# Utilization of LEDs in a Communication Protocol for Endoscopic Submarine Capsules

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KEYWORDS. capsule endoscopy, communication, gastric region, light emitting diode, color sensor

BRIEF. A protocol for communication among a swarm of endoscopic submarine capsules was developed using light emitting diodes and color sensors.

ABSTRACT. The traditional method of screening for diseases within the gastrointestinal tract using flexible endoscopy is effective but poorly perceived among most patients due to the invasive intubation required. Wireless capsule endoscopy, which utilizes a passive pill-sized camera device, presents a diagnostic alternative to flexible endoscopy, but limited functionality prevents its widespread use. This work evaluates the potential advantages, such as increased efficiency and improved visualization, gained by multiple capsules working together as a swarm in the gastric region during endoscopy of a liquid-distended stomach. A communication protocol was developed that utilizes 3-channel color sensors and light emitting diodes (LEDs) of different wavelengths within the visible spectrum. The protocol was tested using endoscopic submarine capsules emitting a distinctive wavelength from their respective LEDs. Each capsule responds specifically to the wavelength of another capsule in the swarm through its color sensor. This allows the capsules to autonomously assemble in a follow-the-leader type fashion. Test results show that the color sensors are able to detect the difference between different wavelengths, and that it is possible to program the color sensor to recognize each wavelength at a specified distance. This work represents the first step in enabling collaboration among multiple endoscopic capsules, which can lead to improved efficiency and diagnostic capabilities for wireless capsule endoscopy.

## INTRODUCTION.

In 2012, gastric cancer was the fifth most common cancer [1] and the third leading cause of cancer mortality [2]. In the United States, the National Cancer Institute reported a 5-year survival rate of only 28.3% for people diagnosed with the cancer between the years 2004 and 2010 [3], mostly due to late detection. Gastric cancer is among the many stomach diseases that can be treated if diagnosed early. Therefore, early detection through effective screening protocols can be lifesaving. The traditional screening method of the gastrointestinal (GI) tract is flexible endoscopy.

Flexible endoscopy utilizes a maneuverable insertion tube that is attached at the end to a camera, which is wirelessly connected to an external monitor [4]. While flexible endoscopy is a generally accepted procedure and its diagnostic accuracy is high (82% of Invendoscope (Invendo Medical GmbH, Kissing, Germany) patients are comfortable without sedation [4]), the process is known to be uncomfortably invasive and not patient-friendly [4]. Patient compliance for doctor-recommended endoscopies is low, with only 62.9% of Americans undergoing regular colonoscopy, the most common endoscopic procedure [4]. Recent years have brought the development of wireless capsule endoscopy (WCE), a diagnostic alternative to flexible endoscopy [4]. In WCE, the traditional endoscope is replaced with a wirelessly monitored pill-sized camera that is swallowed by the patient and moves passively and comfortably through the GI tract [4]. WCE eludes the intubation, sedation, and pain that are often associated with flexible endoscopy. The FDA has approved a few of the capsule endoscopes, including the 11 mm x 32 mm PillCam (Given Imaging, Yoqneam, Israel), which is capable of movement through the small bowel, esophagus, and colon [5]. The PillCam procedure takes between twenty-four to seventy-two hours as the capsule naturally travels through the digestive system [5]. However, patients are able to go about their day as normal, only returning to the doctor for data collection afterwards [5]. The widespread use of WCE is restricted by its currently limited functionality. Limitations include procedural costs, which currently surpass flexible endoscopy costs [4], and capsule retention within the gastrointestinal tract [5]. The capsules, including the PillCam, are also limited by their single capability as a passive camera that cannot be controlled by doctors [4-5].

One potential type of WCE, the endoscopic submarine capsule, has the capability to maneuver using controlled motorized propellers [6], a modification from the current passive capsules that move freely without controlled motion. The varied dimensions of the stomach are not suitable for current WCE technology, which rely on being able to independently glide along the tunnel-like forms of organs such as the colon [7]. In addition, the stomach measures at a minimum of 50 ml in volume during the relaxed state, but is able to expand up to 1400 ml [7]. The capsule endoscope is thus limited in efficacy due to the disproportional ratio of sizes. Several studies [6-8] have published materi-al on the design of endoscopic submarine capsules specifically for the stomach. These studies address the functionality of motorized pro-pellers, including concerns over efficient power supply systems and weight distribution. Efficiency is a concern of WCE, and all three related studies offer solutions for maximum propeller efficiency with regards to the other components within the capsules. However, the noted limitations of the work include high material cost and inconvenient capsule sizes. The presented work aims to evaluate the potential advantages gained by multiple capsules working together as a swarm in the gastric region during endoscopy of a liquid-distended stomach. It is hypothesized that a swarm of wireless capsule endoscopes will increase precision and efficiency of endoscopy in the stomach due to enhanced visual coverage of any given gastric volume.

In this work, a protocol that utilizes light emitting diodes (LEDs) and 3-channel color sensors was developed for communication among a swarm. The LEDs were of different wavelengths within the visible spectrum, representing the colors blue, green, and amber. Each capsule emits one of the three distinctive wavelengths and has a color sensor programmed to detect the emitted wavelength of another capsule. Thus, each capsule shares a unique link to another capsule, which allows the swarm to arrange itself into a follow-the-leader type pattern. The overall product is a chain of communicating submarine capsules. The communication protocol represents the first step in enabling collaboration among multiple endoscopic capsules. This could lead to improved efficiency and diagnostic capabilities for wireless capsule endoscopy. The goal is to turn WCE into an effective, patient-friendly approach to screening for malignant diseases within the gastrointestinal tract.

## MATERIALS AND METHODS.

### *Capsule Configuration*

The capsule shell that encloses all of the required components was designed on Creo Parametric 2.0 (PTC, Needham, MA) and printed using VeroWhite material on the Objet Alaris30 3D printer (Stratasys, Eden Prairie, MN). The shell was 42.65 mm long with a diameter of 14.90 mm. The TAOS TCS3200 color sensors and the light emitting diodes (in blue, green, and amber) were components utilized specifically for the communication protocol. Note that each capsule prototype contained only one LED. Other hardware components that were present in the prototype for functionality were microcontrollers, inertial measurement units, Renata lithium coin cell batteries, motor drivers, motors, and 3-blade propellers. Table S1 (*located in Supporting Information*) lists the dimensions of all the components. The components were arranged so that the color sensor and LED were opposed from each other and faced outwards from the capsule. Each capsule contained four motors and propellers. The research focused exclusively on the relationship between the color sensor and LEDs; motor qualifications were based off previous studies [8]. The three different colors of LED were chosen for their distanced wavelengths.

*Sensitivity Trials*

The TAOS TCS3200 color sensor (ams, Unterpremstaetten, Austria) contains an 8 x 8 array of photodiodes, equally split among blue, green, red, and clear filters. The sensor calculates light intensity and returns outputs in the form of RGB values. A series of tests were conducted to test the sensitivity and functionality of the color sensor in a water environment at various distances from the LED as a simulation of the endoscopy of a liquid-distended stomach. Light that is submerged underwater produces different properties than light that travels in the air [9]. Due to this, a second set of trials was conducted in an air environment for comparison purposes. To simulate the characteristics of a stomach, all trials were conducted within the darkness of an enclosed box. Each of the three LEDs was tested in both conditions (air and water) at distance intervals of 5, 10, 20, and 30 mm away from a color sensor.

The tests were conducted before the color sensor and LEDs were positioned into their respective capsules. Both components rested at 90° angles in separate props placed in one clear container, as shown in Figure 1. The distances were adjusted based on a ruler attached to the bottom of the container. The container was filled with either air or water for the trial environment. Each trial consisted of three seconds of darkness (serving as the control), ten seconds of light from the LED, and three more seconds of darkness. The RGB value outputs from the color sensor were graphed using Matlab (Mathworks, Natick, MA) and visually analyzed. The graphs displayed a light intensity range of 4 units to 800 units, where 4 units represented the absence of light intensity (darkness) and 800 units represented the highest intensity of light.

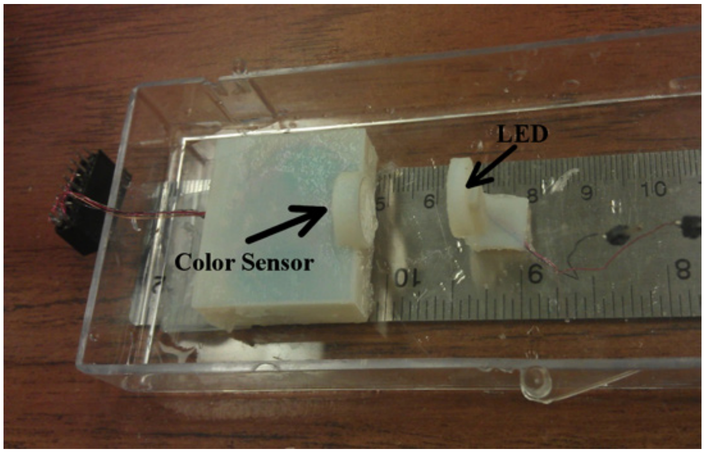


**Figure 1** shows the testing apparatus that was used to assess the color sensor.

*Locomotion Programming*

The capsule's four motors moved independently of each other and individuals were activated only when required. For example, the capsule turned left when only the two rightmost motors were moving. This reduced the amount of power the capsule were required to run on. Each wavelength, in both environments, was characterized by a different range of RGB values, as detected by the color sensor. Furthermore, the RGB values were unique among the three distances of each wavelength, as calculated in Matlab. This allowed the each capsule to be programmed to travel around at random until it detected its leading capsule at 20 mm away. This distance was chosen because the RGB values of each LED at this point maintain uniqueness without compromising capsule intervals (being too close or too far away for proposed camera efficiency). Matlab was also used to clear the outliers from the RGB value ranges for improved wavelength detection precision.

RESULTS.

*Capsule Configuration*

Components of the capsule were chosen based on the smallest size available in the market. They were arranged in the following order within the capsule shell: color sensor, microcontroller, inertial measurement unit (IMU), battery, motor driver, motors, LED, propellers. Figure 2 displays the creation of the capsule prototype.

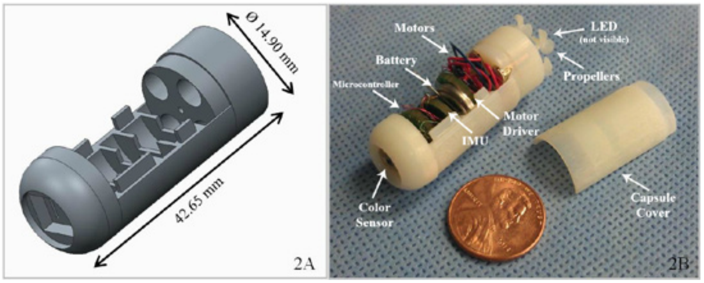


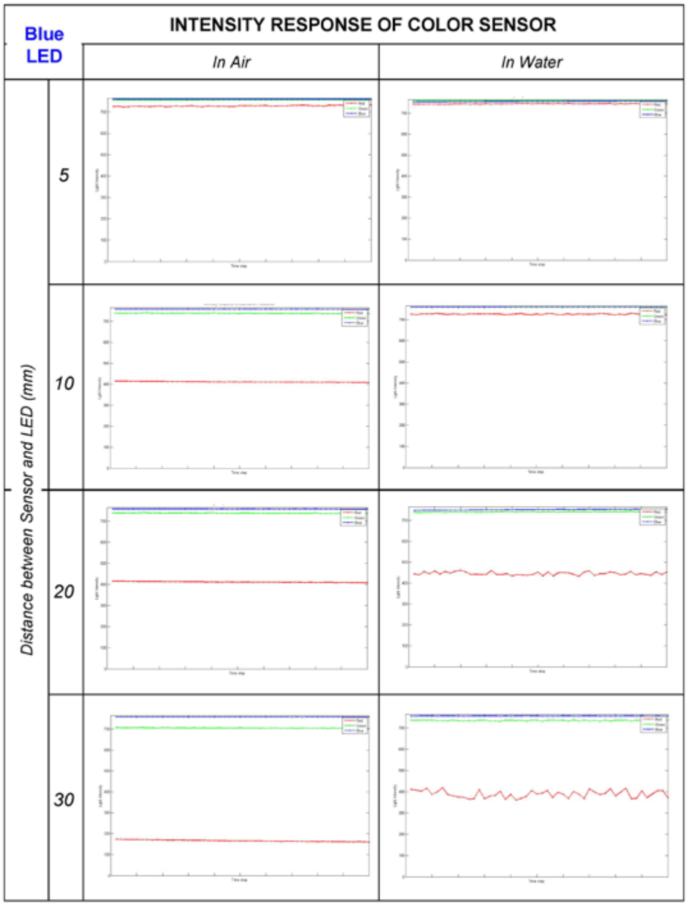
**Figure 2** shows the configuration of the capsule protocol. (2A) Design of the capsule shell as created on Creo Parametric 2.0. (2B) Structural view of the physical capsule prototype.

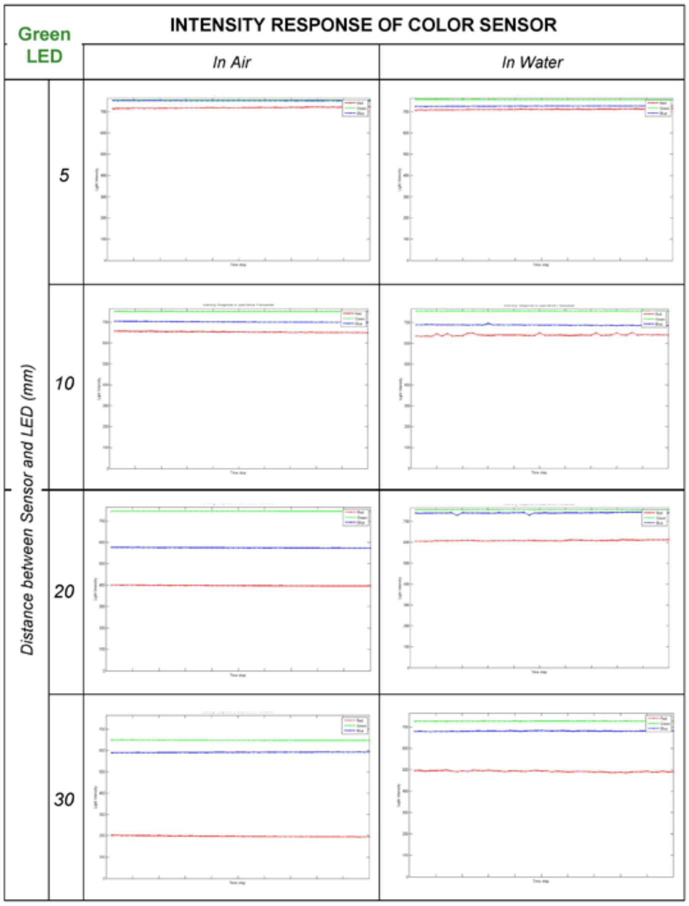
The battery contained 3 V. The amount of voltage used by the motorized propellers was dependent on the number of motors running at the moment. The LEDs had a light intensity of 1300 mcd (blue), 900 mcd (green), and 2500 mcd (amber). At the LEDs' maximum forward voltages, their light intensities passed the maximum detection level for the color sensor; all RGB values reached 800 units. Therefore, each LED was set to maintain a detectable, but still distinctive level of light intensity at specific voltages: 2.6 V (blue), 2.7 V (green) and 1.8 V (amber).

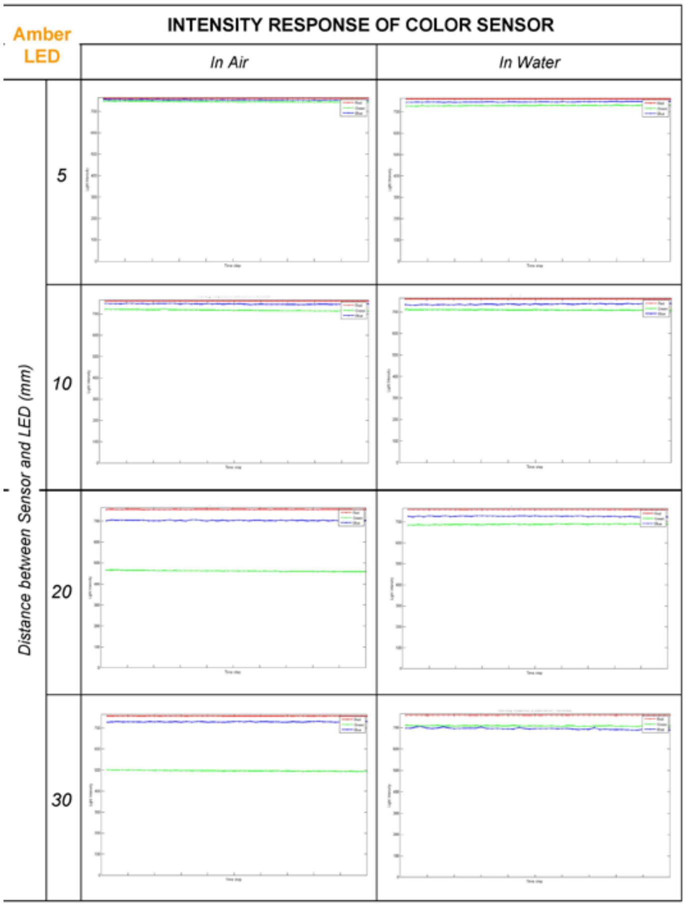
*Sensitivity Trials*

While trials in air maintained concise ranges of RGB values, trials in water displayed expansive ranges of RGB values, as visually shown in Figure 3. In this figure, each individual graph is displayed as light intensity (in RGB values) over time. The flux, or oscillation, in RGB values of the water trials was expected, due to the tendency of light particles to scatter in water [9]. Despite the differences in value outputs, the color sensor displayed the same pattern in color dominance for each wavelength in both environments. Dominance is defined by the color that emitted the highest light intensity, closest to the maximum value of 800. For example, Figure 3 shows that the color sensor detected the amber LED to be dominant in red light, with blue and then green light following. The green LED emitted green light the strongest, followed by blue and then red light. The blue LED emitted mostly blue light, followed closely by green light, and a low level of red light. Therefore, the data supported the color sensor's ability to detect the differences between colors in both air and water environments.

Figure 3 also shows that at 5 mm away from the LEDs, the color sensor yielded RGB values close to the maximum light intensity it could detect. When the distance was increased up to 30 mm, the RGB values were defined at lower and more distinct units. As the distance between the color sensor and the LED increased, the light intensity began declining for all RGB values regardless of the LED being emitted. This observation suggested the color sensor's ability to indirectly distinguish distance. The data supported the programming of the capsule to maneuver itself at a specific distance away from another capsule since the yielded RGB values were dependent on distance.







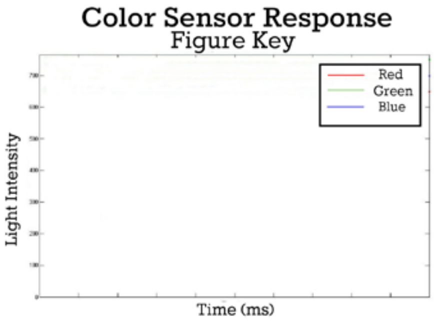


**Figure 3** displays the color sensor response graphs of the three LEDs for visual comparison between wavelengths, as well as distances and testing environment. Each individual graph is displayed as light intensity over time. The graphs show that the set of RGB values differs for each unique condition of light, which allows capsules to be controlled at specified distances away from each other.

### *Locomotion Programming*

At 20 mm of distance between the color sensor and LED, each diode was characterized by specific RGB values, as shown in Table 1. This table numerically shows the ranges of RGB values for each LED at the set conditions. These values excluded outliers. The values from the water trials were used to program the capsules of a swarm to detect each other.

**Table 1** displays the RGB value parameters set for the color sensors.

| **RGB Values at 20 mm Between Color Sensor and LED** | | Testing Environment | |
|---|---|---|---|
| | | *Air* | *Water* |
| LED | *Blue* | **R**: 435-443 **G**: 763-779 **B**: 790-794 | **R**: 361-557 **G**: 766-787 **B**: 792-796 |
| | *Green* | **R**: 424-429 **G**: 779 **B**: 605-609 | **R**: 623-662 **G**: 789-792 **B**: 709-813 |
| | *Amber* | **R**: 785-793 **G**: 481-489 **B**: 726-752 | **R**: 975 **G**: 712-736 **B**: 738-780 |

## DISCUSSION.

Gastric cancer is among many gastrointestinal tract diseases that have preventable deaths if diagnosed early. Advancement in endoscopic technology signifies the potential that robots have in the medical field. The collaboration of multiple endoscopic submarine capsules represents the next step in providing both a patient-friendly and an efficient method of screening within the gastrointestinal tract.

The current endoscopic capsules, as approved by the FDA, are limited by their single function as a camera and independent, passive travel through the gastrointestinal tract [4]. An abundance of research currently seeks to identify the most efficient method of technician-controlled movement as well as other capabilities for the endoscope, including drug delivery [11-12]. The presented research aimed to develop an efficient protocol that would allow multiple capsules amongst a swarm to communicate. The capsules were designed as submarine capsules with motorized propellers that could maneuver through a liquid-distended stomach, similar to those in [6-7]. While comparative data describing the protocol's productivity has not yet been analyzed, test results have supported the swarm's capability to communicate under water. Each capsule's color sensor was able to identify different wavelengths based on their RGB values, which were unique based on color and distance. The color sensor returned RGB values as outputs, which were used by the microcontroller to direct the capsule's movement until the sensor located the LED that the capsule was programmed to follow.

The overall dimensions of the capsule were 42.65 mm by a diameter of 14.90 mm, an inconvenient size for swallowing. The size was limited by market-available components, most of which were not available in smaller proportions. Further research is recommended for the reduction of the capsule size, in respect to neutral buoyancy. An ideal dimension is 32 mm by a diameter of 11 mm, the current size of the PillCam [5]. Another suggestion for future study is the addition of more capsules in the swarm and the study of how order can be maintained until the capsules have assembled into a chain. The color sensor should also be tested under other distance increments for an increased dataset on its capability for underwater communication. In addition, comparative data between a swarm and a single capsule is recommended for analysis on the swarm's efficiency.

In summary, the work presented a novel idea for a protocol that allows a swarm of three submarine capsules to communicate using LEDs and corresponding color sensors. The color sensors were able to output RGB values at different conditions of light. Furthermore, each condition had a unique set of RGB values associated with it, thus supporting the feasibility of an LED-orientated communication protocol. The preliminary data is limited, but represents a novel idea for swarm efficiency in capsule endoscopy.

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## SUPPORTING INFORMATION.

**Supplemental Methods.**

**Table S1** lists the components that appear in the capsule prototype. Note that each prototype contained only one LED. (Ø = diameter)

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