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H-R DATA VISUALIZATION OF THE DISTANCE TO THE OBJECT IN THE COLLABORATIVE ROBOT WORKSPACE BASED ON HC-SR04 SENSOR

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Abstract

The article considers the use of HC-SR04 sensors for measuring the distance to an object in a collaborative robot workspace. Special attention is paid to the visualization of the received data, which allows for effective analysis of information about the robot's environment. The experimental results show that the HC-SR04 can provide satisfactory measurement accuracy, which is important for the safety and optimization of robotic systems. The use of data visualization helps to improve interaction with the environment and increases the tasks efficiency.

Key words: HC-SR04, Collaborative Robot, Data Visualization, Distance Measurement, Robotics, Interaction Environment, Industry 5.0

Introduction

The rapid development of robotics has led to the emergence of the concept of Industry 5.0, which involves the use of joint work of robots and humans. This has created new advantages, as well as difficulties in work [1]-[16].

The relevance of the study of H-R (Human-Robot) systems for visualizing data of the distance to the object in a collaborative robot workspace based on HC-SR04 ultrasonic sensors is due to the growing integration of robotic solutions into production processes within the framework of the Industry 5.0 concept. This concept envisages harmonious cooperation between humans and robots, focused on safe, effective and personalized interaction, which is especially important in conditions of high requirements for accuracy and efficiency [17]-[19].

The use of ultrasonic sensors for distance monitoring allows you to receive information about the position of objects in real time, providing a warning about the approach of the robot to a person or other objects, which increases the level of safety in the work area. Visualization of this data in real time enables the operator to quickly assess the situation and make the necessary decisions, minimizing the risks of collisions [20]-[22]. Various methods and approaches can be used here [23]-[40]. Therefore, the study of such visualization contributes to the development of adaptive technologies and increasing the efficiency of human-robot cooperation, which corresponds to the main principles of Industry 5.0 regarding humanity and an individualized approach in automated systems.

Related works

The use of collaborative robots allows one to obtain the advantages of both a robot and a human working simultaneously. However, this increases the safety requirements for human work. Therefore, it is necessary to provide the robot with the ability to determine the distance to objects, including humans. Many scientific papers are devoted to solving this problem. Let us consider some of these papers.

Let us begin with the work [41]. Leichtmann, B., & Nitsch, V. Give an overview of the literature on interpersonal distances focusing on human-robot interaction. Findings on the most prominent factors are summarized and discussed with respect to findings from distancing in human-human interaction and theoretical considerations.

Group of authors in [42] present an approach for safe, and object-independent human-to-robot handovers using real time robotic vision, and manipulation. Putting a high emphasis on safety, they use two perception modules: human body part segmentation, and hand/finger segmentation.

The article [43] note that generalist robot must be able to complete a variety of tasks in its environment. One appealing way to specify each task is in terms of a goal observation. Learned dynamics models are a promising approach for learning about the environment without rewards or task-directed data, but planning to reach goals with such a model requires a notion of functional similarity between observations and goal states.

Scientists in [44] focus on human-centered robotics. They propose a categorization to organize the use cases of proximity sensors in human-centered robotics. They present the sensing technologies and different measuring principles that have been developed over the years.

The paper [45] presents iSDF, a continual learning system for real-time signed distance field (SDF) reconstruction. Given a stream of posed depth images from a moving camera, it trains a randomly initialized neural network to map input 3D coordinate to approximate signed distance.

So, we see that determining the distance to objects is a multifaceted task that is solved in order to solve more serious problems. Further in this article we will present our methods for solving problems of determining the distance to an object.

Distance to the object data representation mathematical model

The mathematical model for representing distance data to an object in a collaborative robot workspace based on HC-SR04 ultrasonic sensors is based on the principles of displaying and receiving an ultrasonic signal, and also takes into account factors affecting the accuracy of measurements. The HC-SR04 sensor measures the distance by calculating the time the sound wave travels from the transmitter to the object and back to the receiver. The general viewof the HC-SR04 sensor is presented in Figure 1, and its technical characteristics are presented in Table 1.

Figure 1: General view of the HC-SR04 sensor

Table 1: Technical characteristics of the HC-SR04 sensor

Characteristic	Value
Supply voltage	5 B
Current consumption	15 mA
Operating frequency	40 kHz
Measuring range	2 cm - 400 cm
Measurement accuracy	± 3 mm
Trigger pulse width	10 µs
Viewing angle	about 15°
Working temperature	-15°C … +70°C
Output	Digital pulse duration proportional to distance
Reaction time	less than 15 ms
Dimensions	45 mm × 20 mm × 15 mm

As can be seen from Table 1, the characteristics make the HC-SR04 effective for various applications in robotics and short-range object detection systems, including obstacle tracking and real-time object distance measurement.

We maintain the following parameters:

- measured time t, which reflects the interval between signal transmission and reception. Its accuracy is limited by sensor resolution and signal stability;

- speed of sound υ, which varies depending on temperature, humidity and air pressure. To increase accuracy in conditions of variable temperature, correction according to the formula $\upsilon(T)$ reduces errors;

- distance d as the distance value. The larger the value of t, the greater the potential measurement error, as the accuracy is limited by the maximum measured time and speed of sound.

The basic equation for calculating the distance (d) to an object

$$d = \frac{\upsilon \cdot t}{2} \tag{1}$$

d - distance to the object in meters;

υ - speed of sound in air (approximately 343 m/s at a temperature of 20°C);

t - the signal transit time from the sensor to the object and back, measured in seconds.

Division by 2 is carried out because t includes the time for the signal to reflect back to the sensor.

Calculation of measurement error (Δd) depends on a number of factors, including temperature stability, accuracy of time t measurement, and limitations of the sensor itself. Mathematically, the error can be estimated as:

$$\Delta d = d \cdot \Delta\upsilon + \frac{\upsilon \cdot \Delta t}{2} \tag{2}$$

Δd - total error in distance measurement;

$\Delta\upsilon$ - sound speed error, which can change with temperature and pressure;

Δt - error in time t measurement, which can be caused by processing delays or sensor resolution limitations.

Since the speed of sound depends on temperature, its value can be refined to improve accuracy. Taking into account the temperature T (°C), the speed of ultrasound $\upsilon(T)$ is calculated as:

$$\upsilon(T) = 331.4 + 0.6 \cdot T \tag{3}$$

Thus, for each sensor measurement in real environmental conditions, the speed of sound can be adjusted to increase the accuracy of the result.

The final result is presented as the distance to the object, taking into account the error:

$$d_{real} = d - \Delta d \tag{4}$$

d_{real} - the real distance to the object, taking into account the error.

This model makes it possible to obtain an estimate of the distance to an object in a collaborative robot workspace, taking into account the main factors affecting accuracy. Taking into account variables such as temperature, as well as the internal errors of the measurement system, allows for higher accuracy, which is especially important in collaborative systems where safety is a priority.

To test the proposed mathematical models and expressions for calculating the distance to the object in a collaborative robot workspace, a layout was developed, the general view of which is presented in Figure 2.

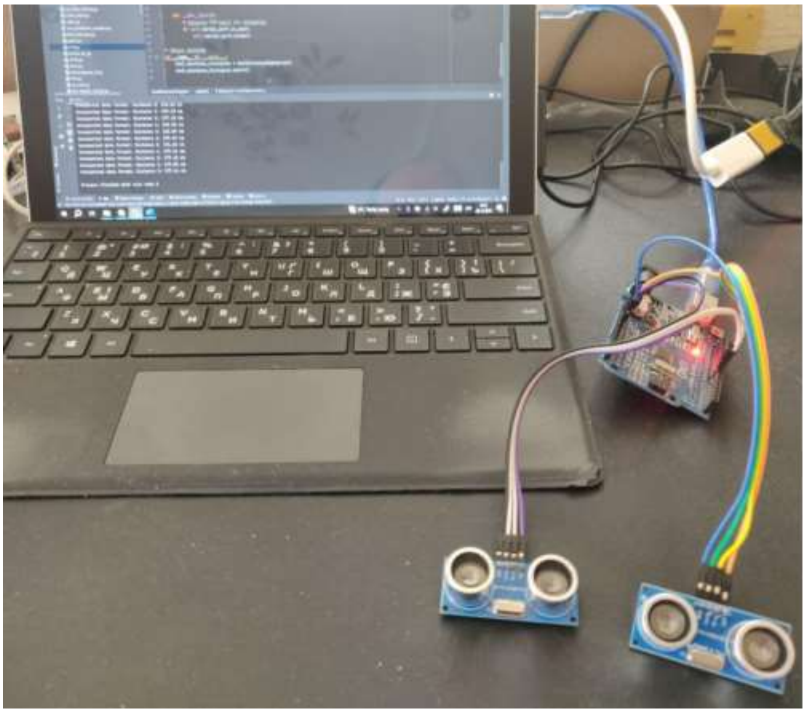

Figure 2: General view of the layout for calculating the distance to the object in a collaborative robot workspace

Development of a program for testing the calculation of the distance to an object in the a collaborative robot workspace

The choice of the Python programming language for the implementation of the H-R (Human-Robot) program for visualizing object distance data in a collaborative robot workspace is justified due to its high performance in the field of scientific and technical application development, as well as convenience in working with real-time data processing . Python has a rich set of libraries for interacting with hardware, such as pySerial, which allows you to efficiently receive data from the HC-SR04 ultrasonic sensors via the serial port. The PyQt5 library provides flexibility and power for the development of a graphical interface, which is important for visualizing information and ensuring convenient interaction of the operator with the system. PyQt5 also supports cross-platform compatibility, which allows you to use the developed solution on different operating systems without significant changes in the code. The pyqtgraph.Qt library is distinguished by the speed of displaying graphs and the ability to process data in real time, which is critical for timely visualization of the distance to objects and assessment of potential threats in the work area. Pyqtgraph has an intuitive interface for creating graphs and allows you to dynamically update them, which increases the efficiency and accuracy of situation assessment. Together, the combination of Python, PyQt5 and pyqtgraph.Qt provides a convenient, powerful and fast tool for implementing a visualization system based on ultrasonic sensors, which makes it the optimal choice for such tasks. We will describe a number of the most interesting functions of the implementations of the developed H-R (Human-Robot) program for visualization of distance data to the object in a collaborative robot workspace.

```
def __init__(self):
  # Initialize the connection to the COM port
   self.serial_port = serial.Serial('COM3', 9600, timeout=1)
```

This piece of code is responsible for initializing the connection to the serial port, which is critical for receiving data from the HC-SR04 ultrasonic sensors. Specifying the port 'COM3' and the data transfer rate of 9600 bps, the program establishes a connection with the hardware device, which allows reading the measured values of the distance to the object. The argument timeout=1 sets the maximum time to wait for receiving data, which prevents the program from hanging in the absence of a signal. Thanks to this initialization, the program can correctly interact with the sensors and provide visualization of the received data in real time.

```
# Histogram for the first sensor
      self.plot1 = self.win.addPlot(title="Sensor 1: Distance (Green) and Error (Red)")
      self.plot1.setYRange(0, 300)  # Діапазон значень по осі Y
      self.plot1.setLabel('left', 'Distance', units='cm')  # Назва осі Y
      self.plot1.setLabel('bottom', 'Sensor 1', units='')  # Назва осі X
      self.distance_bar1 = pg.BarGraphItem(x=[0], height=[0], width=0.6, brush='g')  # Гістограма відстані
```

```
        self.error_bar1 = pg.BarGraphItem(x=[1], height=[0], width=0.6, brush='r')
# Error histogram
        self.plot1.addItem(self.distance_bar1)
        self.plot1.addItem(self.error_bar1)
```

This piece of code is responsible for creating a histogram to visualize the distance and measurement error data from the first ultrasonic sensor. It customizes the graph by specifying a range of values for the Y axis, as well as names for the X and Y axes, which help the user understand what data is being displayed. Next, two histogram columns are created: one for distance, shown in green, and one for error, which is shown in red. By adding these elements to the graph, the program provides clarity and ease of understanding of the received data, which is important for analyzing the operation of the sensor.

```
    # We calculate the error as a percentage of the distance
            error1 = distance1 * 0.05  # 5% error for the first sensor
            error2 = distance2 * 0.05  # 5% error for the second sensor
            return distance1, error1, distance2, error2
```

This code snippet calculates the distance measurement error for two ultrasonic sensors using a specified percentage (5%) of the measured distance. Determining the error is important for assessing the accuracy of the data, as it helps identify possible inaccuracies in the measurements. The result of the execution of this code is the return of distance values and corresponding errors for both sensors, which provides further analysis and visualization of the obtained data. Thus, this fragment contributes to the creation of more accurate and reliable graphs for displaying data in the program.

```
    def update(self):
        # Distance and error readings for each sensor
        distance1, error1, distance2, error2 = self.read_data()
        if distance1 is not None and error1 is not None and distance2 is not None
and error2 is not None:
            # Update the histogram for the first sensor
            self.distance_bar1.setOpts(height=[distance1])  # Green bar for distance
            self.error_bar1.setOpts(height=[error1])        # Red bar for error
```

This piece of code is responsible for updating data in the graphical interface of the program in real time. The update method reads the distance and error values for each sensor, which ensures that the displayed data is up to date. If the received data is correct, it updates the height of the histogram bars: a green bar representing the measured distance and a red bar representing the measurement error. Thanks to this update, the user has the ability to observe changes in measurements in real time, which is critical for monitoring and analyzing sensor performance.

An example of graphic implementations of H-R (Human-Robot) visualization of distance data to an object in a collaborative robot workspace is presented in Figure 3.

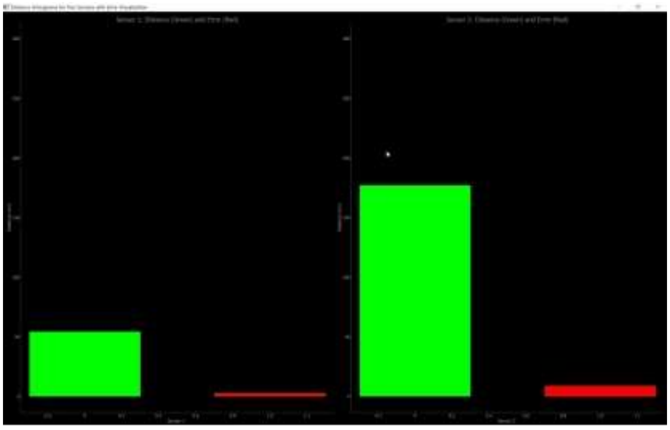

Figure 3: An example of graphic implementation of H-R (Human-Robot) data visualization of the distance to the object with error calculation

Let us conduct a number of experiments to evaluate the developed software for graphic implementation of H-R (Human-Robot) data visualization of the distance to the object with error calculation.

The first experiment of measuring the distance to a stationary object. Place the object at different distances (eg 10 cm, 50 cm, 100 cm, 200 cm) from the sensors and record the values that are measured. Compare the results obtained with the actual distances to determine the average measurement error. The results of the experiment are shown in Table 2, and the combined graph is shown in Figure 4.

Table 2: Results of the first experiment.

Actual Distance (cm)	Measured Distance (cm)	Error (cm)
10	10.5	0.5
50	48.0	-2.0
100	98.0	-2.0
200	205.0	5.0

The average measurement error is 0.375 cm.

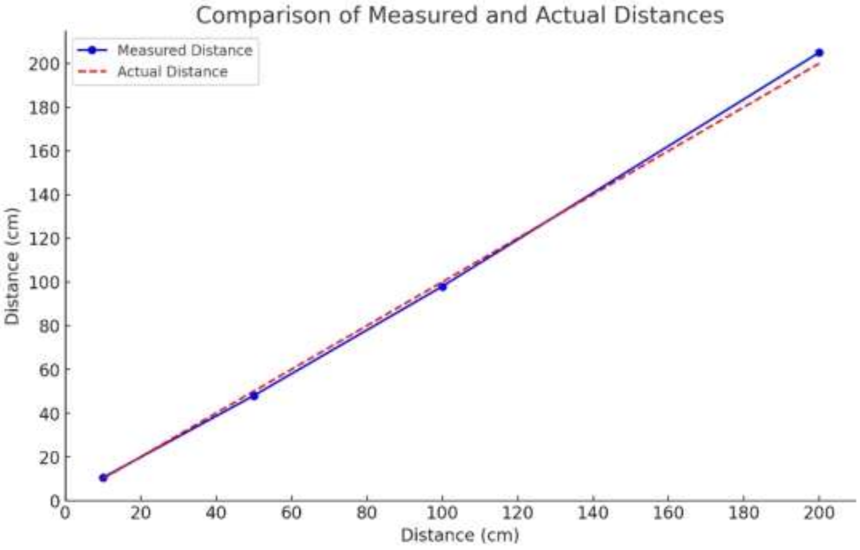

Figure 4: Combined graph comparing measured and actual distances. In the graph, the blue line represents the measured distances and the red dashed line represents the actual distances

The obtained data show that the measured distances are generally close to the actual ones, although minor errors are observed. The largest error was found at a distance of 200 cm, where the measurement exceeded the actual value by 5 cm, while for smaller distances the error remained within ±2 cm. The average measurement error is only 0.375 cm, which indicates the high accuracy of the HC-SR04 ultrasonic sensors at short and medium distances, but with a tendency for the error to increase at long distances.

The second experiment is to use alternative measurement methods (eg laser rangefinders) to compare with the data obtained from the HC-SR04. This will determine the relative accuracy of the sensors. The data obtained during the experiment are shown in Table 3, and Figure 5 shows a combined comparison graph.

Table 3: Results of the second experiment

Measurement No.	Distance (m)	HC-SR04 Reading (m)	Laser Rangefinder Reading (m)
1	1	1.02	1.00
2	2	2.05	2.00
3	3	3.08	3.00
4	4	4.15	4.00
5	5	5.20	5.00

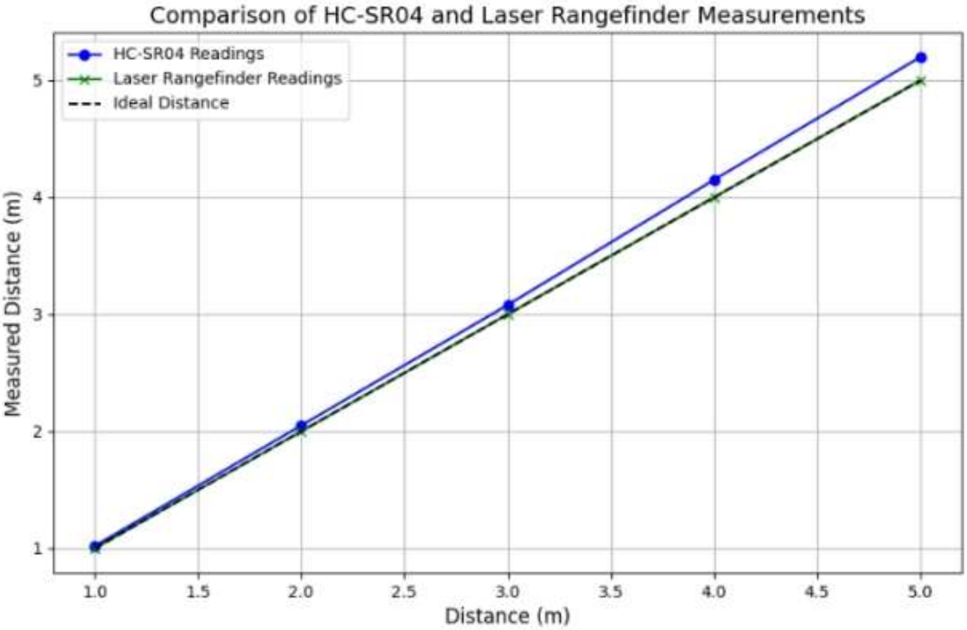

Figure 5: Comparison chart of HC-SR04 and Laser Rangefinder Reading accuracy

According to Table 3, the laser rangefinder shows higher measurement accuracy compared to the HC-SR04 ultrasonic sensor. Laser sensor measurements are more stable and closer to theoretical values at all tested distances. The HC-SR04, on the other hand, is slightly overestimated, especially at longer distances, which may be due to its limitations in scattering ultrasonic waves and sensitivity to changing environmental conditions. This indicates that for tasks where accuracy over long distances is critical, a laser rangefinder will be the better choice. An ultrasonic sensor, despite a certain error, can remain effective for tasks of an average level of accuracy at short and medium distances, where minor deviations are acceptable.

Conclusion

The article considered the use of HC-SR04 sensors for measuring the distance to an object in a collaborative robot workspace and their visualization in the form of graphs, which allows for more effective interaction with the environment. The results of the experiments showed that, despite some limitations in accuracy, the HC-SR04 is able to provide satisfactory data for medium distances. Visualization of the received data allows for quick analysis of information about the robot's environment, which is important for safety and optimization of its work. The study demonstrated that the use of such sensors in real time can significantly improve the efficiency of collaborative systems. In addition, combining data from the HC-SR04 with other types of sensors can further improve the accuracy and reliability of measurements. As a result, this approach opens up new opportunities for the development of robotic systems that require the integration of various technologies to ensure greater flexibility and adaptability in complex environments. Prospects for further research include improving data processing algorithms and testing new types of sensors to increase the accuracy and speed of the robot's reactions.

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