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Design of a Capsule Robot System for Gastric Hemorrhage Detection using Luminol

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***Abstract* - Gastric hemorrhage in upper gastrointestinal bleeding is an obvious indicator of deteriorating gastric disease. This paper proposes a capsule robot system for detecting bleeding in the stomach. The patient ingests a capsule robot containing luminol reagent, which detects bleeding in the stomach via chemiluminescence. The MCU receives the optical sensor signal, and the data is transmitted via radio frequency. The external lower computer receives and forwards the data to the upper computer for processing and display. The data is used to determine the presence and amount of stomach bleeding. Chemiluminescence is an excellent sensor, requiring no external energy supply, and demonstrating excellent sensitivity and selectivity. Combining chemical and electronic sensors presents opportunities for further development. Capsule robot detection reduces the discomfort and risk of secondary injury associated with traditional endoscopy. This paper establishes an experimental platform using porcine blood to simulate human blood, demonstrating the feasibility of the system.**

Index Terms - Upper gastrointestinal hemorrhage, Capsule robot, Luminol, Chemiluminescence

I. INTRODUCTION

Stomach disease has long been a prevalent health issue for humans. Upper gastrointestinal bleeding serves as an evident indicator of deteriorating stomach disease. The causes of upper gastrointestinal bleeding are numerous, including peptic ulcers in the gastric and duodenal regions, mucosal erosive diseases of the esophagus, stomach, and duodenum, malignancies, Mallory-Weiss syndrome, Dieulafoy lesions, "other" diagnoses, or no identifiable cause [1]-[2]. Gastric ulcer, a common chronic disease of the digestive system, results from abnormal damage to the stomach lining. Severe gastric ulcers lead to upper gastrointestinal bleeding, and the amount of bleeding is not dependent on the ulcer stage but rather the bleeding site. Older patients experience greater amounts of hemorrhaging, and males tend to bleed more than females [3]. Gastroscopy serves as the most common and effective means of detecting digestive tract diseases [4]. This procedure utilizes an endoscope to observe the digestive tract to determine the presence of lesions and bleeding in the stomach. Early detection and medical intervention are vital to saving patients' lives [5]. However, traditional gastroenteroscopy causes discomfort to patients and may further harm those with digestive tract lesions. In response, capsule robots are designed to replace endoscopic gastroscopes.

In addition to its traditional function of transmitting gastric images, capsule robots offer a myriad of possibilities [6]-[7]. For instance, the SmartPill Smart Wireless Power Capsule, developed by SmartPill Corporation (Buffalo, NY, USA), received approval from the US Food and Drug Administration (FDA) in 2006. This capsule can record various parameters such as pH value, temperature, and pressure in the stomach, as well as gastric emptying and total gastrointestinal transport time of patients, which can aid physicians in diagnosis and treatment, and researchers in studying the gastrointestinal environment, digestive time, and digestive pressure of different populations [8]. In 2018, the Massachusetts Institute of Technology (MIT) published a bacterial electronic system for monitoring gastrointestinal health in the journal Science. The system utilizes a genetically modified bacterium that illuminates when it encounters heme iron in the blood. The photosensitive sensor in the capsule reads the light-emitting information and transmits it to the receiving end in vitro through the wireless transmission system, in order to detect bleeding in the digestive tract [9]. In 2020, Lining Zhang from the Beijing Institute of Technology proposed a new assembly design of a multifunctional capsule robot and developed the structure of its driving module. The robot consists of a detachable functional module and a driving module based on a threaded structure, allowing for the installation of different functional modules according to clinical needs, enabling the robot to perform a variety of functions [10]. Zixu Wang from Kagawa University proposed a new magnetically driven multi-module drug sustained-release capsule robot in 2022. This robot enables slow-release quantitative drug delivery based on the calculation characteristics of individual start-up frequency and pitch correlation of micromagnets [11]-[12]. Also in 2022, Lingling Zheng from Kagawa University designed a multifunctional capsule robot with active motion, dual drug loading, and selective drug delivery functions. This robot is composed of a moving unit and a drug delivery unit controlled by two orthogonal rotating magnetic fields. The maximum loading capacity is 1.5g, and the maximum forward and backward speeds are 11.8mm/s and 10.4mm/s, respectively. Furthermore, it allows for the release of two different drugs at different targets [13]-[14].

In this paper, a capsule robot system has been developed with the aim of detecting upper gastrointestinal hemorrhage, which is characterized by bleeding caused by lesions of the digestive tract above the Treitz's ligament, including the esophagus, stomach, duodenum or pancreatic biliary. The focus of this paper is mainly on the detection of stomach bleeding. By utilizing the capsule robot to detect the presence and degree of stomach bleeding, the data is wirelessly transmitted to an external lower computer, which receives and sends it to an upper computer for display. This data is then analysed to determine whether the patient is experiencing bleeding and to what extent. By using this non-invasive method, the pain and side effects associated with endoscopy can be avoided.

II. Design of the Capsule Robot System

Patients who are at risk of stomach bleeding can benefit from the capsule robot system proposed in this paper. Once the capsule robot is activated and enters the stomach, it uses the principle of chemiluminescence to detect the stomach in real-time and send the collected data to an external upper computer for display. By analysing the data, it can be determined whether the patient is bleeding or has experienced bleeding recently. Once the diagnosis is complete, the capsule robot is excreted naturally through the patient's digestive process. The capsule robot is self-powered and transmits data wirelessly. Moreover, chemiluminescence is a stable method that performs well in the dark environment of the stomach.

A. *Overview of the System*

The upper gastrointestinal hemorrhage detection capsule robot is designed to detect stomach bleeding and consists of three main parts: the capsule robot itself, the radio frequency receiving module of the lower computer, and the upper computer PC. The capsule robot has a temperature display function that monitors its ingestion and discharge by using the internal and external temperature difference, which also plays a role in aiding the patient's health diagnosis [15]. The principle of bleeding detection is based on the luminol reaction, which is an aminobenzoyl-hydrazine reaction. The reaction produces a fluorescence reaction when it encounters blood, and even small amounts of old blood can still be detected with a very small catalyst dose. In the dark digestive tract, the light sensor can detect the fluorescence reaction. The data collected by the capsule robot can be transmitted wirelessly in real-time through the radio frequency module integrated on the PCB. The external lower computer equipped with another radio frequency module receives the data and sends it to the PC serial port for real-time display. Finally, the data is converted into light intensity. The overall design of the system is depicted in Fig. 1.

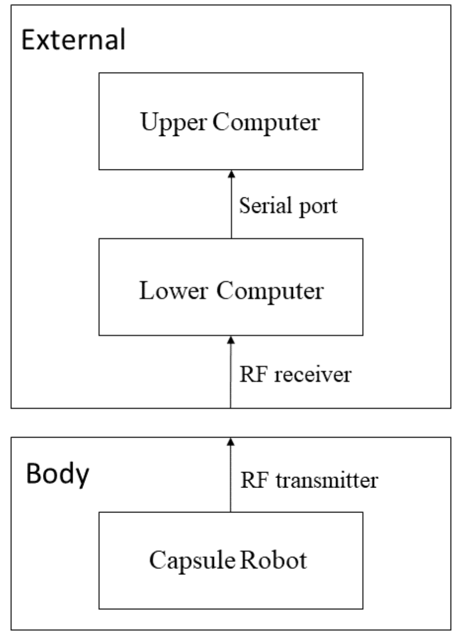


Fig. 1 Overall design of the system

The chemiluminescence sensor used in the capsule robot system has excellent performance, as it does not require an external energy supply and exhibits high sensitivity and selectivity. It has been widely used in various biological detection sensors [16]-[17]. Concerning the toxicological analysis of luminol, existing studies have demonstrated that in vitro experiments, luminol can be oxidized to form three products, including amino-phthalic acid [18]-[19]. However, studies have shown that in vivo, luminol does not form these products. Luminol is rapidly absorbed by the gastrointestinal tract and excreted from the urine, with very small amounts of luminol and its metabolites deposited in the tissues [20]. Due to the lack of skin absorption pathways and rapid metabolic clearance, the US Department of Health and Human Services considers luminol safe. Additionally, a national toxicology program study conducted by the UK Department of Health also revealed that luminol did not possess the essential characteristics of a mutagen [21].

B. *Design of the Capsule Robot*

In the PCB design of the capsule robot for detecting upper gastrointestinal hemorrhage, the main control chip used is the STM32F103C8T6 from ST Company, and the LM75AD chip is used for temperature detection. The wireless transmission is achieved using the RF (radio frequency) module nRF24L01, and a photoresistor is integrated into the entire system of the capsule robot, which is powered by a micro battery. The shell of the robot is 3D printed using photosensitive resin. The luminol reagents are stored in the reagent compartment inside the shell, and a biological semi-permeable membrane is attached to the surface of the shell. The functional architecture of the capsule robot is illustrated in Fig. 2.

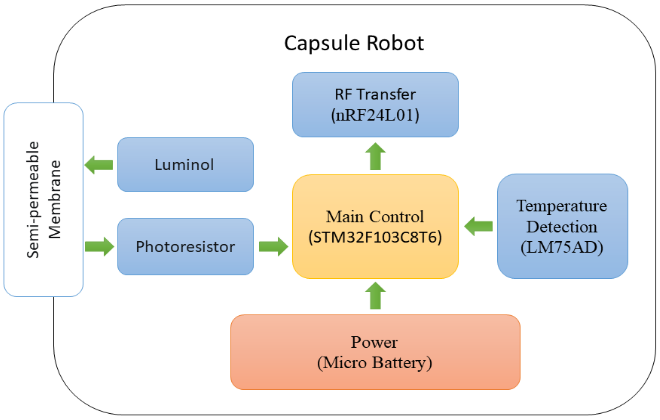
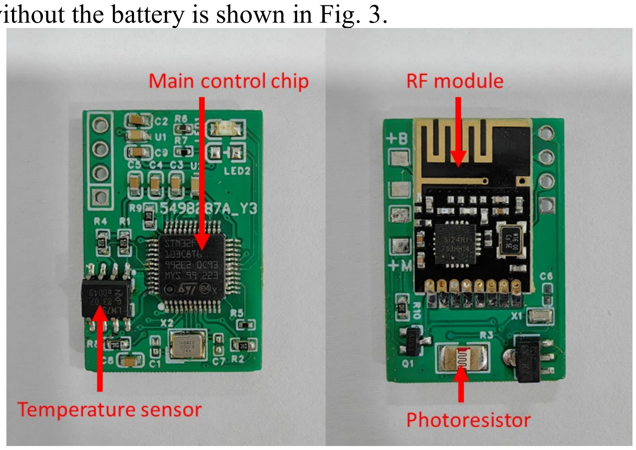


Fig. 2 The functional architecture of the capsule robot

In the capsule robot system designed for detecting upper gastrointestinal hemorrhage, temperature data is transmitted using the I2C bus of the main control chip, LM75AD. The light sensor is implemented through the photoresistor, which receives data on the change in light intensity due to the fluorescence reaction generated by the luminol reaction. This data is then quantized into a voltage change through the ADC function of the main control chip and transmitted in real-time to the upper computer through the RF module. The photoresistor's characteristic is that the resistance value decreases with increasing light intensity. The PCB prototype without the battery is shown in Fig. 3.



(a) Front side of PCB (b) Back side of PCB

Fig. 3 The prototype PCB of capsule robot

The state of the capsule robot inside the stomach can be observed in Fig. 4, where the luminol reagent reacts with any bleeding in the stomach through the semi-permeable membrane, resulting in fluorescence. A section of the capsule robot is shown in Fig. 5, demonstrating how the fluorescence reacts with the photoresistor in the dark stomach environment, decreasing the resistance value and voltage at the pin end. The main control chip then sends the voltage and temperature sensor measurements in real-time to the lower computer via RF transfer. The lower computer receives the data through the RF receiver and sends it to the upper computer for display through the serial port protocol.

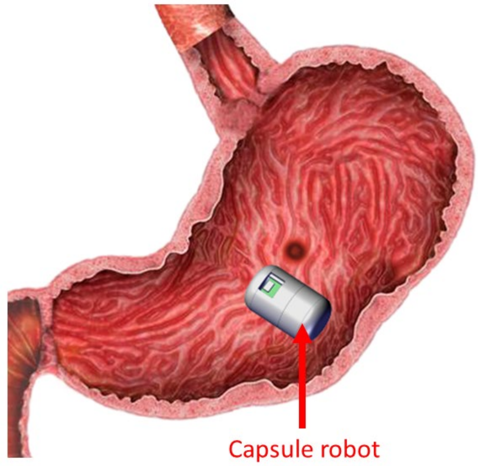


Fig. 4 The detection procedure of the capsule robot

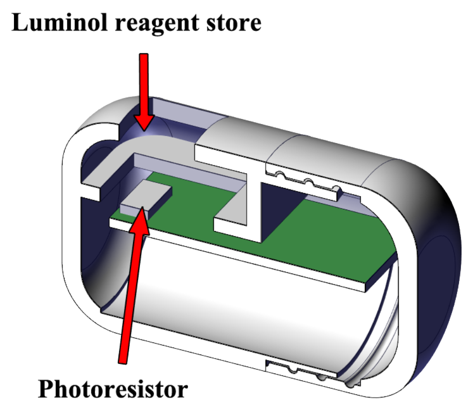


Fig. 5 The capsule robot structural profile

C. Design of the Upper Computer

The PC upper computer is developed using C# and communicates with the lower computer using the serial port protocol to exchange information. Once the upper computer receives the data, it displays the real-time temperature measurement obtained from the temperature sensor and determines the time when the capsule robot for detecting upper gastrointestinal bleeding enters the human body, using a visual window. The users' interface on upper computer is presented in Fig. 6.

The upper computer interface is also equipped with a waveform display window, which shows the changes in voltage analog due to the changes in photoresistor resistance value, allowing the user to determine whether there is bleeding after the capsule robot enters the body. By analyzing and judging the waveform data, the false detection rate can be greatly reduced. Fig.7 displays the waveform display interface, with the horizontal axis representing time in seconds and the vertical axis representing light intensity analog. After obtaining real-time data, the data is converted into light intensity through the PC. The characteristic curves of the photoresistor with respect to light intensity and current are shown in Fig. 8.

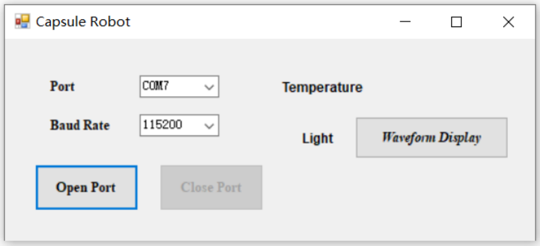


Fig. 6 The upper computer interface

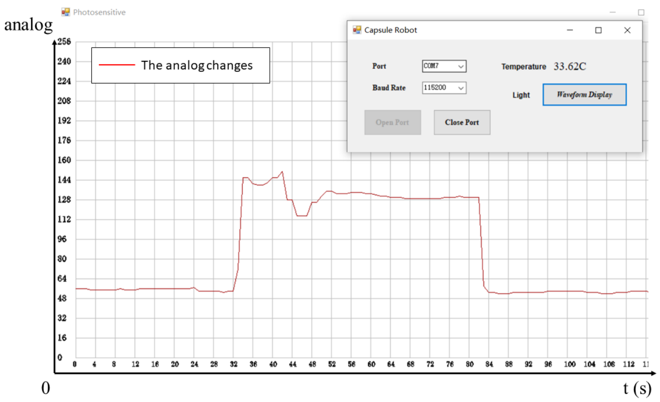


Fig. 7 The waveform display interface

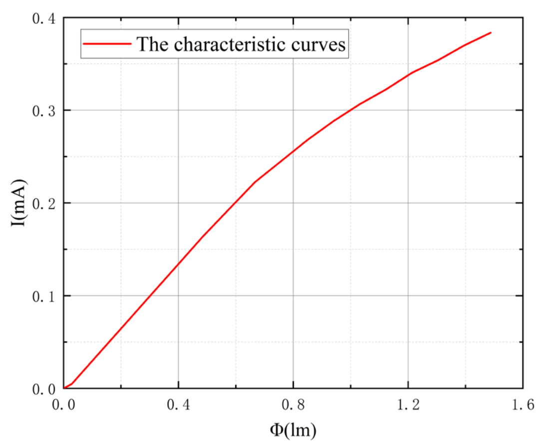


Fig. 8 The characteristic curves of photoresistor

III. EXPERIMENTS AND RESULTS

A. *Experimental setup*

The experimental setup is shown in Fig. 9. The figure includes the capsule robot without luminol and semi-permeable membrane, lower computer, and upper computer. Subsequently, the photoresistor data wireless transmission of the capsule robot was tested. Fig. 10 and Fig. 11 illustrate the analog output curves of the capsule robot under light and dark environments, respectively. Furthermore, the wireless transmission distance of the capsule robot was tested, which ensured sending and receiving within a range of 5 meters under unobstructed conditions and without the need for an additional antenna. In the experiment, the luminol reagent was mixed, and porcine blood was dropped into the beaker containing the mixture in a dark environment, as shown in Fig. 12.

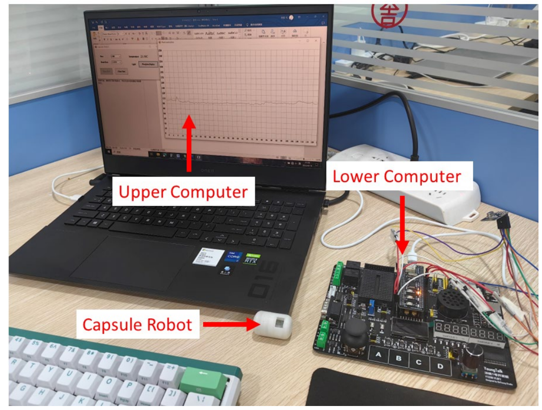


Fig. 9 The experimental setup

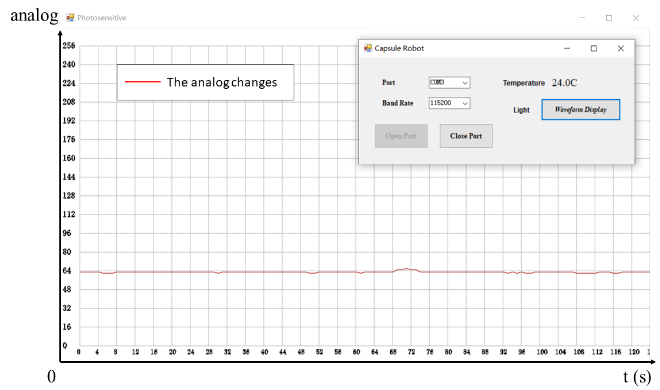


Fig. 10 The upper computer displays data in the light environment

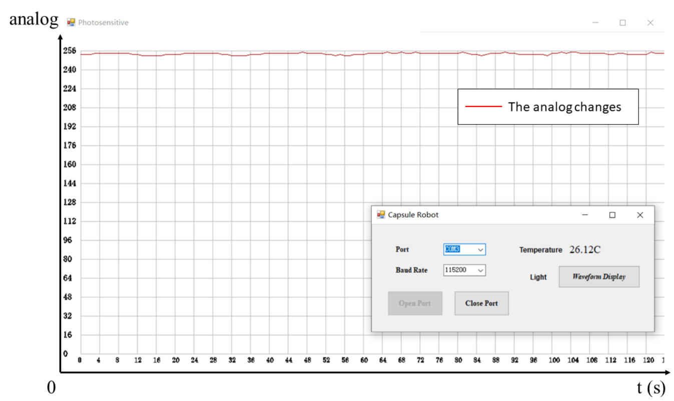


Fig. 11 The upper computer displays data in the dark environment

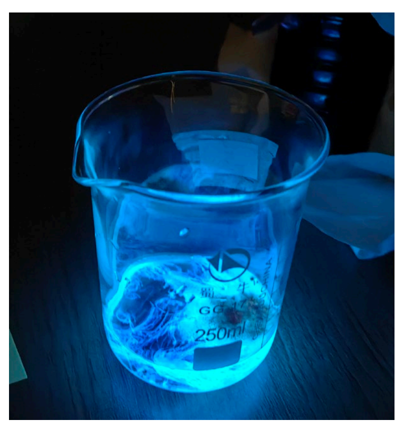


Fig. 12 The luminol chemiluminescence reaction

B. *Experiments on the capsule robot system*

The capsule robot's ability to detect bleeding in the stomach was tested in an experiment. Luminol was injected into the capsule robot and the semi-permeable membrane was sealed, as shown in Fig. 13. The capsule robot was then placed in a beaker with a defatted cotton pellet containing a small amount of porcine blood under dark conditions. The experimental setup is shown in Fig. 14, with the surface of the defatted cotton pellet being dipped with a small amount of porcine blood and a small amount of water on the bottom of the beaker to simulate the stomach environment. The capsule robot was observed in the dark environment, and the experimental phenomenon is shown in Fig. 15. During the experiment, chemiluminescence from the luminol reaction could be observed, which was quite obvious in the dark. The chemiluminescence appeared rapidly and the light intensity was stable for a certain time, followed by gradually weakening. The photosensitive resistance data of the upper computer was also observed during the experiment. The upper computer display during the experiment is shown in Fig. 16, where a sudden drop in the analog can be seen as the reaction occurs. The light intensity was then maintained for some time. The data fluctuation in the middle was due to small shocks given to the beaker. Finally, as the reaction weakened and the environment turned darker, the analog gradually recovered. Fig. 17 is obtained after the data waveform is quantized as light intensity.

(a) The capsule robot prototype (b) After sealing

Fig. 13 Before and after the capsule robot sealing

Fig. 14 The experimental setting

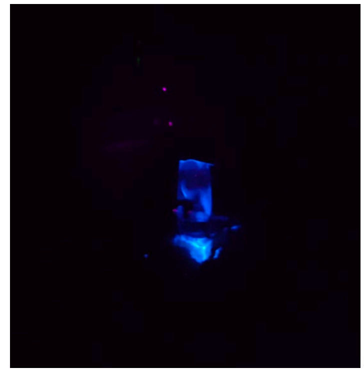
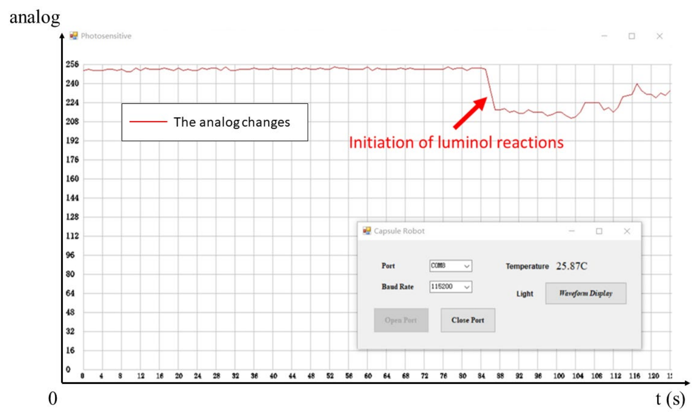
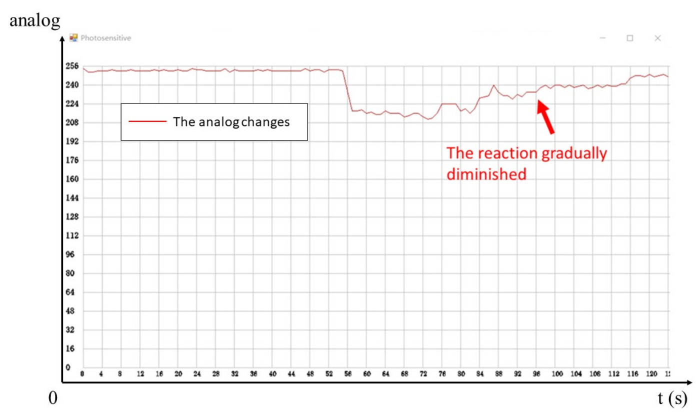


Fig. 15 The experimental phenomenon



(a) The luminol reaction initiation waveform



(b) The luminol reaction diminished waveform

Fig. 16 The upper computer shows the experimental data

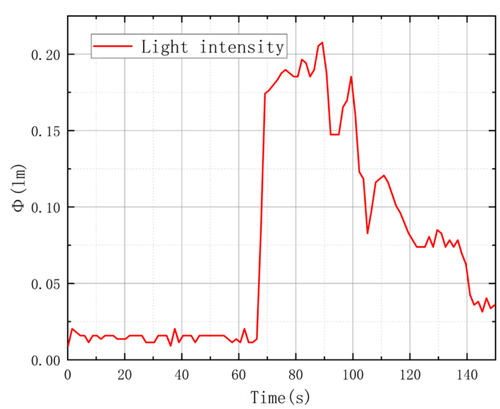


Fig. 17 The light intensity and time waveforms

C. Experimental results and discussion

Based on the experimental procedure and the data displayed on the upper computer, it can be concluded that the capsule robot system is capable of detecting blood with chemiluminescence of sufficient intensity for photosensor detection. However, it should be noted that the light intensity is not solely dependent on the blood volume, but also on the concentration and volume of luminol reagent. Therefore, the luminol reagent needs to be adjusted to a safe range in practical applications. The chemiluminescence can last for a certain time, allowing the capsule robot to collect and send data to the upper computer for further analysis. The reaction was also rapid, with the chemiluminescence appearing shortly after the capsule robot was placed in the beaker. Considering that the capsule robot movement in the stomach is assisted by peristalsis, bleeding can be detected soon after the capsule robot is swallowed.

IV. CONCLUSIONS

This paper proposed a novel capsule robot system that can detect bleeding in the stomach without the need for medical intervention or external drive. By using wireless transmission of data, the capsule robot has the ability of collecting and sending data to the upper computer, which displays the data to determine the presence of bleeding. This system utilizes chemiluminescence as the bleeding sensor, which provides stability and reliability, and avoids the challenges associated with endoscopy. Experimental results have demonstrated the reliability of the wireless transmission data by the capsule robot system. The use of chemiluminescence combined with electronic systems in medicine holds great promise. Overall, this study has presented a promising direction for the development of non-invasive and reliable methods for detecting bleeding in the stomach. In future work, the upper computer data will be combined with bleeding index to evaluate the bleeding situation.

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