

Intelligent Robotics Safeguarding

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ABSTRACT

Recent advances in technology allow machine safeguarding to shift from a system that completely shuts down the hazardous part of a machine, regardless of the action, to one with a controlled response. This intelligent robotics safeguarding can be based on conditions such as the type of task, how it is performed, entry and exit locations, and the operator's movement within the hazard zone. Such a strategy could increase production rates by allowing robots to operate at higher speeds within dynamic environments.

When used as part of a preventative maintenance program, reliability data can predict component failure rates and reduce the probability that operators will access the hazard zone. Programming techniques, such as function blocks to monitor component usage, can be used to evaluate trends.

SQL (Structured Query Language) databases can track access and frequency trends, which can lead to design improvements and indicate changes affecting the system. Advanced 3-D safety sensing devices can provide additional flexibility for using zones and tracking intrusion without creating barriers that interfere with operator movement or increase the likelihood of bypassing safeguards. They can also be used with manual load and unload stations to monitor how frequently safeguarding conditions change and further improve design ergonomics.

Robots can use safe motion to reduce speed and monitor position or control access through zone sets instead of forcing complete shutdowns. The inherently safe design of the power and force limited robots used in collaborative applications allow for more interaction and mobility and, thus, enables operators to quickly adapt to changing needs.

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INTRODUCTION

Traditional robot applications limit operator access to hazards through hard-guarding and protective devices, which either detect and stop the hazard or prevent access into the safeguarding space until the hazard no longer exists. The introduction of power and force limited robots used in collaborative applications changes this environment. Reduced or nonexistent hard-guarding, along with continuous motion and interaction between the robot and the operator, makes the environment inherently dynamic and uncertain [6]. Methods to reduce risks to a tolerable level include limiting forces and speed, but these measures can yield unacceptable production rates.

Traditional robotic safeguarding stops hazardous system motion regardless of the operator's intent or task. A collaborative robot application limits motion to a level where inherent safety designs have time to respond and to stop motion if contact with an operator is made. Currently, collaborative robot application speed is limited by its most hazardous task even though the risks for different tasks may vary. To maintain a safe environment for the operator while optimizing a robot's speed, size and capability, machine safeguarding must transition from traditional preventative procedures to emerging predictive concepts [16].

As functional requirements and demands increase, the robot system will need to be able to identify the current situation, predict how things will change in the near future, decide what to do based on the prediction, and execute the decided action [6]. This involves being able to predict the uncertainties associated with human behavior and adapt to changes in a safe manner.

PREDICTING HUMAN BEHAVIORS

Safety applications determined by human behaviors are based on previous experience and translated into appropriate standards. The preferred method to reduce interaction risk is to design a system so it is inherently safe. Safeguarding is then only required to keep the operator away from the hazards when the design cannot reduce the risks to a tolerable level. Administrative controls such as warning signs, barriers, and training make operators aware of the hazards, but they also rely on the operator's willingness to follow the guidelines. With this methodology the robot's reaction is primarily based on the operator's current behavior.

Power and force limited robots may have inherently safe design through features such as low-inertia servo motors, elastic actuators, and collision detection. These features may reduce the need for additional

safeguarding in collaborative applications. While administrative controls make the operator aware of expected robot paths and shared workspaces, risks still remain. Because the environment is dynamic and uncertain, the robot must be able to adapt its motion based on the operator's intent so interference is minimized [6].

The time for a power and force limited robot to adapt its motion based on the operator's location and with minimal impact to production is optimized when the potential physical Human-Robot Interaction (pHRI) time is limited and infrequent. Maintaining production becomes more challenging when the pHRI is continuous [8] since the robot has to operate at a greatly reduced speed to ensure it can initiate a protective stop quick enough to minimize the impact force if contact is made.

Robot applications are programmed to complete a predetermined path or make an adjustment based on information from sources such as sensors, bar code readers, and vision systems. Rigid programming stops the robot's motion while an operator is in its path. This behavior can encourage an operator to bypass safety to meet production expectations.

Production could potentially be increased if the robot was able to work around the operator. Applying concepts from other sectors, along with data collection, may provide solutions for optimizing safety and enhancing production. An example is automated intelligent vehicles (AIVs) that adapt to their environment. They scan the mapped area and adjust their direction if an operator is in its path or slows down when the operator is in close proximity. This gives them the flexibility to make adjustments based on the operator's movement within a dynamic environment.

Continually sensing the operator's behavior to collect and manage large amounts of data increases the system's processing burden. The future is to learn the operator's motion patterns, derive hidden Markov models (HMMs) from the patterns, and then use the HMMs to estimate future operator positions [5]. This approach could be further refined by creating a task-specific model of the operator's motions and behaviors, and using the information to compute trajectories that reduce potential impacts [14].

Collision

Current collaborative applications detect a collision as it occurs and react by initiating a protective stop. The robot's forces and speeds are limited when the potential for collision is high so harm during a collision is minimized. Collision avoidance methods include detecting collisions through force and torque sensors on the robot, limiting forces through active or passive compliance, limiting the joint robot velocity so damage from a collision is acceptable, and cushioning the blow by using padding [2].

One method to stay within the threshold of pain boundaries defined in the ISO/TS 15066:2016 is to reduce the capability of a power and force limited robot. However, it is difficult to set a collision threshold when different regions of the body have different thresholds of pain and the perceived pain levels differs for each individual [18]. The level of pain also varies based on the type of contact, with transient

being quick and direct and quasi-static being slow and consistent. Additional uncertainty is introduced when the operator's potential contact areas with the robot are unknown. When multiple scenarios exist, the robot's speed and payload is limited to account for the worst-case scenario [17].

Reduction by Data Analysis

The probability of collision could be calculated with an algorithm that continually adjusts the robot's motion, stops moving when it is in a collision state, and maximizes progress toward its goal only when feasible trajectories exist [6]. Finding a collision-free path suitable for all operators is computationally complex and often results in very conservative behavior. It can also be difficult to determine the optimal control functions and balance the injury consequences of a collision or the collision severity based on the point of contact [8]. This algorithm could be optimized by creating specialized limits for each operator based on their tolerable pain levels, tasks, physical dimensions, and capabilities. An example is a task completed by a short person during one shift and a tall person during a different shift. While a collision on the arm could be acceptable for the tall person, the same collision position may not be acceptable for the short person since it would occur on the head. This risk could be minimized if the robot identified which operator was within the collaborative workspace and adjusted its positions.

Reduction by Design

Traditional robot structures are designed to withstand harsh environments and accidental collisions with other machinery. During normal operation, the operator is not exposed to hazards associated with the robot system, which may include fixtures, parts, and end-effectors. However, these risks must be evaluated and changes implemented when an operator will be exposed to hazards in a collaborative application.

Risks can be minimized in a collaborative application by "softening" the potential impact areas [7]. This approach includes using softer and more compliant materials for the structure. For example, padding or spring-based protective covers can absorb some of the force, edges and corners can be smoothed and rounded, and wider surface areas can be used to reduce impact effects.

Perception Affects Design

The operator's perceived safety is important when designing a collaborative system [8]. Traditional robot systems normally have a detectable boundary due to hard-guarding and other visible protective devices. In a collaborative application, safeguarding may be part of the inherent design and not visible to the operator. If operators do not trust the safety part of the system and cannot visualize its boundaries, they may adjust their tasks to fit their own concept of what is safe and how it should be implemented. They may spend most of their time trying to avoid collisions, which may create other hazards. Clearly marking the collaborative workspace areas, using plaques to list tasks, indicating what parts of the system have motion with different colors, and training are needed to help operators perform expected tasks safely.



BOUNDARIES

Safeguarding boundaries must be defined for all robotic systems to reduce risks to a tolerable level. This process is done with a risk assessment, which evaluates the probability of an occurrence and the severity of harm if the operator comes into contact with a hazard.

Direct safeguarding methods create a physical separation between the operator and the robot. They are inefficient in terms of time, floor space, and resources and place limits on the types of tasks that can be performed [2].

Indirect safeguarding methods detect and initiate when a boundary is violated. While they allow the operator to have more convenient access into the safeguarded system when hazards are not present, a stop may be triggered by an unknown object and it may be difficult to evaluate the source.

Zones permit operators to access limited areas of the robot's workspace when no hazards are present, while the robot operates in another area. Shown in [Figure 1](#) is a design method that enables maintenance and operator tasks to be completed in one area without stopping the robot. One difficulty with multiple zones is designing the safeguarding so it efficiently accounts for operator transition between zones without sacrificing the process's cycle time. Events such as an operator's sudden change of movement to quickly reenter a zone he or she just exited need to be accounted for in the design. In [Figure 1](#) a fence is used to prevent the operator from quickly transitioning into the hazardous zone.



Figure 1. Robot system designed with a barrier between the zones limits access to the hazard zone and prevents an operator's unexpected directional change of movement.

SENSORS

Sensors detect system changes and provide status information. For a safety system, activating a protective device changes its state so the signal is sent and the system can respond before the operator enters the hazardous area. Commonly used intrusion-detection sensors for robotic applications include light curtains, single beam safety sensors, safety area scanners, and safety mats. Collecting data when a sensor

was activated and locating the activated devices was typically only useful with safety area scanners, which helped to isolate the intrusion triggering the event.

In the past, the costs of additional sensors for collecting data provided minimal benefit. But sensors are getting better, smaller, cheaper, and easier to integrate. Computing resources for analyzing sensor data also are becoming more effective and affordable [3]. With these changes, sensor systems are now capable of storing and managing detailed data that can be used in future applications for predictive collaborative robotic safeguarding.

Predictive Sensor Systems Used in Automotive

How sensors are being used to enhance automotive safety suggests other applications. A new generation of forward-looking sensors is able to detect pedestrians under different road traffic conditions. In cars equipped with sensors, predictive protection systems can warn the driver and, when necessary, reduce travel speed and even initiate braking and steering actions [7].

Safety area scanners are the type of protective device most commonly used on current automated intelligent guided vehicles in a manufacturing or warehouse environment. While safety area scanners have the capability to use zone sets to send information and take location-dependent actions, such as slowing down the vehicle, they still lack the ability to distinguish between a human being and other objects. This limitation means any detection will cause a reaction. But by looking for ways to incorporate forward-looking sensors, especially ones with sensing infrared radiation, better information could be used to determine when a reaction is needed to ensure an operator's safety. This more sensitive sensor could allow for increased motion when a benign obstacle is present and the vehicle only needs to maneuver around it.

Adapting to the Environment

Without sensors or vision systems, robot cannot adapt to unknown or unpredictable environments [3]. Different types of sensors are currently used in the manufacturing environment, from force sensors on a welding torch that detect where on a part to start to sensors on a conveyor line that detect when to initiate a predetermined task. Some sensors have advanced functions to distinguish between allowed and non-allowed object types. These sensors can detect intentional bypassing of the safety device and initiate a safe shut down of the hazardous part of the system.

Traditional robot systems use sensors with a fixed location and are designed to have specific detection. One function of collaborative applications is the flexibility to transfer the robot to new locations. This may be done manually or it may be done with a mobile robot system. Methods used for vehicle systems to map the environment may be applicable for predictive collaborative applications. Some technology may include light imaging detection and ranging (LIDAR), simultaneous localization and mapping (SLAM), and global navigation satellite systems (GNSS).