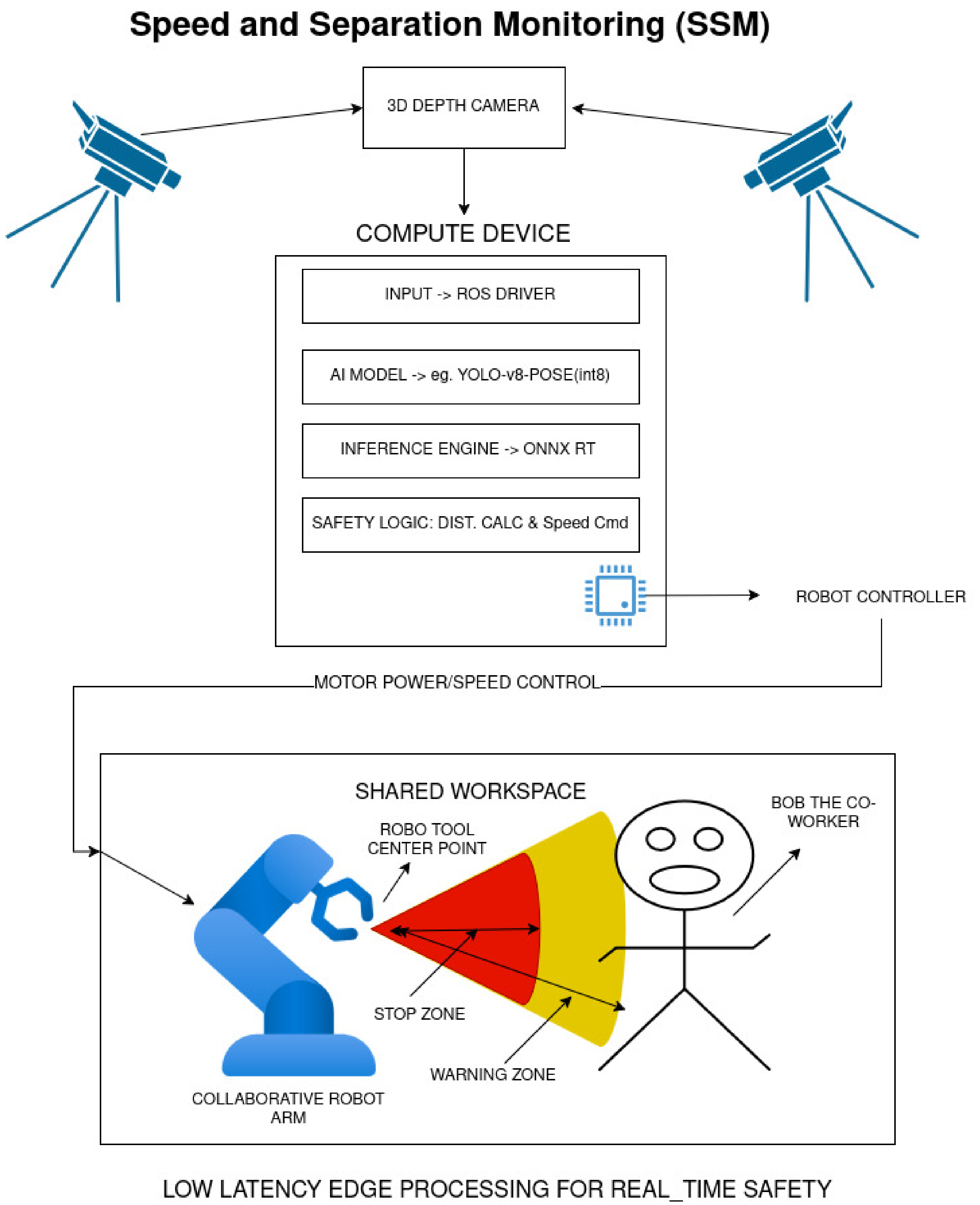
Edge AI Architecture for Human-Robot Collaboration

Transitioning from Rigid Safety Fencing to Dynamic Edge AI Safety System.



1. Summary

Traditional industrial safety relies on physical cages that completely stop production when a human enters the workspace. This "Stop-and-Go" approach kills efficiency. Modern Industry 4.0 standards (ISO/TS 15066) allow for **Speed and Separation Monitoring (SSM)**, where the robot dynamically slows down or alters its path based on the human's proximity.
However, relying on Cloud AI for this task introduces dangerous latency. A 100ms network lag could result in an injury before the robot receives the stop command. This report outlines a **High-Performance Edge AI Architecture** that processes skeletal tracking locally (within 15ms), ensuring compliance with safety standards while maintaining high production throughput.

2. System Architecture Design

The proposed system creates a "Virtual Safety Shield" around the collaborative robot (Cobot). It uses redundant 3D vision to track the human worker's skeletal keypoints (wrists, head, shoulders) in real-time.

2.1 Hardware Components

Component	Specification	Function
Vision Sensors	**2x Intel RealSense D435i**	**Redundancy & Depth:** Two cameras positioned at opposing angles eliminate "blind spots" (occlusion) caused by the robot's own arm. These provide both RGB and Depth (Point Cloud) data.
Edge Compute	**NVIDIA Jetson Nano/Orin**	**Local Inference:** A dedicated System-on-Module (SoM) It processes video streams locally without sending data to the cloud.
Robot Controller	**Universal Robots Control Box**	**Motion Control:** Receives speed scaling commands (0% to 100%) from the Edge device and executes Safety Stop Category 1 or 2.

2.2 Software Stack

- **Input Layer:** ROS 2 (Robot Operating System) nodes capturing raw point cloud data at high fps.
- **AI Model: YOLOv8-Pose**
  - Pose estimation tracks specific joints (e.g., the right wrist). This allows the robot to keep working if the human is nearby but facing away, only stopping if the *hand* reaches toward the danger zone.
- **Inference Engine: ONNX RT**
  - This is the critical optimization layer that compiles the generic PyTorch model into a binary engine optimized.
- **Safety Logic:**
  - A deterministic algorithm that calculates the Euclidean distance between the robot's **Tool Center Point (TCP)** and the nearest **Human Keypoint**.

3. Edge AI Optimization Strategy

Running a modern computer vision model like YOLOv8-Pose at 30+ FPS on a small embedded device requires aggressive optimization. We cannot use the "heavy" models used in cloud servers.

Strategy A: Post-Training Quantization to INT8

Standard AI models compute using **FP32** (32-bit Floating Point) numbers. This is highly precise but computationally expensive.

- **The Technique:** We convert the model weights and activations to **INT8** (8-bit Integers).
- **Implementation:** Using the TensorRT calibrator, we pass a small dataset of "representative images" through the model. The calibrator determines the dynamic range of activation values and maps them to the -128 to +127 integer range.
- **Benefit:** This reduces memory bandwidth usage by **4x** and inference time is lot faster.

Strategy B: Structured Pruning

Many neural networks are "over-parameterized," containing neurons that contribute little to the final output.

- **The Technique:** We use **Structured Pruning** (Channel Pruning). Unlike *unstructured* pruning (which makes matrices sparse but doesn't necessarily speed up hardware), structured pruning removes entire filters (channels) from the Convolutional layers.
- **Implementation:** We identify channels with the lowest L1-norm (least impact) and physically remove them from the network architecture, effectively creating a "thinner" model.
- **Benefit:** This directly reduces the number of FLOPs (Floating Point Operations) required for inference, lowering latency.

4. Impact Analysis: Cloud vs. Edge

According to ISO 13855, the Minimum Safety Distance (S) is calculated as:

$$S = (K \times T) + C$$

- K: Human approach speed (1600 mm/s).
- T: Total system stopping time (Latency + Braking time).

If Latency (T) increases, the Safety Distance (S) must increase, forcing the robot to stop when the human is still far away, ruining productivity.

Note: metrics are relative to each other

Metric	Cloud Solution (Standard)	Edge AI Solution (Optimized)	Impact Analysis
Total Latency (T)	**HIGH** (Network RTT + Inference)	**LOW** (Local Capture + Inference)	Reducing T allows the robot to work much closer to the human without violating safety zones.
Energy	**HIGH**(server side)	**LOW**	Compute devices like Jetson runs on low voltage, easily integrated into the robot's power supply without expensive cooling.

Metric	Cloud Solution (Standard)	Edge AI Solution (Optimized)	Impact Analysis
Model Accuracy	**HIGH**	**LOW**	The precision loss from INT8 quantization is negligible for detecting a large object like a human arm at close range.

5. Risk Assessment:

While optimization is necessary, aggressive compression introduces specific safety risks that must be mitigated.

Risk 1: "The Ghost Effect" (False Negatives)

Description: Aggressive **Pruning** removes "redundant" features. In rare edge cases—such as a worker wearing a grey shirt lying on a grey floor—the compressed model might lack the feature extractors necessary to distinguish the arm from the background.

- **Consequence:** The system fails to detect the human (False Negative), and the robot does not stop.

Risk 2: "The Jitter Effect" (Temporal Instability)

Description: Quantization (INT8) introduces rounding errors. While accurate on average, the detected coordinate of a wrist might jump by 5-10cm between frames even if the human is still.

- **Consequence:** The robot controller receives erratic distance data, causing the robot to "stutter" (rapidly braking and accelerating).

6. Conclusion

By deploying a **Quantized and Pruned YOLOv8-Pose model** on an **Edge device**, we can achieve a safety system that is compliant with **ISO/TS 15066**. This architecture solves the latency issues of cloud computing, enabling an environment where humans and robots work in close proximity without physical barriers.