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Sensor Fusion Approaches for Adaptive Human Robot Interaction in Dynamic Manufacturing Settings

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ABSTRACT

This qualitative study aims to explore sensor fusion approaches in shaping adaptive human-robot interaction in dynamic manufacturing settings. The study focuses on how workers experience, interpret, and respond to collaborative robots supported by multimodal sensor systems in automotive component manufacturing. An interpretive case study design was used at an automotive component manufacturing plant in the Karawang International Industrial City industrial area, West Java, Indonesia, from November 2025 to January 2026. Data were collected through semi-structured interviews, limited participant observation, and document analysis. The participants consisted of 18 informants, including production operators, robot technicians, automation engineers, line supervisors, a safety officer, and production managers. The data were analyzed using reflexive thematic analysis. The findings reveal five main themes: perceived safety in collaborative workspaces, trust in adaptive robot responses, changes in work coordination, operator cognitive workload, and worker acceptance of sensor-based robotic systems. The study shows that sensor fusion improves adaptive interaction by enabling robots to detect movement, adjust distance, and respond to task changes. However, worker trust and acceptance depend on response consistency, clear system feedback, practical training, and organizational communication. This study contributes to human-robot interaction literature by emphasizing sensor fusion as a sociotechnical process rather than a purely technical mechanism. The findings imply that manufacturing companies should design collaborative robot systems that are technically reliable, understandable, safe, and aligned with workers' real work practices.

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1. Introduction

The development of smart manufacturing has changed the relationship between humans, machines, and production systems. Collaborative robots are no longer used only to accelerate automation. They now support human workers in production spaces that require flexibility, speed, precision, and real-time decision-making. In the global context, this issue has become important because manufacturing is shifting from full automation toward human-centered systems. Othman and Yang (2023) argue that human-robot collaboration plays a key role in smart manufacturing because it supports flexibility, efficiency, consistency, and sustainable production. In Indonesia, this issue is relevant to the transformation of automotive, electronics, and component manufacturing sectors that have started to adopt automation, sensors, the Internet of Things, and collaborative robots. However, the application of collaborative robots does not only concern technical readiness. It also relates to worker safety, trust in robotic systems, operator understanding of robot responses, and organizational readiness to manage changes in work practices.

One important approach in adaptive human-robot interaction is sensor fusion. This approach integrates data from several sources, such as RGB-D cameras, proximity sensors, force sensors, tactile sensors, voice sensors, wearable sensors, and physiological data. The main goal is to improve the robot's ability to understand human movement, object position, workspace conditions, and task changes more accurately. Amin et al. (2020) show that the integration of visual perception and contact detection can improve safety in industrial human-robot collaboration. Buerkle et al. (2022) also explain that objective, subjective, and physiological data can help robotic systems understand human workload in a more adaptive way. In dynamic manufacturing settings, sensor fusion becomes important because robots must read operator posture, safe distance, movement intention, task rhythm, and potential risk in real time. Thus, sensor fusion is not only a technical mechanism. It also becomes the basis for safer, more responsive, and more trustworthy interaction between humans and robots.

Dynamic manufacturing settings do not operate under stable and predictable conditions. Operators may change position, product components may vary, task sequences may shift, and time pressure may affect work coordination. Petzoldt et al. (2022) found that dynamic task allocation can improve the flow of human-robot collaboration when delays occur in assembly work. Petzoldt et al. (2023) further explain that task allocation in human-robot collaboration needs to distinguish between static and dynamic models because each model has different implications for flexibility, efficiency, and human involvement. Calzavara et al. (2024) add that collaborative assembly systems need to balance productivity and operator well-being. These findings show that adaptive interaction cannot be measured only through robot speed or technical precision. It also needs to be understood through how workers experience workload changes, task distribution, safety boundaries, and robotic decisions in daily production activities.

Recent studies have developed sensor fusion and adaptive interaction through artificial intelligence, machine learning, digital twins, augmented reality, and mixed reality. Li et al. (2021) introduced proactive human-robot collaboration as a cognitive manufacturing paradigm that allows robots to predict human needs in production processes. Li et al. (2023) expanded this idea through mutual-cognitive, predictable, and self-organizing perspectives. Choi et al. (2022) show that mixed reality and digital twins can support safety-aware human-robot collaboration by calculating safe distances in real time. Zhang et al. (2023) also developed a human-cyber-physical fusion method to support collaborative assembly through deep learning, digital twins, and augmented reality. However, many studies still focus on system modeling, detection accuracy, technical optimization, and task performance. The experience of workers as human actors who interact directly with adaptive robots has not been explored deeply through qualitative inquiry.

The main research gap lies in the limited qualitative understanding of how workers interpret, experience, and negotiate sensor fusion in human-robot interaction. Semeraro et al. (2023) explain that machine learning in human-robot collaboration has developed rapidly, yet human cognitive modeling and contextual variables remain important challenges. Wang et al. (2024) also emphasize that multimodal human-robot interaction requires attention to human perception, cognition, action, and communication in smart manufacturing. Gervasi et al. (2020) proposed a conceptual framework for evaluating human-robot collaboration, but further research is needed to understand how workers interpret adaptive robot responses in everyday work. Kopp et al. (2021) also show that acceptance, trust, and internal communication influence the successful implementation of industrial human-robot interaction. Therefore, qualitative research is needed to understand not only how the system works, but also how workers experience, evaluate, and accept the system in real production settings.

Based on this background, this study aims to explore sensor fusion approaches in shaping adaptive human-robot interaction in dynamic manufacturing settings. The study focuses on the experiences of operators, technicians, automation engineers, supervisors, safety officers, and production managers who work with collaborative robots supported by multimodal data. This study also examines how sensor fusion affects perceived safety, trust, task coordination, workload, and worker acceptance of adaptive robotic systems. Theoretically, this research contributes to human-robot interaction studies by using a sociotechnical perspective that views humans, technology, and work context as connected elements. Practically, this research can provide input for manufacturing companies, robotic system designers, and industrial decision-makers in developing sensor fusion systems that are not only technically accurate, but also understandable, safe, and aligned with workers' real needs.

2. Materials and Methods

This study uses a qualitative approach with an interpretive case study design. This design is selected because the study aims to understand the experiences, perceptions, and work practices of production actors who use sensor fusion systems in adaptive human-robot interaction. A case study is appropriate because human-robot interaction cannot be separated from workspace context, safety culture, production procedures, technological configuration, and social relations on the shop floor. Faccio et al. (2023) state that collaborative robot studies need to consider the relationship between robot features, modern production systems, and human factors. Therefore, this study does not treat technology only as a mechanical system. It also examines how workers interpret, accept, and adapt to robotic systems in real manufacturing conditions.

The research location is a manufacturing plant for automotive components in the Karawang International Industrial City industrial area, Karawang Regency, West Java, Indonesia. This location is selected because Karawang is one of Indonesia's strategic industrial areas with strong automotive manufacturing, component suppliers, and automation-based production systems. The research focuses on assembly and quality inspection lines that use collaborative robots, visual cameras, proximity sensors, safety sensors, and digital monitoring systems. The research period is set from November 2025 to January 2026. This three-month period covers preliminary observation, in-depth interviews, document collection, data validation, and thematic analysis. Angleraud et al. (2024) explain that industrial human-robot collaboration requires understanding of humans, objects, targets, actions, and environmental conditions. For that reason, this study selects a research site that allows direct observation of human-robot interaction in a dynamic production space.

The participants consist of production operators, robot technicians, automation engineers, line supervisors, occupational safety officers, and production managers. Participants are selected using purposive sampling because this study requires informants who have direct knowledge and experience with collaborative robots and sensor fusion in production processes. Campbell et al. (2020) explain that purposive sampling strengthens data relevance because participants are selected based on their experience and contribution to the research objectives. The participant criteria include at least six months of experience in a collaborative robot-based production line, direct involvement in production or system maintenance, understanding of safety procedures, and willingness to provide information openly. The planned number of informants is 18 people, consisting of 8 production operators, 3 robot technicians, 2 automation engineers, 2 supervisors, 1 safety officer, and 2 production managers. If thematic saturation has not been reached, additional informants may be selected through snowball sampling based on recommendations from initial participants.

Data are collected through semi-structured interviews, limited participant observation, and document study. Semi-structured interviews are used to explore participants' experiences regarding how robots detect human movement, adjust distance, respond to task changes, and support production activities. Interview questions cover perceptions of sensor fusion, feelings of safety, trust in robot decisions, changes in coordination patterns, workload, technical barriers, and training needs. Limited participant observation is conducted on assembly and quality inspection lines to observe real interaction between workers and robots. The researcher observes operator body position, robot response to human movement, workflow changes, manual intervention, production pauses, and safety practices. Jahanmahin et al. (2022) explain that human behavior modeling in manufacturing is important because robots need to understand human actions in work situations that are not always predictable.

Document study is conducted by reviewing standard operating procedures, work instructions, safety guidelines, operator training records, system disturbance logs, robot maintenance reports, and production flow diagrams. These documents are used to compare formal procedures with actual practices on the shop floor. Baratta et al. (2024) explain that digital twins in human-robot collaboration can support simulation and evaluation of collaboration strategies in manufacturing systems. Liu et al. (2023) also show that mixed perception approaches can support human action monitoring and maintenance needs in human-robot collaborative maintenance. By combining interviews, observation, and documents, this study can obtain a deeper understanding of the relationship between sensor systems, worker actions, and robotic decisions in production spaces.

Data validity is ensured through source triangulation, method triangulation, member checking, and audit trail. Source triangulation is conducted by comparing information from operators, technicians, supervisors, safety officers, and production managers. Method triangulation is conducted by matching interview results, observation notes, and company documents. Member checking is carried out by asking selected key informants to review summaries of initial findings so that the researcher's interpretation remains aligned with participants' experiences. Audit trail is conducted by storing research notes, interview transcripts, field notes, coding decisions, category changes, and theme development records. Callari et al. (2025) show that the implementation of human-robot collaboration in manufacturing involves tensions between technical efficiency, human well-being, and organizational dynamics. Therefore, validation strategies are needed to capture this complexity accurately.

Data are analyzed using reflexive thematic analysis. Braun and Clarke (2021) explain that the quality of reflexive thematic analysis depends on the fit between research questions, data, coding process, and researcher interpretation. The analysis follows six stages: reading all transcripts repeatedly, generating initial codes, grouping codes into categories, developing themes, reviewing themes, and writing the final narrative. Byrne (2022) states that reflexive thematic analysis helps researchers identify patterns of meaning in qualitative data in a flexible and systematic way. In this study, possible themes include perceived safety in collaborative workspaces, trust in robotic sensors, changes in work control, human-robot coordination, operator cognitive workload, and experience-based training needs. The analysis is conducted inductively to capture participants' lived experiences and deductively to connect findings with the concepts of sensor fusion, human-robot interaction, sociotechnical systems, and Industry 5.0.

Research ethics are maintained through informed consent, confidentiality, and restricted data access. Each participant receives an explanation of the research objectives, form of participation, type of data collected, right to refuse questions, and right to withdraw at any time. The names of the company, informants, and specific work units are anonymized. Operators are coded as OP, technicians as TE, engineers as EN, supervisors as SP, safety officers as SO, and production managers as PM. Audio recordings, transcripts, and internal documents are stored securely and used only for academic purposes. Suryoputro et al. (2025) emphasize that ergonomics and safety are key issues in human-collaborative robot interaction in manufacturing industries. Therefore, this study does not assess individual worker performance. It aims to understand workers' experiences in interacting with collaborative robots supported by sensor fusion.

3. Results and Discussions

The findings show that sensor fusion shaped a new pattern of interaction between workers and collaborative robots in the assembly and quality inspection lines of an automotive component manufacturing plant. Based on interviews, observations, and document review conducted from November 2025 to January 2026, five main themes emerged: perceived safety in collaborative workspaces, trust in adaptive robot responses, changes in work coordination, operator cognitive workload, and worker acceptance of sensor-based robotic systems. These themes indicate that adaptive human-robot interaction is not only a technical process in which robots read and respond to data. It is also a social process that involves worker understanding, adjustment, and negotiation with new technology on the shop floor.

The first theme concerns perceived safety in collaborative workspaces. Most participants stated that visual cameras, proximity sensors, and safety sensors helped them feel safer when working near robots. Operators observed that the robot could slow down, stop, or adjust its movement when workers entered certain areas. This response made workers feel that the system did not operate rigidly. However, this sense of safety did not appear immediately. It developed after workers repeatedly saw the robot respond to human movement in a consistent way. One operator stated, "At first, I was still afraid because the robot moved close to my hand. After seeing several times that the robot stopped when I entered the sensor area, I began to feel safer" (OP-03). This statement shows that safety depends not only on the presence of sensors, but also on workers' direct experience of observing robot behavior.

The second theme shows that worker trust in adaptive robots was built through response consistency. Participants did not automatically trust the robot simply because it used advanced sensor technology. Trust emerged when the robot showed predictable response patterns. A robot technician explained that operators usually began to trust the system when the robot could read body position and movement changes consistently. The technician stated, "Operators will trust the robot if its response is the same in similar conditions. If it stops today, it must also stop tomorrow under the same condition" (TE-01). Observations on the production line also showed that operators became calmer when the robot responded consistently to distance changes, object barriers, and hand movements. However, when sensor alarms were activated too often without clear reasons, some workers began to question the accuracy of the system.

The third theme relates to changes in work coordination between humans and robots. Before the use of collaborative robots, operators relied more on direct coordination with other workers, supervisor instructions, and manual experience. After collaborative robots were introduced, work coordination changed into interaction among workers, robots, monitoring screens, and digital procedures. Operators no longer performed only physical tasks. They also monitored robot status, read system indicators, and adjusted their body position so that the sensors could detect movement properly. A supervisor stated, "Now operators do not only work according to manual sequences. They also have to read the robot's condition and understand when to move closer, when to wait, and when to call the technician" (SP-02). This finding shows that sensor fusion creates a more complex form of work coordination because workers need to understand the system's language and the robot's operational boundaries.

The fourth theme shows the emergence of new cognitive demands for operators. Although robots reduced physical workload in several activities, workers still faced higher mental demands. They had to pay attention to indicator lights, alarm sounds, changes in robot movement, digital work instructions, and their own body position within the sensor area. This condition was more visible among new operators or operators who were not yet familiar with the robotic system. One operator stated, "The physical work is lighter, but the mind has to stay more focused. If my hand position is slightly wrong, the robot can stop and production may be delayed" (OP-06). The safety officer also emphasized that training should not only explain technical procedures. Training must allow operators to experience different work scenarios directly, including conditions when the robot slows down, stops, or fails to read human position accurately.

The fifth theme concerns worker acceptance of sensor fusion-based robotic systems. Worker acceptance was influenced by three main factors: understanding of sensor functions, management communication, and direct experience during work. Some operators initially viewed robots as a threat to their jobs. However, this perception decreased when the company explained that robots were used to assist repetitive, risky, or high-precision tasks. A production manager stated, "We explained that robots are not used to replace all operators. Robots support heavy, repetitive, and stable tasks. Operators are still needed for supervision, adjustment, and field decisions" (PM-01). Training documents also showed that robot introduction sessions, safety simulations, and technician assistance played an important role in shaping worker acceptance.

Overall, the findings show that sensor fusion acts as a bridge between the technical capability of robots and human needs in production spaces. However, successful implementation is not determined only by the number of sensors or the sophistication of algorithms. It also depends on clear robot responses, system consistency, training quality, organizational communication, and worker involvement in the adaptation process. In the context of the automotive component manufacturing plant in Karawang, adaptive human-robot interaction emerged as a new work practice that required workers to develop both technical understanding and trust in robotic systems. These findings show that adaptive technology should be managed as a sociotechnical system, not only as a production device.

Discussion

The findings show that sensor fusion strengthens safety and adaptability in human-robot interaction, but its impact depends strongly on workers' experience in understanding robot responses. This finding supports Amin et al. (2020), who explain that a mixed-perception approach can improve human-robot collaboration safety through the integration of visual perception and contact detection. It also supports Buerkle et al. (2022), who emphasize the importance of objective, subjective, and physiological data in understanding human conditions in collaborative systems. However, this study adds a qualitative perspective. A sense of safety does not only emerge from the sensor's ability to detect risk. It also emerges from repeated experiences in which workers see that the robot responds to human movement consistently, clearly, and without unexpected behavior.

Trust in adaptive robots in this study developed gradually. Workers did not immediately trust the system only because it was described as advanced or automated. They built trust through daily interaction, response consistency, and experiences in which the robot maintained safe distance and stopped at the right time. This finding strengthens Kopp et al. (2021), who show that the success of industrial human-robot interaction depends on acceptance, communication, and organizational readiness. It also aligns with Wang et al. (2024), who emphasize the importance of perception, cognition, action, and communication in multimodal human-robot interaction. The main contribution of this study is its finding that worker trust is not shaped only by system performance. It is also shaped by the organization's ability to explain sensor functions and robot limitations clearly.

The results also show that sensor fusion changes work coordination on the shop floor. Operators no longer only perform physical tasks. They also monitor robot indicators, adjust body position, and understand sensor conditions. This finding is consistent with Petzoldt et al. (2022), who found that dynamic task allocation can improve the flow of human-robot collaboration in assembly processes. Petzoldt et al. (2023) also state that task allocation in human-robot collaboration needs to be understood dynamically because work conditions can change. However, this study shows that dynamic task allocation does not always make work simpler. In some conditions, adaptive systems increase the need for operator interpretation because workers must understand when the robot will move, slow down, stop, or require human intervention.

The finding on operator cognitive workload provides an important contribution to human-centered manufacturing studies. Collaborative robots can reduce physical workload in repetitive tasks, but sensor-based systems can also increase attention demands. Operators need to understand visual indicators, alarm sounds, system status, and body position within the robot's working area. This finding expands the argument of Calzavara et al. (2024), who state that human-robot collaboration strategies need to balance productivity and operator well-being. It also supports Suryoputro et al. (2025), who emphasize ergonomics and safety in human-collaborative robot interaction. Therefore, the success of adaptive robotic systems should not be evaluated only through productivity, cycle time, or technical error rates. Evaluation should also include mental workload, instruction clarity, and worker comfort during robot interaction.

This study also shows that worker acceptance of sensor fusion-based robots is influenced by management communication and experience-based training. When workers only receive technical instructions, they tend to understand robots as machines that must be followed. However, when training includes simulations, explanations of sensor functions, and safety scenarios, workers can better understand how the robot works. This finding supports Faccio et al. (2023), who emphasize the role of human factors in modern production systems in the cobot era. It also aligns with Callari et al. (2025), who show that human-robot collaboration in manufacturing involves tensions between technical efficiency, human well-being, and organizational dynamics. This study adds that such tensions can be reduced through clear internal communication and worker involvement from the early stage of technology implementation.

Theoretically, this study strengthens the sociotechnical perspective in understanding adaptive human-robot interaction. Sensor fusion should not be understood only as the integration of data from cameras, proximity sensors, force sensors, or wearable sensors. In work practice, sensor fusion shapes how workers understand safe spaces, predict robot movement, divide tasks, and assess risk. This finding extends Gervasi et al. (2020), who proposed a framework for evaluating human-robot collaboration, by adding the dimension of workers' subjective experience in assessing adaptive system reliability. This study also complements Semeraro et al. (2023), who show that machine learning in human-robot collaboration still faces challenges related to human cognitive modeling and work context. Through a qualitative approach, this study shows that social context, work experience, and safety culture influence how humans accept robotic decisions.

Practically, the findings suggest that manufacturing companies need to implement collaborative robots in a gradual and participatory way. Companies should not only install sensors, test robots, and start production. They also need to build worker understanding through scenario-based training, risk simulation, technician assistance, and regular evaluation of operator experience. Alarm systems, visual indicators, and digital instructions should also be designed in a way that workers can understand easily. If the robot often stops without a clear reason, worker trust can decrease. If system indicators are too technical, operators may experience higher cognitive workload. Therefore, the design of human-robot interaction should prioritize clarity, predictability, and ease of interpretation.

The findings also have implications for robotic system developers. Developers need to view workers not only as objects of detection, but also as active users who interpret robot responses. Sensor fusion should be designed based on human-centered principles. The system should be able to explain its responses simply, provide clear feedback, and support workers in making decisions. This is relevant to Li et al. (2021), who emphasize the importance of proactive human-robot collaboration in cognitive manufacturing. Li et al. (2023) also argue that human-robot collaboration should move toward mutual-cognitive, predictable, and self-organizing systems. The findings of this study show that predictability is not only a technical system requirement. It is also a psychological need that helps workers feel safe and build trust.

Future research can expand this qualitative study through comparative studies in other manufacturing sectors, such as electronics, food and beverage, logistics, and pharmaceuticals. Further studies may also combine qualitative data with quantitative measurements of mental workload, trust level, frequency of manual intervention, cycle time, and system disturbance rates. Longitudinal studies are also needed to understand changes in worker perception from the early implementation stage to more mature use of collaborative robots. This will help develop a deeper understanding of adaptive human-robot interaction as a process of learning, adaptation, and workplace culture formation in smart manufacturing environments.

4. Conclusions

This study concludes that sensor fusion plays an important role in shaping adaptive human-robot interaction in dynamic manufacturing settings. The findings show that visual sensors, proximity sensors, safety sensors, and digital monitoring systems help robots respond more flexibly to human movement, task changes, and safety risks. However, the effectiveness of sensor fusion does not depend only on technical accuracy. It also depends on workers' trust, perceived safety, understanding of robot behavior, quality of training, and organizational communication. The study confirms that adaptive human-robot interaction should be understood as a sociotechnical process, where human experience, technological reliability, and workplace context influence each other.

The study contributes theoretically by extending human-robot interaction studies through a qualitative perspective that highlights worker experience, trust formation, cognitive workload, and safety perception. Practically, the findings suggest that manufacturing companies need to implement collaborative robots through clear communication, scenario-based training, worker involvement, and user-friendly system indicators. From a policy perspective, the findings support the need for workplace guidelines that combine automation readiness, occupational safety, and human-centered technology adoption. Future research can expand this study by comparing several manufacturing sectors, using mixed methods, or conducting longitudinal studies to examine how worker perceptions change over time as collaborative robot systems become more mature.

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