2026 IEEE/SICE International Symposium on System Integration (SII)
January 11-14, 2026. Cancún, México

Collision Avoidance in Healthcare Robotics Using mm-Wave Radar Fusion: A Hygienic and Fail-Safe Approach

Rolf Schmidt[1,2], Marco Masannek[1,2], Andreas Deinlein, Verena Schmidt, Stefan May[1], Andreas Nüchter[2]

***Abstract*— Autonomous medical systems must meet stringent hygiene and safety requirements while operating reliably in dynamic clinical environments. This paper presents a collision avoidance system based on the fusion of two mm-wave radar technologies - frequency modulated continuous wave (FMCW) and pulsed coherent radar (PCR). The system is fully integrated behind sealed covers of medical devices and enables unobtrusive and hygienic use without compromising functionality. We demonstrate that both radar types provide robust detection of dynamic obstacles, even through layers of disinfectants, blood and polycarbonate materials. A fail-safe system architecture based on redundant sensor paths and dual microcontrollers ensures reliable operation under fault conditions. Experimental validation on a robotic X-ray system confirms the responsiveness, accuracy and suitability of the system for clinical integration. The results show that radar fusion offers a promising path to hygienic and certified safe motion planning in healthcare robotics.**

I. INTRODUCTION

The need for optimized clinical workflows is increasingly driven by demographic change [1], persistent staff shortages [2], and the growing complexity of treatment procedures [3][4]. One promising solution is the autonomous and safe operation of medical systems - such as ceiling-mounted X-ray imaging robot (see Fig. 1) - which can reduce radiation exposure and improve clinical efficiency. These systems typically operate within well-defined workspaces, executing repeated movements between treatment and parking positions. However, dynamic and unpredictable obstacles - such as patients, staff, or medical fixtures (e.g., tables, stands) - can obstruct these paths. To ensure safety and efficiency, reliable obstacle detection and motion prediction are essential for planning collision-free trajectories. Conventional sensing modalities such as cameras or ultrasonic sensors present several limitations in clinical use. These include occlusion susceptibility, sensitivity to ambient conditions, and hygiene-related constraints, as exposed sensor surfaces are difficult to clean and may pose contamination risks. Furthermore, the need for transparent windows or openings in the device housing can complicate disinfection and compromise system integrity. In contrast, radar technology provides robust distance and velocity measurements under varying environmental conditions. Its ability to penetrate non-metallic materials allows for complete integration behind sealed medical-grade covers, avoiding hygiene-critical surface openings and preserving the cleanability, biocompatibility, and usability of the device enclosure. This paper presents a hygienically integrated, fail-safe collision avoidance system based on the fusion of two radar sensors, specifically tailored to the constraints of safety-critical healthcare environments. The proposed approach aims to enable autonomous motion without compromising clinical requirements. This paper is structured as follows: Section II and III outlines the requirements and reviews the state of the art; Section IV and V describes the methodology for hygienic sensing and its transfer to a safety architecture; Section VI discusses the integration into existing medical robotic systems; Section VII presents and discusses the experimental results; and Section VIII concludes with a summary and outlook.

[1]Nuremberg Institute of Technology, Kesslerplatz 12, 90489 Nuremberg, Germany. {rolf.schmidt, marco.masannek, stefan.may}@th-nuernberg.de
[2]Julius-Maximilians-University Würzburg, Am Hubland, 97074 Würzburg, Germany. andreas.nuechter@uni-wuerzburg.de

Fig. 1: Fully motorized ceiling-mounted radiography robot

II. SYSTEM REQUIREMENTS AND CONSTRAINTS

Collision avoidance systems in healthcare robotics generally face more stringent requirements than those typically found in industrial applications. The central role of the patient, strict hygiene protocols, and mandatory regulatory compliance impose significant constraints on system architecture and sensor integration.

A. Clinical and Environmental Constraints

Healthcare settings demand design integrity across multiple dimensions: All sensor-integrated surfaces must be hygienically - sealed smooth, non-porous, and resistant to disinfectants - to minimize contamination risks. Concomitantly, the overall system footprint must remain compact and unobtrusive to preserve clinical ergonomics and workflow efficiency. Resilience is essential: Systems must maintain operational readiness even under degraded infrastructure (e.g., during emergencies). Materials must tolerate repeated exposure to ionizing radiation (e.g., X-rays) and cleaning agents without performance degradation. Finally, electromagnetic compatibility (EMC) per IEC 60601-1-2 [5] must be ensured due to the frequent presence of high-frequency (HF) surgical equipment.

B. Regulatory and Functional Safety Constraints

Systems must comply with medical device safety standards including IEC 60601-1 [6] (general safety) and ISO 14971 [7] (risk-based design). Critically, autonomy mandates *single-fault tolerance*: safety-critical subsystems must remain fully functional in the event of a single hardware or software fault-purely probabilistic or redundancy-free justification is insufficient.

C. Human–System Interaction and Overtrust Risk

As healthcare robotics systems move from supervised operation (e.g., dead-man's grip control) to autonomous operation, there is a well-documented risk of overtrust - users may develop unwarranted confidence in non-safety-rated features [8], potentially neglecting fallback safeguards. Empirical studies in autonomous vehicle research, such as semi-structured interviews with Tesla Autopilot users, demonstrate that users often disengage from vigilance or misinterpret the system's reliability, sometimes even operating vehicles hands-free or watching unrelated content during test drives [9]. Similarly, overtrust in domestic or social robots has been observed in controlled experiments using pet feeding robots, where users reduced supervision after repeated flawless performance - even when the robot later failed catastrophically [10]. Mitigation requires transparent system status communication, logical separation of control and protection channels, and safety mechanisms that are both independently validated and inherently fail-safe.

III. Related Work

A. Human-in-the-loop approach

Due to the specific requirements of this situation, it is still state of the art in healthcare technology [11] for the movements of healthcare systems to be monitored by a human. In practice, this is achieved through a dead man grip (dmg), which integrates the user into the system's safety loop as a control mechanism. The user is solely responsible for ensuring that there are no collisions. The system moves to the target position without acquiring any reliable knowledge of its surroundings.

B. Contact-based approaches

The user is often supported by tactile protective units. These include safety edges and force-sensitive covers.

1) Safety edges, bump strip: Safety edges are widely used in industrial robotics and automation to detect physical contact and stop motion in the event of a collision [12] [13]. These devices operate within the safety circuit and provide a binary signal [14] upon activation, allowing for simple integration. However, their effectiveness is limited to predefined contact zones and they cannot detect or predict collisions proactively, which restricts their use in dynamic or unstructured environments. The selection of an appropriate switching threshold is non-trivial: it must be low enough to ensure user safety while high enough to prevent false positives caused by mechanical tolerances or system dynamics [14]. This trade-off becomes particularly critical in high-speed applications such as automated 3D image acquisition or interventional imaging systems. As a purely contact-based safety mechanism, safety edges are unsuitable in sterile environments and may not eliminate the need for additional protective measures in healthcare robotics.

2) Sensitive Cover: The concept of safety edges can also be extended to force-sensitive cover structures, in which the robots cover either partially or entirely - acts as a distributed contact sensor. This principle can be implemented not only on rigid panels but also on flexible materials, such as coated textiles, synthetic leather, or elastomeric layers. These multilayer structures typically consist of two conductive films separated by a soft, deformable insulating spacer. When pressure is applied, the spacer compresses, allowing electrical contact through predefined zones [15][16]. In contrast to rigid systems, flexible covers introduce additional challenges: fluids may penetrate not only at the edges but also across the surface, especially if the outer material is damaged or insufficiently sealed. A ruptured surface may lead to a permanent short circuit, while a broken signal line could result in a state indistinguishable from normal operation. To address these failure modes, condition monitoring systems are employed. A common approach involves integrating a high-impedance resistor between the conductive layers, allowing the detection of impedance changes. This makes it possible to distinguish between intentional contact, open-circuit faults, and unintended shorting. Nevertheless, material selection and sealing strategies remain critical - particularly in hygienic and high-usage environments such as healthcare robotics.

3) Force and torque limitation: In line with the broader industrial adoption of collaborative robots (cobots), efforts have also been made to apply the concept of intrinsic safety to healthcare robotics - by limiting the maximum force, power, and impulse values during operation. While this approach can improve safety without additional external sensors, its applicability in healthcare contexts is highly restricted. One of the primary limitations stems from the structural requirements of healthcare robots, which often demand high stiffness and load-bearing capacity. These properties inherently lead to larger and heavier designs, which in turn restrict the maximum allowable velocity due to safety constraints - thereby negatively affecting treatment quality in dynamic procedures. Furthermore, force and pressure limits defined in collaborative robot standards such as ISO/TS 15066:2016 [17] impose additional design constraints. Healthcare systems often need to interact with compact and fragile tools or anatomical structures (e.g. endoscopes or catheters), where even small surface forces can be hazardous for humans. As a result, it becomes extremely difficult to achieve adequate acceleration and responsiveness while maintaining low-force operation. Additionally, axes must be sensitive enough to detect minimal contact forces to trigger a safe stop. These conflicting requirements often render intrinsically safe cobot designs inefficient or impractical for many clinical applications.

Contact-based safety systems - e.g. safety edges or force-sensitive covers - activate only after contact, offering detection rather than avoidance. This limits their preventive value, introduces hygiene and comfort risks, and requires overtravel space. In heavy or dynamic robots, these constraints render them suitable mainly as auxiliary safety layers in human-supervised use, but inadequate for autonomous or anticipatory systems.

C. Remote sensing / touchless approaches

Based on these considerations, it becomes evident that tactile or contact-based safety mechanisms alone are insufficient [15] to support the next level of autonomous functionality in clinical environments. To enable proactive collision avoidance, enhanced workflow integration, and uninterrupted operation in sensitive settings, contactless sensing approaches are essential.

1) Capacitive approaches: Given the limitations of contact-based approaches - which inherently require physical contact before responding - capacitive sensing has been explored as a promising contactless alternative. These systems detect nearby objects by measuring changes in the surrounding electric field, thereby enabling interaction prior to physical contact. Moreover, capacitive sensors can often be integrated into or built upon existing force-sensitive cover structures, as their layered design is structurally similar [18]. This compatibility makes them particularly attractive for retrofitting or hybrid sensing concepts. While this approach improves responsiveness and enables basic collision avoidance, capacitive systems are limited by their short effective sensing range ($< 10cm$), resulting in small detection zones that constrain permissible motion speed [19][20][21]. In addition, they are highly susceptible to electromagnetic interference, which is especially critical in clinical environments where high-frequency electrosurgical devices are commonly used [22]. Sensor performance can also be significantly degraded by moisture, residual disinfectants, or applied protective films, which alter the dielectric properties and reduce reliability.

2) Laserscanner(LiDaR) approaches: In general robotics, laser scanners are a widely used and well-established solution for SLAM and safety applications, and are considered state of the art across various safety levels. While the certifications and safety classifications used in industrial robotics are not directly transferable to healthcare systems, several models are available that meet comparable functional safety standards. However, in clinical environments, laser scanners face significant integration challenges. Their physical form factor and optical requirements often interfere with sensitive procedures, such as close-range imaging near anatomical structures (e.g., patella positioning). Although recent developments in solid-state laser scanning technology allow for more compact and robust devices, fundamental limitations persist due to the need for optical openings, protective filters, or transparent recesses in the housing. These requirements conflict with hygienic design principles, as such features complicate cleaning, may accumulate residues, and limit biocompatibility and sterilizability of exposed surfaces. Additionally, repeated contact with disinfectants may degrade optical components or coatings, leading to reduced performance and reliability in clinical use [23].

3) Camera approaches: Camera-based and related sensor technologies, including hybrid 2D/3D systems, such as stereo vision, structured light, and time-of-flight, are capable of reliably detecting even very small objects - provided as long as sufficient spatial resolution is available. Despite this advantage, these systems pose several critical challenges for integration into healthcare robotics. Hygienic integration remains one of the most significant limitations. Cameras and associated projection components typically require transparent windows or housing cutouts, which are difficult to disinfect and may pose contamination risks in clinical environments. In addition, optical systems are inherently susceptible to occlusion and shadowing, especially in cluttered or dynamic operating rooms. From the user perspective, high-resolution imaging in intimate clinical situations may raise privacy concerns, potentially reducing patient acceptance. Active projection methods - such as structured light - require emitter components (e.g., beamers or lasers) that share the same integration and sterilization issues as conventional laser scanners. On a technical level, real-time 3D reconstruction and object recognition demand significant computational resources, which may conflict with the compact, sterilizable form factors required in healthcare systems. In many cases, this also necessitates external computing units and high-bandwidth data transfer, which further complicates integration. Finally, modern diagnostic healthcare robots operate at high speeds, often exceeding the temporal resolution and processing capabilities of available camera systems. This can result in increased latency, reduced responsiveness, and ultimately, a negative impact on clinical performance [24].

4) Ultrasonic approaches: Ultrasound-based collision avoidance, widely used in the automotive industry (e.g. park distance control), has also found applications in healthcare devices due to its ease of integration and the potential to protect transducers via encapsulation. However, cleanability remains the primary limitation, as ultrasonic waves cannot effectively penetrate solid materials. This necessitates either using the device housing itself as a vibrating membrane or embedding protected transducer heads into specific surface regions [25][26]. Both approaches present significant trade-offs. Membrane zones are contamination-prone and the elastic materials required for acoustic transmission must tolerate not only repeated exposure to disinfectants but, in some clinical applications, resist degradation from ionizing radiation such as X-rays. When the device housing is used as the radiating surface, a high number of transducers is typically required to ensure sufficient field-of-view (FoV) coverage - since even relatively large ultrasonic elements produce narrow beam patterns. Moreover, temperature dependence and the low propagation speed of sound in air limit the sensor's responsiveness and accuracy in fast, dynamic environments, as found in many robotic medical procedures.

5) Radar approaches: Radar-based safety systems are beginning to find application in industrial environments - most notably in the form of safety integrity level (SIL) certified sensors such as those from Inxpect [27], which are used for area monitoring in robotics and heavy machinery. While these systems demonstrate the feasibility of integrating radar into safety-relevant control loops, they are designed primarily for rugged industrial settings. Their comparatively large size, open sensor surfaces, and lack of hygienic sealing render them unsuitable for direct use in healthcare devices, where disinfection compatibility, biocompatibility, and form factor are critical. Although radar has shown promise as a safety technology in other domains, no existing implementation currently meets the combined hygienic and functional safety requirements of clinical applications. Radar technology offers a promising path to overcoming these challenges. This work therefore presents a collision avoidance system based on millimeter-wave radar, specifically designed for hygienic integration and single-fault safety. The system fuses two radar sensors, fully embedded behind sealed device covers, to ensure safe operation without compromising clinical usability.

IV. Proposed System Architecture

Based on these findings, radar sensing - in particularly mm-wave technology due to its high integrability and resolutio - emerges as the most promising approach to fulfill the demanding requirements of collision avoidance for robotic systems in medical environments. Its inherent robustness, hygienic integrability, and potential for reliable, contactless obstacle detection address key limitations of previously discussed sensing modalities. The following section outlines the proposed system integration that leverages these advantages.

A. Physical Integration and Sensor Layout

To enable full integration behind sealed, medical-grade covers, the sensor modules must exhibit an extremely compact form factor in both height and surface footprint. Unlike conventional designs with external antenna, radomes or PCB-integrated antenna structures, which increase the system volume and often require complex sealing of external accessories, this work leverages radar chipsets with integrated antenna-in-package (AiP) designs. This approach eliminates the need for external radio-frequency (RF) components and enables flush, unobtrusive mounting within the mechanical shell of the device - without compromising the sterile barrier or requiring additional disinfection - compatible seals or integrating special structures in the outer area of polymer covers.

B. Radar Technology and Frequency Selection

To achieve sufficient spatial resolution and signal penetration through the non-metallic outer housing, the system operates within the 60 GHz industrial, scientific and medical (ISM) band (57–64 GHz), offering:

- Wide bandwidth (up to 7 GHz) for high-resolution detection of small and soft obstacles,
- Relatively high EIRP limits (up to 14 dBm), enabling robust operation even through cover materials,
- License-free usage indoors and favorable coexistence for multi-sensor arrangements.

This frequency choice ensures compatibility with hygienic enclosures while maintaining signal integrity and minimizing antenna aperture requirements.

C. Redundant Sensor Fusion Architecture

To achieve fail-safe behavior, the system integrates two radar sensors placed in close proximity, each operating based on distinct physical principles but covering nearly the same field of view (see Fig. 2). One unit uses frequency-modulated continuous wave (FMCW) radar, while the other operates as a pulsed coherent radar (PCR). Both modalities provide range and velocity information but differ in signal processing characteristics and environmental robustness - enabling cross-validation and improved reliability. In configurations involving multiple sensor modules - for example, to cover larger operational volumes - the system employs time-division multiplexing (TDM) to comply with regulatory emission limits while maximizing temporal resolution and signal-to-noise ratio. Importantly, the resulting mute periods introduced by the TDM strategy remain significantly shorter than the fault-tolerant response time permitted by relevant safety standards. These standards account for system latency, detection uncertainty, and the braking or stop distance required in critical scenarios.

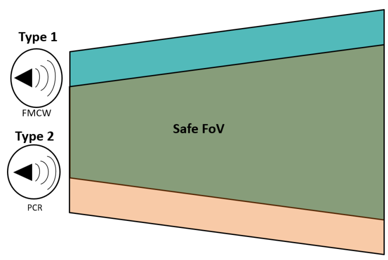


Fig. 2: Overlapping of two co-located mm-wave sensors

D. Safety Shield Software Architecture

To detect critical near-field obstacles, the radar signal processing chain (see Fig. 3) implements a virtual safety shield as described in Algorithm 1.

This shield dynamically surrounds the protected area of the medical device and can assume three states: *intact*, *warning*, or *broken* (requiring immediate stop). Each radar frame is generated by applying a windowed Fast Fourier Transform (FFT) to the averaged ADC signals. The resulting magnitude range spectrum is scaled into physical distance bins. During system commissioning, a calibration phase is executed in which the sensor captures its static environment - including the device cover, surrounding equipment,

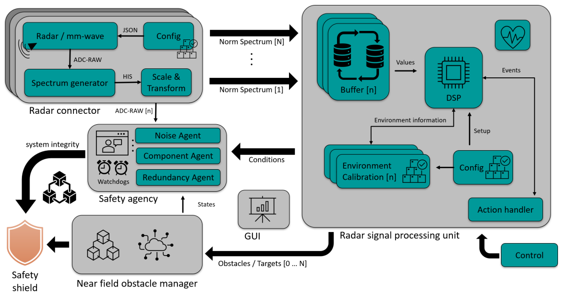


Fig. 3: Software Architecture

and natural multipath reflections. The resulting background signature is stored and used to compute deviation profiles during runtime. In live operation, every incoming range spectrum is processed through a ring buffer that compares it to the learned reference. Deviation envelopes (see Fig. 4) are monitored using statistical thresholds.

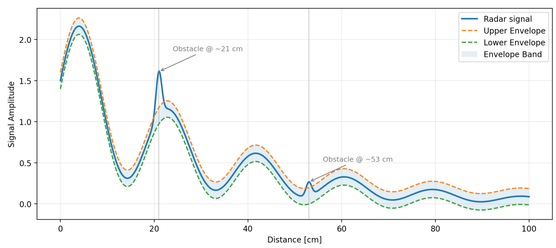


Fig. 4: Envelopes monitoring

If signal anomalies are detected (e.g., unexpected energy spikes or pattern deviations), target candidates are extracted (see Fig. 4). These targets are passed to the Near Field Obstacle Manager (NFOM), which classifies them based on position, signal consistency, and persistence. The shield status is then updated:

- **Intact:** No obstacles detected
- **Warning:** Obstacle detected near the safety zone - system slows down.
- **Broken:** Intrusion into critical zone - emergency stop triggered.

This approach enables the detection of multiple obstacles within a sensor's FoV.

V. Fail-Safe Design Principles

Beyond sensor-level redundancy, the proposed safety architecture integrates a fail-safe embedded design based on two independent signal processing paths (see Fig. 5): the Control Path (C-Path) and the Protection Path (P-Path). Both operate on separate microcontrollers and process the same raw radar data from dual heterogeneous sensors (FMCW and PCR), ensuring diversity in sensing modalities and processing logic.

The C-Path is responsible for calculating the primary state of the radar-based virtual safety shield. It determines zone states (intact, warning, or broken) and may provide optional non-safety-related features such as object detection or user

---

Algorithm 1: Radar signal processing pipline for safety shield generation

Input: Raw ADC samples $s(t)$
Output: Shield state: `intact`, `warning`, `broken`

if *mean removal is enabled* **then**
  $s(t) \leftarrow s(t) - \text{mean}(s(t))$;
Apply window function: $s_w(t) \leftarrow \text{Window}(s(t))$;
Compute FFT: $S(f) \leftarrow |\text{FFT}(s_w(t))|$;
Apply linear thresholding: $S_{\text{thr}}(f) \leftarrow S(f) - T$;
Scale to distance domain: $R(d) \leftarrow \text{Scale}(S_{\text{thr}}(f))$;
Insert $R(d)$ into ring buffer: $\text{RingBuffer} \leftarrow R(d)$;
Retrieve latest $R_{\text{current}}(d)$ from ring buffer;
if *Environment calibration run* **then**
  Compute background signature: $R_{\text{ref}}(d) \leftarrow \text{Mean}(R_{\text{buffer}}(d))$;
  Store $R_{\text{ref}}(d)$ in memory;
Compute deviation: $\Delta(d) \leftarrow R_{\text{current}}(d) - R_{\text{ref}}(d)$;
Detect targets: $\text{Targets} \leftarrow \text{Detect}(\Delta(d))$;
Pass targets to NFOM: $\text{NFOM} \leftarrow \text{Evaluate}(\text{Targets})$;
Decide shield state:
  if *NFOM reports intrusion* **then**
    if *distance $<$ critical threshold* **then**
      return broken
    else
      return warning
  else
    return intact

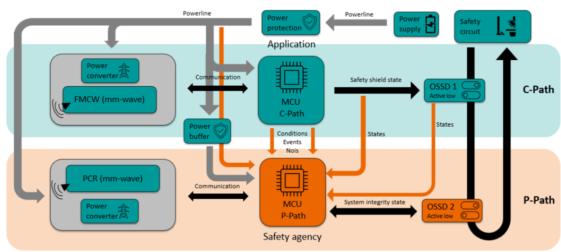


Fig. 5: Hardware Architecture

feedback. These outputs support system ergonomics or navigation but are not safety-certified and have no authority over the autonomous enable/disable functionality. [28] The P-Path, in contrast, functions as the safety enforcement layer. It evaluates the C-Path output independently and supervises its operation in real time. Its architecture is based on a set of modular diagnostic and verification agents, each responsible for specific tasks, including:

- **Signal agent:** Monitors raw radar integrity (e.g., amplitude limits, background noise deviation).
- **Power agent:** Monitors the TDM strategy for compliance with the EIRP limit value [29].
- **Consistency agent:** Compares current C-Path decisions against recent history for plausibility.

- **Deviation agent:** Detects unexpected trends, latency drifts, or internal timing mismatches.
- **Logic agent:** Validates the final shield state transitions and prevents unsafe degradations.

Together, these agents form a "safety agency" that continuously monitors system health and validity. Each agent contributes to a shared decision bus, and if any single agent flags a critical inconsistency, the P-Path triggers a hardware shutdown via a dual-channel safety relay system. This agent-based approach allows the protection logic to remain lean, modular, and independently certifiable. It also facilitates fault isolation and failure analysis, as each agent logs structured diagnostics that can be used for forensic post-event evaluation.

VI. System Integration and Experimental Setup

To evaluate the proposed radar-based safety architecture, multiply radar sensors were integrated into a medical fully motorized ceiling-mounted digital radiography robotic system.

A. Sensor Configuration

An Infineon BGT60TR13C evaluation board was used as the frequency-modulated continuous wave (FMCW) radar. For the pulsed coherent radar (PCR), an Acconeer A121 development kit was selected. Both sensors were mounted side-by-side on the collimator cover plate of the X-ray system, with partially overlapping fields of view. To ensure complete environmental coverage, one radar sensor was mounted in each primary direction of motion. This configuration allows multi-directional obstacle detection and supports redundancy by combining different sensing principles.

B. Mechanical Integration

To simulate a realistic medical product housing, a transparent polycarbonate sheet was mounted in front of the sensors to mimic a sealed device cover. In a second setup, an original housing cover of a X-ray system was used in a static configuration.

C. Data Pipeline and Middleware

The acquisition, processing, and visualization of sensor data were implemented using the ROS2 middleware [30]. Although the final architecture targets deployment on embedded microcontroller units (MCUs), the experimental system was realized in software using modular ROS2 nodes. Each functional component - ranging from raw signal preprocessing to safety state evaluation - was encapsulated into an independent node, simplifying testing, debugging, and system traceability. The system also includes motion control capabilities integrated into the ROS2 environment. Motor commands and system override signals were interfaced via CAN bus between the host CPU and the motor controller, enabling seamless integration with the X-ray ceiling stand. For visualization, RViz2 was used with custom 3D marker arrays to display the dynamic safety shield. In addition, a custom Qt-based analysis tool [31] was developed to inspect raw radar signals and monitor signal processing outputs in real time. This setup enabled comprehensive validation of the safety logic under realistic conditions.

D. Contamination and Environmental Testing

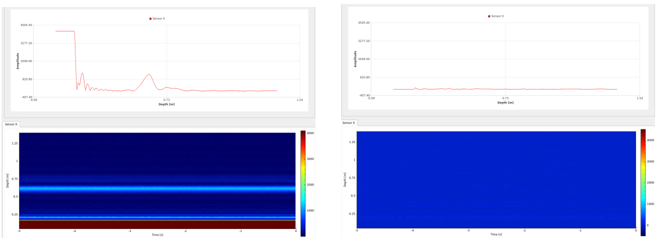
To evaluate the robustness under realistic conditions, the sensor covers were contaminated with water, infusion fluid, disinfectant, cleaning agents and pig blood[1] to simulate clinically relevant contamination scenarios. In the static setup, human arm movements were used as a representative obstacle to evaluate the detection performance in the near field.

VII. Results and Discussion

This section presents the evaluation of the proposed radar-based collision avoidance system behind medical covers. The results are structured into three key aspects: calibration performance, functional integration into a clinical device, and the robustness of the sensor system under hygienic conditions.

A. Calibration and Background Signature Suppression

To verify the effectiveness of the background subtraction and calibration process, the raw radar signal was recorded before and after the calibration phase. Fig. 6 shows the amplitude-distance spectrum of a single radar frame. On the left, strong static reflections caused by the cover structure and surrounding mechanical parts are visible. On the right, the calibrated output clearly suppresses these stationary echoes, revealing only dynamic obstacles. This validates the ring-buffer-based background modeling and its robustness under controlled conditions.



without calibration   with calibration

Fig. 6: Radar signal environment calibration. Static reflections are effectively removed.

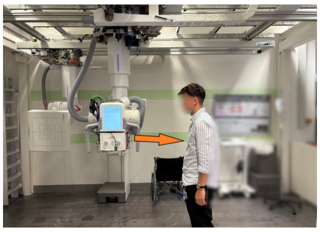
To check the effectiveness of the background subtraction and the calibration process, the raw radar signal was recorded before and after the calibration phase. Fig. 6 shows the amplitude-distance spectrum of a single radar image, as well as the heat map of the signal over time. The left part of the image shows strong static reflections caused by the structure of the cover and the surrounding mechanical parts, as well as from the PCB and the chip itself. On the right, the calibrated

[1] *Ethical considerations:* The animal-derived material used in this study was acquired as a byproduct. No animals were harmed specifically for this research, nor were any animal experiments conducted. Therefore, ethical clearance was not required.

output clearly suppresses these stationary echoes and only shows dynamic obstructions. This confirms the signature-based background modeling obtained from the ring buffer and its robustness under controlled conditions.

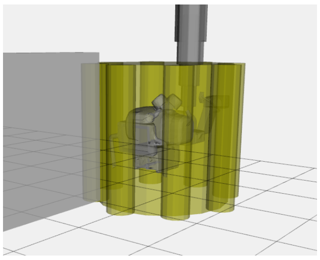
B. Dynamic Operation on X-Ray System

To evaluate the system's real-world applicability, the radar sensor modules were mounted behind a polycarbonate cover on the X-ray collimator housing of a ceiling-mounted radiography robotic system. During experimental trials, a person repeatedly approached the system while it was in motion. As illustrated in Fig. 7, the radar-based safety shield dynamically transitioned between the predefined states (*intact*, *warning*, *broken*) based on the proximity of the subject. Each transition reliably triggered the appropriate response-either reducing speed or initiating a complete motion stop (see Fig. 8). The experiment was repeated multiple times with consistent results, which confirm that the radar system reacts robustly to movements in the near field and can fulfill the dynamic safety requirements in a clinical facility.

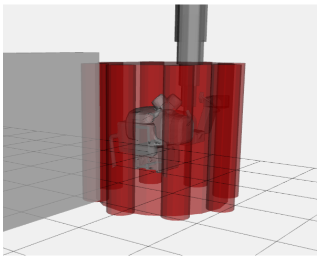


Person in warning area

Person in stop area



safety shield warning mode



safety shield stop mode

Fig. 7: Safety shield states and scene interpretation

To validate the configured protective field boundaries, a human-skin simulator with known spatial coordinates relative to the robot was positioned in the workspace. The robot was then set on a deliberate collision course. When the corresponding safety flags were triggered (see Fig. 8), the measured activation distances matched the configured thresholds, confirming the correctness of the protective field sizes.

C. Hygienic Integration and Contamination Robustness

A central goal of this study was to demonstrate the feasibility of integrating radar sensors fully behind closed, hygienically sealed covers. To simulate realistic clinical conditions, the original x-ray-tube-cover of a commercial X-ray radiography system (see Fig. 1) was mounted in front

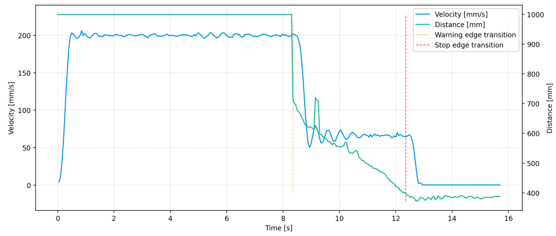


Fig. 8: Result of detection and velocity reduction

of the sensor assembly and deliberately contaminated with common clinical substances, including water, infusion fluid, disinfectant, and pig blood (see Fig. 9). These tests were performed in addition to those using a polycarbonate cover on the ceiling-mounted radiography robotic system.

Technology demonstrator

Real cover

Fig. 9: Contamination test with blood

Despite the applied surface films, both radar systems maintained stable signal quality. As shown in Fig. 10, the radar signal penetrated the contaminated cover and correctly identified multiple nearby obstacles, including a human arm and a chair. The system continued to operate without false suppression or masking effects.

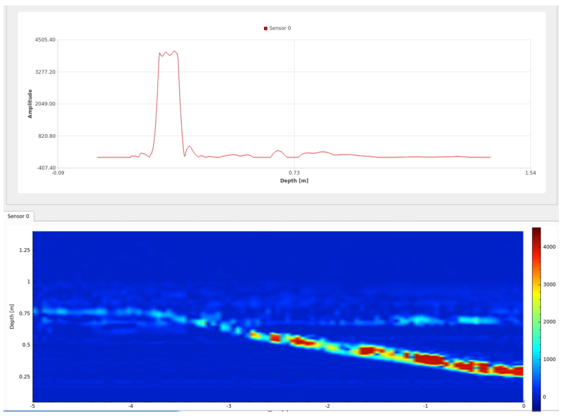


Fig. 10: RSPU detected Obstacle

Of particular note is the superior penetration performance of the PCR compared to the FMCW, which showed greater penetration of both coverage and surface contamination. This is in line with theoretical expectations, as the short pulse width and shorter integration time of the PCR are advantageous in environments with heterogeneous materials or transient contamination.

VIII. Conclusion

This paper presented a hygienically integrated, fail-safe collision avoidance system based on mm-wave radar technology, combining FMCW and PCR sensors. The experimental evaluation demonstrated that the fusion of both technologies is not only feasible behind sealed medical covers, but also complementary in terms of penetration performance and detection reliability and results in a divergent and redundant design. The system successfully maintained operational integrity under realistic contamination scenarios and enabled consistent obstacle detection without compromising hygienic or clinical requirements. These findings support the viability of radar-based safety systems for medical robotics. Future work will focus on implementing the full hardware safety architecture and validating the approach in real clinical workflows. This includes long-term evaluation in dynamic, high-risk environments to further assess system robustness and practical integration.

Acknowledgment

The authors gratefully acknowledge the support of Siemens Healthineers AG for providing systems, materials and access to laboratory space used in this work.

References

[1] European Commission, "The impact of demographic change in europe: Demography report 2020," European Commission, Directorate-General for Employment, Social Affairs and Inclusion, Brussels, Belgium, Staff Working Document SWD(2020) 109 final, 2020.

[2] OECD and European Commission, *Health at a Glance: Europe 2024: State of Health in the EU Cycle*. Paris: OECD Publishing, 2024.

[3] H. Naik, T. M. Murray, M. Khan *et al.*, "Population-based trends in complexity of hospital inpatients," *JAMA Internal Medicine*, vol. 184, no. 2, pp. 183–192, 2024.

[4] A. Thacharodi, P. Singh, R. Meenatchi, Z. H. Tawfeeq Ahmed, R. R. S. Kumar, N. V, S. Kavish, M. Maqbool, and S. Hassan, "Revolutionizing healthcare and medicine: The impact of modern technologies for a healthier future – a comprehensive review," *Health Care Science*, vol. 3, no. 5, pp. 329–349, Oct 2024.

[5] *IEC 60601-1-2: Medical electrical equipment - Part 1-2: Collateral Standard: Electromagnetic disturbances - Requirements and tests*, International Electrotechnical Commission Std., 2024, specifies electromagnetic distrubances.

[6] *IEC 60601-1-2: Medical electrical equipment - Part 1: General requirements for basic safety and essential performance*, International Electrotechnical Commission Std., 2024, general safety.

[7] *ISO 14971: Medical devices - Application of risk management to medical devices*, International Organization for Standardization Std., 2022, specifies safety edges.

[8] L. B. V. J. C. C. C. G. D. W. S. M. A. N. M. Masannek, R. Schmidt, "Safety-oriented semantic-constraint navigation in clinical environments," 2025.

[9] S. Nordhoff and J. De Winter, "Why do drivers and automation disengage the automation? results from a study among tesla users," *arXiv preprint arXiv:2309.10440*, 2023, semi-structured interviews showing degraded vigilance and overtrust of Tesla Autopilot.

[10] D. Ullrich, A. Butz, and S. Diefenbach, "The development of overtrust: An empirical simulation and psychological analysis in the context of human-robot interaction," *Frontiers in Robotics and AI*, vol. 8, p. 554578, 2021.

[11] *IEC 60601-2-54: Medical electrical equipment. Particular requirements for the basic safety and essential performance of X-ray equipment for radiography and radioscopy*, International Electrotechnical Commission Std., 2024, specifies dead-man switch requirement.

[12] *ISO 13849-1:2023 - Safety of machinery - Safety-related parts of control systems - Part 1: General principles for design*, International Organization for Standardization Std., 2023, specifies safety edges.

[13] *ISO 13855:2024 – Safety of machinery - Positioning of safeguards with respect to the approach of the human body*, International Organization for Standardization Std., 2024, specifies safety edges.

[14] *ISO 13856-2:2013 - Safety of machinery - Pressure-sensitive protective devices - Part 2: General principles for the design and testing of pressure-sensitive edges and pressure-sensitive bars*, International Organization for Standardization Std., 2013, specifies safety edges.

[15] C. Scholz, H.-L. Cao, E. Imrith, N. Roshandel, H. Firouzipouyaei, A. Burkiewicz, M. Amighi, S. Menet, D. W. Sisavath, A. Paolillo, X. Rottenberg, P. Gerets, D. Cheyns, M. Dahlem, I. Ocket, J. Genoe, K. Philips, B. Stoffelen, J. Van den Bosch, S. Latre, and B. Vanderborght, "Sensor-enabled safety systems for human-robot collaboration: A review," vol. 25, no. 1, pp. 65–88.

[16] Q. Jiang and L. S. Wong, "A hierarchical safety framework for robots using whole-body tactile sensing," in *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2024, pp. 4567–4574.

[17] *ISO/TS 15066:2016 - Robots and robotic devices - Collaborative robots*, International Organization for Standardization Std., 2016, technical specification providing safety requirements for collaborative industrial robot systems.

[18] M. Leonori, J. M. Gandarias, and A. Ajoudani, "Moca-s: A sensitive mobile collaborative robotic assistant exploiting low-cost capacitive tactile cover and whole-body control," *IEEE Robotics and Automation Letters*, vol. 7, no. 3, pp. 7920–7927, 2022.

[19] A. Hoffmann, A. Poeppel, A. Schierl, and W. Reif, "Environment-aware proximity detection with capacitive sensors for human–robot interaction," in *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2016, explores capacitive proximity sensing for enhanced safety in HRI.

[20] C. Scholl, A. Tobola, K. Ludwig, D. Zanca, and B. M. Eskofier, "A smart capacitive sensor skin with embedded data quality indication for enhanced safety in human–robot interaction," *Sensors*, vol. 21, no. 21, p. 7210, 2021.

[21] Z. Wang, H. Gao, A. Schmitz, S. Somlor, T. P. Tomo, and S. Sugano, "Safe skin-a low-cost capacitive proximity-force-fusion sensor for safety in robots," in *2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2021, proximity up to 400 mm; active shielding to reduce EMI.

[22] B. Aksoy, Y. Hao, G. Grasso, K. M. Digumarti, V. Cacucciolo, and H. Shea, "Shielded soft force sensors," *Nature Communications*, vol. 13, 2022.

[23] J. Smith, Y. Lee, and H. Kim, "Autonomous systems: The essential guide to using lidar," *IEEE Tech News*, 2024, discusses FOV limitations of solid-state vs mechanical LiDARs.

[24] T. Beyl, P. Nicolai, M. D. Comparetti, J. Raczkowsky, E. D. Momi, and H. Wörn, "Time-of-flight-assisted kinect camera-based people detection for intuitive human-robot cooperation in the surgical operating room," *International Journal of Computer Assisted Radiology and Surgery*, vol. 11, no. 7, pp. 1329–1345, Jul 2016.

[25] ScanMed, "Omnitom® elite - mobile ct scanner," 2024. [Online]. Available: https://scanmed.com.sg/omnitomelite, note = Accessed: 2025-07-30

[26] N. Shah, J. Burns, D. G. Rigby, and R. J. Morhard, "Mobile ct scanner," Patent WO2 016 125 980A1, international Publication Number WO 2016/125980 A1.

[27] Inxpect S.p.A., "Lbk-s01 safety radar system," https://www.inxpect.com/en/products/s101a/, 2025, accessed: July 25, 2025.

[28] A. Baranov, T. Starecki, and A. Piotrowski, "Safety of control systems with dual architecture based on plcs," *Applied Sciences*, vol. 12, no. 19, p. 9799, 2022.

[29] H. Forsten, T. Kiuru, M. Hirvonen, M. Varonen, and M. Kaynak, "Scalable 60 ghz fmcw frequency-division multiplexing mimo radar," *IEEE Transactions on Microwave Theory and Techniques*, vol. 68, no. 7, 2020.

[30] Open Source Robotics Foundation, "Ros 2 - humble," https://docs.ros.org/en/humble/index.html, 2022.

[31] The Qt Company, "Qt," https://www.qt.io, 2025.