

**Autonomous Platform for the  
Remote use of Colorimetric Color Sensors**

by

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## **ABSTRACT**

We describe here a device for the autonomous use of Draeger colorimetric sensor tubes (CSTs) at large stand-off distances ( $> 1$  km). CSTs are an attractive option for the detection of hazardous chemicals thanks to their high sensitivity and simplicity but present several challenges when considered for automation. Here, these challenges are discussed, and a proof-of-concept device that demonstrates viable solutions is detailed. Our realized prototype is capable of processing thioether CSTs without human interaction and demonstrates comparable sensor fidelity to manually processed tubes.

## **Chapter 1**

### **INTRODUCTION AND BACKGROUND**

The United States military, emergency first responders, and others are exploring the use of colorimetric chemical sensors in the form of small glass tubes, manufactured by Draeger Inc., for high sensitivity detection of chemical warfare agents and other airborne chemicals. The device described in this paper was developed as a proof-of-concept for the remote automation of these sensors.

#### **1.1 Chemical Warfare Agent Detection**

Chemical warfare agents (CWAs) are toxic chemicals and materials that could be used to injure or incapacitate adversaries. Although the production, stockpiling, and use of CWAs is officially banned by international law under the 1993 Chemical Weapons Convention [1], they are a persistent threat in warfare and terrorism, and there is potential for future proliferation of advanced chemical weapons [1]-[4]. Because CWA exposure result in rapid and severe symptoms even at low concentrations [1], there is significant incentive for swift, robust detection—preferably at a large standoff distance to prevent contact. Sensing technologies are commercially available for both point and standoff detection [2], [5]. Each category presenting a range of performance vs. costs trade-offs. Creative innovation and engineering design using autonomy can enable new capabilities for affordable sensing and alarm at remote distances to avoid contamination, enhance safety, while reducing cognitive burden on operators and saving money.



Figure 1: Traditional CWA testing exposes personnel to potentially hazardous situations.

Force protection and costs motivate interest in point detection of CWAs. Colorimetric sensor tubes (CSTs) are one attractive option. CSTs operate on the principle of chemical discoloration, wherein exposure of a substrate or liquid reactants to analytes causes an observable color change without the use of further instrumentation. Although typically less specific than an analytical method, CSTs benefit from extremely low cost, minimal necessary training, and low sensitivity to environmental conditions [5]. Remote detection can be achieved with CSTs and other point detection methods via automation and wireless communications.

## 1.2 Thioether Sensor Tubes

A thioether CST manufactured by Draeger Inc. (Figure 2) was used for the design and demonstration of the device that is described herein. Its fundamental operating principle is described by the chemical reaction



where the presence of an organic sulfide causes an orange color to develop within the tube's reactive area [6]. Mustard gas, a well-known CWA, is one such sulfide [7].

Use of the thioether CST involves a series of steps; (1) the sealed glass ends are broken along score marks, (2) a hand pump is used to draw a given volume of air sample through the tube, (3) the tube is snapped in half along a score mark, breaking an inner ampule and releasing liquid reactants, (4) the tube is shaken to distribute reactants within a spongiform reaction area, and (5) the sensor result is determined by the color of the reaction area. Currently, this process is conducted manually at the point of use and requires the user to wear full hazmat gear in case of possible exposure (see Figure 1). An automated detection system that could be used at large stand-off distances would reduce the risk to the user and allow for deployment in remote locations that are difficult to reach. While manual operation of the thioether CST is relatively straightforward, the necessity of multiple mechanical actions complicates attempts at automation. The shaking step is particularly challenging; depending on the orientation of the tube and the shaking strength of the device, different shake durations are required to optimally distribute the reactants.

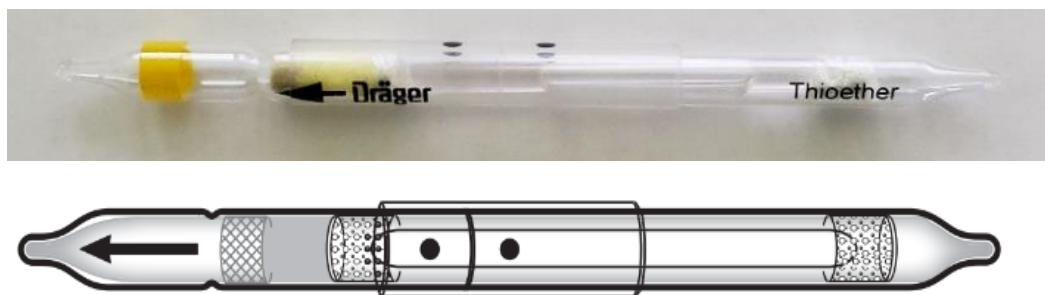


Figure 2: Thioether colorimetric sensor tube used in device design and testing [6].

## Chapter 2

### DEVICE OVERVIEW

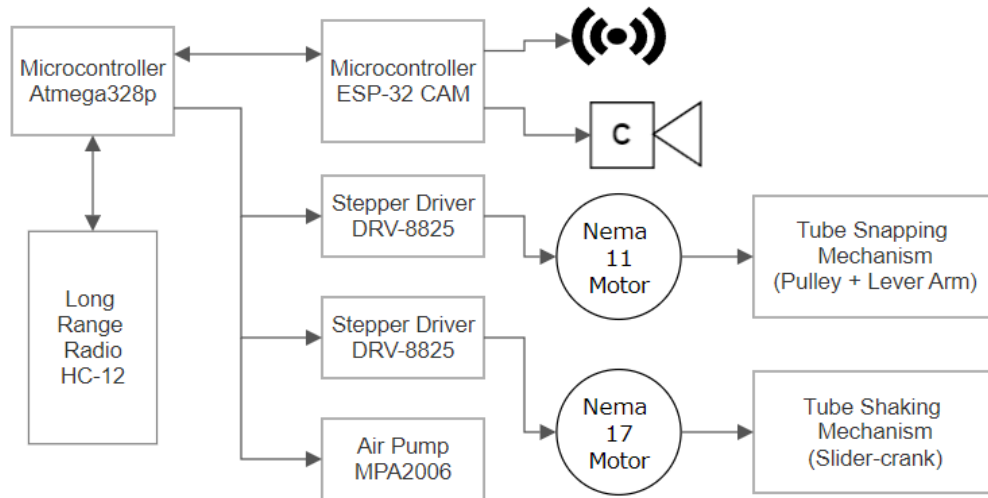


Figure 3: Prototype block diagram.

The device described below was developed to demonstrate the automation of a thioether CST. Design metrics were prioritized in the order of (1) faithful replication of manual operation, (2) minimum size and weight, (3) minimum cost and design complexity, and (4) ease of operation. The overall device design is illustrated in the block diagram of Figure 3. The various subsystems and order of operation are (1) a pump to draw air through the CST, (2) a stepper motor, pulley, and lever arm to snap the CST, (3) a stepper motor and slider-crank mechanism to shake the CST, and finally (4) a microcontroller-connected camera to record and transmit the sensor result.

## Chapter 3

### SUBSYSTEM DESIGN AND TESTING

#### 3.1 Pumping Subsystem

If both ends of a thioester CST have been pre-cut, the first step in its use is to draw a volume of air through the tube. The thioether CST is specified for eight (8) pumps of the supplied hand pump (Figure 4a). This is approximately one liter of total airflow. To automate this step a small air pump (MPA2006) used primarily in home aquariums was used. This 12V air pump was chosen for its balance of size and power (Figure 4b). A balloon was used to experimentally match electric pumping duration to the volume of air moved by eight hand pumps; with an MPA2006 12V pump the required duration is 45 seconds. Air is drawn through the tube rather than forced to avoid contaminating the ambient air within the pump or tubing.



Figure 4: (a) Drager hand pump and (b) 12V air pump.

### 3.2 Snapping Subsystem

After pumping, the CST must be snapped to approximately 45 degrees to release the liquid reactants. A flexible gasket prevents the tube from fully parting. The torque required to snap the thioester CST was experimentally determined; results are listed in Table 1.

Table 1: Snapping torque in N-cm (n = 11)

<b>AVERAGE</b>	<b>160</b>
<b>MAX</b>	204
<b>STD. DEV.</b>	37

To reduce torque requirements, a motor-pulley configuration was used. Because the motor is only in operation for short periods of time, the applied current can safely exceed the maximum ratings. A Nema 11 style stepper motor, when combined with the lever arm shown in Figure 5 and a DRV8825 stepper motor driver configured for maximum current, produced at least 415 N-cm.

Care must be taken to avoid elasticity in the snapping mechanism. Too much elasticity will cause the tube to jerk after snapping, which may result in mechanical failure of the overall glass tube and corresponding loss of measurement. In the demonstrated prototype, the combination of a stepper motor with inelastic string eliminates this possibility.

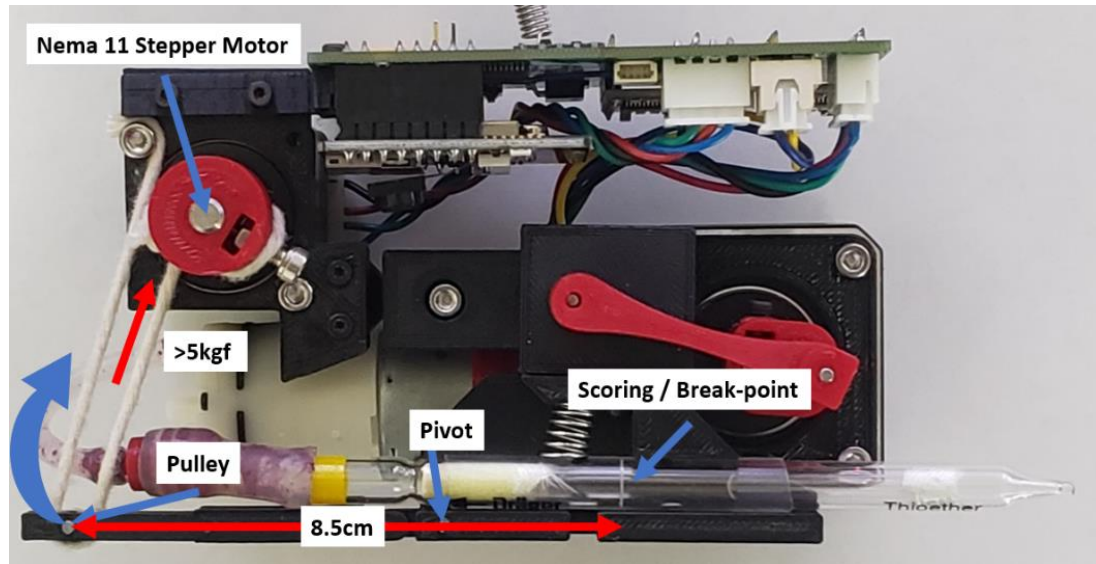


Figure 5: Tube snapping mechanism. The tube is held in place by a friction fit with the shaking mechanism actuator. The shaker motor is energized to hold the tube still.

### 3.3 Shaking Subsystem

The final mechanical step is to vigorously shake the CST. This distributes the reactant liquid throughout a high-surface-area foam to produce the final color change output. When used manually, the CST is shaken until the liquid has visibly transferred and a color front is discernible as in Figure 6. In this design, a stepper motor was used to drive a slider-crank carriage.

The required duration and intensity of shaking varies considerably with angle to the ground and technique but is usually still consistent thanks to visual feedback employed by the operator. Unfortunately, an automated device cannot rely on feedback in this way. In this design, this issue was mitigated through the use of a motion processing unit (MPU) to determine the spatial orientation of the prototype prior to the shaking routine. Depending on how the device is mounted, different

shaking durations and intensities are used to ensure that the CST is not over-shaken, which could result in loss of sensor result.

Because the device is battery operated, there may be situations where a sensor reading is initiated while the battery is depleted or otherwise compromised. The stepper motor and driver used in this design do not provide feedback, so precautions must be taken that the motor does not stall. In this case, an acceleration profile is used to bring the stepper motor up to speed, and a spare analog-to-digital converter (ADC) is used to monitor the effective battery voltage. If the voltage drops too low, the maximum motor speed is reduced in software. While this may slightly offset the CST's color front, it is preferable to complete stalling of the motor, and the shaking duration can be adjusted in software to correct the offset.

In all cases, the microcontroller in charge of the shaking motor keeps track of the step count and ensures that at the end of the shaking cycle the CST is correctly positioned for imaging.



Figure 6: An unprocessed CST (top) and processed CST with slight discoloration in sponge (bottom).

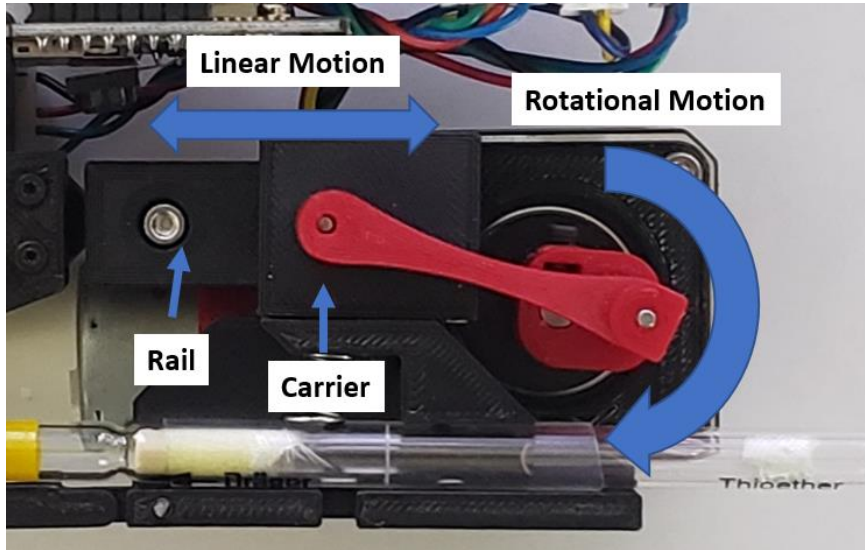


Figure 7: Shaking subsystem.

## Chapter 4

### COMMUNICATIONS AND RESULT DETECTION

#### 4.1 On-board Communication Options

To relay commands to the device and send back sensor data to the user, our prototype is equipped with two wireless communication devices, as well as an exposed I-2C interconnect for wired integration (summarized in Table 2). Sensor processing is initiated by a command signal from the long-range serial link. A rough prototype of a battery-operated control device, shown in Figure 8, was created for testing purposes.

The ESP-32 CAM is used for Wi-Fi communication as well as image capture and image processing. Future prototypes may implement a smartphone application to control sensor operation over Wi-Fi.

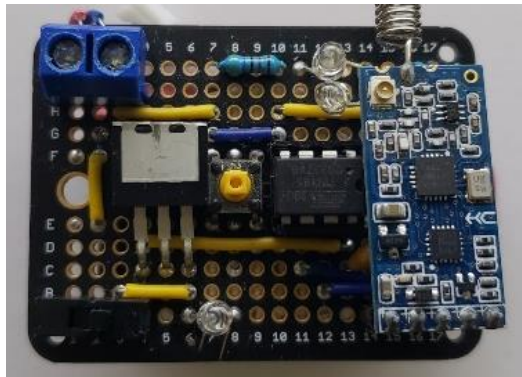


Figure 8: Wireless control module

Table 2: Communication Devices

DEVICE	PROTOCOL	RANGE	USE	UNIMPLEMENTED FEATURES
ATMEGA328P	I <sup>2</sup> C	Wired	Device integration	
ESP-32 CAM	Wi-Fi	~100 ft	Image capture and transmission	Smartphone application
HC-12	Serial	~1 km	Device control Result transmission	Serial image streaming

## 4.2 Image Capture and Processing

Once the mechanical steps have completed the CSTs are imaged with a small camera connected to the ESP-32 CAM microcontroller module to identify if any color change had occurred.

Image data is stored in local flash memory, from which the microcontroller can either upload the image to a webpage/app or perform detection algorithms to estimate sensor results. Currently only raw image data is sent back to the user although a simple color threshold detection algorithm may be an effective method of identifying positive results. We intend to implement this in a future version.

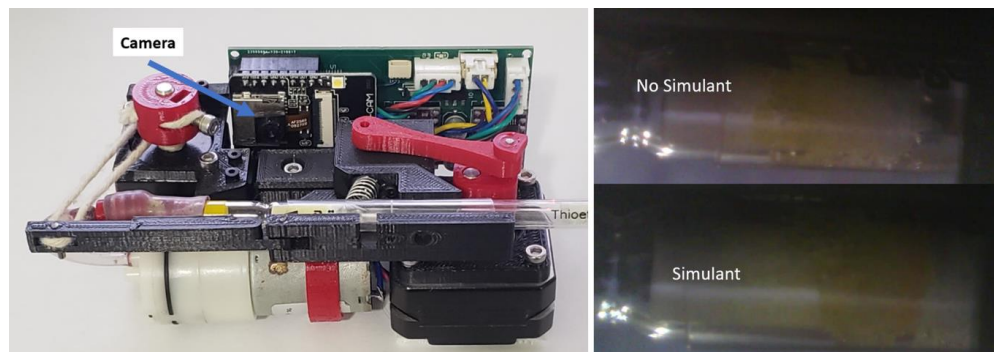


Figure 9: Camera system (left) and imaged CSTs (right). Orange discoloration in the CST that was exposed to simulant indicates a positive result. Visibility is hindered by inconsistent lighting and represents a significant area of improvement for future designs.

## Chapter 5

### SPECIFICATIONS

Table 3: Miscellaneous specifications.

DIMENSIONS	180X80X45 MM
MASS	1kg
NOMINAL VOLTAGE INPUT	12.4V
QUISCENT CURRENT	100mA
PEAK CURRENT	3A
MOTOR CONTROLLERS	Pololu DRV8825
SNAPPING MOTOR	NEMA 11
SHAKING MOTOR	NEMA 17
AIR PUMP	MPA2006
CONNECTIVITY	Wi-Fi, I <sup>2</sup> C, UHF Serial
IMAGE MEMORY	2 Mb
RANGE	~1km
BATTERY CAPACITY	300mAh

## **Chapter 6**

### **DISCUSSION**

The device described in this paper represents a proof-of-concept of the automation of colorimetric sensor tubes. By electromechanically emulating each step of the manual process, results are expected to be indistinguishable from use by personnel directly, while also sparing them from potential exposure to toxic gasses. The device as presented has several notable limitations, including a suboptimal battery life, high noise during operation, and lack of support for sensors other than the Draeger thioether CST, but demonstrates a clear potential for such devices to enable CST use at a standoff distance.

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