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Advancing Human-Robot Collaboration: A Focus on Speed and Separation Monitoring

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Abstract

Human-Robot Collaboration (HRC) is increasingly integrated into industrial settings, combining the efficiency of automation with the flexibility of human workers. To ensure safety, the ISO/TS 15066:2016 standard outlines four types of collaborative operation. Among these, Speed and Separation Monitoring (SSM) emerges as the most promising for enhancing accessibility in shared workspaces while maintaining high throughput. However, current implementations of SSM face significant challenges due to hardware, software, and regulatory limitations. Realizing the full potential of dynamically changing safety zones requires precise, real-time data on speed, trajectory, and intent of both human and robot. Unfortunately, existing monitoring sensors and algorithms are unable to reliably acquire these measurements. Moreover, even if such data were obtainable, it is not yet safety-rated for industrial applications. Ambiguities within ISO/TS 15066 and the lack of standardized terminology for different SSM methods further complicate integration. This paper introduces a refined classification of SSM based on separation distance calculation (Fixed Sized, Variable Sized, Variable Shaped) and monitoring approach (Static, Mobile), providing a structured framework for evaluating SSM implementations. While Fixed Sized SSM is widely used due to its simplicity, it lacks the real-time adaptability required for optimal collaboration. In contrast, Variable Sized and Variable Shaped SSM dynamically optimize safety zones but remain underutilized due to technological and regulatory barriers. The second categorization distinguishes between Static Monitoring, where the zones have a fixed position, and Dynamic Monitoring, where they adapt to the movement of the robotic system. By providing a structured terminology and exploring these categories with examples and research, this paper aims to advance the understanding and implementation of SSM. Addressing current challenges and ambiguities in standards is critical for the broader adoption of SSM, paving the way for safer, more efficient, and accessible collaborative robotic systems.

Keywords

Human-Robot Collaboration, Speed and Separation Monitoring, Safety Zones, Industrial Robot

1. Introduction

Human-Robot Collaboration (HRC) has become a cornerstone of modern manufacturing and will play an even more significant role in the transition to Industry 5.0 [1]. The shift towards mass customization across various industrial sectors has increased the demand for flexible, easily programmable, and safe robotic systems [2]-[4]. Collaborative robots, or cobots, have seen rapid growth in market adoption, with projections estimating an annual growth rate of approximately 30% from 2025 to 2030 [5]. From an academic perspective, there is an increase in the number of publications and patents containing the words "collaborative robot", illustrated in **Figure 1**.

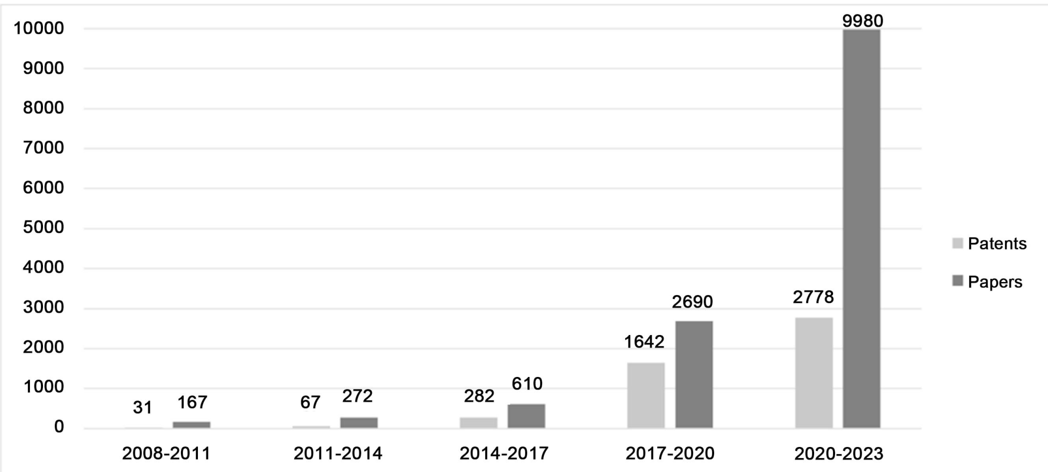

Figure 1. Number of patents and scientific papers with "collaborative robot" as a search term over the years.

To implement HRC, several standards are available, with the most notable being ISO/TS 15066:2016—"*Robots and robotic devices—Collaborative robots*" [6] and ISO 13482:2014—"*Robots and robotic devices—Safety requirements for personal care robots*" [7]. While ISO 13482 focuses on robots for physical assistance tasks, including wearable robots like exoskeletons [8] [9], ISO/TS 15066 provides guidelines for collaborative industrial robots operating alongside human workers. The latter standard describes four key collaboration types: "Power and Force Limiting (PFL)", "Hand Guiding (HG)", "Safety-rated Monitored Stop (SRMS)", and "Speed and Separation Monitoring (SSM)". While exosuits are actively researched for industrial tasks [10] [11] and certain principles of PFL and HG can also apply to exoskeletons, this paper primarily focuses on industrial robots, which are more representative of today's industrial landscape. The four collaboration types can be further classified based on collision detection and contact distance, illustrated in Figure 2.

1.1. Post-Collision Detection

PFL and HG belong to the post-collision detection category, requiring design measures involving both the software and hardware of the robot. PFL-enabled robots, such as the UR10e, ABB GoFa, and Yaskawa HC10, enter a safety stop upon detecting unexpected interactions, typically caused by collisions. Collision detection mechanisms rely on built-in force or torque sensors, motor current readings [12], or alternative technologies like "artificial skin", *i.e.* distributed pressure sensors [13], proximity sensors [14], or combined sensor systems [15] [16]. While ISO/TS 15066 does not mandate specific sensors, it requires that force and energy transfer during impacts remain within limits to prevent operator injuries.

Despite their safety features, post-collision applications still require comprehensive risk assessments. For instance, handling sharp objects with a cobot's end effector would require avoiding direct contact. Additionally, commercial cobots generally have limited payload capacities, speeds, and reaches compared to traditional industrial robots. A notable drawback of PFL systems is their reliance on post-collision detection, which inherently triggers safety measures only after a collision has occurred. While suitable for simple tasks like pick-and-place operations, more complex applications often require industrial robots.

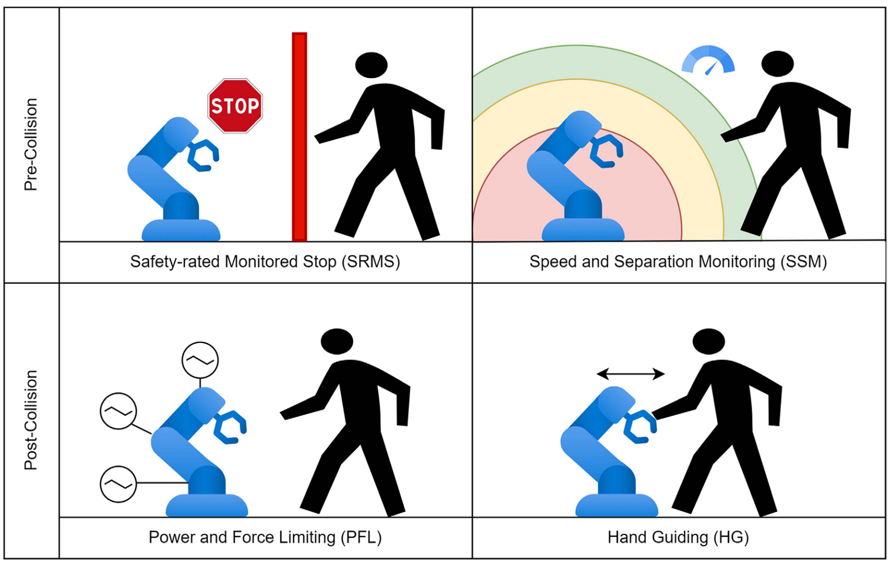

Figure 2. The four types of collaboration categorized into post-collision and pre-collision detection.

1.2. Pre-Collision Detection

Pre-collision detection enables industrial robots to achieve collaborative functionality through software-based adjustments, without requiring hardware modifications. SRMS ensures a controlled halt when an operator enters the robot's workspace, while SSM dynamically adjusts the robot's speed and distance to the operator to ensure safe interactions. Both approaches utilize area monitoring systems independent of the robot's core hardware, enabling collision prevention through early intervention in the control mechanisms.

Area monitoring often employs protective measures categorized under the Machinery Directive [17] as separating or non-separating guards:

- Seperating guards can be:
  - Fixed guards: e.g., safety fences
  - Movable guards: e.g., safety doors
- Non-separating guards or protective devices include:
  - Pressure or touch-sensitive protective equipment: e.g., pressure-sensitive mats
  - Electrosensitive protective equipment (ESPE):
    - Light curtains
    - 2D scanners: e.g., radar, lidar
    - 3D scanners: e.g., radar, lidar

From top to bottom, the guards allow better accessibility to the robot's workspace. The level of collaboration a certain robotic system can implement, is dependent on the used monitoring system and the collaboration type. As illustrated in **Figure 3**, higher levels of collaboration, such as responsive collaboration, require advanced safety measures. While PFL cobots currently dominate this space, emerging technologies are making it feasible to implement other types for more intricate applications, enabling closer human-robot interactions.

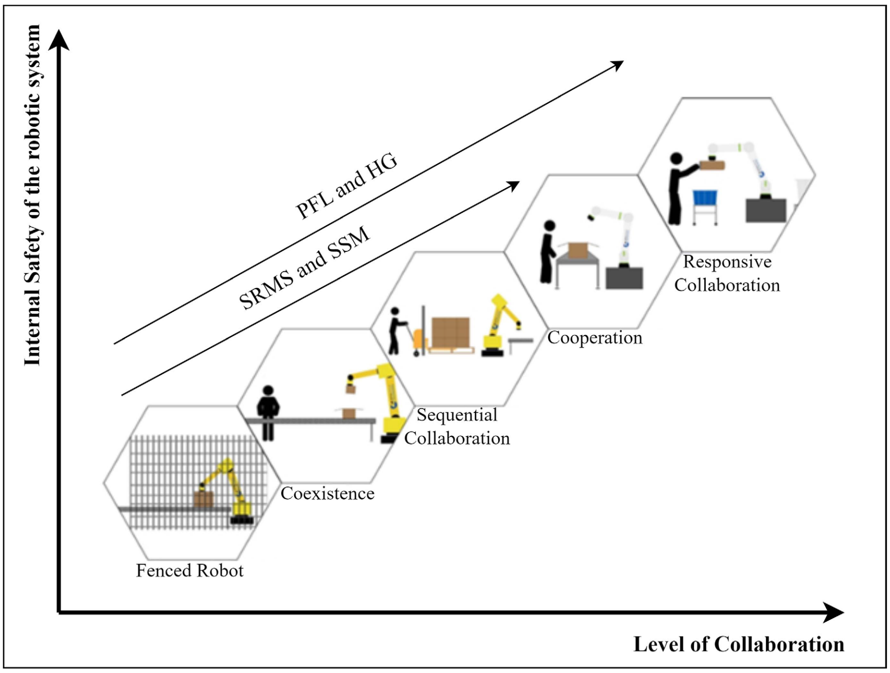

Figure 3. Different levels of collaboration: based on [18]. Coexistence (independent operations in a shared workspace), Sequential Collaboration (shared tasks with alternate turns), Cooperation (simultaneous tasks without feedback), and Responsive Collaboration (feedback-driven cooperation).

1.3. Space for Improvement

Balancing workspace accessibility with robot throughput is a fundamental challenge in HRC environments. Increased accessibility often results in reduced throughput, as the robot may need to stop more frequently or operate at slower speeds to maintain human safety. Figure 4 depicts the trade-offs between accessibility and throughput. The different monitoring systems are categorized in separation, pre- and post-collision.

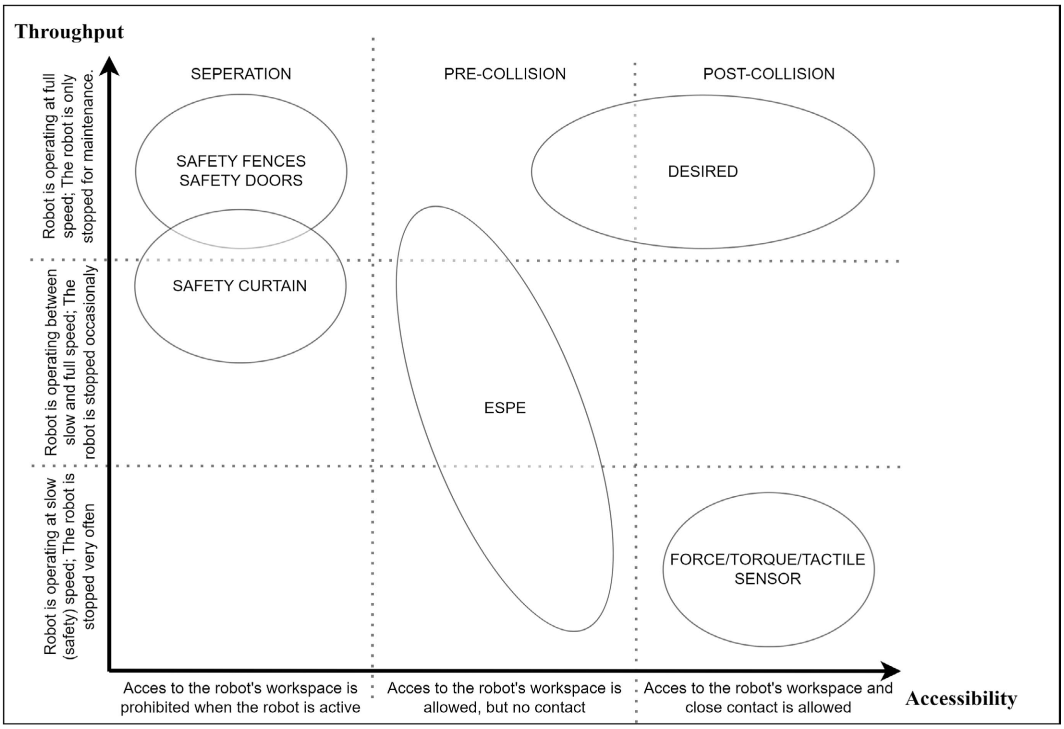

Figure 4. Balancing accessibility and throughput in Human-Robot Collaboration.

Physical Barriers

Physical barriers such as safety fences and doors ensure high robot throughput by completely restricting human access during the robot's operation. This allows the robot to work continuously at high speeds, maximizing productivity. The system only halts during maintenance or when issues arise, ensuring minimal disruption.

Safety Curtains

Safety curtains allow operator access to the robot's workspace. However, entry into the workspace triggers a process halt. This results in a lower throughput than safety fences as the robot is halted more often. The more interaction, the lower the throughput. Safety curtains also require a manual reset to resume their task. They are installed further from the robot than physical barriers, confiscating larger workspaces.

Contact Sensors

PFL-enabled systems operate at reduced speeds to prioritize safety in the event of unexpected interactions. While PFL enables closer collaboration and higher accessibility, its low operating speed significantly reduces throughput. Attempts to increase throughput by raising speed compromise accessibility due to the higher energy impact, which exceeds safety limits outlined in Annex A of ISO TS 15066.

ESPEs

ESPEs, that apply SSM, provide a balanced approach. The robotic system can operate at full speed if no danger is present in the workzone. Throughput will only reduce if operators need more access to the robots workspace (higher collaboration levels). Within the SSM framework, there exists significant potential for improvement. By optimizing algorithms and sensor technologies, it may be possible to enhance both accessibility and throughput without compromising safety. Moreover, advancements in artificial intelligence and machine learning could enable more precise and adaptive control strategies.

The desired output is a combination of pre- and post-collison, that is obtainable by combining SSM and PFL methods. The robot can work at full speed when no danger is present. When an operator enters the workspace, it will adapt its speed accordingly. PFL enables when (close) contact is desired.

This paper explores the state-of-the-art and difficulties of SSM applications and the possible advancements in sensor technology and control algorithms to improve access and throughput. Chapter 2 explains the core concept of SSM, followed by detailed analyses in Chapters 3 through 5, each focusing on specific SSM categories and practical examples. Chapter 6 concludes the discussion with key takeaways and future directions.

It is worth noting that the terms "collaboration" and "cobot" are used inconsistently in both literature and practice [19]. A cobot is not necessarily a robot embedding the PFL principle, but can also be an industrial robot with SSM. For clarity, unless otherwise specified, this paper primarily refers to industrial robots employed in collaborative contexts.

2. Speed and Separation Monitoring

2.1. Definition of SSM

"*The robot system and operator may move concurrently in the collaborative workspace. Risk reduction is achieved by maintaining at least the protective separation distance between operator and robot at all times. During robot motion, the robot system never gets closer to the operator than the protective separation distance. When the separation distance decreases to a value below the protective separation distance, the robot system stops.*"—ISO/TS 15066, 5.5.4.

In systems employing SSM, the robot workspace is divided into three zones:

- Full Speed Zone (Green): the robot may operate at full speed.
- Safe Speed Zone (Yellow): the robot speed is reduced. Not always implemented.
- Safe Stop Zone (Red): the robot either stops entirely (SRMS) or switches to a safety-reduced speed (PFL) mode if permitted.

The protective separation distance S_p is calculated using the following formula:

$$S_p(t_0) = S_h + S_r + S_s + C + Z_d + Z_r \tag{1}$$

where:

- t_0: The current time;
- $S_p(t_0)$: The protective separation distance at time t_0;
- S_h: The distance attributable to the operator's change in location from the current time until the robot has stopped;
- S_r: The distance attributable to the robot system's reaction time from the person entering the sensing field up to the control system activating a stop;
- S_s: The distance due to the robot's motion during robot stopping;
- C: The intrusion distance, as defined in ISO 13855; this is the distance that a part of the body can intrude into the sensing field before it is detected;
- Z_d: The position uncertainty of the operator in the collaborative workspace (uncertainty of the sensor);
- Z_r: The position uncertainty of the robot system.

The formula can be expressed in greater detail as:

$$S_{p(t_0)} = \int_{t_0}^{t_0+T_r+T_s} v_h(t)\,\mathrm{d}t + \int_{t_0}^{t_0+T} v_r(t)\,\mathrm{d}t + \int_{t_0}^{t_0+T_r+T_s} v_s(t)\,\mathrm{d}t + C + Z_d + Z_r \tag{2}$$

where:

- v_h: The directed speed of an operator in the direction of the robot;
- v_r: The directed speed of the robot in the direction of the operator;
- v_s: The directed speed of the robot in the stopping direction;
- T_r: The reaction time of the robot system;
- T_s: The stopping time of the robot.

If the real-time separation distance S falls below S_p, the robot will go into a safety stop or lower its speed, illustrated in **Figure 5**.

2.2. Limitations and Ambiguities of SSM

Although Equation (2) provides dynamic calculation for S_p, real-time implementation poses challenges:

Measuring Human Speed

Current monitoring devices, such as lidar or vision-based systems, are typically limited to detecting intrusions into predefined safety zones. They don't distinguish between humans and other (non)-hazards. While algorithms exist to detect and classify intrusions as human operators, their reliability is insufficient for safety-critical applications [20]. They often fail to ensure no operator is present in the workspace. Moreover, even when a sensing system successfully detects and locates a human operator, the tracking has to be accurate. Detection delay and latency in reporting can lead to inaccuracies in the calculated separation distance [21] [22].

Signal Transmission

Another critical limitation is the ability to transmit measured data in compliance with safety standards. For SSM systems to meet standards such as Performance Level d[1], the communication of sensor data must be both fast and highly reliable. Currently, most sensing systems and their associated data transmission technologies are not safety-rated. For instance, real-time Ethernet-based communication between sensors and controllers, while capable of transmitting position and velocity data is not safety-rated.

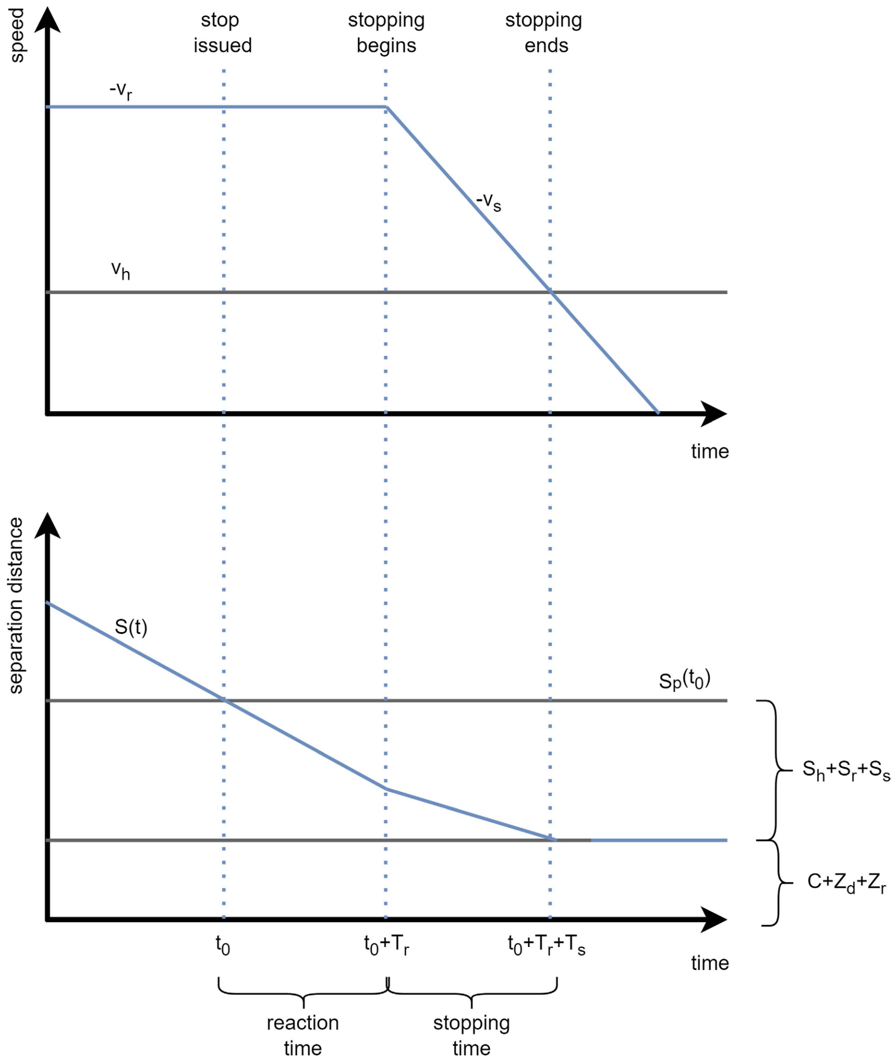

Figure 5. Evolution of the separation distance between operator and robot.

Directed Speed

The concept of directed speed for both the robot and the operator can lead to confusion in calculating the separation distance. Consider a scenario where the robot and operator are moving toward each other at an angle θ, as illustrated in **Figure 6**. In this case, the directed speed at any given instance is reduced by a factor of $\cos(\theta)$ relative to their trajectory speeds. This reduction in directed speed

[1]The Performance Level (PL) is a discrete level used to specify the ability of the safety-related parts of the control system to perform a safety function under foreseeable conditions [45]. The higher the risk of a machine, the higher the PL level.

results in a smaller separation distance, S_p, which can create unsafe conditions if not properly accounted for. The ISO/TS 15066 standard attempts to address such cases by stating: "The system shall be designed to account for v_h and v_r varying in the manner that reduces the separation distance S the most." This implies that the trajectory speed must be used in calculations to ensure safety. However, this directive is open to interpretation, particularly in complex motion scenarios. For example, consider a robot moving parallel to an operator who remains stationary. As the robot approaches, its directed speed relative to the operator decreases. Intuitively, one might expect the safety zone to grow as the distance between the robot and operator decreases. However, there is no explicit guideline in the standard to handle such situations dynamically. The conclusion is that the standard lacks a clear, absolute rule for interpreting the speeds of the robot and operator. It only emphasizes the need to account for the worst-case scenario.

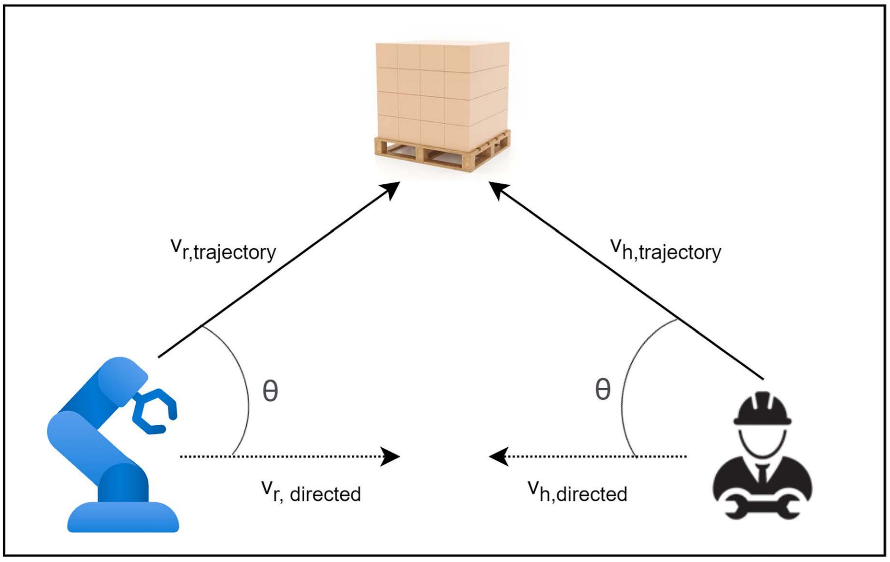

Figure 6. The directed speed is smaller than the trajectory speed. Causing S_p to be smaller, resulting in unsafe situations.

Current Situation

Therefore, in practice, static estimates are often used for protective distances, considering worst-case scenarios. Equations (3) and (4) can be used to estimate a constant value for respectively S_h and S_r if the operator and robot speed are not monitored.

$$S_h = v_h * (T_r + T_s) \tag{3}$$

$$S_r = v_r * T_r \tag{4}$$

Simplifying Equation (1) results in the minimum distance formula presented in ISO 13855 [23]. Equation (5) gives the minimum protection distance S_p for stationary machines:

$$S_p = (K * T) + S_m + D_{DS} + Z \tag{5}$$

where:

- K: The operator's approach speed, analogous to v_h;
- T: The overall system response time, a combination of T_r and T_s;
- S_m: The change in position of the hazard, analogous to $S_r + S_h$, the braking distance;
- D_{DS}: The reaching distance, analogous to C;
- Z: A supplemental distance factor, a combination of position uncertainties.

A recent revision of ISO 13855:2024 added a "dynamic" distance factor S_m to account for moving hazards, such as AGVs or industrial robots mounted on an external axis. The operator's speed is typically assumed to be 1.6 m/s per ISO 13855. The robot's speed is set to its maximum programmed or limited value. In the Safe Speed Zone, for example, the robot speed is often reduced to 250 mm/s, corresponding to the safety speed of the Tool Center Point (TCP) [24].

Dynamic safety systems must overcome current technological limitations to measure operator and robot speeds reliably. Until then, in industrial settings, protective separation distances are calculated conservatively to ensure compliance with safety standards.

2.3. Different Types of SSM

ISO/TS 15066 does not prescribe detailed methods for implementing SSM. Designers have the freedom to select the appropriate sensors, determine their configuration, and define the geometry of the safety zones. This section aims to categorize SSM techniques for clarity and adaptability, facilitating the incorporation of existing methods and potential future advancements.

SSM types can be divided based on the monitoring method and based on the separation distance calculations. This results in six different SSM possibilities: Fixed Sized, Variable Sized and Variable Shaped SSM with either Static or Mobile Monitoring **Figure 7** gives an overview of the categories.

2.3.1. Monitoring Method

The monitoring method depends on the position of the defined safety zones relative to the environment. The zones can have a fixed center position, static monitoring, or moving center, mobile monitoring. Mobile monitoring can be used to secure an Automated Guided Vehicle (AGV) or Autonomous Mobile Robot (AMR). Mobile monitoring does not necessarily mean that the monitoring device is moving. It can also be a software adjustment where the safety zones are programmed to move with the robotic system. Another example of mobile monitoring in [25], where the safety zone around every robot link move according to the joint position.

2.3.2. Separation Distance

Depending on how the protective separation distance S_p is calculated, there is:

- Fixed Sized SSM: S_p is predetermined before system operation. The zone size remains unchanged, with one or more yellow zones to reduce the robot's speed to a fixed value when an operator enters the workspace. Only the distance between robot and operator is monitored.

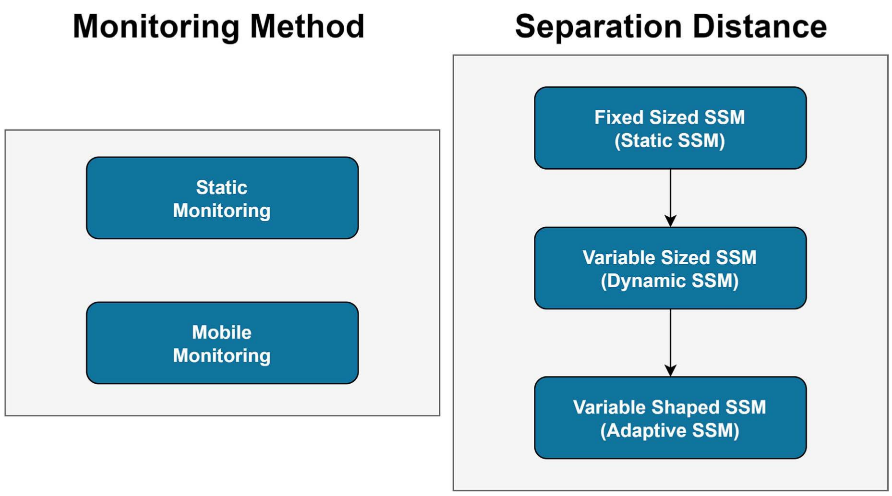

Figure 7. Two categories to divide SSM methods into.

- Variable Sized SSM: S_p is continuously updated based on real-time parameters, such as the speed of the robot and the operator. While the size of the safety zones changes dynamically, their shape remains constant. Both distance and speed are monitored.
- Variable Shaped SSM: Throughput can be further enhanced by adjusting not only the speed but also the current path or task of the robotic system. In variable-shaped SSM, the robot responds dynamically to the operator's position by altering both speed and spatial positioning. For example, the robot could move away from the operator as they approach, reshaping the safety zones accordingly. The intentions of both the robot and operator, their direction/velocity, are monitored.

In literature, terms such as static, dynamic, and adaptive SSM are frequently used. While they align with the above categories, they can sometimes cause confusion. For example, a dynamic SSM may employ static monitoring, or a fixed sized zone may move with the robotic system, appearing dynamic. The zones may move but S_p isn't necessarily dynamic. Therefore, the two proposed categories.

3. Fixed Sized SSM: Implementations and Improvements

Fixed Sized SSM, Figure 8, is the method currently employed in most industrial settings. The protective separation distance is calculated once, typically for the worst-case scenario, and does not change dynamically during operation. The limitations of the available hardware only allow for distance monitoring.

This chapter explores different sensor types and methods to implement Fixed Shaped SSM, evaluates the advantages and disadvantages of each method, and highlights how advanced sensor technology can enhance safety and efficiency by enabling mobile safety zones, even without physically moving the sensors.

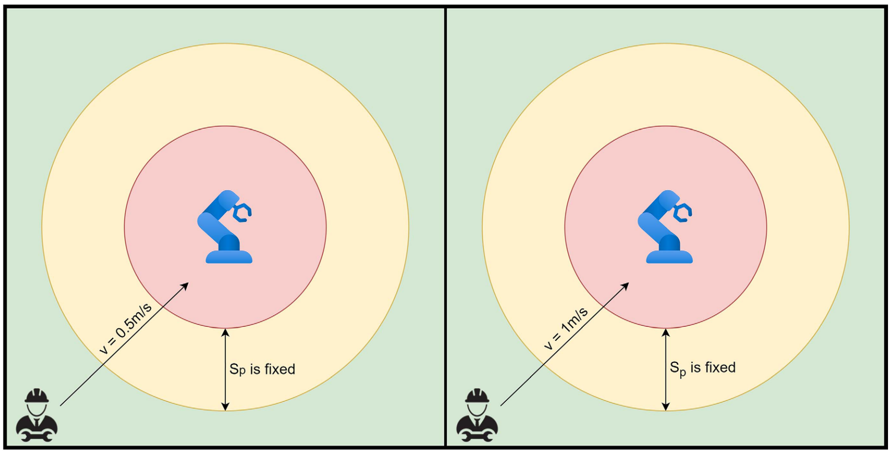

Figure 8. Fixed Sized SSM; S_p is fixed and calculated for the worst-case scenario. The size and shape of the safety zones is constant during operation.

3.1. Sensor Types

2D safety laser scanners are commonly used to define fixed safety zones. Devices from manufacturers such as SICK and PILZ offer safety performance levels up to PLd. These scanners can monitor both Safe Speed (yellow) and Safe Stop Zones (red), with some models supporting up to 8 independently configurable zones [26] [27]. Modern solutions like Safe Robotics Area Protection simplify integration with robot controllers, enabling straightforward implementation of speed reduction [28].

3D safety sensors are emerging as an advanced alternative to traditional 2D scanners, providing a more comprehensive understanding of the workspace [29] [30]. This is clearly visible in **Figure 9**. Examples include sensors using time-of-flight, radar, or vision-based technologies [31] [32]. While 3D systems are in their infancy, ongoing research and development promise significant improvements in reliability and safety compliance [33] [34].

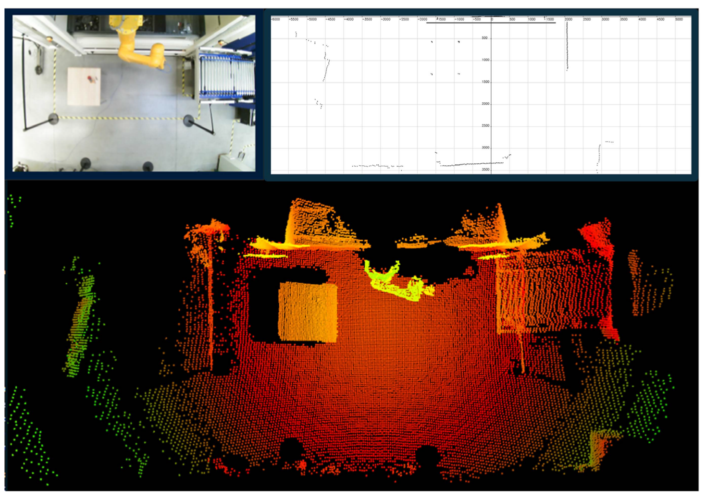

Figure 9. Difference between a 2D scan and 3D scan of the robot's workspace. A 3D scan provides more information (points) about the environment and has fewer dead zones.

***Advantages of 3D methods*:**
- Enhanced detection of operators, including their full body, reducing blind spots.
- More robust against environmental clutter and unintended object intrusion, e.g. AGVs.
- Easier to secure areas against people bypassing sensors by jumping over or crawling under; Reducing the intrusion distance C.
- Object detection training is easier and more reliable. Objects can be distinguished easier.

***Disadvantages of 3D methods*:**
- Higher cost and complexity compared to 2D systems.
- Currently limited to PLc safety levels (except for radar-based solutions, which can achieve PLd).
- Object detection capabilities may not yet meet safety standards.

3.2. Monitoring Type

Mobile monitoring has advantages when the robot has a large workspace. Unlike static monitoring, mobile safety zones dynamically adjust their position to the robot's position. Importantly, this concept does not necessarily require physically moving the sensors; instead, it can rely on software-controlled adjustments of the zone position.

***Advantages of Mobile Monitoring*:**
- Smaller, dynamically positioned zones reduce downtime and improve productivity.
- One sensor can suffice for large workspaces, such as robots on horizontal rails or AGVs.
- Enhanced safety by adapting zones based on the robot's current position and movements.

***Disadvantages of Mobile Monitoring*:**
- Requires more sophisticated algorithms and integration with the robot controller.
- Signal transmission of the position change may not yet meet the safety requirements. Available safety sensors don't support dynamic zone implementation.

***Example*:**

Consider a six-axis industrial robot (TX2-90L, Stäubli) mounted upside down on a horizontal rail **Figure 10**. The rail is positioned in front of a vertical storage warehouse (Logimat, SSI Schäfer), where the robot retrieves and stores goods. In the centre of the rail, a 2D safety scanner (nanoScan3, Sick) is mounted. Above the robot, a LIDAR + RGB camera (Titan S2, Neuvition), is mounted that moves with the rail.

S_p is calculated from Equation (6) [35], which is derived from Equation (1) for constant robot and operator speed. **Table 1** shows the calculated values. A comparison is made between a robot mounted on the floor. The reach of the robot is not added to the total distance as it remains the same in every situation.

$$S_p = v_h * (T_r + T_s) + v_r(t_0) * T_r + B + C \tag{6}$$

Figure 11 shows that a too large safety zone must be set in the case of static monitoring. A red zone of 7348 mm long is required, as the position of the robot is not accounted for. Therefore, the red zone extends over the whole length of the external axis.

Conclusion:

Fixed Shaped SSM offers a straightforward approach to ensuring robotic safety but comes with limitations in static implementations, particularly for dynamic workspaces or mobile robots. Advances in sensor technology, especially 3D safety scanners and mobile safety zones, provide promising solutions to these challenges. By adopting these modern methods, systems can achieve higher safety levels while minimizing operational dead time and improving overall efficiency.

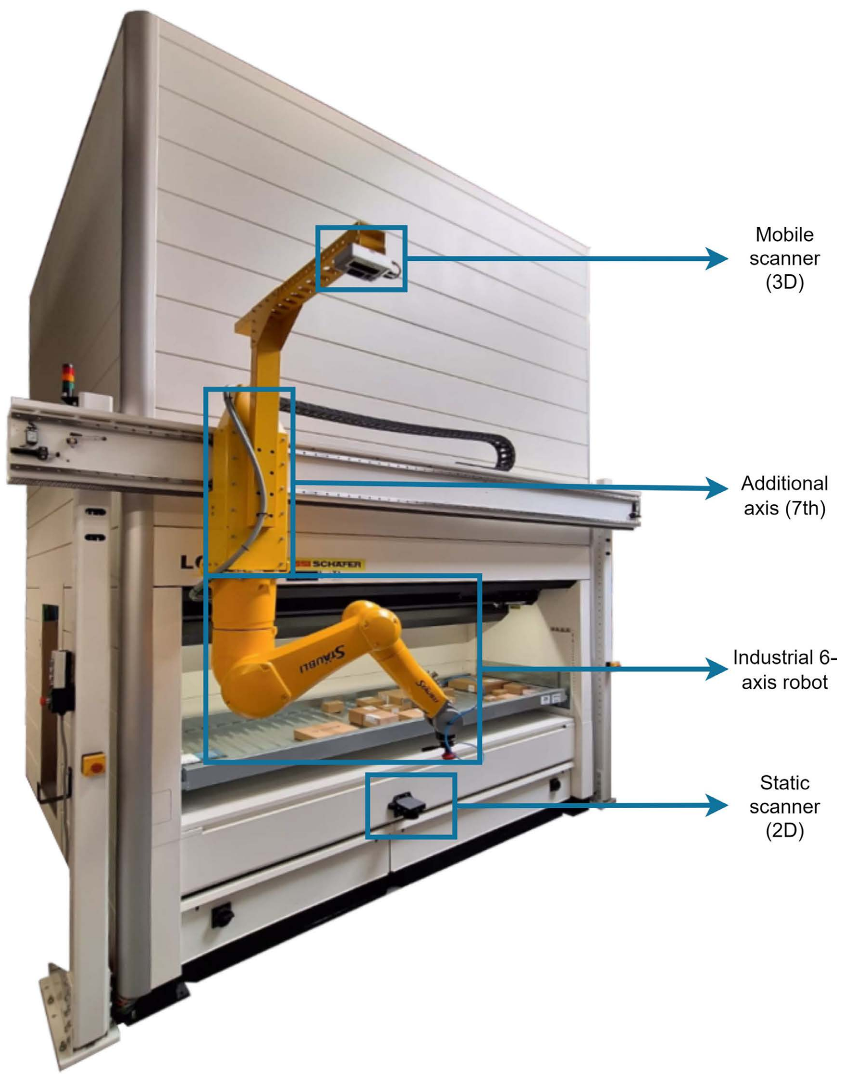

Figure 10. An industrial robot mounted upside down in front of a storage lift, expanded with a safety laser scanner (fixed) and LIDAR + RGB camera (mobile).

Table 1. Calculated values for S_p. The robot and external axis move at nominal speed in the green zone. They reduce their speed to 0.250 m/s when entering the yellow zone. The maximum speed of the external axis is 1 m/s with a maximum acceleration of 5 m/s^2.

	Safe Stop	Safe Stop and Safe Speed
Static Robot	$S_{p,red}$ = 2134 mm	$S_{p,red}$ = 1644 mm $S_{p,yellow}$ = 1955 mm
Moving Robot	$S_{p,red}$ = 2327 mm	$S_{p,red}$ = 1674 mm $S_{p,yellow}$ = 2104 mm

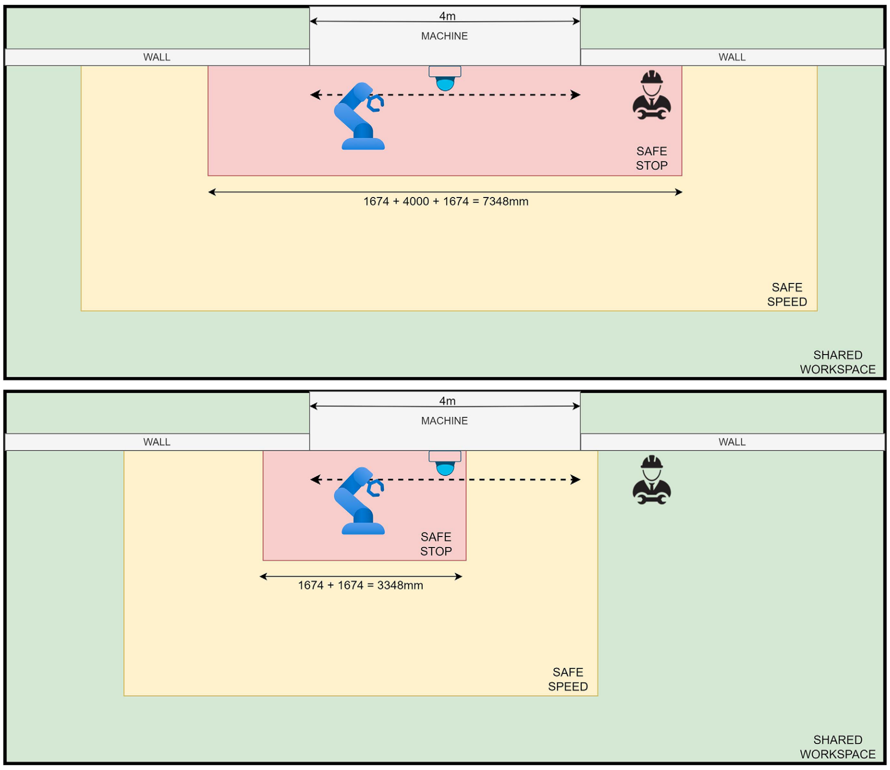

Figure 11. Difference between static (up) and mobile (down) monitoring. In the static case, the robot is halted, even when there is no danger present.

4. Variable Sized SSM

Variable Sized SSM, Figure 12, involves dynamically adapting the size of safety zones based on the speed of the robot and operator, as well as their separation distance. This approach uses Equation (1) to calculate the protective separation distance continuously. A key challenge is determining the real-time separation distance S.

Modern robot manufacturers, such as Stäubli, ABB, Yaskawa, UR, have a wide range of safety functions to maintain the position and speed of each axis (in joint and Cartesian coordinates) within desired limits. If these are exceeded, the robot goes to a safety stop. Information about position and speed can be obtained and monitored with safety functions. However, robot position data is generally not safety-rated, not deterministic and can have very high latency [21].

Measuring human position and speed is not as obvious, although progress is being made in this regard. Current safety scanners can detect the entry into the scene of unexpected objects. On the one hand, they cannot distinguish between an operator and e.g. a box with sufficient certainty anyway. On the other hand, the distance from the robot often cannot be transmitted as a safety signal to the safety controller.

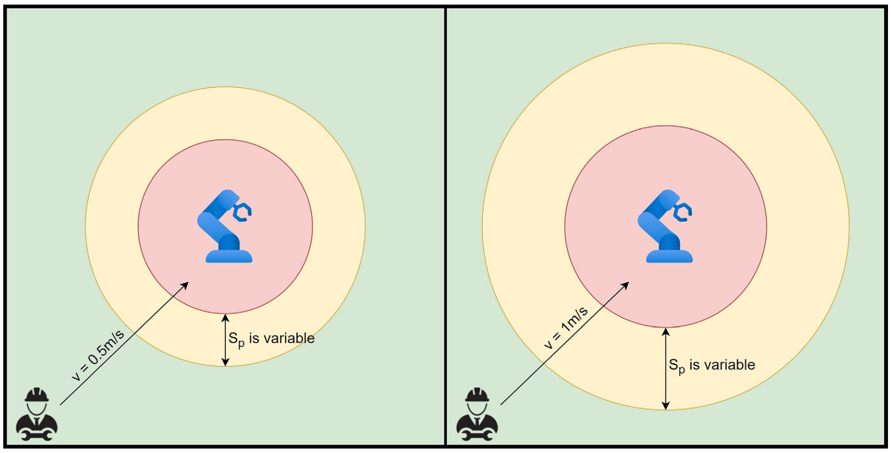

Figure 12. Variable Sized SSM; S_p is variable and dependent on different parameters such as the speed of the operator and robot. The shape remains the same.

Innovative research addresses these limitations. In [36], a pressure-sensitive floor equipped with projectors visualizes safety zones that adapt dynamically to the robot's speed and position. This approach not only enhances operator awareness but also provides a visual representation of safety zones. Similarly, [37] proposes dividing the workspace into predefined compartments with safety zones assigned distinct colors. While this method is more affordable than pressure-sensitive floors, it offers less accuracy in tracking operator movement. In [38], Variable Sized SSM, was compared to conventional zone monitoring. The study showed a cycle time shortening up to 11%. Similar results were obtained in [39] [40]. However, the latter scored worse on reaction time (time to detect human and issue a stop) due to higher computational costs.

5. Variable Shaped SSM

Variable Shaped SSM, **Figure 13**, can optimize throughput further by adjusting the robot's control based on its relative position to the operator. Unlike Variable Sized SSM, which primarily accounts for distance, Variable Shaped SSM modifies both the robot's speed and trajectory, allowing it to move out of unsafe situations. For instance, the robot could dynamically relocate to a safe distance and continue an alternate task. Additionally, Variable Shaped SSM can incorporate human motion intent [41]. Zones may adjust differently depending on whether an operator moves towards or away from the robot, even if the distance remains unchanged.

A limitation of the current SSM formula, Equation (2), is its assumption of a worst-case scenario where the robot and operator move directly toward each other

[42]. This conservative approach often triggers unnecessary safety stops, even when no real danger exists (**Figure 14**).

Further advancements require robotic systems to better understand their environment. For instance, [43] describes using an object directory to identify known items in the workspace. This allows the robot to maintain higher speeds when non-threatening objects, such as chairs or walls, enter the safety zones. In quasi-static environments, this method proves advantageous. On-the-fly object detection could further enhance adaptability, as demonstrated in [44], where both robot and human motion are tracked to optimize trajectory planning.

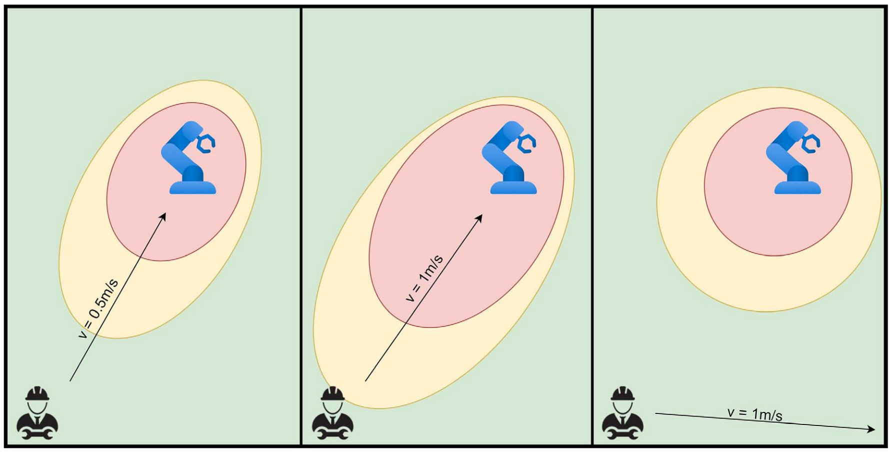

Figure 13. Variable Shaped SSM; S_p is variable; The intentions of the operator and robot have an influence on the shape of the zones.

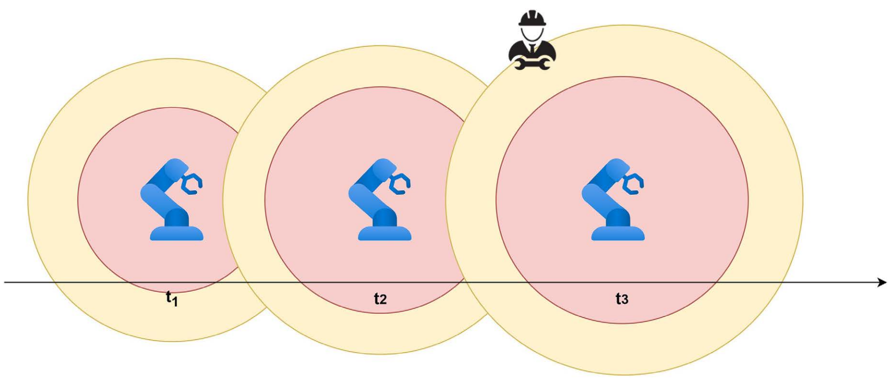

Figure 14. At t_3 the robot slows its speed, even if it has already passed the operator. The robot will continue to move away from him, so there is no dangerous situation.

6. Conclusions

The proposed SSM classification enhances clarity in implementation choices and highlights areas requiring further development. Fixed Sized SSM is the type that is the most commonly implemented in the industry today. The simplest form that requires little computation and customization. With a commercially available 2D sensor, the most common robotic applications can be secured. Future improvements of Fixed Sized SSM would be the implementation of 3D sensors to enlarge the monitoring capabilities and implementing mobile monitoring to decrease the safety area. While Variable Sized and Variable Shaped SSM offer substantial advantages, their industrial application remains limited due to safety certification constraints and computational demands. Empirical studies suggest that transitioning from Fixed Sized to adaptive SSM methods can significantly improve throughput and accessibility.

Now that there is a clearer framework, future research will focus on exploring different sensor types, developing redundant systems to ensure safety-rated information, and designing advanced algorithms for reliable human identification. These advancements will help address the existing challenges and pave the way for safer and more efficient human-robot collaboration.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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