Analysis of Ultrasonic Sensors Regarding Their Use in Safety Systems in Industrial Environments

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***Abstract*—This paper analyses if the security of human-machine interactions in an industrial environment can be improved by ultrasonic sensors. Therefore, the effect of different clothing fabrics on the measurement of ultrasonic sensors is analyzed. To prevent the safety system of false alarms due to random noise, a median filter is applied. In addition a conceptual approach how the ultrasonic sensors could be arranged is given. To avoid missing objects, which move through the range of the sensor, it is considered how the detection delay could be decreased.**

***Keywords*—Ultrasonic based measurement, Human detection, Safety sensing system, Distance measurement, Industrial environment.**

I. INTRODUCTION

Human-machine interactions are a growing part of industries and the manufacturing process. Thereby, safety of humans is always a top priority, especially when it comes to automatically moving parts. To avoid accidents, machines have to be turned off automatically in situations, where continued operation could pose a threat to human health. However, workers tend to ignore safety-precautions, which is why humans have to be recognized when entering potentially dangerous areas, to initiate precautionary measures for the workers safety. Lately, there has been a great emphasis on recognizing humans with camera systems. But not only is the use of cameras computationally expensive, it is also very difficult to prove their reliability to the extent required by human safety concerns. Another concern is that cameras and other optical sensors often fail under poor lighting conditions caused by e.g. dust during the production process, typical to industrial environments [1]. The goal is to analyze whether the aforementioned problems can be overcome, by using simple and low cost ultrasonic sensors.

II. STATE OF THE ART

Ultrasonic sensors are widely used in automated safety alert systems. They perform well for robots to detect obstacles, avoid collisions [2], [3] and in reverse collision warning systems for cars [4]. Guo et al. [5] propose the concept of a safety alert system to detect moving and stationary objects in the vicinity of agricultural machinery. Tracking and mapping autonomous vehicles is another use case of ultrasonic sensors [6]–[8].

Generally, ultrasonic sensors estimate the time-of-flight of an ultrasonic pulse generated by a transmitter and the echo produced by the nearest obstacle in its range [9], see Fig. 1.

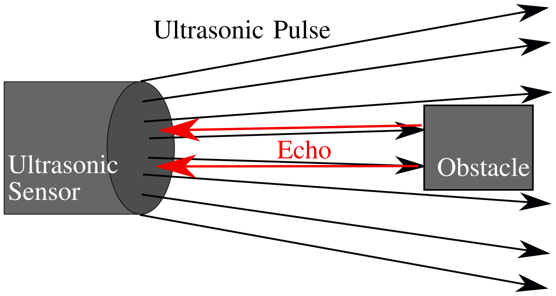

Fig. 1. Time-of-flight estimation.

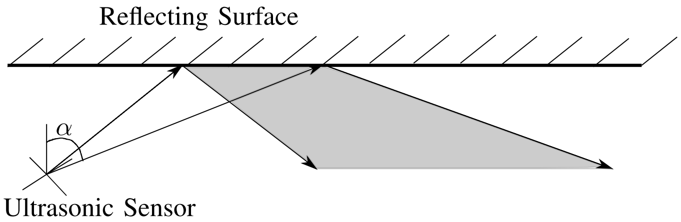

Fig. 2. Specular reflection.

One disadvantage of ultrasonic sensors is, that they often produce false readings due to specular reflections [10]. In Fig. 2, when the angle α is increased to a particular value, the ultrasonic sensor fails to receive the echo signal [11]. The criticial incidence angle may range from 7 or 8 degrees for glass to nearly 90 degrees for rough surfaces [12].

Gageik et al. [13] claim, that ultrasonic sensors lack on detecting soft targets like people wearing clothes, due to absorption. The acoustic properties of many solid materials are specified [14], but the characteristics of soft targets like cloth, skin etc. are barely identified. In his bachelor thesis [15] Rothe compares ultrasonic sensors with infrared sensors. In one experiment he describes measuring the distance to a moving person. Thereby, the infrared sensor is superior to the ultrasonic sensor. Unfortunately, no further details on the experiment are given, e.g. which cloth the person wears. Furthermore, the measurement is run on a moving person. Thus it is not precluded that the false readings are caused by the movement instead of the cloth. Therefore, the ability of ultrasonic sensors detecting soft targets has to be examined further. In another experiment he measures distances to objects in a smokey environment. There, in contrast to infrared sensors the ultrasonic sensor performs very well.

To determine the position of a mobile robot using ultrasonic sensors different Kalman filters are used in [9], [16]–[18]. In these papers, the sensors are mounted on the moving object which has to detect obstacles, avoid collisions or localize itself. Here, on the contrary, the use case is reversed. The sensors are mounted statically and measure the distance to moving objects. Irregularities have to be found in the movements. Therefore, it has to be examined what filters are useful in this particular situation.

As described above, ultrasonic sensors are already a useful enhancement for many applications. Nevertheless, they are still not well analyzed when it comes to their ability to reliably detect humans in safety critical industrial applications.

III. PROBLEM STATEMENT

The main goal is to decide if ultrasonic sensors can reliably detect humans in safety critical industrial environments and increase the safety of humans during human-machine interactions. To this end, the ability of ultrasonic sensor to detect humans as well as their reliability is analyzed. A special focus in this work is set on the following questions:

- How do different clothing fabrics affect the measurements of the ultrasonic sensors?
- Can different filters improve the performance by filtering outliers or other effects caused by noise or specular reflections?
- What are the limitations, due to the sensors properties, in detecting fast moving people?

Because of the impeded circumstances to specify the size of dust particles or the dust concentration in the air, the influence of dust on the measurement is not further investigated.

IV. METHODOLOGY

To determine if it is possible to detect humans with an ultrasonic sensor the characteristics of the used sensor is required. In an experiment it is analyzed how different fabrics affect the reliability of the measurements with the ultrasonic sensors. An appropriate filter to prevent a safety alert due to measurement noise is found. Because of the sampling rate of the sensors, a detection delay occurs. It is analyzed how this delay can be reduced, to avoid missing objects. Finally, a formula to determine the maximal speed at which objects can still be reliable detected is developed.

V. ANALYSIS OF ULTRASONIC SENSOR

An inexpensive and widely used ultrasonic sensor is the SRF05 sonar sensor. It is a 40 kHz ultrasonic transducer that acts as both, transmitter and receiver [19]. Two important characteristics of the sensor are mentioned bellow, since they are important for the further steps of the paper.

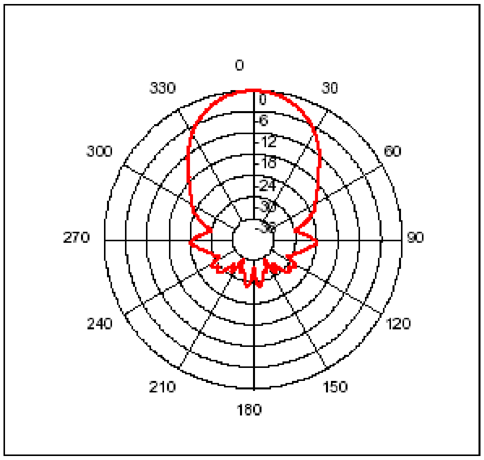

Fig. 3. Beam pattern SRF05 from [19].

A. Beam Pattern

The detection zone, called beam pattern of the SRF05 is shown in Fig. 3. The detection range of the sensor is from 1 cm to 400 cm. In contrast to e.g. laser emitters, the beam pattern of the ultrasonic sensor is not punctual. The advantage of the beam pattern, in contrast to laser emitters is, that a wider range can be tracked with one sensor. But that also means that no precise identification of humans as a special shape is possible. The sensors are more suitable for finding irregular movements or obstacles in its range instead of looking for humans in particular.

B. Trigger Frequency

To avoid wrong readings, due to previous echos, an ultrasonic sensor has to be triggered with a sufficiently low trigger frequency. That frequency can be determined in the data sheet of the SRF05 [19].

VI. EXPERIMENTS

To determine how cloth affects the measurement, the behaviour of different fabrics is tested with an experiment. Therefore, a cardboard box is placed in a room, such that no other objects are in the sensitive area of the sensor. The distance from a fixed reference point to the box is measured with a yardstick as reference and afterward with an ultrasonic sensor SRF05. The whole box is covered by one fabric after another and the distance is measured by the ultrasonic sensor. This experiment was repeated at distances between 10 cm to 400 cm. For each sample point measurement, a minimum of 50 measurements are carried out. Different fabric materials and different thicknesses of fabrics are used.

At a particular distance, depending on the different fabrics, the sensor does no longer identify the fabrics as object in its range, although the box was recognized at this particular distance. Probably because the ultrasonic signal is absorbed too much by the fabric. Fig. 4 shows the percentage of these out of range

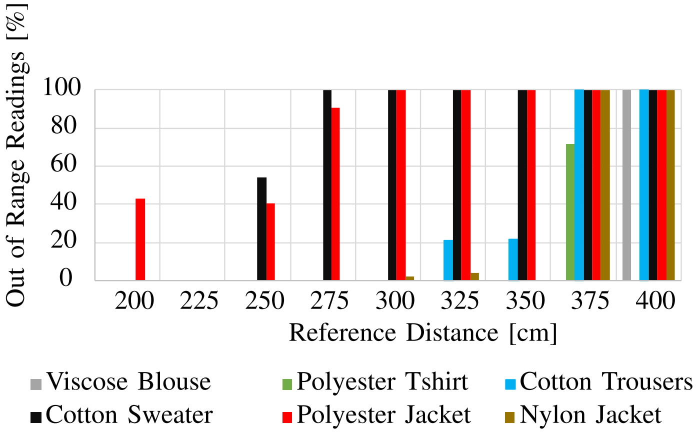

Fig. 4. Percentage amount of out of range reading by measuring the distance to different clothes with an ultrasonic sensor. There were no out of range readings before the distance of 200 cm.

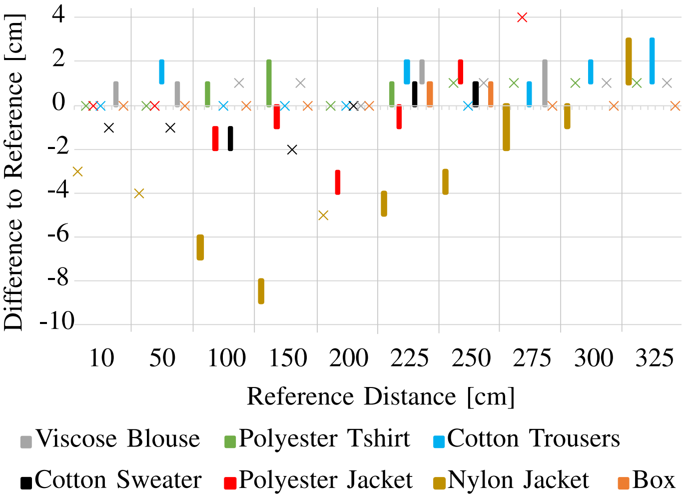

Fig. 5. The difference between the reference distance and the measured distance with the ultrasonic sensor to different clothes. A cross is used when all measurements returned the same value. The lines represent the range of distances measured in one reading. The distances higher than 325 cm are not shown, since only few types of cloth are recognized at this or higher distances.

readings out of all 50 readings of that fabric at the particular distance.

Fig. 5 shows the difference of the distances measured by the ultrasonic sensor to the fabrics and the reference distance to the box. The out of range readings are not considered in Fig. 5. Comparing the distances to the bare box measured by the reference and the ultrasonic sensor, the distances are mostly identical to each other. The box was not moved during the measurements at one sample point, to ensure, that the measurements at this point are not affected by a changed position of the box e.g. angle of the box. Since thicker clothes decrease the actual distance to the sensor by its thickness, the reference distance is higher as the actual distance. This results in the measured distance sometimes being smaller than the actual distance. The thickness of the clothes varied, due to e.g. tucks in the cloth and thus can not generally subtracted from the reference distance. Especially during the measurement of the nylon jacket, the yardstick showed up to 10 cm less than the position of the box due to the thickness of the cloth. Also the cotton sweater and the polyester jacket were thicker than 1 cm. On the contrary, the measured distances to the thinner clothes by the ultrasonic sensor was in most of the measurements higher than the reference distances. The measurements to the fabrics not listed in Fig. 5 showed the same behaviour.

Especially the difference of the nylon jacked to the reference distance is clearly increasing in Fig. 5 from 200 cm on. Probably due to the absorption of the ultrasonic signal, the signal gets with increasing distance even lover and so it looks further away than it actually is.

Both Fig. 5 and Fig. 4 show that the same fabric material, but with different thickness lead to different measurement results. But also fabrics with approximately the same thickness and different materials lead to different results as well. For example, the polyester jacket is almost as thick as the nylon jacket. Anyhow the nylon jacket is recognized longer than the polyester jacket. But the surface of the polyester jacket is much rougher than of the nylon jacket and probably due to that, the ultrasonic signal is more absorbed of the polyester jacket.

During the whole experiment, there was one outlier, which was significantly lower than the other measured distances. Probably the outlier occurred, due to random noise.

VII. DISCUSSION

A. Median Filter

Since outliers, such as that one observed during the experiment, would result in a false safety alert, a filter has to be applied. Mostly used in combination with ultrasonic sensors are the Kalman filter and its derivatives [9], [16], [17], [18]. The derivatives of the Kalman filter are mainly used for sensor fusion or time-of-flight estimation to localize robots at least with ultrasonic sensors. In general, Kalman filters and its derivatives have an extensive application area. But neither are slight fluctuations decisive in detecting humans nor is the localization of the detected human a matter of importance. More important is to get rid of rare random outliers. Thus a much simpler filter like a median filter can be used. As Moshnyaga et al. [20] describe, a median filter sorts the last measured $N = 2M+1$ distances and takes the median value as the output. By increasing the buffer size N, more bad readings are filtered out. But as trade-off, the time increases at which an object is detected. By measuring with one sensor, the detection delay t_{one} in the worst case is given by

$$t_{one} = \frac{1}{f_t} \cdot \lceil N/2 \rceil \tag{1}$$

where f_t is the trigger frequency of the sensor.

B. Arrangement of Ultrasonic Sensors

To secure a larger industrial area, the use of multiple sensors is necessary. Due to the beam pattern schematically shown in Fig. 6, the distance between the sensors to each other strongly depends on the distance of the sensors to the object that should be detected. The authors of [21] analyzed the beam pattern of SRF05 more precisely. Using their findings

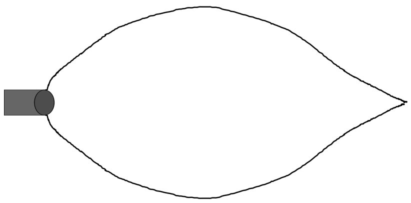

Fig. 6. Schema of beam pattern.

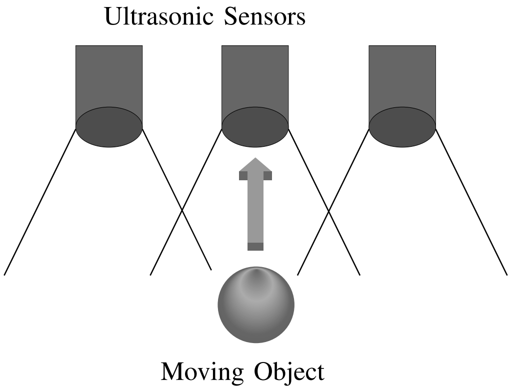

Fig. 7. Schema of moving object crossing sensors in a row.

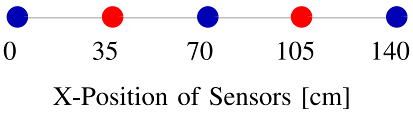

Fig. 8. Arrangement of sensors triggered in groups. Every dot represents the top view of one sensor. All sensors with the same colour can be triggered simultaneously and sensors with different colours can be triggered successively.

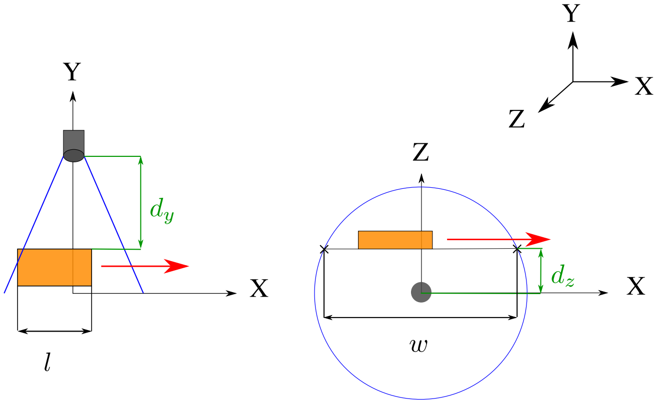

Fig. 9. Example of object moving through sensor range.

the individual distances between the sensors to each other can be determined. To avoid wrong readings, due to sensor interference, the ultrasonic sensors are triggered successively with a sufficiently low trigger frequency. As all sensors must be scanned and filtered first before an object detection algorithm can be applied, the detection rate decreases with an increased number of sensors. By measuring with multiple sensors, the detection delay $t_{multiple}$ in the worst case is given by

$$t_{multiple} = M \cdot \frac{1}{f_t} \cdot \lceil N/2 \rceil \tag{2}$$

where M is the amount of sensors.

C. Decreasing Detection Delay

To increase the speed at which an object is detected, groups of ultrasonic sensors can be triggered simultaneously. Referring to the maximal width of the beam pattern of the SRF05 [21], the simultaneously triggered sensors have to be at a distance of at least 45 cm to each other, to avoid direct sensor interference. Specular reflection could increase the distance of 45 cm. Occasionally occurring specular reflections could be filtered out. One example could be a setup as shown in Fig. 7, where several sensors are placed in a row. How sensors could be triggered to decrease the time at which an object is detected is shown in Fig. 8.

D. Missing Objects

Looking at a arrangement of sensors as shown in Fig. 7, the detection delay could lead to a miss of an object that moves at a certain speed. An approach of the maximal speed v_{max} up to which an object is reliably detected, can be calculated with

$$v_{max} = \frac{w + l}{G \cdot \frac{1}{f_t} \cdot \lceil N/2 \rceil} \tag{3}$$

where G is the amount of sensor groups that are triggered successively, w is the width of the range of the sensor that is crossed by the object and l is the length of the moving object.

As an example, Fig. 9 shows a schematic of an object (orange) moving through the range (outer edge marked blue) of an ultrasonic sensor (grey) in the direction of the red arrow. If the distance of the object to the sensor d_y (for example 140 cm) and the objects offset from the beams center d_z (for example 10 cm) are known, the distance the object has to cross through the beam w can be determined in [21] (here 70 cm) for the SRF05. With these values, the length of the object l (assumed as 15 cm), the trigger frequency (here 30.3 Hz can be determined as optimal in [21]) and equation 3, the maximal speed at which this object can be reliable detected can be calculated. Fig. 10 shows the maximum speed depending on the buffer size of the filter and the number of successively triggered sensor groups.

E. Out of Range Readings

The tests showed that although the fabrics were in the range of the sensor, all fabrics have a maximal distance from which on they are not detected anymore. The object covered in the fabric seems then to be invisible to the sensors. As mentioned in section VI the distances measured by the ultrasonic sensors tend to be longer than the actual distance. Both are assumed to be an effect of the absorbing characteristics of the fabric.

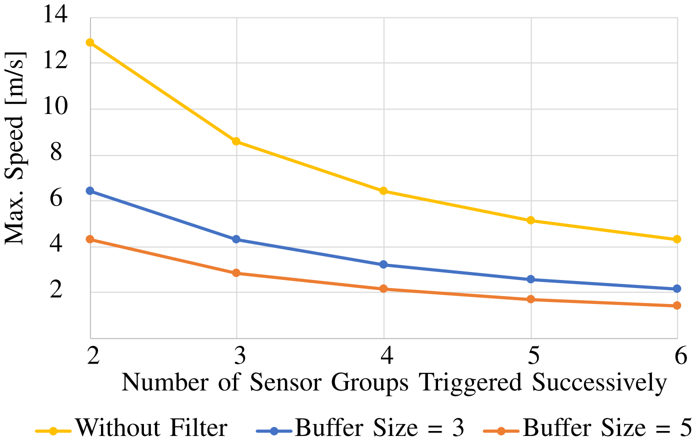

Fig. 10. Speed of objects up to which detection is reliable.

At the distance where the signal absorption is too high, out of range readings occur. This means, that measuring with the sensor without a fixed background in the sensor range, the fabric would not be detected from these particular distances on, since there is no way to distinguish between the fabric and a free space. On the other hand, when measuring against a fixed background in the range of the sensor, out of range readings due to fabrics can be distinguished from the normal maximal distance to the fixed background. However, a further experiment showed, that for this case almost the complete area of the circle of the beam pattern of the sensor has to be covered with the fabric at an absorbing distance. That is why this case is not useful, since it is not guaranteed that the whole area of the circle of the beam pattern is covered by the human, who should be detected.

VIII. CONCLUSION

An experiment has been performed to determine the affect of cloth on ultrasonic measurements. The cloth, that affects the measurement most, is reliably detected up to a distance of 2 m. This limits the application of ultrasonic sensors in an industrial environment to settings where the sensor only has to identify humans from a distance smaller than 2 m. Exceptions are cases, where out of range readings due to big enough fabric surface can be distinguished from a maximal distance reading, occurring during normal operations by e.g. a fixed background. Besides the out of range readings, the difference of the measured distances to the fabric with the ultrasonic sensor and the reference distance are never more than few centimeters. Thus, it can be concluded that cloth does not hinder the detection of humans. But at least at the distances, where humans get ”invisible” to the ultrasonic sensor, the safety is not longer ensured. To prevent false alarms, a median filter can be applied. Despite the detection delay, the system can be fast enough to detect trespassers, if sensors are triggered in groups. To sum up, the safety of human-machine interactions in an industrial environment can be improved using ultrasonic sensors to detect workers. However, further investigations have to be conducted, especially in relation to dust and the movement of humans.

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