Performance Metrics for Collaborative Robots: A Literature Review

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ABSTRACT

This literature review will go through the available performance metrics to consider assessing how effective cobots applied in different sectors are. In a world where automation seems to be ever-growing and becoming increasingly successful with the implementation of more cobots in manufacturing, warehousing, and precision tasks, clarity must be brought to clear, encompassing metrics that can view both productivity and safety. This review starts with an introduction into cobots: their uniqueness and the historical context of their development. Then, based on the existing literature on productivity and safety measurement, gaps in research are identified, and industry applications reviewed. Methodologies of such an evaluation, also including both qualitative and quantitative ones, are considered. In addition, challenges of performance evaluation such as variability from industry to industry and human-related issues have been encountered as it considers future research directions. This review synthesizes the existing literature to help identify insights that would inform the effective implementation and assessment of cobots, adding value to the workplace.

Introduction

A collaborative robot, or cobot, is designed to work alongside humans, enhancing efficiency and safety in various industrial processes. According to Saseekala et al. (2024), Unlike those regular ones, which work solo in most times over a completely safe environment and require safety barriers, cobots are designed incorporating all advanced aspects of safety features and ergonomic designs that directly enable interaction with humans without any compromise on the safety issue. This is inspired by the underlying principles of the technologies of Industry 4.0 and 5.0, which call for flexibility, adaptability, and sustainability in manufacturing. Experts believe that cobots meet these demands through novel technologies, such as mixed reality for programming and real-time monitoring systems that enable seamless cooperation between humans and robots. This is augmented by the size and the design of cobots, which would greatly affect user experience. Usually, larger ones create the aspect of safety and efficiency among users. In a nutshell, cobots are a revolutionary takeover of robotics in terms of human-centric interaction and operational efficiency (Ranjan et al., 2024; Gervasi et al., 2024; Calderón-Sesmero et al., 2024).

Since then, cobots have emerged as the most meaningful development in industrial automation through their safety and flexibility compared to traditional industrial robots. According to Patil et al. (2023), the driving force behind the cobot development is the human-robot collaboration in various industries, especially small and medium-sized businesses. As several researchers emphasized, some key advantages of cobots include safety, flexibility, and cost-effectiveness. However, despite the above advantages, several barriers to adoption persist, from lack of knowledge among the workers in possible applications, legislation on safety, down to ease of use. Experts claim that new research focuses on improving human-robot interaction, developing new control strategies, and enhancing safety features. Cobots will increasingly be more relevant to Industry 5.0, in turn, opening a new stage that will revolutionize manufacturing processes in a far more efficient and sustainable factory (Şahan et al., 2023; Aaltonen & Salmi, 2019; Bisen & Payal, 2021).

Market dynamics play an important role in introducing and integrating cobots into manufacturing. According to Simões et al. (2019), the operational efficiency, ergonomics, and human factors are among the key reasons. Factors-internal, external, and technological-have demonstrated different intentions towards accepting cobot from the managers, with various factors identified across contexts. According to experts, to integrate a cobot into society, it is required to understand complicated socio-technical dependencies between the cobot, product, human operator, and workplace. The safety concern also remains the key issue in adoption because of the system-wide nature of safety. The paradox that arises due to tension created between competing system-wide requirements leads to low adoption rates. Companies align cobot adoption with strategic objectives such as improving productivity, flexibility, and quality. Understanding these market dynamics and addressing associated challenges can facilitate cobot adoption and help organizations reap the benefits of this technology (Guertler et al., 2023; Berx et al., 2022).

The productivity and safety measures need to be carried out to evaluate cobots since they have a massive influence on the industrial process and human-robot collaboration. Berx et al. (2024) argue that, indeed, cobots may bring about benefits in terms of productivity and flexibility; however, their specific interaction model introduces extra safety aspects. The Cobot Safety Readiness Assessment Tool is designed to assess the safety readiness of cobots from a system-wide perspective. Some studies further indicate that the adoption of cobots would reduce the posture and biomechanical stresses among operators as well as decrease musculoskeletal disorders but, according to many experts, productivity may be lost in the short run by cobot capabilities compared to human-to-human interactions. As has been observed by Cohen et al. (2021), productivity analysis procedures are required in informing the acquisition and deployment decisions for cobots. The analyses also showed higher operator satisfaction and productivity when carrying out comparative activities with cobots.These findings highlight the importance of measuring both productivity and safety to optimize human-robot collaboration in industrial settings (Bouillet et al., 2023; Caiazzo et al., 2023).

A number of objectives are ascertained by introducing cobots in manufacturing, which fall under the broader categories of efficiency, flexibility, and productivity in terms of operation, safety, and ergonomics for workers. According to Simões et al. (2019), cobots are designed to enhance cooperation in human-robot collaboration in performing tasks that are complex and require highly skilled operations. As such, time saving, higher production volume, and less waste are all realized in accord with principles of lean management as underlined by Pizoń et al. (2022). Another main point which emerges for cobot adoption is regarding safety, with much emphasis on proper risk assessment and adherence to the appropriate standards and directives. Experts think that the integration of cobots into already existing manufacturing systems without great modification is a very important consideration, making it in terms of the new systems a cost-effective solution for those who want to enhance their processes. Overall, cobot implementation aligns with strategic objectives of productivity, flexibility, and quality improvement in manufacturing (Bejarano et al., 2019; Vagaš et al., 2020).

The perceptions of cobot safety and productivity metrics are indeed reflections of complex challenges in human-robot collaboration. According to Berx et al. (2023), key stakeholders often underestimate safety-related concerns when launching cobots. To address this, the Cobot Safety Readiness Assessment Tool (CSRAT) was developed to evaluate safety readiness from a system-wide perspective, enhancing awareness and facilitating stakeholder alignment. Experts note that in safety, it sometimes also includes aspects such as the motion planning algorithms. Generally, algorithms with fixed paths are more secure than real-time planning, whereas Berx et al. (2022) observe that efficacy is a trade-off that poses a challenge to the adoption of cobots. These findings underscore the need for comprehensive safety assessment tools and improved stakeholder education to promote successful cobot implementation in industrial settings (Tusseyeva et al., 2022).

Recent literature in performance metrics for cobots holds a great variety of disadvantages. As it increasingly becomes a part of modern manufacturing, as noted by Knudsen and Kaivo-oja (2020), there still remains no standard benchmark for human-robot teaming different approaches and about observing improvements. The impacts on human factors such as ergonomics or even more concerning mental stress due to the interaction with the robots are little addressed by current research. There is not sufficient understanding about what collaboration actually means, and what are the implications for developing appropriate performance measurement systems. Future research should outline the study of the nature of collaboration as well as developing characteristics of performance indicators to support it. Furthermore, there is a pressing need for comprehensive metrics that consider safety, human factors, and team performance in collaborative assembly, handling, and industrial cobot applications (Riedelbauch et al., 2023; Faccio et al., 2022; Busi & Bititci, 2006).

Theoretical Framework

Understanding Productivity in Industrial Settings

Output-input ratio is the most common description of productivity in industrial operations; however, its measure would depend on the context. Productivity improvements in manufacturing can be attained through better methods, increased performance, and utilization according to Cosmetatos and Eilon (1983). Human resource management, organizational culture, methodology of production, management strategy, and performance are the primary factors that result in productivity. It is challenging to measure productivity for roles such as industrial salespeople, who work in non manufacturing industries, as their inputs and outputs cannot be measured. Experts argue that the process of selecting a productivity measure has significantly more importance because it is likely to affect evaluation of performance and decision-making sharply. Furthermore, misconceptions about productivity, often associated with increased workload, can hinder improvement efforts, highlighting the importance of clear communication and understanding of productivity concepts in industrial settings (Almström, 2012; Zabriskie & Browning, 1979).

Recent studies have investigated different models for measuring the productivity of human-robot collaboration systems. Some recent attempts proposed an integrated model with flow time for productivity and strain index for ergonomical performance by Zhang et al. (2021). Latest research done by Calvo and Gil (2022) has also proposed some parametric models that are used for assessing the economic and social dimensions by cobot implementation. The current research highlights the increase in productivity as one of the key factors. Cohen et al. (2021) outlined a broad framework for cobot deployment decisions as part of which is productivity analysis for single workstations and assembly lines. The state of the art can be seen in Liu et al. (2022), which proposed an optimization framework to allocate tasks between humans and cobots, based on trade-offs between productivity, physical workload, and mental workload. These studies further imply the high complexity associated with measuring productivity when humans and robots work together together and raise questions about whether ergonomics and economic feasibility also determine aspects of productivity when humans and robots work together. Altogether, the papers call for holistic approaches to assessing productivity where cobots are used in manufacturing environments (Calvo & Gil, 2022; Cohen et al., 2021; Liu et al., 2022).

Principles of lean manufacturing and Industry 4.0 concepts, like cobots, are integrated nowadays to optimize the production processes and increase productivity. According to Dossou et al. (2021), "cobots present flexible manufacturing environments with increased performance." Based on these concepts, Cohen et al. (2021) defined the characteristics, capabilities, and economic value of cobots when implementing them. Productivity analysis techniques can be used to aid in the choices regarding cobot purchase and implementation at specific workstations and on lines. A structured methodology along the design principles of engineering will aid in the implementation of cobots within a pre-existing assembly cell, as stated by Malik and Bilberg (2017). Virtual simulation, on the other hand, is useful for verification and optimization of work conditions for humans and robots. Thus, although cobots would offer more excellent performance in the processes they are applied to, their success factors would be expected to be in line with Lean Manufacturing methods to avoid the non-value-added activities and improve productivity generally (Dossou et al., 2021; Quenehen et al., 2019).

Safety Considerations in Collaborative Environments

Measuring productivity with respect to cobots is very important for several reasons. Firstly, from the valuables economic value analysis point of view, as Yuval Cohen et al. (2021) point out, measuring productivity plays a significant role in making decisions in acquiring cobots and deploying them. Secondly, the goal of productivity improvement is essential since it is a strategic one, while productivity improvement A. Simões et al. (2019) actually considers productivity improvement one of the leading drivers of cobot adoption in manufacturing companies. For example, Li Liu et al. (2022) show that the adaptation of cobots into manual jobs requires a peak balance between productivity and physical and mental workload in work tasks. Finally, the adoption of cobots aims at maintaining or improving productivity while keeping human operator health, according to Kévin Bouillet et al. (2023). However, numerous studies have demonstrated that cobot implementation often leads to mixed effects; sometimes, it even causes a fall in productivity with the low capabilities of such cobots. It is thus important to measure productivity so as to take care that the collaboration of human and cobot is efficient. Further, it helps find a premise on changes and caters to the integration of cobots within the organization's boundaries and respect toward workers' well-being.

As cobots are introduced into the workplace, several safety considerations must be accounted for to ensure proper human-robot collaboration. Such consideration includes installing advanced safety systems, such as Time of Flight Vision, to "observe or track" the speed of robots and spatial distance "to avoid collisions by human operators", as suggested by AUTHOR_ID (2024). Moreover, the Cobot Safety Readiness Assessment Tool, CSRAT, helps organizations to measure their safety readiness and also raises awareness of risks that may potentially occur to facilitate better communication among stakeholders, suggest Berx et al. (2024). It is also important to understand human behavior in shared workspaces; for instance, machine learning methods have generated high accuracy in predicting collisions. Ethical considerations and safety standards can be seen more strongly, especially as cobots interact with more and more non specialized people in the work environment across different settings, requiring emphasis on not only the physical but also the ethical safety factors that Różańska-Walczuk (2023) emphasizes. Of course, answering such issues would result in safer integration of cobots and make the industrial stages function better.

Productivity and safety in cobots, or collaborative robots, seem synergistic: more direct applications of superior safety measures can result in enhanced productivity. Cobots could be programmed to operate seamlessly along with humans, improving working operations' efficiency without affecting their safety standards. For example, frameworks that integrate safety constraints into their learning algorithms have led to a notable increase in task success rates (Abbas et al., 2024). Improved communication between cobots and human workers make this mutualism work best; the humans can make task transfers without a hitch. In such a scenario, human time can be spent on more complex activities, as argued by Cohen in 2024. Cobots are not used in garment manufacturing industries, for example, mainly due to technology barriers and cost implications, as maintained by Nguyen and Jin in (2024). Tools such as the Cobot Safety Readiness Assessment Tool (CSRAT) help organizations in assessing and improving their safety measures for improvement toward a safer and more productive work environment, according to Berx et al. (2024). In this regard, the functionality of cobots calls for safety as the highest priority in terms of keeping productivity on high levels.

Review of Existing Performance Metrics

Productivity Metrics

Some of the key productivity metrics to be considered while evaluating cobots could include performance indicators that are indicative of efficiency and impact on human-robot collaboration. Such metrics include task completion time, energy expenditure, and cognitive workload and, therefore, prove crucial for monitoring overall effectiveness in manufacturing settings. They claim that minimum makespan is engineered for the cobot system, which is the sum of time it would take to complete all the tasks. Additionally, the energy consumption by the human during his period of work will be reduced as noted by Granata et al. (2023). The cognitive workload assessment by physiological measures, including EEG and fNIRS, reflects the mental burden of the workers-the rationale behind the productivity of the worker according to Zakeri et al. (2023). Recent literature lays a strong emphasis on the urgency of specific performance indicators for human-robot collaboration, their identification and systematization in order to improve productivity as well as operator satisfaction. Altogether, all these metrics make up for a full assessment of the performance of cobots in modern manufacturing environments.

Research on cobot applications in manufacturing focuses on optimizing throughput and ergonomics. Methodologies for calculating throughput include analyzing assembly-time performance (ATP) using stochastic processes and gamma distribution approximations, as noted by Chen (2021). Collaborative Assembly Line Balancing (C-ALB) models, according to Boschetti (2021), consider task parallelization and collaboration to improve system performance. Furthermore, throughput can be enhanced by selecting optimal part presentation methods, considering factors like lifespan quantity and development times, as discussed by Pocachard (2020). Additionally, a model, which combines both productivity and ergonomic performance, has been assessed using flow time and strain index as metrics; that indicates the possibility of a unified measure of throughput rate per unit of work effort time (Zhang, 2021). Together, these approaches seek to decrease processing times, increase flexibility, and improve system efficiency in the cobot-assisted manufacturing context to overcome the challenges posed by the characteristic high-mix, low-volume production scenarios that are common in Industry 4.0 applications.

Industry standards have such an effect on measurement cycle time of various industries. ISO and ANSI standards are applicable to robot repeatability for evaluating the significance of measuring systems and cycle numbers over long-term performance, according to Jeswiet and Helferty (1995). In organizational processes, measurement of cycle time is mostly unstandardized where most firms utilize anecdotes or common units of clocks as noted by Ketchen (2003). Jayaram et al. (2000) express their opinion that information system infrastructure and process improvements directly reflect changes in the performance of supply chains based on time, and different aspects of cycle time depend on design-manufacturing integration, manufacturing technology, and information technology. However, the tobacco industry's development of ISO standards for its products regarding tobacco is related to the adequacy of these standards for regulatory policies, as expressed by Bialous and Yach (2001). This calls for considering the impact of the industry when standards are applied to measure and regulate cycle time across different sectors.

Operation systems errors play an essential role in maintaining quality improvement and efficiency. In health care, critical errors refer to preventable morbidity or mortality, while Falessi et al. (2014) defined the notion of criticality as having a very high impact on system effectiveness in other domains. Non-critical errors are less rigorous than critical ones but may also affect the system's performance. As argued by Nawrocki et al. (1973), categorizing errors into groups will allow a view of where repetition could be suspected and through which areas improvement efforts should then be focused. However, the impact of classification errors on operational efficiency can vary significantly depending on the failure type, with some types being more sensitive to misclassification than others (Falessi et al., 2014). Polian et al. (2007) explained that psycho-visual models can be applied to distinguish between critical and non-critical faults based on their visibility to end-users for imaging applications. In this regard, proper error categorization and analysis will lead to more targeted fault detection and selective system hardening, thereby showing improved reliability and efficiency.

Safety Metrics

Safety metrics within other industries include both outcome-focused and process-focused measures. According to Spear (2010), after-the-fact or outcome metrics include injury rates and workers' compensation claims. Process metrics indicate how much of what was planned gets done but do not necessarily imply that the outcomes will be achieved (Spear, 2010). In the aviation sector, Kaspers et al. (2019) assert that traditional safety measurement has been based on adverse event indicators, but with such low incidence of adverse events in comparison with operations, has shifted to a monitoring-based approach where the focus is on being proactive. For ADS, Wishart et al. (2020) recommend metrics encompassing proximal surrogate indicators, driving behaviors, and violations of the rules-of-the-road, from on-board and off-board sources. However, the diversity of safety models and the lack of empirical evidence linking safety proxies to outcomes have hindered the widespread adoption of process metrics (Kaspers et al., 2019). Ideally, a combination of outcome and process measures should be used, tailored to different organizational levels (Spear, 2010).

The study on safety metrics for cobots incorporates objective and subjective measures into a worker-centric outcome regarding health and system performance. According to Zakeri et al. (2022), physiological indicators, including brain activity as well as heart rate besides behavioral and subjective measures, can be utilized for mental stress measurement in human-robot collaboration. Subjective metrics need emphasis, such as perceived safety, risk assessment, and user satisfaction, according to Fraboni et al. (2023), with regard to establishing the efficacy of guidelines on technology integration at the organizational level. As defined by Mühlemeyer (2019), the BDS-System is referring to the standardized process of measuring ergonomic and holistic aspects during employee-cobot interaction. Another method for covering situations, known to Lesage and Alexander (2021), through the utilization of simulation-based practice, can also recur to dangerous scenarios without putting real operators into danger. Such metrics go on to set out safety parameters for cobot systems. These approaches are relevant to addressing the need of bringing together objective and subjective measures of safety so that one could fully assess and improve cobot integration in a working setting while also considering both physical and psychological requirements for worker safety and satisfaction.

This does not offer an appropriate measure of the productivity and safety impact of cobots in current performance metrics. It restricts what traditional metrics are able to measure toward realizing the relevant potential of cobots. Murphy and Schreckenghost (2013) say conventional methods do not usually refer to capabilities but rather to individual agents, hence it is tough to correctly determine suitable autonomous functions for specific tasks. Malik and Pandey (2022) propose that although cobots offer many advantages in manual operations, the benefits are heavily dependent on the design of application rather than manipulator due to the speed constraint in performing tasks while working in tandem with humans. To overcome these limitations, researchers design the human-centered design approach that accounts for productivity as well as well-being of operators in the workplace. Boschetti et al. (2022) introduce multi objective task allocation strategies to minimize makespan and operator workload, as well as real-time collision avoidance systems by using multi camera setups and skeleton tracking. Among other needs to push forward cobot technology, Patil et al. (2023) state further research in technical and ethical issues, further development of standards and regulations, and impact on employment.

Industry-Specific Applications of Cobots

Warehousing

Collaborative robots (cobots) are increasingly applied in warehouse settings, particularly for order picking tasks. These systems can significantly reduce picking time by up to 33.57% (Koreis et al., 2023) and are most effective for short-distance orders with low pick density (Meller et al., 2018).However, the business case for cobots is still limited by pricing structures and congestion in high-throughput operations. As a result, it is meaningful for the performance evaluation to include task completion time, productivity, and waiting time (Meller et al., 2018). Lambrechts et al. (2021) stated that careful consideration of human factors-the resistance of change and organizational culture-is a significant factor for the successful implementation of cobots." The "phased implementation" along with the "strong leadership at the team level" is prudent to overcome the fear among the employees and thus to ensure the smooth adoption of cobot technology in the warehouse. In this regard, Meller et al. (2018) and Lambrechts et al. (2021) argued that both operational efficiency and human factors come into play as critical determinants for the efficient introduction of cobots in the warehouses.

Automotive Manufacturing

Collaborative robots (cobots) in automotive manufacturing face several productivity and safety challenges. Safety assurance is a primary concern, requiring mechanisms to protect humans in shared workspaces (Bi et al., 2021). Key challenges include real-time data processing for risk classification and effective control updates. Cobots aim to enhance manufacturing flexibility and productivity while addressing ergonomic issues (Liu et al., 2022). However, the integration of cobots into the given processes requires task scheduling optimization and workstation design. The proposed low-load universal cobot systems with innovative security solutions can enhance the flexibility of automotive metalworking according to Tokody et al. (2020). Balancer productivity and safety within cobot cells must be approached from a human-centered design point of view, focusing on multiple objectives in the task allocation task to minimize makespan and workload of the operator, maintaining real-time collision-free status (Boschetti et al., 2022). Overall, Bi et al. (2021) and Liu et al. (2022) highlight the importance of addressing both safety and efficiency in the integration of cobots in automotive manufacturing.

Precision Tasks

Cobots are increasingly utilized for precision tasks in industrial settings, offering improvements in productivity, safety, and cost-effectiveness (Bloss, 2016). These collaborative robots introduce never-before-solved applications and the complexity out of programming processes. Săvescu et al. (2022) highlighted that the most significant factors for measuring the performance of cobots are task precision and productivity. Cobots diminish the risk of musculoskeletal disorders through improved operator posture. Nonetheless, Bouillet et al. (2023) found out that cobots initially decrease the production rate compared to a human-human team. According to Riedelbauch et al. (2023), standardized benchmarks factoring in security and human factors are essential to measure the effectiveness of human-robot teams. Generalizing, both Bloss (2016) and Bouillet et al. conclude that careful productivity measurement with safety ensures the proper deployment of cobots.

Case Studies

Collaborative robots (cobots) have shown effectiveness across various industries. In manufacturing, cobots have improved process performance and productivity while addressing ergonomic concerns (Quenehen & Bouras, 2019). A case study in wire harness assembly demonstrated a significant reduction in ergonomic risks for workers when using cobots (Navas-Reascos et al., 2022). However, the actual implementation of cobots has its own challenges, as correctly stated by Cheon et al. (2022), that "a breakdown of work into finer tasks," and thus also poses the threat of a loss of job identity for workers. Key aspects for successful cobot introduction include considerations of the essential design factors of emerging challenges (Kadir et al., 2018). The same, Cheon et al. (2022), have introduced the term "bounded collaboration" to represent human-cobot interaction in industrial contexts that is bounded in scope. If considering Quenehen & Bouras (2019) and Navas-Reascos et al. (2022), it could be deduced that cobots indeed have a prospect to enhance operations in industry provided the whole set of techniques, which includes lean manufacturing principles, is offered appropriately. Methods used in these studies were not uniform because they varied from ergonomic evaluation, case study analysis, expert interviews, qualitative case multiple analysis, and many others to determine the effectiveness of cobots across different industries.

Methodologies for Evaluating Performance Metrics

Quantitative Approaches

Real-time cobot performance metrics can be captured through various data collection techniques. According to Kolvig Raun et al. (2023), event-driven architectures, such as Event-Driven Data Exchange, enable better introspection of cobot applications because program events are acquired related to state variables. For instance, RGB-D cameras, like the Microsoft Azure Kinect, enable real-time body tracking data in cobot control but environmental factors can impact the estimation uncertainty (Romeo et al., 2021). The metrics of human-robot interaction are approached with a systems approach focusing on a work system in total, using field-based data collection methods such as the Robot-Assisted Search and Rescue Coding System to get comprehensive data regarding performance. Moreover, Mitrea & Tamás (2018) regard the potential improvement that can be brought about in Manufacturing Execution Systems through data mining techniques applied to cobot parameters, through root cause analysis, and even the accurate prediction of target variables. Such approaches have been shown to offer real-time performance metrics of cobots together.

Statistical analysis is an important tool in the assessment of cobot performance metrics, especially concerning productivity and safety data. According to Caiazzo et al. (2023), comparative studies about manual vs. collaborative assembly tasks, aimed at measuring productivity improvements and operator satisfaction have been conducted. Boschetti et al. (2022) stated that multiobjective task allocation algorithms were developed targeted at simultaneously maximizing productivity and the well-being of the operator with respect to the makespan and the mental workload. Another approach of Cohen et al. (2021) is productivity analysis procedures supporting decisions on the procurement of cobots, including computational calculations of economic value in workstations and assembly lines, among others. Lesage & Alexander (2021) focus on utilizing simulation-based coverage methods in terms of computation of different metrics for the quantification of a safety gap and to assist with test generation for hazardous cases. In general, these methods provide numerous insights into the efficiency and safety of cobots.

Qualitative Approaches

Qualitative approaches included interviews, semi-structured interviews, and co-creation tasks for deriving insights from human cobot operators. In the view of Siebert-Evenstone et al. (2020), interviews with robotics experts highlight that safety is one of the major issues when designing and monitoring the cobot application. Rossato et al. (2021) reported that semi-structured interviews with workers aged between 20 and 65 years highlighted that workers considered cobots useful as well as safe to use. Cao et al. (2024) also mentions that co-creation activities carried out by factory workers involved in the process added to the interaction interfaces designed for operators' needs and preferences. Cheon et al. (2022) used a case study with analyses of case studies and interviews with cobot manufacturers and users in order to reveal several important findings about supportive production workers during cobot adoption and the changing meaning of collaboration in cobothuman workspaces. These qualitative approaches are rich enough to provide insight into the observable cultural practices existing between human operators and cobots and the collaboration dynamics in an industrial scenario.

Observational studies are intended to provide insight into human-cobot interaction in real settings. Michaelis et al. (2020) indicate that research has revealed that cobots might be expected to collaborate at the highest level but are used with little interaction and require traditional robotics skills for advanced applications. From the work of Šabanović et al. (2006), it is shown that social interactions can be evaluated both quantitatively and qualitatively through observational methods, especially in roles such as conference and receptionist tasks, producing design recommendations. Oppenheim et al. (2021) mention that look and backchannel cues are significant in grounding mutual understanding in task demonstrations that influence robot teaching and learning. In a health care setting, Chang et al. (2014) concluded in long-term observation studies that human-robot interactions usually demand facilitation by staff or family members, with people interacting with robots differently based on their needs. General Conclusion As has been pointed out from these results, the general conclusion is that observational studies are important in informing design for robots and enhancing human-robot interaction across contexts.

Simulation and Feedback

Simulations play a crucial role in predicting and optimizing cobot performance before deployment. They enable efficient work cell design, layout planning, and validation of human-robot work environments (Raza et al., 2021). In many fields, virtual visualization of collaborative manufacturing setups helps to solve real plant problems and evaluate cobot compatibility, as put by Malik & Bilberg (2017). Also, simulations are very beneficial for evaluating safety in the context of home environments in which cobots execute without the protection of safety fences (Kaonain et al., 2021). They support the act of simulating safety mechanisms, for example, reduction of the speed of a robot to prevent potential collision. Raza et al. (2021) indicate that if simulations are integrated with procedures such as PDCA, companies will solve most of the challenges that have emerged, including misuse of cobots and poor design of work cells. Collectively, all of these findings suggest the fact that simulations constitute the most important initial aspect of R and D in ensuring effective launch of cobots in the industrial and household environments as well.

Research on human-cobot interaction also underlined the importance of implementing feedback loops in improving cobot performance and outcomes of operators. Maske (2014) mentioned that collaborative learning algorithms allow cobots to learn from expert operators and support novice operators to improve task performance. According to Paliga (2022; 2023), HRI fluency enhances job performance and operator satisfaction, and work engagement functions as a mediator in these relationships. However, an elevated workload may moderate the influence of HRI fluency on the above benefits (Paliga, 2023). Gillespie et al. (1999) develop a general framework on cobot control based on the principles of feedback linearization that allows for path following and adaptability across various architectures of cobots. Overall conclusion of these studies reiterates the importance of well-designed human-cobot interactions for improvement in both performance and well-being of operators in industrial settings, showing that improvement in cobot performance is indeed possible through continuous feedback loops that incorporate operator experience, operator skill, and workload when designing or developing cobot performance.

Challenges in Performance Evaluation

Variability Across Industries

Performance evaluation of cobots is challenging due to variability in applications and environments. According to Jocelyn et al. (2023), variability in such performance is primarily due to the type of collaboration, characteristics of cobots and human, and spatial and temporal aspects in the entire lifecycle of the application. Variability of human behavior and advanced control laws increase complexity in the assessment of collaborative tasks, as emphasized by Silva et al. (2023). Benchmarking of human-robot teamwork requires consideration of aspects including safety and human factors (Riedelbauch et al., 2023). In a similar direction, aspects that relate to organizational factors include managerial intentions about cobot adoption, which depend on multiple contexts and have an impact on performance evaluation; these are reported by Simões et al. (2020). In summary, these factors produce a mix of the complexity in creating standard and repeatable benchmarks for cobot performance across the different applications and environments.

Human Factors

Organizational culture and worker-readiness would significantly impact the successful adoption of cobots in the workplace. According to Jones et al. (2005), a good organizational culture especially that is human relation and open systems value-oriented, is positively related to readiness for change among employees. This readiness would predict the successful introduction of technologies such as cobots (Jones et al., 2005). Whereas the size of an organization does not affect its innovative culture, other types of organization may have some influence, according to Ziaei Nafchi & Mohelská (2020). In relation to human factors, Lambrechts et al. (2021) indicate that resistance to change, communication, and leadership are the most prominent factors in the adoption of cobots. Good communication and leadership on the side of the leaders help to reduce resistance among the employees and thereby facilitate the process of integration. The authors Andrew & MohanKumar (2016) also found organizational culture to be positively correlated with employee readiness for change, pointing to its significance in the successful smooth implementation of technological change.

Ethical Considerations

The ethical considerations in measuring cobot performance encompass employee safety, job displacement, and privacy concerns. According to Jayalakshmi & Panchanatham (2017), workplace safety is paramount, with organizations obligated to provide a safe environment. However, Ajslev et al. (2024) note that while safety monitoring technologies are beneficial to workers, they also pose a threat to the autonomy and well-being of workers. They advance the Duty, Utility, Virtue (DUV) framework for the ethical evaluation of such technologies. In contrast, Shrader-Frechette & Cooke (2004) conclude that ethical issues arise when performance standards are not designed to promote the welfare of workers but only relate to the specification and the performance standards. Jacobs & Kleiner (1995) presents a case that the traditional corporate performance measures tend to more concentrate on financial results than on the outcomes of non-financial elements like employee relations and ethics. To address these shortcomings, there is a need for a more holistic approach rather than limiting oneself to financial or purely nonfinancial metrics while involving HR departments in tracking and improving health and safety outcomes among the employees. (Jayalakshmi & Panchanatham, 2017).

Balancing Trade-offs

This creates a trade-off between productivity enhancement through cobots and security in an industrial setting. Liu et al. (2022) identify that, for companies to assign tasks between humans and cobots, there must be a balance for productivity on the one hand and between the physical workload and mental workload on the other hand. To enhance the cobot's performance while being safe within the same shared workspace, Palleschi et al. (2021) offer a new algorithm approach to trajectory planning. Berx et al. (2022) further add that a readiness assessment for system-wide safety awareness must be conducted to bridge this gap and clarify the cobot implementation ambiguities. Human-robot collaboration design should be holistic, as emphasized by Pinheiro et al. (2021), stressing the incorporation of factors from engineering, ergonomics, safety, sociology, and psychology in order to include cognitive, safety, physical, and organizational ergonomic factors, therefore. Addressing these will help companies overcome the challenges while optimizing its benefits in terms of safety and well-being for workers.

Future Directions in Research

Emerging Trends

Recent research suggests that cobot technology is emerging in a manner that is likely to redefine performance metrics. According to Sutikno (2023), "the applications of artificial intelligence and machine learning can make the cobots appear more intelligent and flexible forms of automation." Improved control strategies with advanced safety features like collision detection and avoidance have also led Patil et al. (2023) to indicate improved human-robot interaction. According to Riedelbauch et al. (2023), standardized benchmarks for cobots' performance are needed to ensure that safety and team efficiency are assessed correctly. Such comparisons would enable proper and accurate assessments across approaches as well as the measurement of improvements in collaborative tasks. Lefranc et al. (2022) report that the new metrics will pay attention to the economic effects of cobots, an example being healthcare and agriculture, for possible benefits to developing countries and small manufacturers. Technically speaking, it means future performance metrics need to handle technical abilities together with broader societal implications of adopting cobots.

Collaborative Intelligence

The increasing significance of cobots in manufacturing sectors is underlined by recent research, suggesting a need for standardized benchmarks for evaluating their performance. According to Riedelbauch et al. (2023), the improvements with Industry 4.0 have increased the flexibility and human-machine interaction potential of cobots, thus calling for changes in the metrics of their performance to place a premium on human factors as well as team performance. According to Silva et al. (2023), intelligent cobot evaluation is challenging because of variations in human behavior and the integration of artificial intelligence systems. Research for the development of cobots in the future is towards collaborative intelligence that allows hybrid flexibility, enhancing humans' dexterity and adaptability with a precision by a robot in ameliorating further degrees of flexibility. Borboni et al. (2023) argue that the emergence of the human-robot coevolution is driving the need for novel metrics pertaining to safety, dependability, and the overall effectiveness of teams, while moving beyond the traditional industrial robot assessment methodologies. Collectively, the studies argue that the evaluation criteria should be adapted to fit the complexity of human-robot interaction (Riedelbauch et al., 2023; Borboni et al., 2023).

Proposed Frameworks

Latest research papers present frameworks which will help in inculcating the utilization of data analytics in real-time into the assessment of cobot performance. Salimbeni and Mamani (2020) suggested that the five-factor analysis should be accounted for: technological, ergonomic, quality, economic, and regulatory. Kumaraguru et al. (2014) proposed a system based on continuous performance management integrated with real-time analytics accompanied by industrial process data. Sibona and Indri (2021) have proposed a data-driven framework for human-robot collaboration in flexible manufacturing, addressing the modeling and control issues. Sharma and Wang (2017) have proposed an edge-cloud collaborative framework for live data analytics in IoT networks by integrating cloud resources with real-time processing by the edge. Collectively, these frameworks have been aimed at cobot integration to enhance human-robot collaboration and allow for real-time evaluation of performance in manufacturing settings. Future research directions then target including interoperability solutions, standardization work, and overcoming the barriers to successful human-robot interaction in a flexible manufacturing environment (Salimbeni & Mamani, 2020; Sibona & Indri, 2021).

Cross-Industry Learning

Cross-industry learning helps improve the cobots' effectiveness by breaking free from the inherent bottlenecks of implementation and training. According to Michaelis et al. (2020), despite all the various cobot advantages based on their flexible deployment, they are mainly used with little interaction between them and their operators, which therefore causes a requirement for efficient training and interface designs. In breaking education barriers, Mayrhofer et al. (2021) argue that adaptive learning systems, moderated by modular "learning nuggets", can be designed to suit individualized experiences toward different types of users.

A hands-on approach based on a cognitive apprenticeship has proved highly effective in the transference of programming skills to novice operators, thus aiding in increasing the adoption of more flexible use of robots in manufacturing, as found by Hansen et al. (2024). Moreover, a program such as Cobot Learning Center (COLEAC) helps SMEs and multi-level educators to become effective with modular educational frameworks in integrating cobot technology into virtual and augmented reality for preparing for the workforce of the future in manufacturing (Dam et al., 2021). Together, these approaches collectively contribute to enhancing cobot effectiveness across industries (Michaelis et al., 2020; Dam et al., 2021).

Conclusion

Summary of Key Findings

This literature review focuses on the diversity of evaluation approaches, from statistical analysis and simulation-based methods to capture performance in real time. It underlines the need to balance the improvement of productivity with considerations for safety issues. Some of the challenges here include task fragmentation and job identity loss, where the impact of negative factors can be made less significant. Real-time tracking is of equal importance for a holistic comprehension of cobot performance. Appropriate KPIs for human-robot collaboration should be defined to improve productivity and ergonomics and also increase the satisfaction of operators. Most of the competencies of standardized benchmarks and impacts from human-robot interaction on ergonomics and mental stress are to be further improved. The future work should concentrate on metrics that reproduce the complexities of collaboration along with the high integrations of artificial intelligence in cobot applications. Therefore, the inclusion of cobots in industrial processes requires not only technical metrics but also an optimization of all human factors.

Broader Implications

The improvement of the performance metrics for cobots seriously impacts work in different sectors in the future. Performance metrics can enhance human-robot interactions by maximising more collaborative interactions, thus enhancing productivity and job satisfaction. Safety metrics in assessments can become a focus area for an organisation as it becomes more concerned with workers' safety and tries to minimize accidents at work with the hope of lower insurance premiums. Standardized performance metrics will make it possible to compare one industry with another and will be very instrumental in driving innovations. As industries make their way to Industry 4.0, more advanced technologies such as

AI will be integrated, requiring new metrics to maximize the operational efficiency and responsiveness of the companies.

The integration of cobots can alter roles for the workforce, as human workers can redirect their efforts to more complex, creative tasks that would be more satisfying on the job and open new career avenues. Improved metrics also help further quantify the economic benefits of integrating cobots, support investment decisions, and provide the potential to boost growth in small and medium enterprises. An organization has the opportunity to ensure that the well-being of employees is paid attention to by ensuring that cognitive workload and ergonomic factors are being assessed, therefore leading to an increased performance and retention. Ultimately, identification of gaps in current metrics can stimulate further research and development in cobot technology, hence keeping them effective and adaptable.

Recommendations for Practice

The findings of this performance metric literature review on cobots are rich and also can inform industry practice and decision-making to a better extent. It offers methodologies on how one can effectively evaluate the performance of cobots, hence developing strategies for organizations about deployment after having proper implementations. By identifying the KPIs, companies can then prioritize investments in cobot technology to drive maximum productivity and safety. Further, the report contains existing gaps in metrics for human-robot interaction, thus requiring enhanced training programs that will equip workers with abilities to effectively work with cobots. Second, the advancement of safety metrics also directs companies to present their parameters for carrying out safety protocols and creating a safer workplace atmosphere that decreases the chances of accidents occurring.

Standardized performance metrics enable organizations to benchmark the performance of their cobots against industry standards, foster the sharing of best practices, and encourage further improvement. This thorough analysis will inform the adoption and implementation of cobots within strategies and workforce and operational goals. Second, the review contributes to cross-industry learning by providing examples of successful cobot applications from other sectors so that companies can draw insights from those sectors. The research gaps and emerging trends are identified, thus guiding R&D efforts into enhanced capabilities of cobots. Last, workforce issues related to the displacement of jobs can be assuaged, as the collaborative nature of cobots also can increase the positive outlook on automation.

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