A Study of Safety Radar as a Three-Dimensional Electro-Sensitive Protective Equipment

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ABSTRACT

This paper investigates the intersection of safety standards, in particular ISO 13855, and the specific characteristics of three-dimensional radar electro-sensitive protective equipment (ESPE) in the context of industrial production systems. This study focuses on adapting ISO safety distance standards, originally tailored to optical ESPEs, to the capabilities introduced by the IEC TS 61496-5 standard for radar ESPEs. Conventional optical ESPEs present a trade-off between installation flexibility and required safety distance length to meet standard requirements because of their two-dimensional detection zone. In contrast, radar ESPEs can achieve both short safety distances and flexible installations due to their three-dimensional detection zone, which can be interpreted as distributed imaginary light curtains from the start to the end.

However, applying these parameters directly to the standards requires theoretical and practical consideration. This study provides fundamental insights into methodologies for maximizing the advantages of radar ESPEs while meeting safety distance standards. The section on theoretical framework explains radar detection theory and outlines the calculation of safety distance in accordance with ISO 13855. A case study is presented using a conventional series-fed two-patch antenna to demonstrate the radar ESPE's ability to detect a human fist within a specific three-dimensional zone. Additionally, this study showed that a fabricated radar ESPE can suffice the detection capability and the short safety distance can be achieved. The aim of this study is to contribute to the advancement of safety and efficiency in contemporary production environments.

1 INTRODUCTION

The standard IEC TS 61496-5, which is a standard of radar ESPEs, was published in August 2023 [1]. ESPEs are employed for risk reduction of production systems. Due to the use of the different frequencies of electromagnetic waves for detection, radar ESPEs have different detection characteristics. In general, conventional optical ESPEs have a two-dimensional detection zone, and laser beam intervals. In contrast, radar ESPEs can be easily designed to have three-dimensional detection zone.

To ensure adequate protection by ESPEs, it is necessary to follow the ISO 13855 safety distance standard [2, 3]. This standard calculates the safety distance based on the overall system stopping performance, approach speeds of the target, and intrusion distance. The value of intrusion distance depends on the installation and detection capability of the ESPE. When the ESPE is installed orthogonal to the approaching target direction and has a detection capability of 40 mm or less, a short intrusion distance can be applied. However, the orthogonal installation may not be flexible to install and could pose residual risks in enclosed hazardous areas. In contrast, when the ESPE is installed parallel to the approaching target direction, the intrusion distance of 850 mm or more is applied. For orthogonal installation, this value also applies when the detection capability exceeds 40 mm. Therefore, while parallel installation offers flexible solutions, it requires a longer safety distance.

As previously mentioned, radar ESPEs can resolve this trade-off with their three-dimensional detection zone. However, ISO 13855 assumes that ESPEs are optical detection devices, so some points in the standard may be difficult to apply directly to radar ESPEs. Additionally, IEC TS 61496-5 only specifies the detectability of a human body. This study investigated basic methods to ensure safety with a three-dimensional detection zone. This study also considered means of applying ISO 13855 to radar ESPEs. Consequently, this study shows that radar ESPEs can make production systems more efficient with their detection capability.

2 Background

2.1 Radar equation

Radar systems typically consist of an antenna for transmitting and/or receiving electromagnetic waves. The detection process involves capturing reflected waves, similar to optical ESPEs. Radar ESPEs can detect the target with sufficient received power, following the radar equation. The equation is as follows: where Pr is the received power, λ is the wavelength, Gt and Gr are the gains of the transmitting and receiving antennas, σ is the radar cross section (RCS) of the target, R is the range between the radar and the target, Pt is the power supplied.

$$P_r = \frac{\lambda^2 G_t G_r \sigma}{(4\pi)^3 R^4} P_t \quad (1)$$

Antenna gain is generally defined as a characteristic of the maximum radiation direction, but it may also function as a radiation pattern dependent on azimuth and elevation angle. The detection zone of a radar ESPE is defined by the RCS of the minimum detection target, the distance, and the angle at which sufficient gain can be obtained.

2.2 Calculating safety distance

According to ISO 13855, when the installation is orthogonal and the detection capability "d" of the ESPE is 40 mm or less, the safety distance "S" is calculated by the following equation: where "K" is the approaching speed, "T" is the overall system stopping performance, "C" is the intrusion distance.

$$S = K \times T + C \quad (2)$$

$$C = 8(d - 14) \quad (3)$$

This equation assumes that a human finger is able to intrude into the danger zone due to the interval of the laser beam of optical ESPEs, as shown in Figure 1. The standard specifies that the slope of the human hand is 8 and the tip of the finger is 14 mm.

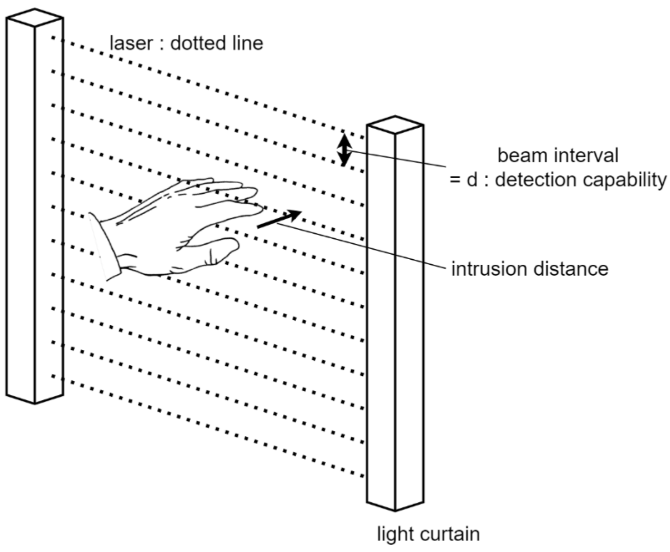

Figure 1. Intrusion distance and detection capability with orthogonal installation

When the parallel or orthogonal installation has a d over 40 mm, a value of at least 850 mm is applied as C. This situation assumes that a human arm intrudes into the danger zone as shown in Figure 2.

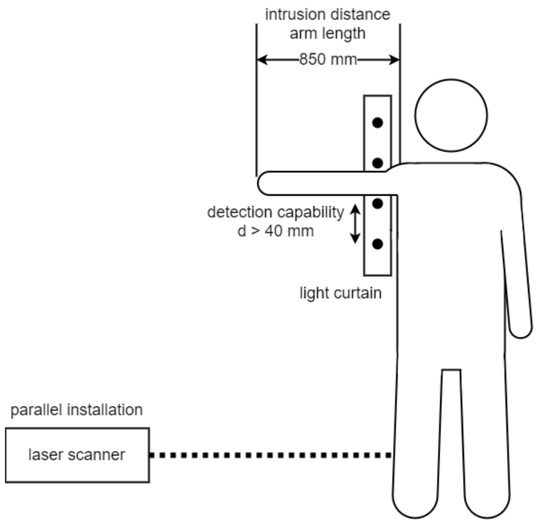

Figure 2. Situation requires consideration of a long intrusion distance.

3 Theoretical study

3.1 Designing the three-dimensional detection zone

This study investigates the radar ESPE within a typical series fed two patch antenna as an example. The antenna has a gain of approximately 9.0 dBi. Figure 3 illustrates the postulation at 60 GHz. In Figure 3a, the same antenna is used for both transmitting and receiving, resulting in equal gains (Gt = Gr = G). Figure 3b shows the half-beamwidth line (solid line), which represents the angle of radiation power larger than half of its maximum. The dashed line represents the specified line to ensure detection at an azimuth of ±45° in the half-beamwidth line. This study assumes a typical scenario for specifying the angle of detection within its half beamwidth. The elevation angle derived from the dashed line is ±16°. Therefore, the detection zone of radar ESPE can be specified with an azimuth of ±45° and an elevation of ±16°. The entire half-line area can be used to specify a wider detection zone, but the dimensions become more complex.

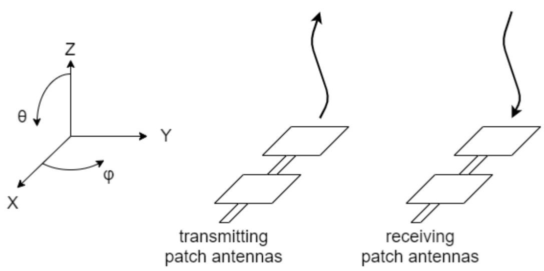

Figure 3a. Typical antenna system

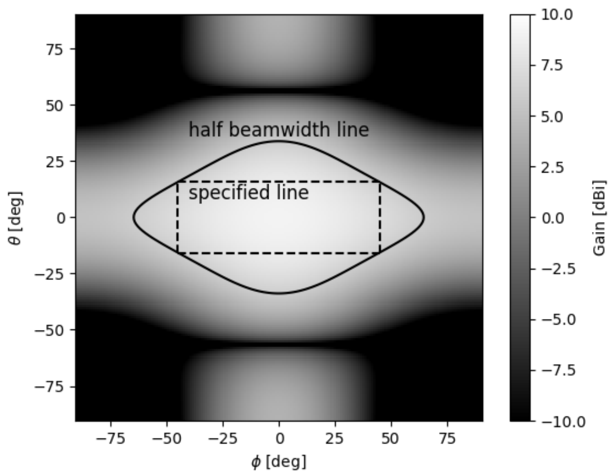

Figure 3b. Typical directivity of antenna

When the limited detectable Pr is -98 dBm, Pt is 4 dBm, σ is -35 dBsm, and G is 9.0 – 3.0 = 6.0 dBi, the wavelength λ is 5.0 mm, and the maximum detectable distance can be calculated by the dB scaled equation (1). These parameters assumed values that are technically and legally possible.

$$40 \log_{10} \mathrm{R} = 20 \log_{10} 5 \times 10^{-3} + 6 + 6 - 35 + 4 - 30 \log_{10} 4\pi - (-98)$$

$$\mathrm{R} \cong 1000 \; [\mathrm{mm}]$$

The value of σ is based on the size of a human fist [4]. Therefore, the radar ESPE can be designed to detect a human fist at a distance of 1000 mm, with a three-dimensional detection zone of azimuth ±45° and elevation ±16°, as shown in Figure 4.

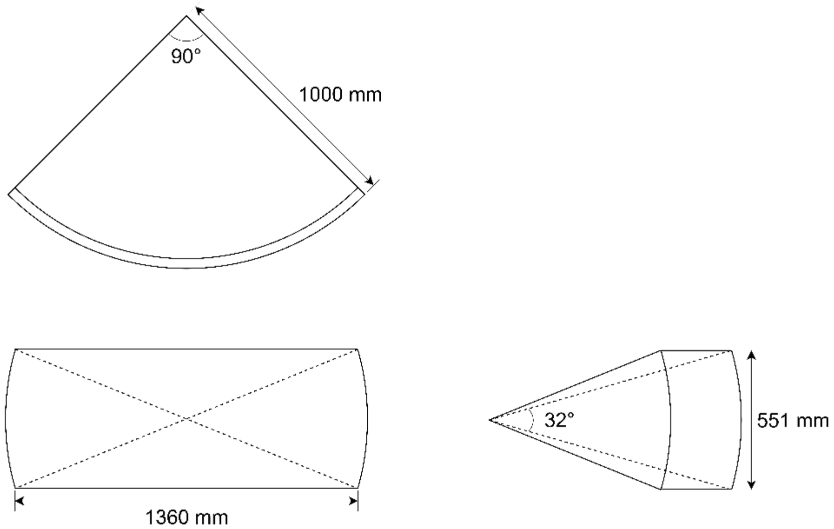

Figure 4. Dimensions of detection zone configured with range 1000 mm, azimuth ±45° and elevation ±16°

3.2 Study for installation and safety distance

As shown in Figure 5, a simple installation in front of an automation system. The installation can be configured with the largest orthogonal detection plane in the detection zone in parallel.

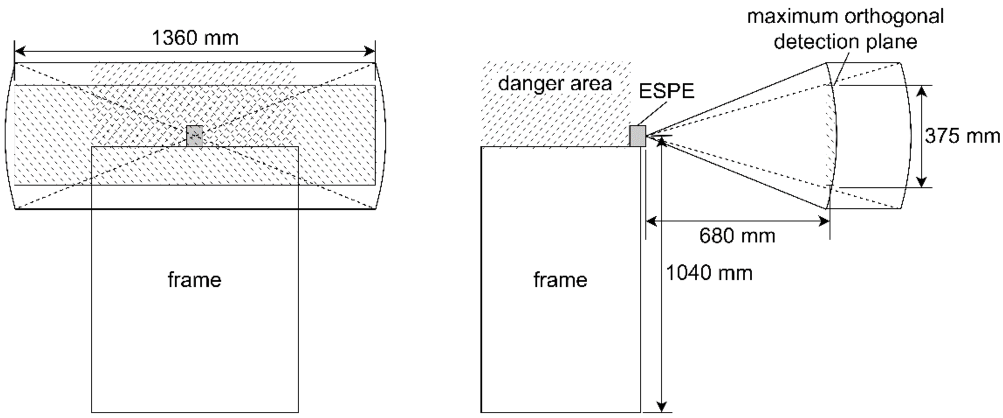

Figure 5. Parallel installation of ESPE

When the system stopping performance is 150 ms, the response time of the ESPE is 100 ms, and K can be applied at 1600 m/s as an example, the safety distance can be calculated by equation (2). However, the detection capability of the ESPE is not defined by the physical dimensions, but by the RCS. To mitigate the risk of finger intrusion, the d can be set to 40 mm in equation (3). This is based on the minimum target size of a human fist in this postulation. When the detection capability of the ESPE is -45 dBsm, the value of d can be set to 14 mm.

$$S = 1600 \times 0.25 + 208 = 608 \text{ [mm]}$$

This distance can be configured by the presented detection zone shown in Figure 5. This installation is considered as a light curtain with a height of 335 mm and a width of 1216 mm. When the same system is configured with a safety laser scanner, the safety distance is as follows.

$$S = 1600 \times 0.25 + 850 = 1250 \text{ [mm]}$$

In this case, the radar ESPE can shorten the safety distance with a value of 642 mm, as shown in Figure 6. Additionally, ISO 13857 specifies the additional safety distance considering the approach to avoid detection. The simple installation shown in Figure 5 allows approach avoidance to be considered in accordance with the standard.

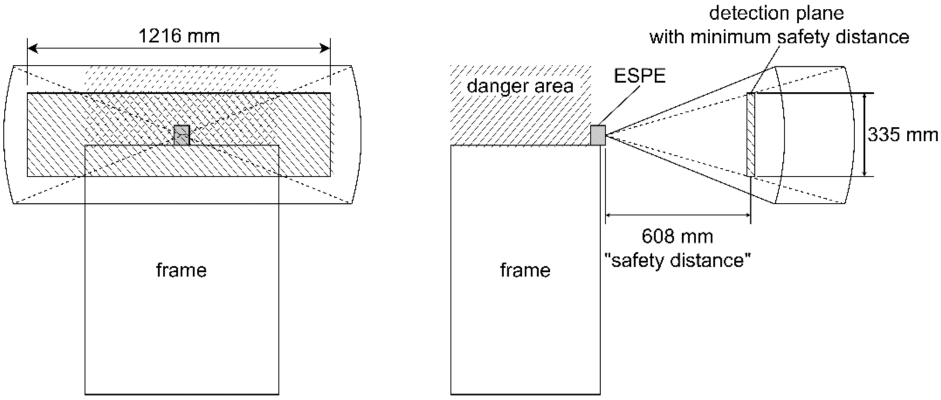

Figure 6a. Radar ESPE installation with minimum safety distance

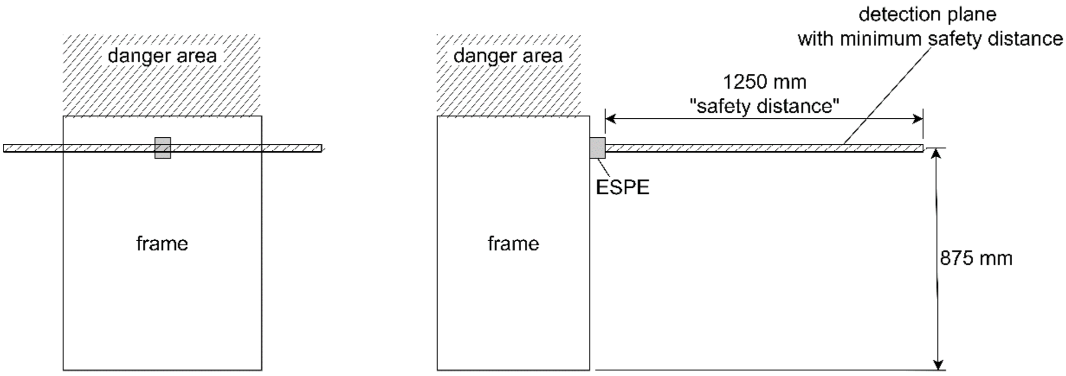

Figure 6b. Optical ESPE installation with minimum safety distance

4 Experiments

4.1 Verification of fabricated radar ESPE

The fabricated radar ESPEs were used to verify the detection capability. The detection zone was configured with a range of 900 m, an azimuth of ±45°, an elevation of ±15° and a maximum response time of 158 ms. For verification, the test was carried out in accordance with IEC TS 61496-5. The test target selected was a 20 mm diameter spherical reflector simulating an RCS of -35 dBsm. Figure 7 shows, as a representative of the verification, the mechanical slider with the test target moving into each point of the detection zone. The intrusion tests are conducted using 9 patterns in a 3x3 configuration. The test passed all 1,000 tests at each point.

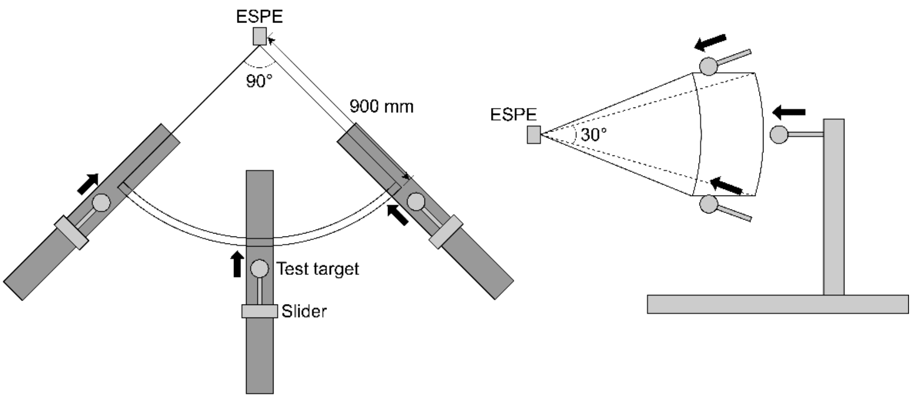

Figure 7. Representative of verification for the detection capability of the fabricated radar ESPE.

4.2 Demonstration of a robot installation

This study presents a practical installation of a collaborative robot. a table-mounted DOBOT CR3 collaborative robot. The CR3 was programmed to move left and right across the table without exceeding its edge. Therefore, the origin of the safety distance can be considered from the edge of the table. The maximum stopping time of the CR3 is 223 ms, which is used to calculate the safety distance.

$$S = 1600 \times (0.158 + 0.223) + 208 = 817.6 \text{ [mm]}$$

In this demonstration, the robot's stopping was successful, verifying the feasibility of this study.

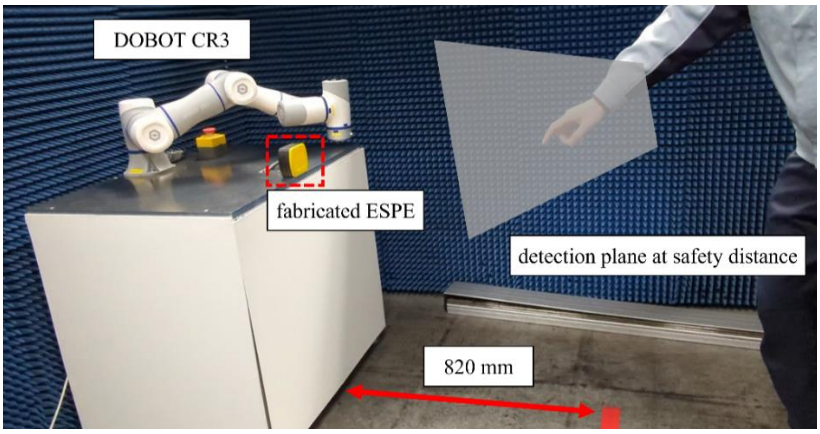

Figure 8. Demonstration of radar ESPE installation.

5 CONCLUSION

This paper presents a fundamental investigation of the radar ESPE. The study demonstrates that radar ESPE can be designed with a three-dimensional detection zone, capable of detecting targets as small as a human fist. Furthermore, the study indicates that radar ESPE, with its three-dimensional detection zone, can reduce the safety distance for small targets. To achieve this advantage, modifications to the standards for radar ESPEs are necessary. More specifically, ISO 13855 needs to consider radar ESPEs and IEC 61496-5 needs to consider the RCS of human body parts. The advantages of the radar ESPEs proposed in this study will become more apparent as technology develops and ESPEs with even larger detection zones and shorter response times emerge.

6 REFERENCES

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