European Journal of Interdisciplinary Research and Development
Volume- 48 February- 2026
Website: www.ejird.journalspark.org ISSN (E): 2720-5746

DETERMINING THE NEED FOR THE APPLICATION OF INDUSTRIAL ROBOTS IN HIGH-TEMPERATURE FURNACES

Yusupbekov Nodirbek Rustambekovich 1,
Matokubov Nurbek Rustamovich 2*,
Xolmanov O'tkir Uktam ugli 3,
Iskandarov Zohid Ergashboevich 4
1, 2, 3, 4 Tashkent State Technical University. Address: 2 Universitet st., 100095, Tashkent City, Republic of Uzbekistan
Email: 1 dodabek@mail.ru, 2 nm85@mail.ru, 3 xolmanov0902@mail.ru, 4 Zohid0059@gmail.com
*Corresponding Author

Abstract
High-temperature industrial furnaces are widely used in metallurgy, glass production, ceramics, and casting processes, where operating temperatures typically range from 800°C to 1600°C. Such extreme conditions pose serious risks to human operators and impose strict technical requirements on equipment. This study analyzes the technological, safety, and economic justification for implementing industrial robotic systems in high-temperature furnace environments. The research integrates mechanical design considerations, thermal management strategies, intelligent control systems, and organizational factors affecting robot deployment. Special attention is given to heat-resistant manipulators, passive and active cooling technologies, sensor protection mechanisms, and AI-based predictive control algorithms. The results demonstrate that robotization significantly enhances occupational safety, improves process stability, and increases energy efficiency. The study also discusses prospects for implementing robotic furnace systems in the context of industrial modernization in Uzbekistan.

Keywords: Industrial robots, high-temperature furnaces, human-robot collaboration, digital twin.

Introduction

High-temperature furnaces constitute a critical component of modern industrial production, particularly in metallurgy, glass manufacturing, ceramics, and casting operations. In these systems, process temperatures frequently range from 800°C to 1600°C, significantly limiting direct human involvement due to severe thermal exposure, hazardous materials, and physically demanding working conditions.

Recent advances in robotics and digital manufacturing have created new opportunities for automating furnace-related operations. Industrial robots are increasingly employed to reduce human exposure to hazardous environments, enhance production accuracy, and stabilize technological processes. International experience demonstrates that robotic systems in casting, glass forming, and heat-treatment processes can improve product quality by 15–25% and increase energy efficiency by 10–12% [1, 9-10].

However, the deployment of robots in high-temperature environments presents substantial technical challenges. These include thermal protection of mechanical and electronic components, selection of heat-resistant materials, integration of advanced cooling systems, and development of adaptive control algorithms capable of operating under extreme thermal loads. Therefore, determining the technological feasibility and strategic necessity of robot implementation in furnace operations represents a significant scientific and industrial task.

Numerous studies [1-5] identify three main areas for designing robots operating in high-temperature environments:

1. Design and thermal stability of mechatronic devices;
2. Automated control and monitoring systems;
3. Economic efficiency and safety factors.

The introduction of robots for technicians working in high-temperature metallurgical furnaces will increase work efficiency and ensure safety. Several scientific works have been conducted by foreign and domestic scientists aimed at solving these issues, in particular, Colla and colleagues [1] conducted a comprehensive study on the design and testing of a robotic workstation based on human-robot collaboration to automate the maintenance of a sliding gate in a large Italian steelmaking enterprise. The article notes that the maintenance operations of the sliding gate in the steel casting process involve high temperatures and physical loads, putting workers at risk for manual labor. The robot station automates hazardous operations, such as lifting heavy components and performing hazardous tasks, significantly reducing the risk of workers being exposed to high temperatures and injuries. In addition, it is based on human-robot collaboration - robots provide stability in performing difficult and dangerous tasks, while human operators manage complex and sensitive tasks. This approach combines technological capabilities with human experience and ensures effective task division. Overall, the study by Colla and colleagues [1] shows that human-centric robotization in high-temperature manufacturing environments increases safety, reduces worker physical workload, stabilizes processes, and develops operators' digital skills. This approach serves as a theoretical and practical basis for the implementation of robotic systems in high-temperature furnaces and the glass or metallurgical industries.

In addition, digitization and robotization processes in the metallurgical and glass industries have been fundamentally changing the industry over the past decade [11-14]. Branca et al. [2] argue that the introduction of digital technologies in the steel industry is not just about increasing production efficiency, but also about reshaping the entire industrial structure. Miśkiewicz and Wolniak [3] analyzed the practical application of the Industry 4.0 concept and scientifically substantiated the increase in automation, energy efficiency, and environmental sustainability in metallurgical enterprises through digital integration.

At the same time, the introduction of robots in high-temperature stages of production is of particular importance from the point of view of safety and reliability. Gerstorfer et al. [5] analyzed real-world practices for improving safety using robots in melt shops and showed that automation in the melt shop environment minimized human risk. The MultiROB system developed by Hansert and Stech [15] is one of the advanced solutions in this direction, combining high accuracy, safety, and performance.

A study by Meisel and Pfeil [6] on the practical aspects of robotization analyzed 10 years of experience in continuous casting technology and demonstrated that robots can increase production stability and reduce the number of failures. In this direction, the “zero-operator” casting line developed by Demetika and Ferrari [7] allows for continuous production without human intervention.

The role of robots in kiln technology is particularly important. González-Ciordia and Fernández [8] demonstrated the improvement of reliability by redesigning mechanical components in kiln conveyor systems based on failure analysis. Meanwhile, Salcedo-Hernández et al. [9] developed a stable H_2-based temperature control system for steel plate reheating furnaces, achieving 98% accuracy.

Along with the mechanical part of robotic systems, vision, sensing, and path optimization systems are also important. Although the Q-Robot ROLL developed by Visentini and Demetlica [16] is an automatic cold billet cleaning system, its 3D vision and detection algorithms can also be successfully applied in high-temperature conditions. Also, collision-free path optimization methods developed by Wang et al. [17] provide effective trajectory control for conveyor robots in the metallurgical industry.

Significant progress has also been made in the area of sampling and hazardous materials management. Soltani [18] developed a 3R manipulator system for automatic sampling of molten metals, reducing human intervention. Schwarzbach [19] reported on the implementation of an automatic sampling system for liquid steel at the Lech Steelworks. Egger and Priesner [20] improved mechanical accuracy by upgrading sublance manipulators, which improved heat resistance by 40%.

Furthermore, Sedano and Baños [21] report that they have developed robots to safely handle slag and molten steel, dramatically reducing process risks. These results are consistent with the concept of human-robot collaboration (HRC) proposed by Deshpande et al. [22], in which robots perform heavy and dangerous operations while humans control the system remotely.

A study by Mandeep Dhanda and colleagues [23] highlights the importance of human-robot collaborative robotic systems in metallurgy as a means to protect human health, improve production safety, and automate processes. Such systems are particularly effective in processes such as molten steel sampling, slag cleaning and transportation, and furnace temperature control [24-29]. Metallurgical robots based on the human-robot collaborative concept operate in a remote or semi-autonomous mode, which ensures safety while maintaining production stability [30-36]. Therefore, such approaches to the development of robotic systems for high-temperature furnaces can improve efficiency by integrating AI algorithms, thermal sensors, and predictive monitoring systems.

This integration of digital industrial technologies allows for reduced human intervention, increased safety, and continuous digital control of production [26]. The HRI (Human-Robot Interaction) model developed by Laudante and Greco [37] extends this approach: through human-robot interaction, a balance is achieved between precision, ergonomics, and production quality [36-39].

In the scientific work conducted by Elankavi et al. [40], robot models for inspection tasks in pipelines and harsh environments were analyzed. These robots are aimed at overcoming the problems of movement in complex shapes and confined spaces in industrial environments, and the stability of movement and the continuity of the contact surface are ensured by the placement of wheels at uneven angles [41-44]. This approach serves as an important theoretical basis for industrial robots operating in high-temperature furnaces or inside process pipes, as it allows the design of mechatronic mechanisms that can adapt to thermal deformation and spatial constraints. Therefore, such movement strategies can be used to create industrial robots that maintain stable contact, balance, and heat resistance in high-temperature environments.

In addition, the analysis conducted by Sekhar et al. [45] shows that global development trends in the field of robotics within the framework of Industry 4.0 have emerged in 2011–2022. According to the results of the study, more than 3,000 scientific articles are published annually on the application of robots in heavy-duty work, which indicates intensive scientific activity aimed at integrating robots into intelligent manufacturing systems. At the same time, artificial intelligence (AI) and machine learning (ML) stand out as leading technologies in the automated control of robots, their application in thermal and manufacturing processes [46]. The article identifies promising directions for creating robot interoperability, sensor integration, and control mechanisms that are adaptive to thermal and load in Industry 4.0 systems.

Engelbert Harsandi Erik Suryadarma et al. [47] conducted a very effective analysis in the field of remote control of robots, namely, a systematic review of scientific works in the field of control using gaze estimation. According to them, they analyzed 237 articles published in the Scopus database from 2013 to 2023 and found that the average number of publications in the field of remote control of robots is 21.5 per year. Using gaze estimation, 44 articles were identified on robot control, most of which are related to the fields of health and social care (17), transport (12), and professional and scientific activities (8) [48-51]. This indicates that today the desire to use industrial robots in harsh environments is increasing day by day and can be a relevant topic for future research.

AI and predictive control technologies are also playing an increasingly important role in robotics. Saparrat and Monti [10] developed AI-based temperature prediction in electric arc furnaces, reducing energy consumption by 15% [27-29]. Ganesh et al. [52] proposed a model-based predictive control to accurately control the outlet temperature of an austenitizing furnace. The development of intelligent control systems is essential for the stable operation of modern industrial robots in high-temperature environments. In this regard, Yang et al. [53] proposed an integral fuzzy-sliding control method based on neural networks and developed a specification for real-time error correction in symmetric nonlinear systems. In addition, Lam, Xiao, and Chen [54] analyzed interval type-2 fuzzy models and showed their advantages in increasing accuracy and flexibility, which is relevant for control systems that are resistant to parameter changes under high temperature conditions. Zhang et al. [55] developed an observer-based algorithm that provides stable control against network delays and signal distortions. Tumari et al. [56] simplified the control of uncertain dynamic processes using a fuzzy logic-based fluid vibration suppression method. Meanwhile, Zhang et al. [57-58] developed a fast convergent control based on fixed-time sliding mode and disturbance observer for robot manipulators, which is a useful method for manipulators operating in high-temperature furnaces. Therefore, these scientific approaches justify the need to develop fuzzy, neural, and observer-integrated hybrid systems

European Journal of Interdisciplinary Research and Development
Volume- 48 February- 2026
Website: www.ejird.journalspark.org ISSN (E): 2720-5746

for effective control of robots in high-temperature furnaces.

Thus, the introduction of robotic systems for high-temperature furnaces not only ensures safety, but also combines digital sustainability, energy efficiency and technological innovation in the context of Industry 4.0. This direction is not only of technical but also strategic importance, becoming a key factor determining the competitiveness of modern metallurgical enterprises.

Temperature control in robots and its adaptation to high-temperature furnace conditions

The operation of robots in high-temperature furnaces imposes significant thermal loads on their mechanical and electronic components. The most important factor for the stable operation of the robot system in such conditions is the thermal management system. Thermal management methods in robots are divided into two main types: passive and active systems [26].

Passive thermal management systems

Passive systems do not require an external energy source and operate primarily on the principle of heat storage or dissipation (Table 1).

TABLE I. PASSIVE THERMAL MANAGEMENT SYSTEMS

№	Management system	Basic working principle
1.	Phase Change Materials (PCM)	absorbs or releases heat by changing from solid to liquid phase. These materials can be used to compensate for short-term thermal fluctuations in robotic manipulators near furnaces.
2.	Thermal Interface Materials (TIM)	Increases heat transfer between hot parts of the robot (motor, servo, actuator) and cold parts, thereby reducing uneven temperature distribution.
3.	Thermal insulation layers	It is installed in the metal body of the manipulator and reduces the impact of external radiation by 30–40%.

These passive methods provide mechanical durability to the robot without increasing energy consumption. They are particularly effective for short-term contacts in glass or metal melting furnaces.

Active thermal management systems

Active methods require active heat removal or cooling. Such systems consume energy but are highly efficient (Figure 1).

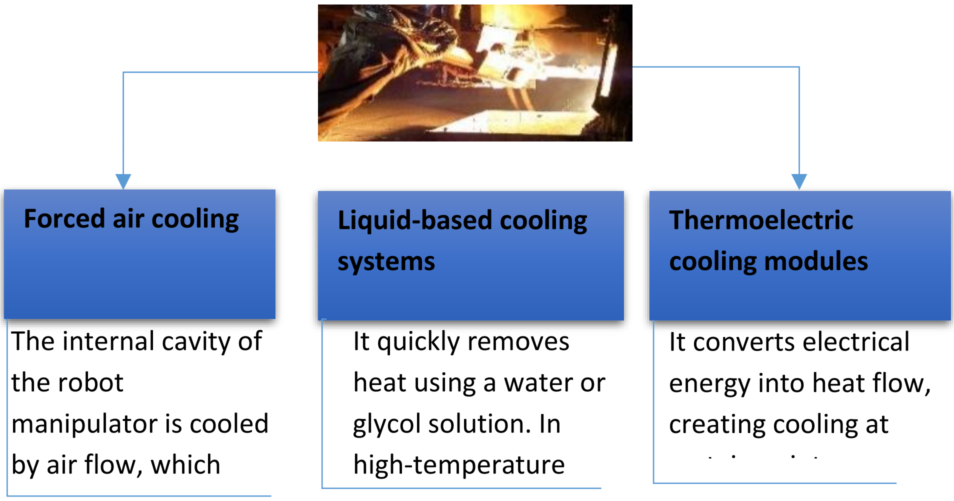

Fig. 1. Active thermal management systems technologies

European Journal of Interdisciplinary Research and Development
Volume- 48 February- 2026
Website: www.ejird.journalspark.org ISSN (E): 2720-5746

Active cooling systems can reduce heat by 60–75%, but they require additional energy consumption and maintenance.

These systems can be quite effective in using robots in high-temperature furnaces, but in some cases they may require additional energy, which means that they need to be improved. The most effective solution for this is to combine active and passive methods. For example, for a robot arm: inside - a liquid cooling system, outside - a ceramic-based thermal insulator, in the control unit - thermoelectric sensors, etc. Such systems can increase the service life of robots in high-temperature furnaces by 1.5–2 times, and reduce the frequency of servo motor failures by up to 40%. In addition, today we can observe a sharp development in the use of artificial intelligence in industrial robots.

As a result, temperature control can be developed in the following areas:

- artificial intelligence-based thermal monitoring systems - receive real-time information from sensors and select the optimal cooling mode.
- new generation materials (Advanced TIM, Graphene coating) - graphene coatings with high thermal conductivity increase the thermal stability of robots.
- digital Twin models - create optimal cooling designs by modeling temperature effects in a virtual environment.

The above analysis shows that in harsh production conditions, at temperatures from -30 to +1700, industrial robots are considered to be the closest partners of humans. In this regard, the leading scientists in the USA and China have a great advantage [45]. Today, high-temperature furnaces are widely used in the metallurgical and glass industries of Uzbekistan, but in most cases, manually controlled systems prevail. Therefore, the implementation of the following tasks in the high-temperature manufacturing industry should be the first scientific goal of Uzbek scientists:

- Introduction of robotic manipulators with cooling modules in local manufacturing plants;
- Reducing costs through the production of ceramic and composite insulation materials;
- Implementing temperature control through sensor networks and AI algorithms.

These areas serve the technological modernization of the country's industry, increase energy efficiency and labor safety. A number of works are also being carried out in this regard at the Islam Karimov Tashkent State Technical University. In particular, under the leadership of Academician Yusupbekov, a practical project is being implemented under the state program under the theme “Development of control and management systems that allow increasing energy efficiency and improving product quality in industrial gas-fired furnaces”. Based on this project, indicators of the relationship between the level of robotization and energy consumption and safety were determined [27-29, 59-60]. Based on this, the following results are expected to be achieved:

- Increase safety performance on robotic lines by 72%;
- Reduce energy consumption by 11–15%;
- Reduce labor participation by up to 70%;

Technical Results

Based on the technical analysis of robotic systems for high-temperature furnaces, the following considerations can be considered as the most important factors:

- Heat-resistant materials: titanium-aluminum alloys, ceramic coatings based on SiC and Al_2O_3;
- Cooling system: liquid nitrogen, water-glycol mixture or air flow;
- Sensor protection: ceramic shield covering of thermocouples and IR sensors;
- Actuator design: fully sealed servo motors and thermally insulated gearboxes.

Taking the above factors into account, high-temperature robot models developed by modern robot manufacturers KUKA, ABB, and Kawasaki have been found to be capable of performing short-term operations in zones up to 1200°C. However, for continuous operation, it is necessary to integrate reflectors and cooling modules that limit heat dissipation.

Conclusion

The transition toward robotic automation in high-temperature furnace environments represents both a technological necessity and a strategic industrial objective. Robotization significantly enhances occupational safety, reduces human exposure to extreme thermal conditions, and improves production stability and energy efficiency. Effective deployment requires the integration of heat-resistant materials, hybrid thermal management systems, intelligent control algorithms, and digital twin technologies. While initial investment costs may be substantial, long-term operational benefits—including improved safety, reduced downtime, and optimized energy consumption—justify implementation. For industrial sectors undergoing modernization, particularly in emerging economies, high-temperature robotic systems constitute a critical component of sustainable and competitive manufacturing development.

V. Acknowledgment

This scientific research was conducted within the framework of the practical project AL-9224104261 in the field of technical sciences - “Development of control and management systems that allow increasing energy efficiency and improving product quality in industrial gas-fired furnaces.”

References

1. Colla, V., Matino, R., Schröder, A.J., et al. (2021). Human-Centered Robotic Development in the Steel Shop: Improving Health, Safety and Digital Skills at the Workplace. Metals, 11(4), 647.
2. Branca, T. A., Fornai, B., Colla, V., Murri, M. M., Streppa, E., & Schröder, A. J. (2020). The challenge of digitalization in the steel sector. Metals, 10(2), Article 288. https://doi.org/10.3390/met10020288
3. Miśkiewicz, R., & Wolniak, R. (2020). Practical application of the Industry 4.0 concept in a steel company. Sustainability, 12(14), Article 5776. https://doi.org/10.3390/su12145776

4. Hansert, P., Stech, R., & Quant, M. (2016). Performance experience of the MultiROB at BSW—How safety, productivity and accuracy go hand in hand. Iron & Steel Technology, 13, 70–76.
5. Gerstorfer, G., Keplinger, T., Priesner, A., Sedivy, C., Traxinger, H., Voraberger, B., & Watzinger, S. (2018). Robotics applications continuously enhancing safety in melt shops. European Oxygen Steelmaking Conference (EOSC), Taranto, Italy.
6. Meisel, J., Pfeil, S., Prinz, G., Hugel, M., Priesner, A., & Scheidegger, R. (2014). Experience and evolution after 10 years of robotics in continuous casting technology. 8th European Continuous Casting Conference, Graz, Austria.
7. Demetika, P., Ferrari, R., Galasso, L. M., & Romano, F. (2014). Robotic system for a "zero-operator" continuous casting floor. AISTech Iron and Steel Technology Conference, 3, 3481–3486.
8. González-Ciordia, B., Fernández, B., Artola, G., Muro, M., Sanz, Á., & López de Lacalle, L. N. (2019). Failure-analysis based redesign of furnace conveyor system components: A case study. Metals, 9(8), Article 816. https://doi.org/10.3390/met9080816
9. Salcedo-Hernández, J., Rivas-Perez, R., & Sotomayor-Moriano, J. (2020). Design of a robust H∞ state feedback temperature controller for a steel slab reheating furnace. Applied Sciences, 10(5), Article 1731. https://doi.org/10.3390/app10051731
10. Saparrat, M., Monti, F., & Ibarra, J. (2020). AI application to melting temperature prediction in an electric arc furnace. AISTech Iron and Steel Technology Conference, 1, 526–532.
11. Wang, B., Zhou, H., Li, X., Yang, G., Zheng, P., Song, C., Yuan, Y., Wuest, T., Yang, H., & Wang, L. (2024). Human digital twin in the context of Industry 5.0. Robotics and Computer-Integrated Manufacturing, 85, Article 102626. https://doi.org/10.1016/j.rcim.2023.102626
12. P. Zangeneh, B. McCabe, Ontology-based knowledge representation for industrial megaprojects analytics using linked data and the semantic web, Adv. Eng. Informatics 46 (2020), https://doi.org/10.1016/j.aei.2020.101164.
13. Xu, Y., Zhang, R., Sun, J., Zhang, D., Zhao, Q., Duan, J., & Yang, L. (2024). A flexible proximity-pressure–temperature tri-mode robotic sensor with stimulus discriminability, high sensitivity and wide perception range. Materials & Design, 247, Article 113407. https://doi.org/10.1016/j.matdes.2024.113407
14. Javadi, Y., Mohseni, E., & Gachagan, A. (2021). High-temperature in-process inspection followed by 96-h robotic inspection of intentionally manufactured hydrogen crack in multi-pass robotic welding. International Journal of Pressure Vessels and Piping, 192, 104428. https://doi.org/10.1016/j.ijpvp.2021.104428
15. Hansert, P., Stech, R., & Quant, M. (2016). Performance experience of the MultiROB at BSW—How safety, productivity and accuracy go hand in hand. Iron Steel Technology, 13, 70–76.
16. Visentini, I., Demetlika, P., Martin, M., & Ardesi, A. (2016). Q-robot ROLL: Vision-based automatic deburring robot for cold billets. Iron & Steel Technology, 13, 142–147.
17. Wang, X., Xue, L., Yan, Y., & Gu, X. (2017). Welding robot collision-free path optimization. Applied Sciences, 7(1), Article 89. https://doi.org/10.3390/app7010089

18. Soltani, E. (2010). An investigation on continuous steel slabs casting line and mechanical design of a 3R robot for sampling from melting arc furnaces. Advanced Materials Research, 31–35. https://doi.org/10.4028/www.scientific.net/AMR.83-86.31
19. Schwarzbach, L. (2014). At the Lech Steelworks, a robot takes samples from ready-to-pour liquid steel: Well measured. Stahl Eisen, 134, 50–51.
20. Egger, M. W., Priesner, A., Lehner, J., Nogratnig, H., Lechner, H., & Wimmer, G. (2014). Successful revamping of sublance manipulators for LD converters at Voestalpine Stahl GmbH. AISTech Iron and Steel Technology Conference, 3, 973–980.
21. Sedano, E., Baños, R., & Zanelli, U. (2020). Safe slag and liquid steel handling. AISTech Iron and Steel Technology Conference, 1, 593–601.
22. Deshpande, N., Ortiz, J., Sarakoglou, I., Semini, C., Tsagarakis, N., Brygo, A., Fernandez, J., Frigerio, M., Saccares, L., & Toxiri, S. (2018). Next-generation collaborative robotic systems for industrial safety and health. WIT Transactions on the Built Environment, 174, 187–200. https://doi.org/10.2495/SAFE180181
23. Dhanda, M., Rogers, B. A., Hall, S., Dekoninck, E., & Dhokia, V. (2025). Reviewing human-robot collaboration in manufacturing: Opportunities and challenges in the context of Industry 5.0. Robotics and Computer-Integrated Manufacturing, 93, Article 102937. https://doi.org/10.1016/j.rcim.2025.102937
24. Fernández, B., González, B., Artola, G., López de Lacalle, N., & Angulo, C. (2019). A quick cycle time sensitivity analysis of boron steel hot stamping. Metals, 9(3), Article 235. https://doi.org/10.3390/met9030235
25. Yusupbekov, N., Matyokubov, N., & Rakhimov, T. (2024). Electromagnetic mechatron module control algorithm based on linear performance element of industrial robots. AIP Conference Proceedings, 3119(1), 060012.
26. Sevinchan, E. (2018). A Review on Thermal Management Methods for Robots. Applied Thermal Engineering. Volume 140, Pages 799-813.
27. Yusupbekov, A. N., & Kholmanov, U. U. (2024). Intelligent glass production process control system. Lecture Notes in Networks and Systems, 912, 103–109. https://doi.org/10.1007/978-3-031-53488-1_12
28. Kholmanov, U. U., & Shamsutdinova, V. H. (2024). Application of gas mixture detectors for automatic control systems. AIP Conference Proceedings, 3119(1), Article 030005. https://doi.org/10.1063/5.0214844
29. Yusupbekov, N. R., & Kholmanov, U. U. (2024). System of automatic control of the technological process of combustion in gas combustion furnaces. AIP Conference Proceedings, 3119(1), Article 060011. https://doi.org/10.1063/5.0214847
30. Michalos, G., Makris, S., Tsarouchi, P., Guasch, T., Kontovrakis, D., & Chryssolouris, G. (2015). Design considerations for safe human-robot collaborative workplaces. Procedia CIRP, 37, 248–253. https://doi.org/10.1016/j.procir.2015.08.014
31. Aaltonen, I., Salmi, T., & Marstio, I. (2018). Refining levels of collaboration to support the design and evaluation of human-robot interaction in the manufacturing industry. Procedia CIRP, 72, 93–98. https://doi.org/10.1016/j.procir.2018.03.214

32. Marvel, J. A., Bagchi, S., Zimmerman, M., & Antonishek, B. (2020). Towards effective interface designs for collaborative HRI in manufacturing. ACM Transactions on Human-Robot Interaction, 9(4), Article 3385009. https://doi.org/10.1145/3385009
33. Frazzon, E. M., Agostino, Í. R. S., Broda, E., & Freitag, M. (2020). Manufacturing networks in the era of digital production and operations: A socio-cyber-physical perspective. Annual Reviews in Control, 49, 288–294. https://doi.org/10.1016/j.arcontrol.2020.04.008
34. Bi, Z. M., Chen, B., Xu, L., Wu, C., Malott, C., Chamberlin, M., & Enterline, T. (2022). Security and safety assurance of collaborative manufacturing in Industry 4.0. Enterprise Information Systems, 16(1), Article 2008512. https://doi.org/10.1080/17517575.2021.2008512
35. Leopold, T. A., Ratcheva, V., & Zahidi, S. (2016). The future of jobs: Employment, skills, and workforce strategies for the Fourth Industrial Revolution [Report]. World Economic Forum. https://www.weforum.org/reports/the-future-of-jobs-report-2016/
36. Mukherjee, D., Gupta, K., Chang, L. H., & Najjaran, H. (2022). A survey of robot learning strategies for human-robot collaboration in industrial settings. Robotics and Computer-Integrated Manufacturing, 73, Article 102231. https://doi.org/10.1016/j.rcim.2021.102231
37. Laudante, E., Greco, A., Caterino, M., & Fera, M. (2020). Human–robot interaction for improving fuselage assembly tasks: A case study. Applied Sciences, 10(17), Article 5757. https://doi.org/10.3390/app10175757
38. Manzoor, S., Rocha, Y. G., Joo, S. H., Bae, S. H., Kim, E. J., Joo, K. J., & Kuc, T. Y. (2021). Ontology-based knowledge representation in robotic systems: A survey oriented toward applications. Applied Sciences, 11(9), Article 4324. https://doi.org/10.3390/app11094324
39. Castro, A., Silva, F., & Santos, V. (2021). Trends of human-robot collaboration in industry contexts: Handover, learning, and metrics. Sensors, 21(12), Article 4113. https://doi.org/10.3390/s21124113
40. Elankavi, R. S., Krishnakumar, S., & Ramachandran, M. (2022). Design and motion planning of a wheeled type pipeline inspection robot. Journal of Robotics and Control (JRC), 3(5), 542–550. https://doi.org/10.18196/jrc.v3i5.14742
41. Kakogawa, A., & Ma, S. (2020). Robotic search and rescue through in-pipe movement. In Unmanned Robotic Systems and Applications. https://doi.org/10.5772/intechopen.88414
42. Zhang, H., Dong, J., Cui, C., & Liu, S. (2020). Stress and strain analysis of spherical sealing cups of fluid-driven pipeline robot in dented oil and gas pipeline. Engineering Failure Analysis, 108, 104294. https://doi.org/10.1016/j.engfailanal.2019.104294
43. Tourajizadeh, H., Rezaei, M., & Sedigh, A. H. (2018). Optimal control of screw in-pipe inspection robot with controllable pitch rate. Journal of Intelligent & Robotic Systems, 90(3–4), 417–429. https://doi.org/10.1007/s10846-017-0658-7
44. Elankavi, R. S. (2020). Developments in in-pipe inspection robot: A review. Journal of Mechanics of Continua and Mathematical Sciences, 15(5), 382–394. https://doi.org/10.26782/jmcms.2020.05.00022
45. Sekhar, R., Shah, P., & Iswanto, I. (2022). Robotics in Industry 4.0: A bibliometric analysis (2011–2022). Journal of Robotics and Control (JRC), 3(5), 583–613. https://doi.org/10.18196/jrc.v3i5.15453

46. Singh, S., Solke, N., & Sekhar, R. (2015). Design and modification of stacker mechanism for seal pressing machine. International Journal of Applied Engineering Research, 10(10), 26641–26656.
47. Suryadarma, E. H. E., Laksono, P. W., Priadythama, I., & Herdiman, L. (2024). Controlling robots using gaze estimation: A systematic bibliometric and research trend analysis. Journal of Robotics and Control (JRC), 5(3), 786–803. https://doi.org/10.18196/jrc.v5i3.21686
48. Schaupp, S. (2023). COVID-19, economic crises and digitalisation: How algorithmic management became an alternative to automation. New Technology, Work and Employment, 38(2), 311–329. https://doi.org/10.1111/ntwe.12246
49. Fabris, G., Scalera, L., & Gasparetto, A. (2024). Playing checkers with an intelligent and collaborative robotic system. Robotics, 13(1), Article 4. https://doi.org/10.3390/robotics13010004
50. Riva, G., & Riva, E. (2020). DE-ENIGMA: Multimodal human–robot interaction for teaching and expanding social imagination in autistic children. Cyberpsychology, Behavior, and Social Networking, 23(11), 806–807. https://doi.org/10.1089/cyber.2020.29200.ceu
51. Hooge, I. T. C., Holleman, G. A., Haukes, N. C., & Hessels, R. S. (2019). Gaze tracking accuracy in humans: One eye is sometimes better than two. Behavior Research Methods, 51(6), 2712–2721. https://doi.org/10.3758/s13428-018-1135-3
52. Ganesh, H. S., Edgar, T. F., & Baldea, M. (2016). Model predictive control of the exit part temperature for an austenitization furnace. Processes, 4(4), Article 53. https://doi.org/10.3390/pr4040053
53. Yang, G., Bekiros, S., Yao, Q., Mou, J., Aly, A. A., & Sayed, O. R. (2024). Enhanced control of nonlinear systems under control input constraints and faults: A neural network-based integral fuzzy sliding mode approach. Entropy, 26(12), 1078. https://doi.org/10.3390/e26121078
54. Lam, H.-K., Xiao, B., & Chen, M. (2025). A review on interval type-2 fuzzy-model-based control systems: Membership-function-dependent perspectives. IEEE Transactions on Fuzzy Systems, 33(11), 3856–3870. https://doi.org/10.1109/TFUZZ.2025.3609627
55. Zhang, P., Wang, J., Liu, Y., & Lee, S. (2025). Event-triggered generalized extended state observer-based control for nonlinear networked systems under gain variation and multi-channel attacks. International Journal of Robust and Nonlinear Control, 35(3), 828–842. https://doi.org/10.1002/rnc.7681
56. Tumari, M. M., Saat, S., Johal, M. S., Bahari, M. F., Ahmad, M. A., et al. (2019). Single input fuzzy logic controller for liquid slosh suppression. International Journal of Electrical Engineering and Applied Sciences (IJEEAS), 2(1), 45–52.
57. Zhang, D., Hu, J., Cheng, J., Wu, Z.-G., & Yan, H. (2024). A novel disturbance observer based fixed-time sliding mode control for robotic manipulators with global fast convergence. IEEE/CAA Journal of Automatica Sinica, 11(3), 661–672. https://doi.org/10.1109/JAS.2023.123948
58. Hizarci, B., Kıral, Z., & Şahin, S. (2022). Optimal extended state observer-based control for vibration reduction on a flexible cantilever beam using an air thrust actuator. Applied Acoustics, 197, 108944. https://doi.org/10.1016/j.apacoust.2022.108944

59. Rustamovich, M. N., Omonboevich, R. T., & Gayratovich, B. S. (2024). Group control of functional linear actuation elements of mechatronic modules. Transactions of the Korean Institute of Electrical Engineers, 73(6), 995–1003.
60. Çigdem, S., Meidute-Kavaliauskiene, I., & Yıldız, B. (2023). Industry 4.0 and industrial robots: A study from the perspective of manufacturing company employees. Logistics, 7(1), Article 17. https://doi.org/10.3390/logistics7010017