High precision on-line liquid level detection system based on microwave penetration method

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Abstract. In order to meet the high precision and low cost of liquid level detection for bottled drinks in industrial production line, based on microwave transmission principle a liquid level detection method was designed on the basis of radar level meter. The rectangular microstrip antenna sent and received specific microwave signals. The signal was processed by the embedded ARM(Advanced RISC Machines) processor and digital signal processing method, and finally the data was transmitted. It was verified by experiments that the microwave penetration method can be used for liquid level detection, and the detection accuracy can reach ±1mm. Due to the use of microwave for measurement, the system has high stability and can be applied to the liquid level detection of bottled drinks on the production line.

1. Introduction
With the development of the Industry 4.0 era, the national strategic deployment of intelligent industrial production demand has further increased, and the detection equipment is also developing in the direction of precision, convenience and intelligence. In industrial production, liquid level measurement is widely used in pipeline water level measurement and filling level measurement. Accurate measurement of liquid level plays a key role in automatic control of industrial production and high product quality. For the industrial intelligence of the beer industry, companies can detect the liquid level in beer bottles online on the assembly line to determine whether it meets my country's food quality inspection standards.

The traditional liquid level detection methods are artificial naked eye inspection and artificial light inspection. This method is inefficient and has large errors due to visual fatigue. With the continuous development of technology, intelligent liquid level detection methods mainly include: X-ray liquid level detection, infrared liquid level detection, ultrasonic liquid level detection, radar liquid level detection, capacitive liquid level detection [1-2], etc. Among them, X-ray liquid level detection is used for beer beverages packaged in cans and other packaging materials, and the detection effect for packaging materials such as glass and ceramics is poor. Infrared liquid level detection requires a significant temperature difference between the liquid to be measured and the surrounding environment, which makes it vulnerable to material and environmental constraints. Ultrasonic liquid level detection has a lot of reflection and interference phenomena, so it is not suitable for liquid level measurement that is prone to foam. The radar liquid level detection method uses the time difference generated by the propagation of pulsed electromagnetic waves on the surface of the liquid to be measured to measure
the liquid level. It has high accuracy and is not affected by the surrounding environment, but its detection equipment is more complicated and expensive, and is suitable for large industrial liquid levels Measurement [3].

In order to simplify the equipment structure and reduce the cost, based on the original radar liquid level detection method, this paper uses the characteristics of microwave transmission to propose a liquid level detection method based on the microwave penetration method. A set of high-precision online liquid level detection system based on microwave penetration method is designed.

2. Materials and methods

2.1. Fundamental

2.1.1. Analysis of dielectric properties of water molecules at microwave frequency

Microwaves are electromagnetic waves with a frequency between 300MHz-30000GHz and a wavelength between 0.1mm and 1m. When microwave interacts with other media, it will present, reflect, penetrate, absorb and other characteristics [4]. Water molecules are polar molecules. In the normal state, it is a chaotically distributed dipole. In the state of an external electric field, the dipoles will be aligned. Under the action of the electric field, the dipole gains energy and continuously releases energy. The dielectric constant \( \varepsilon \) can be expressed as [5]:

\[
\varepsilon = \varepsilon' - a \varepsilon''
\]

In the formula, \( \varepsilon' \) is a measure of energy storage. \( \varepsilon'' \) is a measure of attenuation. \( a \) is a constant.

2.1.2. Microwave penetration method

When the microwave signal passes through the liquid, the water molecules are polarized. The strength of the polarization is positively related to the dielectric constant of the substance. The dielectric constant of water molecules is relatively large, so the amplitude attenuation and phase changes of microwave signals are mainly caused by the water content. By establishing the functional relationship between the magnitude of amplitude attenuation and phase change and water content, the detection of the liquid level of the measured liquid can be achieved [6]. The law of microwave propagation in the medium conforms to the following formula:

\[
P_2 = P_1 \exp(-aD)
\]

In the formula, \( P_1 \) is the microwave receiving power, W. \( P_2 \) is the microwave transmitting power, W. \( D \) is the thickness. The attenuation is:

\[
A = 10 \ln \left( \frac{P_1}{P_2} \right) = 10 \ln \left( \frac{P_1}{P_2 \exp(-aD)} \right) = k a D
\]

For ease of measurement and calculation, the formula (3) into the relationship of the signal voltage attenuation:

\[
A = 20 \ln \left( \frac{V_1}{V_2} \right) = k a D
\]

In the formula, \( V_1 \), \( V_2 \) are expressed as the voltage of the microwave signal before and after attenuation, V. According to formula (4), when the thickness is constant, the attenuation and the attenuation constant show a linear relationship. The water content can be obtained by measuring the signal voltage before and after the attenuation.

The microblog penetration method is to transmit and receive antennas are placed on both sides of the test substance, which can not only reflect the change of the liquid level to be measured, but also realize real-time online measurement. Detection principle is shown in figure 1.

![Figure 1. Schematic of microwave penetration method.](image-url)
2.2. Design method
In order to detect in the industrialized assembly line beer and other drinks at the factory level height of its compliance with the standard, the design system requires non-contact, real-time online accurate detection. According to the above basic principle, the microwave transmission method is used to detect the power level before and after the attenuation, and the received voltage signal is collected and calculated to realize online detection.

2.2.1. Antenna design
Detection systems are required by the antenna when the liquid level detector for transmitting and receiving microwave signals. Antenna design is a key link in the microwave detection system design. Its basic function is to convert microwave signals on transmission lines into microwaves transmitted in free space and media.

This system selects the microstrip antenna according to the actual situation. In communication technology, the microstrip antenna is an internal antenna manufactured by the related microstrip technology printed on the circuit board. Compared with other antennas, it has the following advantages: miniaturization, simple processing, light weight, easy integration, low production cost, and easy mass production [7].

The microstrip antenna is composed of a conductor patch, a dielectric base layer, and a ground plane. When the antenna is excited by the signal source, a resonant cavity is formed between the patch and the metal ground plate, which radiates to the surroundings through the gap in the conductor patch and the surrounding ground plate.

This system chooses the coaxial probe to feed the microstrip antenna, and the relevant calculation formula is [8]:

\[ W = \frac{c}{2f_0 \sqrt{\varepsilon_{r}+1}} \] \hspace{1cm} (5)
\[ L = \frac{c}{2f_0 \sqrt{\varepsilon_{r}}} - 2\Delta L \] \hspace{1cm} (6)

In the formula, L, W are the length and width of the microstrip antenna conductor patch. h is the thickness of the substrate. \( \varepsilon_r \) is the dielectric constant. \( f_0 \) is the center frequency of the microstrip antenna, Hz. c is the speed of light, \( c = 3 \times 10^8 \text{ m/s} \).

2.2.2. Hardware design
The overall structure of the online liquid level detection system with microwave penetration method is shown in figure 2. The system includes audio square wave modulation, microwave signal source, isolator, attenuator, transmitting and receiving antenna, amplification and detection circuit, ARM processor, data communication and other modules.

![Figure 2. Block diagram of detection system.](image)

After the microwave signal is transmitted by the microstrip antenna and absorbed by water molecules, it is interfered by the surrounding environment and is not easily processed and detected by subsequent circuits. Therefore, the circuit system needs to increase amplification and detection circuits. Figure 3 is a circuit diagram of amplification and detection. The amplifying circuit adopts the dual operational amplifier JRC2904D chip, which integrates two operational amplifiers. The chip has the
characteristics of wide common mode range, low distortion, stable operation and good temperature stability. The S042P chip is an intermediate frequency amplifier with demodulation function. It can convert the peak value of the AC signal into the voltage value of the DC signal. The output is a volt-level voltage signal.

![Figure 3. Amplification and detection circuit.](image)

2.2.3. Software design
ARM processor chooses ARM series STM32F429IGT6 chip as the core chip of this module [9]. Under the action of photoelectric switch and encoder, it sends out detection trigger signal. Perform level detection on the bottle to be tested in the assembly line, and reject unqualified bottles. The software design process is shown in figure 4.

![Figure 4. Software flow chart.](image)

3. Results and discussion
The theoretical basis for the system to determine the frequency of the microwave signal source is that the energy storage and attenuation measures of water molecules at this frequency are both large and easy to be detected. According to relevant data, when the wavelength of the microwave is 2-3 GHz in the S band, the energy storage and attenuation measures of water molecules are both large [3]. Therefore, the system chooses the microwave signal source frequency as 2.45GHz.

3.1. Antenna simulation
According to the actual needs of the system, the microstrip antenna is designed in a printed circuit board with a length and a width of 34mm and a thickness of 1mm. The conductor patch is a polyimide
conductor board with a length of 18mm and a width of 14mm that is pasted on the other side of the PCB circuit board. Polyimide is the main material of PCB printed circuit boards, so polyimide is chosen as the dielectric base layer of the microstrip antenna. Its dielectric constant is $\varepsilon_r = 3.4^{[10]}$.

Use HFSS (High Frequency Structure Simulator) simulation software to simulate the above antenna. Figure 5 shows the simulation result of the return loss $S_{11}$ of the microstrip antenna in the frequency range of 1-3.5GHz. The result shows that the value of $S_{11}$ is about -29.95dB when the frequency is 2.45GHz. It means microstrip antenna has reached a relatively good matching impedance state. Figure 6 shows the input voltage standing wave when the frequency range is 1-3.5GHz. In frequency 2.45GHz, the voltage standing wave ratio VSWR<2, which meets the technical index requirements of the actual project $^{[11]}$.

![Figure 5. Curve of microstrip antenna S11.](image1)

![Figure 6. VSWR curve of microstrip antenna.](image2)

### 3.2. Circuit measurement

The waveform before and after the signal is amplified and detected by the circuit is shown in figure 7.

![Figure 7. Magnified and detected waveforms.](image3)

### 3.3. Experimental detection

Select conventional glass bottled beer drinks as the detection object. The drink has a capacity of 330ml and a bottle height of 23cm. Set the standard value of the height of the liquid level of the bottle to be tested to 19cm, and adjust the height of the liquid level to be tested to increase or decrease regularly for testing. The relationship between the amplitude of the received signal and the height of the liquid level in the bottle to be measured presents a monotonous relationship, as shown in figure 8. The liquid level value displayed by the online detection system corresponds to the liquid level height in the bottle to be measured, as shown in table 1.

These results indicate, microwave transmission method enables online level detection. The system can accurately detect the height of the beverage liquid level, and its detection accuracy can reach $\pm1$mm. It can meet the accuracy requirements of intelligent industrialization.
Figure 8. Relation curve between liquid level height and signal amplitude.

Table 1. Display data table of corresponding liquid level height.

| Liquid level height (cm) | Detection display value | Liquid level height (cm) | Detection display value |
|--------------------------|-------------------------|--------------------------|-------------------------|
| 18.0                     | 586                     | 19.1                     | 426                     |
| 18.5                     | 538                     | 19.2                     | 408                     |
| 18.7                     | 499                     | 19.3                     | 389                     |
| 18.9                     | 460                     | 19.5                     | 352                     |
| 19.0                     | 445                     | 20.0                     | 300                     |

4. Conclusions
Through the study of liquid level detection method in recent years, as well as the needs of enterprises with the gradual development of intelligent industry, on the principle of liquid level detection radar designed to improve a set of high-precision line liquid level detection system based on microwave penetration method. By the microwave transceiver antenna, the change of the liquid level is presented to the change of the output voltage. The signal is processed by the signal processing module, collected, and to perform data transmission to realize online detection. In the present system to ensure accuracy while simplifying the device structure, the device further reduce costs, the process of industrialization can be achieved.

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