

Improvement of Safety Integrity Level by Multiplexing Radio Wave Sensors

Eugene Kim¹ Yoji Yamada¹ and [REDACTED]

Abstract—Human presence sensing is essential to a human-robot collaborative operating system, and has attracted increasing research attention in the field of manufacturing. This study involves investigating the application of a high-speed response, light weight, and compact size radio wave sensor to detect human motion. Specifically, there is a paucity of studies on the usage of radio wave sensors for human detection in the field of machine safety. In this study, an experiment was performed by using a 24 GHz radio wave sensor to detect the location and speed of a moving sample object. The statistical error of the sensor was distinguished by using the variance of the measured values, and the concept of coverage interval was used in reliability evaluation of the sensor. The safety integrity level was improved by multiplexing the radio wave sensors to meet the requirements of IEC/TS 62998

I. INTRODUCTION

Following the advancement of building highly reliable controllers, occupational safety regulations were used in 2006 to allow workers to work collaboratively with robots during their operation [1], [2]. But still there have not been so many applications reported simply because it is far from easy to build highly efficient collaborative operation systems under current regulations of considerably low speed robot operation. As will be described later, human monitoring techniques are indispensable for realizing a collaborative operation system of high practicability. Due to such problems, there is a growing need for research on human-robot collaboration.

Our study focuses on the human position detection techniques for collaborative robot operation. It is required to comply with international standards to ensure worker's safety. Amongst the technical requirements to fulfill, human position shall be monitored with required integrity performance to maintain a separation distance between the robot and the worker. The integrity performance for electro-sensitive protective equipment(ESPE) shall comply with the relevant standard of IEC 61496 series(eq. [3]). Moreover, a careful consideration is necessary to check the interval coverage of the sensor system based on IEC/TS 62998 [4].

We focus on the application of radio wave sensors because they are promising enough to build high performance human monitoring systems with low cost through abundant achievements in the automotive industry. However the integrity performance of radio wave sensors was not investigated in the field of machine safety, where it is necessary to

fulfill stringent requirements. Furthermore, previous research studies only confirmed the principles of sensors and did not report on the evaluation of sensors based on performance requirements. In order to achieve the required safety integrity level by using 24 GHz radio wave sensors, it is necessary to investigate the performance of a distance measurement system and check if the system precision satisfies the requirements.

In this study, the application of a multiplexing sensor system to detect human presence was investigated. The goal was systematic and random error estimation of a target object location and proposing a method to reduce random errors. Speed detection is an important issue [5], and thus the possibilities of applications with respect to velocity are also investigated. The experimental results indicated that errors were reduced by using the new method.

II. SENSOR SYSTEM DESIGN

A. 24 GHz Radio Wave Sensor

A 24 GHz band is used for high precision moving object detection. The 24 GHz band is a common area used throughout the world for the purposes of intrusion detection. In previous studies, a 24 GHz radio wave was used to monitor pedestrians in the automotive industry [6], human gait analysis [7], and medical applications [8], [9]. Additionally, the 24 GHz radio wave sensor is light and small and can be installed without relying on the environment with respect to detection orientation and position.

B. Frequency Modulated Continuous Wave Method

The FM-CW (Frequency Modulated Continuous Wave) method is used to detect the distance and velocity of stationary and moving objects. Sawtooth modulation allows for the simultaneous measurement of distance and velocity, and thus the use of sawtooth modulation is selected. The working principle of FM-CW is shown in Fig. 1.

The transmitted wave sweep frequency is f_w and the sweep sample time is $t_w (= 1/f_w)$. When the transmitted wave travels a round trip distance between the sensor and the target object, the difference of frequencies can be expressed as

$$f_b(t) = f_r(t) - f_t(t) \quad (1)$$

where f_r denotes the frequency of the received wave and f_t denotes the frequency of the transmitted wave. In this condition, the Doppler effect f_d appears and affects the received wave.

*This work was supported by Knowledge Hub Aichi

¹All authors are with Department of Mechanical Systems Engineering, Nagoya University, Nagoya, 464-8603, Japan (kim.eugene@a.mbox.nagoya-u.ac.jp)

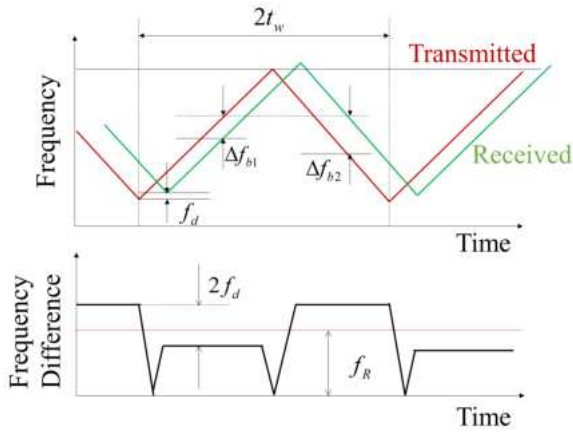


Fig. 1. Principle of FM-CW method

In order to obtain the distance $r(t)$ and velocity $v(t)$ of the object, it is desirable to use an average frequency, especially when the modulation changes [10], [11], as shown in (2) and (3). These equations are represented by using the frequency difference $f_b(t)$ between the transmitted and received waves. Here, $f_{b1}(t)$ and $f_{b2}(t)$ are, respectively, the frequency differences while the sweep frequency is ascending and descending.

$$r(t) = \frac{ct_w(f_{b1}(t) + f_{b2}(t))}{2f_w} \quad (2)$$

$$v(t) = \frac{f_{b1}(t) - f_{b2}(t)}{4} \lambda_c \quad (3)$$

In each process, the distance values obtained from each sensor is compared and the mean value of distance is used to express the final distance and velocity as follows:

$$\bar{r}(t) = \frac{ct_w}{2f_w} \sum^n \frac{(f_{b1}(t) + f_{b2}(t))}{n} \quad (4)$$

$$\bar{v}(t) = \sum^n \frac{(f_{b1}(t) - f_{b2}(t))}{4n} \lambda_c \quad (5)$$

C. IQ Data and Application to Velocity Measurement

IQ data is a method of data transmission that is generally used with a Fourier transform in radio wave sensors. Specifically, components I and Q are defined by

$$I(t) = \cos \{2\pi(f_r(t) - f_t(t))t + \phi\} \quad (6)$$

$$Q(t) = \sin \{2\pi(f_r(t) - f_t(t))t + \phi\}. \quad (7)$$

where the initial phase of the transmitted wave is represented as ϕ .

In order to measure the distance and velocity, the difference between the frequencies of the transmitted and received waves are calculated by applying the reverse tangent on the rate of (6) and (7),

$$f_b(t)t = -\frac{\tan^{-1}(\frac{I(t)}{Q(t)})}{2\pi}. \quad (8)$$

$f_b(t)$ is then given by differentiating this equation.

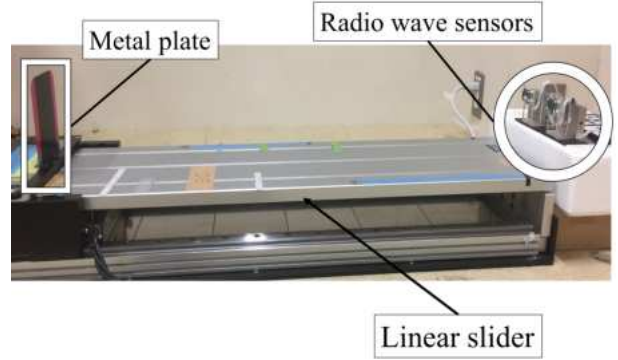


Fig. 2. Experimental setup for distance and velocity measurement

III. EVALUATION OF SENSING PERFORMANCE

There are several criteria, such as Performance Level (PL) [12] and Safety Integrity Level (SIL) [13], to indicate a relative level of risk-reduction which is provided by safety functions. However, the quantification of the safety level, especially including the random error of the sensors, has not been investigated. From a validation viewpoint, we statistically estimated the measured values of the sensor and proposed a method to apply values in the region of $\pm 3\sigma$ to indicate the cumulative region corresponding to 99.7%, and to evaluate it as a chance of error for outliers. Based on this, we calculated the statistical data that forms the basis of the judgment according to a request level such as PL and SIL.

Table I shows the correspondence of PL and SIL defined by probability of failure per hour (PFH). PL_r is the performance level required for the safety-related part. Additionally, the condition of $PL_r = d$ is applied when serious injuries by the machine malfunction are expected. For example, in case where the worker is exposed to high risk but can avoid the dangerous situation, or the worker is at the low or rare frequency and it is impossible to avoid the danger. As the performance of the safety sensor system that satisfies $PL_r = d$, at which a dangerous side failure occurs per 1 million to 10 million trials, is required. In a manufacturing field, under the circumstances of human-robot collaborative environment, satisfying practical standard of $PL_r = d$ is necessary to secure the safety.

A. Experiment Setup

Fig. 2 shows experimental condition using a linear slider and radio wave sensors¹. A simple metallic iron plate was used as the target object. A linear slider was used to move the target object, characteristic of low control inertia and positioning error. Conversely, the synchronization of the time axis of the sensor and linear slider was performed by synchronizing the read time of the radio wave sensor and

¹Because of contractual obligations, the manufacturer, and details of the calculating algorithm cannot be mentioned, to avoid the evaluation of this particular sensor.

TABLE I
CORRESPONDENCE OF PERFORMANCE LEVEL AND SAFETY INTEGRITY LEVEL

Probability of Failure per Hour (PFH)	Performance Class (PL)	Safety Integrity Level (SIL)	Probability of failure per hour (PFH)
$10^{-4} \leq \text{PFH} \leq 10^{-5}$	PL_a	-	-
$3 \times 10^{-6} \leq \text{PFH} \leq 10^{-5}$	PL_b	-	-
$10^{-6} \leq \text{PFH} \leq 3 \times 10^{-6}$	PL_c	SIL_1	$10^{-6} \leq \text{PFH} \leq 10^{-5}$
$10^{-7} \leq \text{PFH} \leq 10^{-6}$	PL_d	SIL_2	$10^{-7} \leq \text{PFH} \leq 10^{-6}$
$10^{-8} \leq \text{PFH} \leq 10^{-7}$	PL_e	SIL_3	$10^{-8} \leq \text{PFH} \leq 10^{-7}$
-	-	SIL_4	$10^{-9} \leq \text{PFH} \leq 10^{-8}$

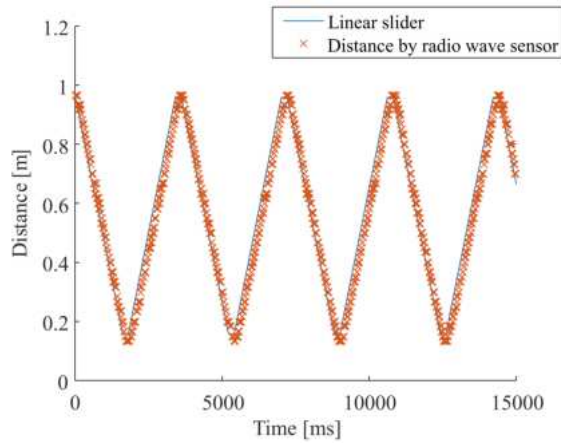


Fig. 3. Distance measured by using radio wave sensor

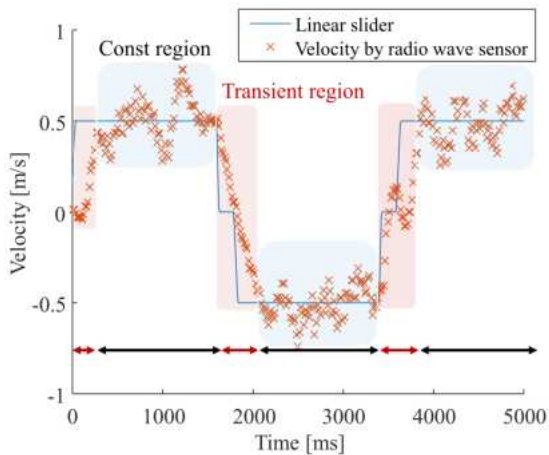


Fig. 4. Velocity measured by using radio wave sensor

operation stating of the linear slider using an electronic signal. Finally, the encoder value obtained from the linear slider and the distance obtained by the sensor were compared.

Fig. 3 shows a comparison of the obtained distances from the linear slider and radio wave sensor. For the frequency analysis, the FFT method was used to calculate distance and velocity. The sampling frequency was set as 200 kHz, and 2048 points of data were used in each process to calculate distance. The linear slider was controlled to move at a speed of 0.5 m/s, and repeat its movement for 15 min. The linear slider was set to move from 1.0 m to 0.2 m from the sensor.

Simultaneously, the velocity was obtained by using the

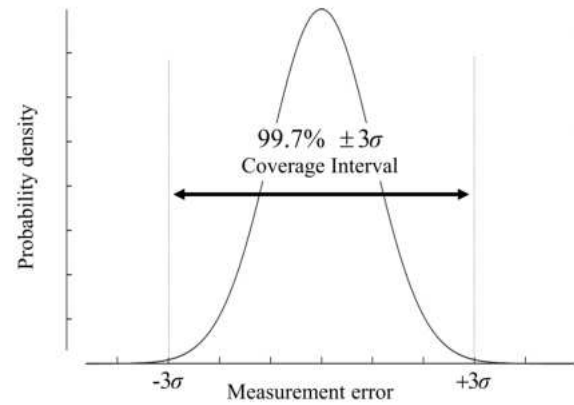


Fig. 5. Concept of coverage interval in IEC/TS 62998. Gaussian distribution of measurement error. The interval containing the set of values within $\pm 3\sigma$ is defined as the coverage interval.

Doppler effect. Fig. 4 shows the velocity obtained from the linear slider and radio wave sensor.

B. Measurement of Standard Deviation of Distance Error

First, variance of the distance error between the linear slider and the sensor was obtained to investigate the characteristics of a single sensor. Fig. 5 shows the concept of a coverage interval that is defined in IEC/TS 62998. The coverage interval is also defined as level of confidence according to ISO/IEC Guide 98-3 [14]. In other words, coverage interval implies idea of statistically normalizing and quantifying the error range of the sensor. For example, in the Gaussian distribution, the coverage interval corresponds to the region where 99.7% of the data is included. In contrast, data that is beyond the region of the coverage interval is defined as the outliers of the measurement. From the viewpoint based on this statistical interpretation, the coverage interval was used as a framework to enable the reliability evaluation from the measurement results of the sensor.

In the experiment, the coverage interval was experimentally obtained by comparing the difference in the distances measured by the linear slider and radio wave sensor. As a condition for ending the measurement, the variance of the value is measured until the variance is lower than the resolution of the sensor which is obtained by FFT variables. The calculated variance of the data is shown in Fig. 6. As a result, the variance measurement value converged to $\sigma =$

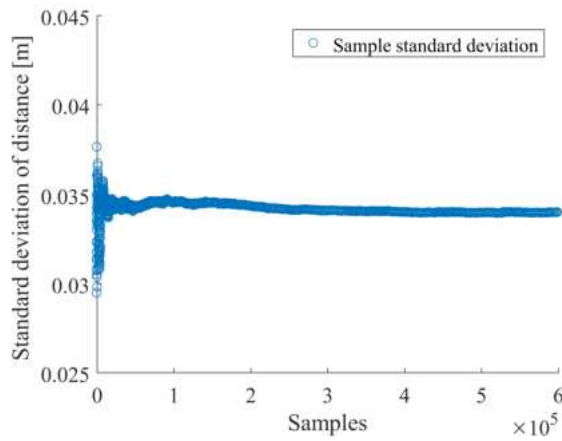


Fig. 6. Sample standard deviation of distance measured by a single sensor

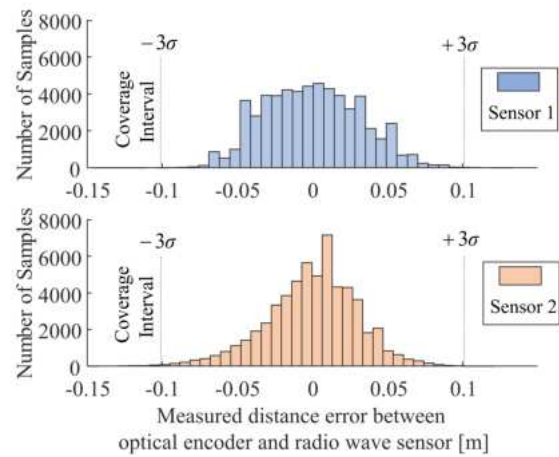


Fig. 8. Histogram of errors between the slider position and that of each sensors

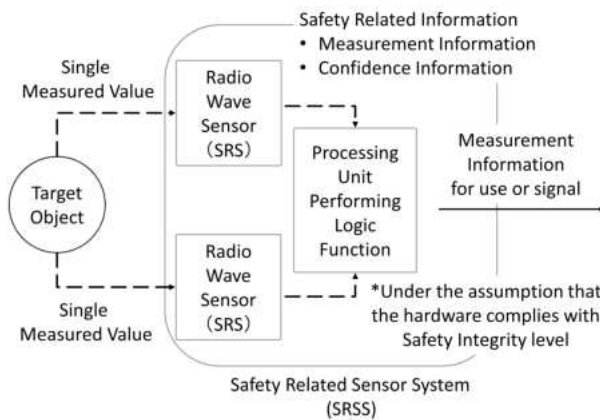


Fig. 7. Structure of sensor system when used for safety related sensors system

0.034 m.

C. Distance Measurement by Using Multiplexing Sensor System

In order to perform duplication of two sensors, synchronization was performed on the time axis by adjusting the reading start time of each sensor. Fig. 7 shows the structure of safety related sensor system (SRSS). SRSS implies more than one of the safety related sensors (SRS) are integrated in the system. When multiple SRS units measure the same target object, each of the single measured values is managed by a processing unit. The processing unit receives the data from each SRS and fuse them. Assuming that the hardware of each sensor complies with the safety integrity level, the whole system of the sensors including processing unit can be expressed as SRSS. The purpose of sensor fusion by use of one or more SRSS is to improve of the safety integrity level compared to a single SRS.

In the experiment by use of double sensors at the same time, it was observed that the variance value was reduced by using the mean value of the two sensors. Fig. 8 shows the histograms distance errors of the two sensors compared

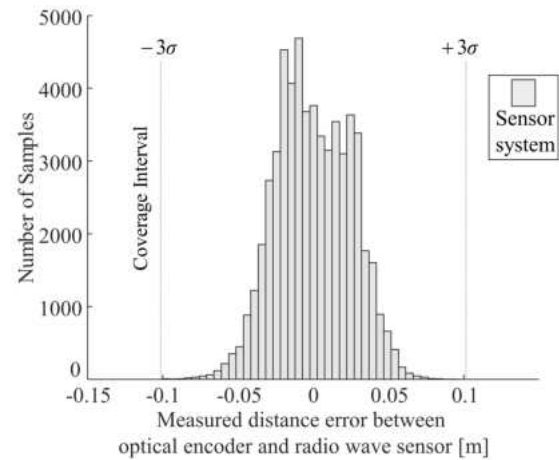


Fig. 9. Histogram of errors between the slider position and that of the multiplexed radio wave sensor

with linear slider each. Fig. 9 shows the histogram of error by comparing the duplicated sensor system and linear slider.

According to Fig. 6, the of standard deviation of a single sensor is 0.034 m. As a result, it can be specified up to ± 0.10 m that is six times the deviation value of the coverage interval. A random error of the sensor can be identified from the value of the coverage interval.

From the result of sensor1, 46 of 57673 data points were beyond the coverage interval. Furthermore, the result of sensor 2 indicates that 135 of 57680 data points were beyond the coverage interval. By taking the average of the values of each sensor at the same time, the results indicated that all data were successfully fit within the coverage interval as shown in Fig. 9.

D. Measurement of Standard Deviation of Velocity

Sample standard deviation of velocity is measured to evaluate velocity of object. Fig. 10 shows the measured sample standard deviation of velocity from a single sensor when the object was moving 0.5 m/s.

In Fig. 10, the calculated standard deviation was estimated

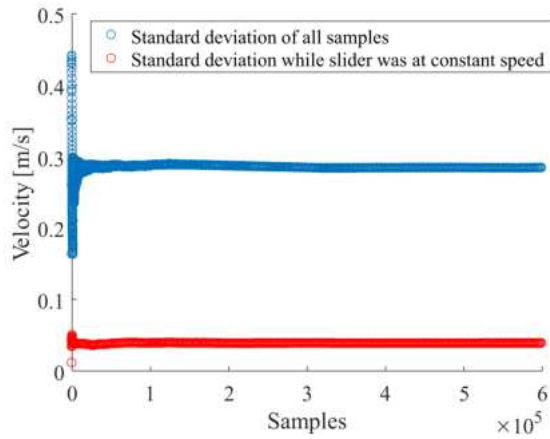


Fig. 10. Sample standard deviation of velocity measured by a single sensor

as 0.28 m/s. As a result, the coverage interval can be specified to a maximum of ± 0.85 m/s, which does not confirm to IEC/TS 62998. The delay in the response of speed is observed as the dominant reason for the high coverage interval. When measuring the distance, FFT which calculates the frequency difference between the transmitted and received waves at a specific time is used. However, as already shown in (3), the measurement of the speed is made by comparing the frequency difference between up sweep and down sweep. In other words, when compared with the distance, the delay occurs in the speed measurement because the measurement method is different. In addition, it was observed that the velocity is vulnerable with respect to the noise as compared with the measurement of the distance. In Fig. 4, the measured velocity was noisy even when the target objects moved at a constant speed, which is the result of insufficient filtering samples. For this reason, coverage interval considering response delay was investigated. From the Fig. 4, only the velocity obtained from constant region of the radio wave sensor and velocity of linear slider used in coverage interval estimation. As a result, the standard deviation is observed as 0.036 m/s by ignoring the transient region of speed and selecting data in constant region of speed. The transient region is observed as 0.2 m/s in average.

IV. RESULTS AND DISCUSSION

This study involved reporting the results of an experiment that was performed to compare the distance values obtained from a linear slider and a sensor. The variance value of a single sensor was used to create a frame that defines random errors by quantifying the sensor variations and covering 99.7% of the data. Results of the variance value for the distance of a single sensor shows that the coverage interval converges to ± 0.10 m.

Additionally, from the sensor safety viewpoint, a multiplexed sensor system was developed for error suppression in the distance measurement of the target object. In the data processing, the target object location was measured by arranging two sensors in the same direction and using the

mean value. The variation of the sensors data was measured as 0.030 m and 0.032 m. It was observed that the sensor system that uses the mean value exhibits a variation of 0.025 m.

The method was used to reduce the variance value of each sensor to 17.7% and 23.3%. Our proposed method was able to achieve a reduction in the variance value, which was the objective of this study. Additionally, the probability of failure that is defined in IEC/TS 62998 was computed to be and each of the sensor. While using the sensor system, the standard error of distance decreased and fit in the coverage interval. Furthermore, the proposed method provided a higher integrity level and satisfied the requirements based on IEC/TS 62998.

Conversely, given the same condition for distance measurement, the velocity of the moving object was measured and compared with the velocity of a linear slider. As a result, the coverage interval of the velocity measurement converged into ± 0.85 m/s, and this corresponds to an unacceptable value for the current speed condition of 0.5 m/s. Instead, coverage interval of considering only the constant value of speed is estimated as ± 0.12 m/s, which can be accepted for current speed condition.

However, the fundamental reason for unacceptable coverage interval of the whole velocity is that the waveform of the velocity is accompanied by sudden change. As long as the speed is controlled as a trapezoidal shape, the coverage interval depends on the response time, irrespective of how short the response time is.

V. CONCLUSIONS

In conclusion, the experiment indicated the possibility of enhancing the safety integrity level for distance measurement by using multiple sensors. Nevertheless, the proposed method involves certain limitations. For example, the movement of the object only exhibits linear motion, and the velocity obtained by the Doppler effect includes a delayed response time. Therefore effort of reducing response time in velocity measurement is critical point for further analysis of statistical evaluation. A future study will involve using the IQ data. It is desirable to simultaneously use both the Doppler effect and IQ data to explore the data diversity, to achieve a high response for the velocity detection. Furthermore, from the viewpoint of measuring speed, in contrast to the distance measurement, temporal and spatial restrictions exist with respect to maintaining the same speed. Therefore, a different type of evaluation for velocity such as a method which is suggested in this paper is required.

ACKNOWLEDGMENT

This research study was conducted through the “Knowledge Hub Aichi” project (Stage II).

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