Case Study: Adaptive Extension to Safety Monitoring for a Cobot*

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Ensuring safe interaction between humans and robots remains a fundamental challenge in cobots. A widely used safeguarding technique is Speed and Separation Monitoring (SSM) [3], where a minimum separation distance between robot and operator has to be maintained during operation.

In industrial practice, SSM is often realized through static protective zones guarded by light curtains or LiDAR sensors that stop the robot whenever the zone is breached. While this guarantees safety, such static envelopes tend to be overly conservative: they treat all intrusions as equally risky and therefore limit production efficiency by imposing unnecessary stops in low-risk situations. This tension between strict safety requirements and efficient task execution motivates more adaptive safety mechanisms that can take context into account [6], [7].

To address this, our case study extends the SSM approach by combining it with Power and Force Limiting (PFL) [3] and Human Pose Estimation (HPE) from multiple RGB-D cameras, following similar approaches as in [2]. The system continuously detects, identifies, and tracks humans in proximity to the robot, classifying if and which specific body parts intersect with the protective zone. This enables distinguishing between various risk scenarios, where the proximity of a human head is classified as a higher risk than that of a hand, resulting in a correspondingly greater speed reduction of the robot. The calculation of this adjusted speed is performed using a model-based PFL approach [1] that incorporates the biomechanical limits specified for each body part. Consequently, the robot can apply stricter safety measures where necessary, increasing uptime while maintaining human safety.

HPE relies on a probabilistic neural network, which introduces its own set of challenges. In particular, HPE models may produce inaccurate predictions,

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jitter, or anatomically implausible anomalies. To mitigate these risks, additional safety monitoring is needed.

In this case study, we consider four categories of relevant properties:

1. **First-principle:** domain-specific constraints on HPE derived from structural and kinematic anatomical rules [5]. For example, the anatomical length of each limb segment must remain constant over time and all joint angles must stay within their anatomically permitted ranges.
2. **Safety standard:** properties that ensure compliance with established safety standards [8]. For example, monitoring compliance with ISO/TS 15066:2016 [3] regarding force and pressure limits on different body parts according to the associated impact or pinching risks.
3. **Dynamic Software Updating (DSU):** properties defining under which conditions new pose estimation models may be safely deployed. For instance, updates may only occur when no human is present in the workspace, to prevent inconsistent time-series data between the old and new models.
4. **Social inclusion:** ad hoc rules defined by safety experts to accommodate individual differences. For example, the system may allow predictions of a missing limb for a particular operator without triggering false safety violations.

As a concrete case study, we consider a collaborative manufacturing cell where a Universal Robots UR10e manipulator services a Computer Numerical Control (CNC) machine by loading and unloading metal workpieces. Human operators periodically enter the shared workspace to retrieve finished parts, creating situations that demand continuous safety assurance while balancing production efficiency.

Our preliminary results include the implementation of a real-world setup in which the UR10e implements the described case study. To increase confidence in system correctness, we employ Stream Runtime Verification (SRV) monitors where current work focuses on defining *DynSRV* [4] specifications that capture the desired properties.

Early experiments reveal that the HPE model exhibits noticeable jitter in certain frames, particularly for arm positions. Initial experiments with first-principle properties suggest that SRV is suitable for detecting such inaccuracies. For the DSU and social inclusion properties, we anticipate that dynamic SRV introduced in [4] will play a central role. Ultimately, we aim to realize a self-adaptive control loop in which the PFL risk model parameters are adjusted dynamically based on HPE confidence levels as assessed by DynSRV.

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