# Radio Wave Sensor System Which Enables Determination of Protective Separation Distance

Kim E., Yamada Y., Okamoto S.

Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464 8601, Japan

kim.eugene@a.mbox.nagoya-u.ac.jp
yoji.yamada@mae.nagoya-u.ac.jp
okamoto-shogo@mech.nagoya-u.ac.jp

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## ABSTRACT

In the study, we propose a safety-related sensor system that enables human approaching motion detection in the three-dimensional space by using radio-frequency sensor system with a Frequency Modulation-Continuous Wave (FM-CW) method the components of which are widely used in automotive industry and nursing facilities. Not only the position of human and robot, but also their relative velocity is an important parameter for maintaining the Protective Separation Distance (PSD) in Speed and Separation Monitoring (SSM). Nonetheless, the uncertainty of velocity detection is not yet intensively discussed in the SSM. Therefore, we carried out an experiment to examine whether the uncertainties satisfy the safety integrity level of the position and the speed measurements required in the framework of IEC/DTS 62998. We demonstrate those by integrating the data from multiple radio wave sensors which could measure the position and the speed simultaneously.

## 1 INTRODUCTION

A safety function that maximizes the efficiency of manufacturing is demanding [1] for highly interactive collaborative robot systems. Especially, when an industrial robot possesses a highly hazardous tool which can easily harm the operator, non-contact based safety securing function shall be introduced to the workspace. In this study, we focus on the speed and separation monitoring (SSM) function listed in the ISO/TS 15066 standard and discuss a method for determining the measurement uncertainty that satisfies the safety integrity level [2]. With extant human detection technology, safety sensors which ensure the human safety and to increase productivity at the same time are still being expected for development. We use a radio wave sensor as a safety sensor [3] and evaluate its performance of human presence detection based upon the requirement that is stated in IEC/DTS 62998: we follow the procedure of determining the interval of the measurement uncertainty based on the measurement error including position and speed measurements. Specifically, the originality of this paper lies in the evaluation of speed measurement uncertainty.

## 2 SAFETY STANDARDS AND ITS TREND

In this section, safety requirements of the cooperative robot described in the International Safety Standard (ISO/IEC), especially the safety guidelines of safety related sensors are highlighted.

### 2.1 Protective Separation Distance

The protective separation distance (PSD) is a minimum tolerable distance between human and the robot which is a distance function involved in the SSM safety function [4]. According to the protective stop function of ISO 13855, operation or task generation of the robot that violates the PSD is not allowed [5]. Equation of PSD $S_p$ at time $t_0$ can expressed as follows.

$$S_p(t_0) = S_h + S_r + S_s + C + Z_d + Z_r \qquad (1)$$

where $S_h$ , $S_r$ and $S_s$ denotes distance that is expected for human to travel until the robot reacts and completely stops, for the robot to travel until it reacts to a human approach, and for the robot to travel from reaction until it stops completely, respectively. In addition, $C$, $Z_d$ and $Z_r$ represent an intrusion distance which is listed in the ISO 13855, an uncertainty for measuring the human position and determination of the robot position, respectively.

Here, letting the reaction time of the robot as $T_r$ and estimated stopping time as $T_s$, equation (1) can be rewritten as follows.

$$S_p(t_0) = v_h(t_0)(T_r + T_s) + v_r(t_0)\,T_r + B + C + Z_d + Z_r \quad (2)$$

where $v_h$ and $v_r$ represent the velocity of the human and the robot respectively which can be the function of time excluding the worst case where the $v_h$ is constant (=2.0 m/s) [5]. Here, $B$ is the distance that the robot travels during the robot issues to stop and stops completely, and it depends on the deceleration of the robot. The $B$ can be written as follows:

$$B = \int_{t_0+T_r}^{t_0+T_r+T_s} v_s(t)dt \quad (3)$$

where $v_s$ denotes the velocity of the robot when is in the state of braking along the $T_s$.

## 2.2 Measurement uncertainty and coverage interval

Human and robot collaborative system, especially the safety-related parts are required to meet the required safety integrity level PLr = d [6]. However, the measurement uncertainty which is the component of the protective separation distance has no strict rule on its determination and neither discussed in the ISO/TS 15066. In the latest IEC/DTS 62998 standard issued in 2018, an idea of coverage interval is suggested which allows quantitative evaluation of measurement uncertainty assuming that the measurement error follows Gaussian distribution [7]. Letting the probability of failure in hour as *PFH*, the coverage probability as $C_p$ can be written as follows:

$$C_p \leq 1 - \frac{PFH_u}{r^d} \quad (4)$$

where $r^d$ represents the demand rate of collaborative system. In the case of required safety integrity level is PLr = d, the upper limit of *PFH* is $10^{-6}$ and the suggested demand rate $r^d$ is around $4h^{-1}$. Therefore $C_p$ which satisfies corresponding safety integrity level is calculated as $1-2.5\times10^{-7}$. Finally, the coverage interval that includes such probability is $\pm 4.76\sigma$ which can be derived by statistical measurement error of the sensor system. The calculated width corresponds to acceptable error and measurement data which belongs to the beyond the border is treated as unacceptable error.

# 3 EVALUATION

## 3.1 Experiment Setup

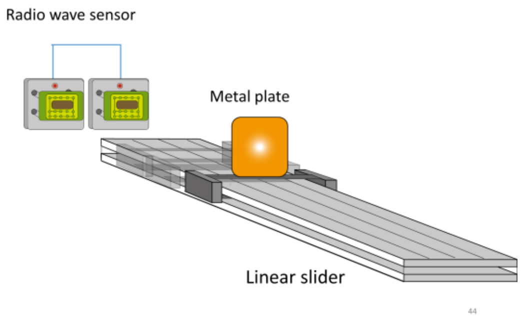


***Figure 2***. *Experiment setup using linear slider.*

Figure 2 shows the experiment setup using radio wave sensors and a linear slider. The target object was a metallic plate. Though we do not mention in detail about other materials also tested as target objects, we can tell that they exhibited similar characteristics in terms of motion (distance and speed) detectability. The linear slider was used to move the target object. The couple of wave sensors were allocated side by side, 5 mm apart from each other and placed as a sensor system facing the slider's moving direction. The motion data of the linear slider based upon the encoder values and the values directly measured by the two sensors and integrated as a system were compared to evaluate the sensor system. The sampling frequency of the radio wave sensors was 200

KHz. FFT analysis with 2048-point window size was used to obtain the modulation frequencies to compute the distance and velocity of the target object [8], [9].

## 3.2 Experiment Results

Figure 3 shows the histogram of measurement errors of distances between the optical encoder of the linear slider and the single radio wave sensors. The speed of the linear slider was set as 0.5 m/s and moved along the slider 0.2 m to 1.0 m from the radio wave sensors were placed. The whole experiment was conducted during 15 min.

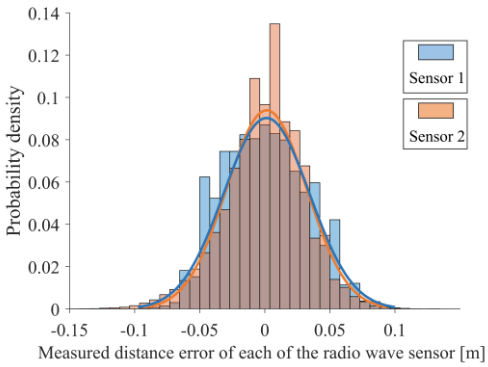


***Figure 3***. *Measurement error of distance between linear slider and single radio wave sensors*.

The standard deviations of the errors were 0.030 m and 0.032 m for each of the two radio wave sensors. In order to investigate the improvement of measurement performance when multiplexing the couple of sensors, the identical experiment was conducted using the radio wave sensor system. Figure 4 shows the histogram of the measurement error between the distance measured by the linear slider and that as the sensor system. Average was taken integrally from the values read from the two sensors The standard deviation of the measurement error was 0.025 m. Compared to the single radio wave sensor, the performance of distance measurement improved by 17.7% and 23.3%.

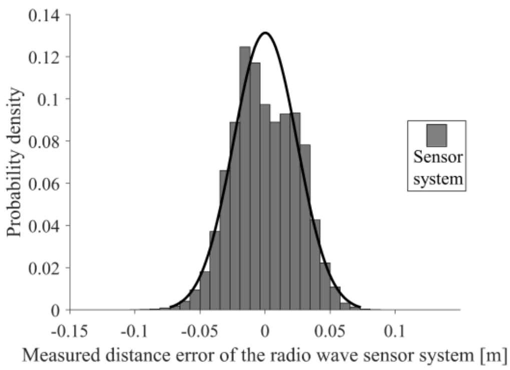


***Figure 4***. *Measurement error of distance between linear slider and radio wave sensor system*.

Next, the speed measurement error of the radio wave sensors was investigated. Figure 5 shows the histogram of speed measurement error of a single radio wave sensor when the linear slider was accelerated and decelerated at ±1.25 $m/s^2$ and maximum speed was 1 m/s.

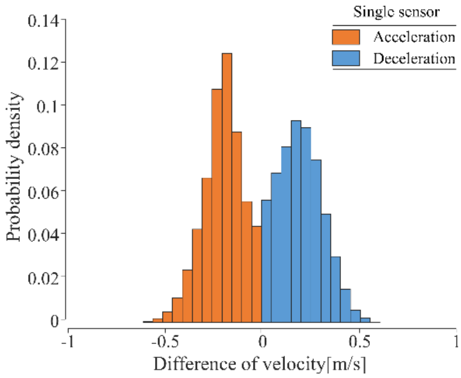


***Figure 5****. Measurement error of velocity between linear slider and radio wave sensor*.

The standard deviation of the velocity measurement error of the single radio wave sensor was 0.098 m/s and 0.110 m/s when accelerating and decelerating phases, respectively. The velocity measurement error was also investigated when the radio wave sensors were multiplexed to construct a radio wave sensor system. Figure 6 shows the histogram of velocity measurement error of the radio wave sensor system.

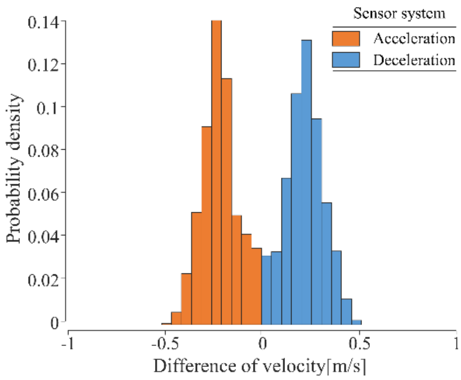


***Figure 6****. Measurement error of velocity between linear slider and radio wave sensor system*.

The standard deviation was 0.081 m/s and 0.083 m/s when the target object was accelerated and decelerated respectively. Therefore, the error produced as the radio wave sensor system decreased by 17% and 25% in the acceleration and deceleration respectively.

## 4 DISCUSSIONS

First, the integrally obtained values of both distance and speed well agreed with the statistics that the standard deviation of the average value is reduced by $\sigma^{-1/2}$. Secondly the measurement uncertainty of the relative speed is not being explicitly considered in the ISO/TS 15066 to formula (2). In the study, however, the uncertainty of the relative speed was measured based upon the actual experiment. The $Z_d$, which literally represents position uncertainty of the human, can also include another uncertainty term originating in speed measurement. We propose $Z_d$ comprising $Z_v = ( T_s + T_r )\times\Delta v_h$ which can be substituted with obtained uncertainty of the relative speed. Where Ts, Tr and $\Delta v_h$ are the stopping time, reaction time of the robot and uncertainty of the speed measurement. Therefore, it unnecessary to take the worst case $v_h$ in the calculation of the protective separation distance by which the shared workspace between human and the robot can be eventually saved by adopting expense of the additional $Z_v$.

## 5 CONCLUSIONS

In this study, we dealt with evaluation of radio wave sensors for the purpose of constructing a safety-related sensor system. Since ISO/TS 15066 does not specify determination of measurement uncertainty in speed and separation monitoring safety function, we adopted the concept of coverage interval specified in IEC/DTS 62998 that defines a level of confidence meeting safety integrity level. We exemplified this concept by using the measurement data of radio wave sensors. The uncertainty of distance measurement of single radio wave sensor which meeting PLr = d was 0.14 (4.76σ) m. In addition, the uncertainty of velocity measurement of single radio wave sensor was 0.46 m/s and 0.51 m/s at the accelerating and decelerating phases, respectively. By use of the two radio wave sensors at the same time, the uncertainty of distance measurement decreased by 0.11 m, and the uncertainty of velocity by 0.38 m/s and 0.39 m/s at the accelerating and decelerating phases, respectively. Therefore, by use of the Coverage Interval stated in the IEC/DTS 62998, measurement uncertainty of human position and speed can be quantitatively evaluated.

## ACKNOWLEDGMENT

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