

System Design for Adaptive Safety Monitoring and Intelligent Warning of Collaborative Robots Based on Mechatronics Theory

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Abstract. With the rapid development of robotics technology, an increasing number of industries are adopting robots as essential components of their productive forces. Among various robotic applications, collaborative robots have emerged as a particularly prevalent technology, finding extensive use in diverse fields such as precision component assembly, medical surgery assistance, and logistics order picking. While collaborative robots offer significant advantages in terms of flexibility and efficiency by working alongside humans, ensuring operational safety in shared workspaces remains a critical challenge that must be addressed. Current safety strategies predominantly employ reactive mechanisms that trigger deceleration or emergency stops only after potential hazards are detected, lacking the capability for proactive risk prevention and adaptive response to dynamic human behavior. This paper employs analytical and argumentative methods to investigate the system design for safety monitoring and intelligent warning of collaborative robots, centered on mechatronics theory as the foundational framework. By integrating principles from mechanical engineering, electronic control, and information processing, we propose a comprehensive safety monitoring and early warning system. The core innovation lies in the development of a dynamic risk assessment model that continuously evaluates human-robot interaction status based on real-time multi-sensor data fusion. This model incorporates hierarchical safety zone definition and predictive behavior analysis to achieve proactive safety management. Furthermore, the system implements a graded warning and response mechanism that balances safety requirements with operational efficiency. The proposed design represents a significant advancement from traditional reactive safety approaches toward intelligent, predictive safety management in human-robot collaborative environments, providing both theoretical foundations and practical guidance for future research in this field.

Keywords: Mechatronics Theory, Collaborative Robots, Safety Monitoring

1. Introduction

Nowadays, collaborative robots have become a vital part of production due to their high efficiency and ability to operate in extreme environments. For example, Zheng Xuejun mentioned that in automated assembly, human-robot collaborative robots can effectively improve assembly quality and reduce assembly rework rates [1]. However, because some collaborative robots need to work alongside humans, their safety during operation cannot be ignored.

The International Organization for Standardization has established technical specifications such as ISO/TS 15066 for the safety of collaborative robots, defining various collaborative operation modes. Current safety strategies are mostly reactive--triggering deceleration or shutdown after a hazard occurs or a distance threshold is breached--lacking the capability to predict personnel behavior and proactively intervene in risk situations [2]. Research indicates that traditional methods based on 3/27/2026 static safety zones often sacrifice production efficiency due to being overly conservative and struggle to adapt to the uncertainties of human behavior.

Based on mechatronics theory, this paper designs an adaptive safety monitoring and intelligent warning system for collaborative robots. Through multi-modal perception fusion, dynamic risk assessment, and behavioral intention prediction, this system can achieve real-time adaptive adjustment of safety zones and early warning of potential collisions, maximizing robot operational efficiency while ensuring personnel safety. The fundamental parts of this system are divided into four components: the perception layer, decision layer, execution layer, and data flow. Furthermore, to enhance the accuracy of the perception and decision layers in detecting worker behavior and assessing the current safety situation, this paper also proposes adding a dynamic risk assessment model to monitor worker conditions in real time, providing a theoretical foundation for future research in related directions.

2. Mechatronics theory

The main content of mechatronics theory involves designing mechanical systems and electrical control systems as an integrated whole, relying on the coordination of internal system modules to achieve various functions. For the collaborative robot safety monitoring system proposed in this paper, mechatronics theory primarily provides guidance in two aspects:

First, the safety system design proposed here and the collaborative robot itself are considered an integrated whole. Such a safety system design is better tailored to the collaborative robot, more specifically, improving work efficiency and quality. The perception layer, decision layer, execution layer, and data flow transmission paths will all be established within the robot.

Second, the overall system adopts a closed-loop control relying on feedback information. The perception layer monitors external information and converts it into data flow transmitted to the decision layer. The decision layer determines the next actions, and the execution layer is responsible for executing commands. The perception layer is also responsible for monitoring work progress and the working environment, feeding this information back to the decision layer.

3. Overall system scheme and key technical foundations

3.1. Requirements analysis for collaborative robot safety monitoring

According to the ISO/TS 15066 technical specification and practical application requirements, a collaborative robot safety monitoring system needs to meet certain functional requirements:

(1) Safety Perception

Safety perception needs to cover the complete spatial range from long distance to contact. The perception space can be divided into three levels:

Long-distance layer: Used for personnel intrusion detection and trajectory prediction.

Medium-distance layer: Used for fine approach monitoring.

Contact layer: Used for collision detection and force control response.

(2) Dynamic Risk Assessment Capability

The system needs the ability to assess the risk of human-robot collision in real time, for example, sensing the minimum distance between the robot and the operator, determining the safety distance threshold, and predicting risk evolution trends for the next 1-3 seconds.

(3) Hierarchical Warning and Response Mechanism

To balance safety and efficiency, the system adopts a hierarchical response strategy:

Normal state: The robot operates at full speed to ensure work efficiency.

Warning state: When a person enters the warning area, an audible and visual alert is activated, and the robot decelerates appropriately.

Danger state: When the safety distance is insufficient, the robot decelerates to a safe speed or performs a controlled stop.

(4) Behavior Prediction and Intention Understanding

The system needs the capability to predict human behavior, including predicting future positions of personnel based on historical trajectories, and identifying personnel operation intentions to adjust robot behavior.

3.2. Overall system architecture design

Based on the above requirements analysis, this paper proposes the overall system architecture shown in Figure 1.

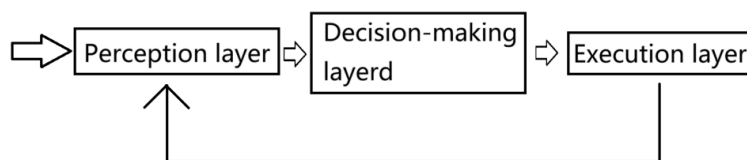


Figure 1. Overall system architecture

The perception layer consists of a visual sensing subsystem and a proximity sensing subsystem. The visual subsystem can use LiDAR and visual sensors as core sensors. The LiDAR could adopt a 16-line scanning mode, with a ranging accuracy of $\pm 1\text{mm}$ and an angular resolution of 0.5° . The visual sensor could be configured with a binocular camera, with a baseline distance of 150mm , and a depth calculation error of $< 2\text{mm}$ [3].

Combining the two allows for mutual verification, ensuring the reliability of the detected information.

The proximity subsystem could use capacitive flexible pressure sensors. Liu Zenghui et al. designed a capacitive flexible pressure sensor with both high sensitivity and a wide pressure sensing range. Its maximum measurement distance is 25mm , measurement resolution is approximately 0.2mm , pressure sensing range is $0\sim 4\text{kPa}$, and sensitivity is 34.4kPa , meeting the system's requirements for proximity sensors [4].

The decision layer contains two key modules: Dynamic Risk Assessment Model: Based on the human-robot relative distance, relative speed, and personnel position predictions input from the perception layer, it dynamically adjusts the behavior strategy in real time. Behavior Intention Judgment Module: Based on the personnel's current posture and work environment, it infers the personnel's short-term behavioral intentions, providing a basis for the warning strategy.

The decision algorithm can combine deterministic models with probabilistic models. Deterministic models are used for quickly identifying action patterns that have already occurred, while probabilistic models are used to generate multiple possible future scenarios, enabling the system to prepare for the most dangerous situations.

The execution layer receives control commands from the decision layer and implements speed adjustment, trajectory replanning, or impedance control through the robot's underlying servo drives.

The system data flow follows the closed-loop direction of "perception-decision-execution." While the decision layer uses perception layer data to predict future states, the actual control effects of the execution layer (such as the actual deceleration trajectory) can serve as feedback for optimizing decision model parameters.

4. Dynamic risk assessment model

4.1. Real-time dynamic safety zone assessment

The core task of dynamic safety zone assessment is to determine in real time the upper limit of the robot's operating speed, ensuring that the actual distance between the human and the robot at any moment is greater than the standard minimum safety distance.

(1) Safety Distance Calculation Model

According to ISO/TS 15066, the minimum safety distance in Speed and Separation Monitoring mode can be expressed as:

$$S(t) = K \cdot (tr + ts) + C + df \quad (1)$$

Where K is the human-robot relative speed, tr is the system response time, ts is the robot stopping time, C is the intrusion distance (typically taken as the operator's body thickness), and df is the measurement error compensation term. In practical applications, the safety distance needs to be updated in real time.

(2) Establishing a Reasonable Dynamic Risk Assessment System

To further refine the dynamic safety zone assessment, it is necessary to establish a reasonable dynamic risk assessment model and determine specific safety zone boundaries based on the model's calculation results.

(3) Hierarchical Safety Zone Design

The outermost layer is the warning zone. When personnel enter, it triggers an audible and visual alert, and the robot begins deceleration preparations. The middle layer is the deceleration zone, where the robot's speed is forcibly limited to a lower range. The innermost layer is the stop zone, which also has the lowest safety factor; once a worker enters this area, the machine stops immediately. The boundaries of the stop zone can vary depending on the task being performed. The boundary dimensions of each zone are dynamically adjusted based on personnel speed--the faster the personnel's movement speed, the larger the safety zone expands, reserving more response time for the system.

4.2. Intention judgment module based on behavior analysis

Understanding personnel intention is key to achieving safety. The goal of the intention judgment module is to infer the personnel's short-term action goals based on observed behavior patterns and input the inference results into the risk assessment model, enabling the system to adjust its behavioral strategy in advance. This module draws on the "skeleton-RGB video fusion method for online prediction of highly similar human actions" proposed by Zhang Yaqian et al., achieving online judgment of the operator's short-term intentions through multi-modal behavior analysis, providing a forward-looking basis for dynamic risk assessment [5].

A. The basis of intention judgment is extracting effective features from multi-modal perception data:

Skeletal Sequence Features: Utilize a human perception camera (such as the Microsoft Azure Kinect DK) to capture the 3D coordinates and movement speeds of 19 key points on the operator's upper body. A multi-scale graph convolutional network (MS-G3D) is used to extract spatiotemporal features of assembly actions from the skeletal sequences. This method is robust to illumination changes and background interference.

Visual Semantic Features: Extract contextual information from the scene using convolutional neural networks, such as whether the person is reaching for an object or looking at the robot.

B. Based on the idea of hierarchical intention tracking, this module divides operator intention into two levels:

Action-level Intention: Identifies the micro-action the operator is currently performing and provides real-time output through the aforementioned online prediction model.

Task-level Intention: Infers the operator's macro-goal within the current process by analyzing the context of the action sequence.

C. Intention-Risk Mapping Mechanism:

The final output of the intention judgment will be mapped into a risk level correction factor:

If the intention judgment indicates the operator will move away from the robot, the safety zone can be appropriately reduced, and the operating speed increased.

If the intention indicates the operator will enter the robot's workspace, the warning zone is expanded in advance, and the deceleration slope is increased.

If the intention uncertainty is high, a conservative strategy is adopted, preparing for the most dangerous scenario.

5. Conclusion

Based on mechatronics theory, this paper proposes a design scheme for an adaptive safety monitoring and intelligent warning system for collaborative robots. The main work includes: a. System Architecture Design: A "perception-decision-execution" three-layer closed-loop architecture was constructed. The perception layer integrates visual sensing and proximity sensing for full spatial coverage. The decision layer integrates a dynamic risk assessment model and a behavior intention judgment mechanism. The execution layer implements hierarchical adaptive responses. B. Dynamic Safety Zone Model: A method for dynamically adjusting safety zones based on safety distance calculation and dynamic risk assessment was designed, enabling safety boundaries to adaptively change according to the real-time human-robot relative status. C. Behavior Intention Judgment Mechanism: A hierarchical intention tree representation and probabilistic motion prediction model were introduced, enabling the system to perceive personnel behavioral intentions in advance, shifting the warning trigger from "distance-based" to "intention recognition-based."

This design applies the methodology of mechatronics theory throughout the entire safety system design process--achieving deep integration of perception and control through integrated design, coordinating safety and efficiency through closed-loop optimization, and realizing overall optimization from the mechanical body to intelligent algorithms through multi-domain modeling.

With the continuous advancement of artificial intelligence and sensing technologies, safety systems for collaborative robots are evolving from "passive protective devices" into "proactive intelligent partners." In this evolution, mechatronics theory will continue to leverage its methodological value of "integration and synergy," providing robust support for building a safer, more efficient, and more intelligent future for human-robot collaboration.

However, the research in this paper is still limited, as it did not employ modeling and experimental research methods to analyze the specific debugging parameters of each component. It is believed that with the development of research efforts, this missing part will be supplemented.

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