olib borganlar. Ularning ilmiy qarashlariga ko'ra, qolgan foydalanish muddatini (Remaining Useful Life - RUL) bashorat qilish PdM tizimlarining asosiy vazifasi hisoblanadi. Bu yondashuv texnik xizmat ko'rsatish vaqtini optimal aniqlash va kutilmagan nosozliklarning oldini olish imkonini beradi.

Tadqiqot metodologiyasi

Tadqiqot metodologiyasi nazariy va amaliy yondashuvlarning uyg'unligiga asoslangan. Avvalo, SI asosidagi bashoratli texnik xizmat bo'yicha ilmiy adabiyotlar va xalqaro tajribalar tahlil qilindi. Qiyosiy tahlil usuli orqali Rolls-Royce, Caterpillar, ThyssenKrupp va SKF kabi yetakchi kompaniyalarning ilg'or amaliyotlari o'rganildi. Bundan tashqari, asosiy PdM samaradorligi ko'rsatkichlari - Mean Time Between Failures (MTBF), Mean Time To Repair (MTTR), Overall Equipment Effectiveness (OEE), Unplanned Downtime va Maintenance Cost - indikator sifatida qo'llanib, SI PdM tizimlarining samaradorligi baholandi. Tadqiqotda turli SI algoritmlarini taqqoslash, keys-stadi tahlili va iqtisodiy samaradorlikni baholash usullaridan foydalanilgan.

Tahlil va natijalar

Tadqiqot davomida, SI asosidagi PdM tizimlarining asosiy komponentlari va ularning samaradorlik ko'rsatkichlariga ta'siri (MTBF, MTTR, OEE, Downtime, Maintenance Cost) tahlil qilindi. Zamonaviy sharoitda sanoat korxonalari SI texnologiyalarini quyidagi asosiy yo'nalishlarda qo'llash orqali uskunalar holatini bashoratlamoqda.

1. Tebranish tahlili (Vibration Analysis). Tebranish tahlili aylanuvchi uskunalar - elektr motorlar, nasoslar, kompressorlar, reduktorlar va turbinalar holatini aniqlashning eng keng tarqalgan usuli hisoblanadi. SI

algoritmalar tebranish signallarini tahlil qilib, muvozanatsizlik, noto'g'ri tekislash, podshipnik eskirishi va boshqa nosozlik turlarini aniqlaydi. Fast Fourier Transform (FFT), Wavelet Transform va Envelope Analysis kabi signal qayta ishlash usullari SI modellari uchun xususiyatlarni ajratib olish imkonini beradi. Amaliy tadqiqotlar shuni ko'rsatadiki, SI asosidagi tebranish tahlili nosozliklarni 90 foizdan yuqori aniqlik bilan bashorat qilishi va podshipnik nosozliklarini 1-3 oy oldin aniqlashi mumkin.

2. Harorat monitoring (Thermal Monitoring). Uskunalar harorat o'zgarishlari ko'pincha yaqinlashib kelayotgan nosozliklarning dastlabki belgisi hisoblanadi. SI algoritmalar harorat sensorlari va infraqizil kameralar ma'lumotlarini tahlil qilib, normal harorat diapazonidan og'ishlarni aniqlaydi. Elektr uskunalarida ortiqcha qizish, mexanik uskunalarida ishqalanish muammolari va issiqlik almashinish tizimlarida samarasizliklar harorat tahlili orqali aniqlanadi. Chuqur o'rganish algoritmalar, ayniqsa konvolyutsion neyron tarmoqlar (CNN), infraqizil tasvirlarni tahlil qilishda yuqori samaradorlik ko'rsatadi. Tadqiqotlar shuni ko'rsatadiki, SI asosidagi harorat monitoring elektr uskunalaridagi nosozliklarni 85-95% aniqlik bilan bashorat qilishi mumkin.

3. Akustik emissiya va ultratovush tahlili. Akustik emissiya (AE) va ultratovush tahlili uskunalaridagi mikro-yoriqlar, sizib chiqishlar va eskirish jarayonlarini aniqlash imkonini beradi. SI algoritmalar akustik signallarni tahlil qilib, normal ishlash tovushlaridan farq qiluvchi anomaliyalarni aniqlaydi. Bu usul ayniqsa bosim ostidagi idishlar, quvurlar, klapanlar va payvandlash choklarini tekshirishda samarali. Rekurrent neyron tarmoqlar (RNN) va LSTM arxitekturalari vaqt qatorlari ko'rinishidagi akustik ma'lumotlarni tahlil qilishda qo'llaniladi. Amaliy tajribalar shuni ko'rsatadiki, SI asosidagi akustik tahlil sizib chiqishlarni 95% dan yuqori aniqlik bilan, yoriqlarni esa ular kritik darajaga yetishidan oldin aniqlashi mumkin.

4. Moylash va yog' tahlili (Oil Analysis). Moylash moyi tahlili uskunalarining ichki holatini baholash va eskirish jarayonlarini kuzatish imkonini beradi. SI algoritmalar moydagi metall zarrachalar, ifoslanish darajasi, qovushqoqlik o'zgarishlari va kimyoviy xususiyatlar haqidagi ma'lumotlarni tahlil qilib, uskunalar holatini baholaydi. Spektral tahlil natijalarini SI modellari bilan qayta ishlash tishli uzatmalar, podshipniklar va gidravlik tizimlarning eskirish holatini aniqlash imkonini beradi. Tadqiqotlar shuni ko'rsatadiki, SI asosidagi yog' tahlili uskunalar eskirishini 80-90% aniqlik bilan bashorat qilishi va texnik xizmat xarajatlarini 20-30% ga kamaytirishi mumkin.

5. Ko'p sensorli integratsiyalashgan diagnostika. Zamonaviy PdM tizimlari turli sensor ma'lumotlarini birlashtirib tahlil qiladi - tebranish, harorat, bosim, elektr toki, akustik signallar va boshqalar. Ko'p sensorli yondashuv uskunalar holatini to'liqroq baholash va nosozliklarni yuqoriroq aniqlik bilan bashorat qilish imkonini beradi. SI algoritmalar, ayniqsa chuqur o'rganish modellari, turli sensor ma'lumotlaridan murakkab bog'liqliklarni aniqlash va yashirin nosozlik belgilarini topish qobiliyatiga ega. Sensor Fusion va Multi-modal Learning yondashuvlari ko'p sensorli ma'lumotlarni samarali qayta ishlash imkonini beradi. Tadqiqotlar shuni ko'rsatadiki, ko'p sensorli SI tizimlari bitta sensor turiga asoslangan tizimlarga nisbatan 20-30% yuqori aniqlikka erishadi.

6. Qolgan foydalanish muddatini bashorat qilish (RUL Prediction). Qolgan foydalanish muddatini (Remaining Useful Life - RUL) bashorat qilish PdM tizimlarining asosiy vazifasi hisoblanadi. SI algoritmalar sensor ma'lumotlarini tahlil qilib, uskunaning buzilishiga qancha vaqt qolganini bashorat qiladi. Bu ma'lumot texnik xizmat ko'rsatish vaqtini optimal rejalashtirish, ehtiyot qismlarni o'z vaqtida buyurtma qilish va kutilmagan to'xtashlarning oldini olish imkonini beradi. LSTM, Transformer va Physics-Informed Neural Networks (PINN) kabi arxitekturalar RUL bashoratida yuqori aniqlik ko'rsatadi. Amaliy tajribalar shuni ko'rsatadiki, SI asosidagi RUL bashorati uskunaning haqiqiy buzilish vaqtini $\pm 10-15\%$ aniqlik bilan aniqlashi mumkin.

Xalqaro tajribani o'rganish natijasida yetakchi kompaniyalarning SI asosidagi PdM tizimlari va erishgan natijalari taqqoslandi. Quyidagi jadvalda dunyo yetakchi kompaniyalarining PdM amaliyotlari keltirilgan (1-jadval).

1-jadval

Yetakchi kompaniyalarning SI asosidagi PdM amaliyotlari

№	Kompaniya	PdM yondashuvi va erishilgan natijalar
1	Rolls-Royce (Buyuk Britaniya)	- Aviatsiya dvigatellarini real vaqtda monitoring qilish, TotalCare xizmati; - SI yordamida dvigatel nosozliklarini 50% oldin bashorat qilish; - Kutilmagan to'xtashlarni 75% ga qisqartirish, xarajatlarni 30% ga kamaytirish.
2	Caterpillar (AQSh)	- Cat Connect platformasi orqali 500,000+ uskunani monitoring qilish; - SI asosidagi bashoratli tahlil orqali uskunalar ishlash muddatini 25% ga oshirish; - Mijozlarga proaktiv texnik xizmat tavsiyalari, ROI ni 2-3 barobar oshirish.
3	ThyssenKrupp (Germaniya)	- MAX platformasi orqali 120,000+ liftni real vaqtda monitoring; - SI yordamida nosozliklarni 50% oldin bashorat qilish va oldini olish; - Lift to'xtab qolish vaqtini 50% ga qisqartirish, mijozlar qoniqishini oshirish.
4	SKF (Shvetsiya)	- Podshipniklar va aylanuvchi uskunalar uchun SI asosidagi diagnostika; - SKF Enlight platformasi orqali avtomatlashtirilgan tebranish tahlili; - Podshipnik nosozliklarini 3-6 oy oldin bashorat qilish, 90%+ aniqlik.

Jadvaldan ko'rinib turganidek, Rolls-Royce aviatsiya dvigatellarini real vaqtda monitoring qilish va bashoratli texnik xizmat ko'rsatishda yetakchi hisoblanadi. Caterpillar og'ir texnika sohasida keng miqyosli PdM platformasini muvaffaqiyatli joriy etgan. ThyssenKrupp liftlar va eskalatorlar sohasida SI asosidagi proaktiv texnik xizmat modelini yaratgan. SKF esa podshipniklar va aylanuvchi uskunalar diagnostikasi sohasida dunyo yetakchisi sifatida tan olingan.

Bizning fikrimizcha, SI asosidagi PdM tizimlarini samarali joriy etish uchun quyidagi asosiy omillarga e'tibor qaratish kerak:

- **Sensorlar infratuzilmasini yaratish** - bu PdM tizimlarining samarali ishlashi uchun asosiy shart hisoblanadi. Sifatli sensor ma'lumotlarisiz SI algoritmlari aniq bashorat bera olmaydi.

- **Tarixiy ma'lumotlarni to'plash va tahlil qilish** - SI modellarini o'rgatish uchun uskunalarining normal ishlashi va nosozliklari haqida yetarli tarixiy ma'lumotlar zarur.

- **Texnik xizmat jarayonlari bilan integratsiya** - PdM tizimlari natijalarini texnik xizmat jarayonlari, ehtiyot qismlar boshqaruvi va ishchi kuchi rejalash tizimlari bilan integratsiyalash zarur.

XULOSA VA TAKLIFLAR

SI asosidagi bashoratli texnik xizmat tizimlari sanoat korxonalarida uskunalar ishonchliligini oshirish va texnik xizmat xarajatlarini optimallashtirishning eng samarali vositasi hisoblanadi. Yuqorida ko'rib chiqilgan yo'nalishlar - tebranish tahlili, harorat monitoring, akustik tahlil, yog' tahlili, ko'p sensorli diagnostika va RUL bashorati - korxonalarga uskunalar holatini to'liq nazorat qilish imkonini beradi. Yetakchi xalqaro kompaniyalar tajribasi ko'rsatmoqdaki, SI asosidagi PdM kutilmagan to'xtashlarni 50-75% ga qisqartirish, texnik xizmat xarajatlarini 25-30% ga kamaytirishga va uskunalar umrini 20-40% ga uzaytirishga erishishi mumkin.

Shu bois, sanoat korxonalari rahbariyati va texnik mutaxassislari uchun bugungi kun talabi - SI asosidagi PdM tizimlarining imkoniyatlarini o'rganish, xalqaro tajribaning eng yaxshi usullarini tatbiq etish va o'z korxonalari uchun optimal PdM strategiyasini ishlab chiqishdir. SI asosidagi bashoratli texnik xizmatni muvaffaqiyatli joriy etgan korxonalar uskunalarining ishonchliligini ta'minlaydilar va barqaror raqobat ustunligiga ega bo'ladilar.

Foydalanilgan adabiyotlar ro'yxati

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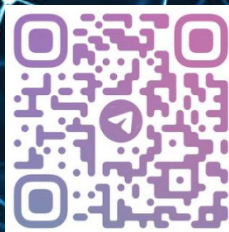
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