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Remote Laboratory for Nuclear Security Education

Anthony R. Galindo

Texas A & M University - College Station

Craig Marianno

Texas A&M University

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Remote Laboratory for Nuclear Security Education

Anthony R. Galindo and Craig Marianno

Texas A&M University

Abstract

Laboratory experiences for online students are very limited. To fill this gap, educators in the Department of Nuclear Engineering at Texas A&M University developed a series of radiation detection experiments for their remote students. Radiation detection is only one piece of nuclear security. The objective of the current research is to describe the development and execution of three online laboratories that investigate the basic application of physical security sensors that use light, ultrasonics, and heat to detect adversaries. This laboratory complements lecture material from the department's Nuclear Security System and Design course. Using the Remote Desktop Application, students connect to a laboratory computer at Texas A&M to control the apparatus and record data. The sensors from a LEGO MINDSTORMS EV3 Education Core set were employed because of their ease of connectivity and their ability to show in a simplistic way how more complex security systems use light, ultrasonics, and heat. Additionally, LabVIEW software was used to control ethernet stepper motors for lateral and rotary motion to move sensors and other apparatus. The three laboratories are described in detail in addition to their learning objectives and results.

Keywords: remote, laboratory, nuclear, security, education, engineering, radiation, detection, sensor

1. Introduction

As demonstrated during the COVID-19 pandemic, remote education capabilities have proven to be an essential component of an institution's services. Transitioning courses and laboratories from the traditional in-person format to an online interface is a challenge; the lack of face-to-face communication and activities that are ordinarily present in a traditional educational setting are now replaced with chat windows, videos,

and conference calls. Effectively shifting a laboratory to an online interface is made more difficult because most of the learning in this setting is traditionally done through hands-on work and functional demonstrations. Additionally, some institutions do not have access to the equipment and materials necessary to complete experiments. For instance, radiation sources are essential for completing radiation detection experiments, but legal, safety, and security realities exist that restrict the ease of access. To work around these restrictions in an educational setting pertaining to nuclear radiation training, researchers at Texas A&M University developed and continue to use remote techniques for online radiation detection laboratories [1]. This institution also wanted to expand this educational platform to include nuclear security laboratories that use sensors that do not include radiation detection.

In nuclear security, the primary functions of a physical protection system are detection, delay, and response. Detection can be incorporated into security systems to track radiation source movement, as well as sensors that use sound, light, and heat to register adversary intrusion. The purpose of this work was to develop a series of online-accessible experiments to explore how sensors can use light and sound to detect and monitor movement. The learning objectives of these laboratories were to provide the students with a basic understanding of how physical security sensors can be used, as well as to demonstrate their limitations. These objectives were accomplished through three experiments: (1) using a light sensor to understand how different materials and colors affect the performance of a physical protection system, (2) using an ultrasonic sensor to ascertain a moving object's velocity, and (3) incorporating techniques from the light and ultrasonic experiments with an infrared sensor to measure the shape of a moving object. These experiments are meant to complement a radiation detection portion of the remote laboratory that was developed by the authors [1]. These remote educational opportunities were expected to provide a basic understanding of a nuclear facility's physical protection system to online students. These simplistic experiments are not meant to match the complexity of actual systems used in security; they are only meant to provide to students a basic understanding of how light and sound can be used for detection.

2. System Components

For remote education purposes, it is essential that the online student is able to move the apparatus to conduct the experiments. For simplicity, only linear and rotational motion was used. This motion was accomplished by using National Instruments' LabVIEW software to control Ethernet stepper motors that were connected to a rotary table and linear actuator. How these components are used to move the apparatus is discussed in detail by Galindo et al [1]. A webcam was connected to the remote system to provide a live video feed for the remote student.

Additional equipment is employed to provide three related physical security experiments that introduce key concepts; these concepts help an individual understand how sensors operate as part of a facility's physical protection system. The sensors employed in these experiments also need an additional support apparatus capable of transmitting and storing data to a host computer. Lastly, video-conferencing software is necessary to

provide the opportunity for collaboration in the remote laboratory, as is normally available in a traditional laboratory setting.

a. Equipment

The LEGO Mindstorms EV3 (LME3) Education Core Set is a system designed to let students explore programming for engineering and robotics applications [2]. The core set includes the Evolution 3 (EV3) Intelligent Brick, three servo motors, five sensors (gyro, ultrasonic, color, and two touch), an EV3 rechargeable direct current battery with a charging cable, connecting cables, and a variety of LEGO assembly parts. The sensors included in the set are not actually employed in security facilities; however, they perform well enough to teach concepts to students. In addition to the core set, the EV3 infrared sensor is used by the remote laboratory for a more-encompassing physical security curriculum [3].

b. Software

LEGO Education developed the EV3 MicroPython programming language, which is an optimized version of Python specific to programming the motors, sensors, and other components [4]. Visual Studio Code is the integrated development environment (IDE) that executes EV3 MicroPython programs and contains the necessary libraries for operation [5]. By creating EV3 MicroPython, LEGO Education provided to students the opportunity to learn fundamental Python programming that is applied to machine learning and artificial intelligence concepts.

The host computer had Visual Studio Code installed on it, which was needed to develop and execute the Python programs necessary for completing the series of remote physical security experiments. LEGO Education developed EV3 MicroPython to be compatible solely with Visual Studio Code, so it is within this IDE that all the accessibility, libraries, and other features exist.

Video-conferencing software is used to allow remote students the opportunity for collaboration found in traditional in-person laboratories. Additionally, video-conferencing software is used to facilitate in-laboratory discussions between a remote student and a teaching assistant (TA) or instructor. To enable these opportunities for virtual collaboration and instruction, the desktop of the host computer is shared to other users using the video-conferencing software, which can then be controlled by all users in the call. This setup allows all students in a group setting the opportunity to use industry-standard software and control the placement of laboratory equipment.

3. Light Sensors for Material Reflectivity

Different colors reflect light in varying ways, with lighter colors reflecting greater amounts of light compared with darker colors. This phenomenon also occurs with different material types; emissive and polished materials will reflect more light than dull and unpolished surfaces. Light from the sun contains wavelengths corresponding to all visible colors to produce an overall white light. Darker-colored objects, in contrast, do not reflect much of the light incident on the surface of the object. Light that is not reflected from a surface is absorbed as heat.

The light sensor experiment was developed to introduce students to scenarios that make use of the color-dependent reflectivity of light. From a security standpoint, light sensors can be used to process images in surveillance applications based on varying intensities of reflected light. Different materials and colors absorb different amounts of light that are retained as heat. By understanding which materials and colors will be the most difficult to image or analyze based on reflection or absorption, proper decisions can be made to supplement any possible inadequacies in a surveillance system with other sensors.

The apparatus of the light sensor experiment, shown in Figure 1, includes the EV3 Intelligent Brick, EV3 Color Sensor, rotary table, foam board layout template, a set of assorted-color 3 × 3 in. (7.62 × 7.62 cm) squares of construction paper, and 3 × 3 in. (7.62 × 7.62 cm) squares of aluminum, copper, and lead. The foam board template has 10 squares with black outlines to show a TA where to place each material. The center of each square is placed equidistantly to ensure a consistent angle separation of 36° as measured on the rotary table. The color sensor was suspended 3 cm over the rotary table. The EV3 Color Sensor was referred to as a *light sensor* for this experiment because it detects the intensity of the reflected ambient light and outputs a value of this intensity in units of lux [2].

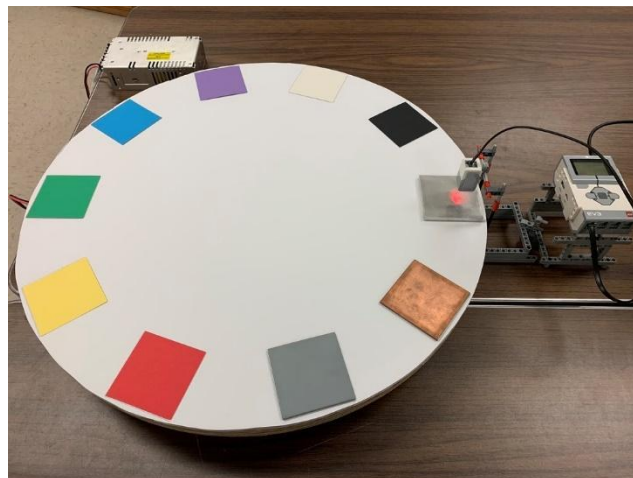


Figure 1. The light sensor experiment apparatus.

The interface to control the rotary table is a LabVIEW Virtual Instrument (VI) with a drop-down menu that lists each material. When a material is selected in the drop-down menu, the corresponding absolute position is used by the motor to position it under the sensor. This interface is shown in Figure 2.

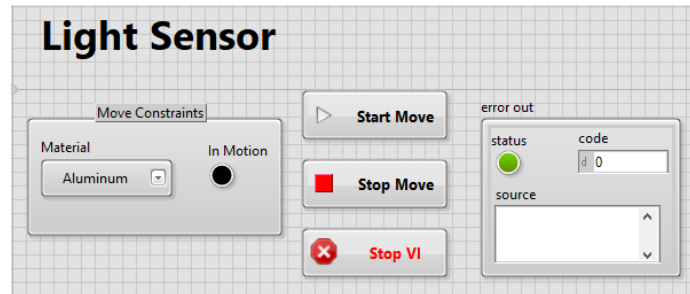


Figure 2. Light sensor experiment LabVIEW VI for controlling the rotary table.

The experiment starts with a light intensity measurement of aluminum. The piece of aluminum is set in place underneath the light sensor so that its ambient light is shining onto the surface. To retrieve data from the light sensor, students need to run a MicroPython program in Visual Studio Code. In preparation for this laboratory, students are assigned a task to prepare a MicroPython program using a detailed instructional video as an aid. This task provides students with an understanding of general Python programming, as well as how sensors collect data according to the code. After retrieving the light intensity value, the student will record the value and cycle the rotary table to the next material. This procedure is repeated until each material has a recorded light intensity value.

After the data are collected, the student calculates a reflectivity ratio of each material normalized to the light intensity value of aluminum. The percent reflectivity of each material is based on the amount of light reflected by aluminum because it reflects the most light out of all the materials tested. The equation for calculating the percent reflectivity is shown in Equation 1, and an example of collected data for the experiment is shown in Table 1.

$$\text{Reflectivity Ratio} = \frac{\text{Amount of Light from Sample}}{\text{Amount of Light from Aluminum}} \times 100\% \quad (1)$$

Table 1. Collected data from a run-through of the light sensor experiment

Material	Light intensity (lux)	Reflectivity ratio (%)
Aluminum	93	100
Copper	58	62
Lead	22	24
Red paper	42	45
Yellow paper	63	68
Green paper	10	11
Blue paper	13	14
Purple paper	34	37
White paper	76	82
Black paper	3	3

Several discussion questions are provided to the student to expand on the concepts they learned, as shown in the following list. For reference, the results of a run-through of the light sensor experiment are shown in Table 1.

- How might materials be difficult to image in a security application?
 - Darker-colored materials would be difficult to detect if there is a collection of shades of dark colors in one area. Analysis would require a much more sensitive sensor to distinguish the varying low-value light intensities from each other. Materials such as aluminum and white paper, which reflect more light, would produce a similar issue but with distinguishing high-value light intensities from each other.
- How would the results change for metallic materials if they were more or less polished?
 - If metallic materials were more polished, more light would be reflected from the surface of the materials, resulting in less heat retained in the material. Polished materials reflect more light because they have a more even, smooth surface. Therefore, the reflected light rays travel parallel to each other away from the surface.

4. Ultrasonic Sensors for Velocity Determination

In security and surveillance scenarios, ultrasonic sensors are advantageous because they register moving objects by sending and receiving ultrasonic sounds. The time between these sound waves is indicative of the distance between the sensor and the object being tracked. Ultrasonic sensors are employed in physical protection systems to register movement. In this laboratory, not only is movement being registered, but data from the sensor are also used to determine velocity.

The ultrasonic sensor experiment incorporates a 3D-printed wall, a linear slide, and the EV3 Ultrasonic Sensor. The wall's base was designed to seamlessly move onto the linear slide's tracks as it travels to and from the ultrasonic sensor. As the wall is moving, the sensor sends and receives ultrasonic sounds to and from the wall using a MicroPython program the student created for the experiment with the supplemental instructional video. The experiment apparatus is shown in Figure 3. The experiment is conducted in parts (A, B, and C), each with a different velocity to determine.

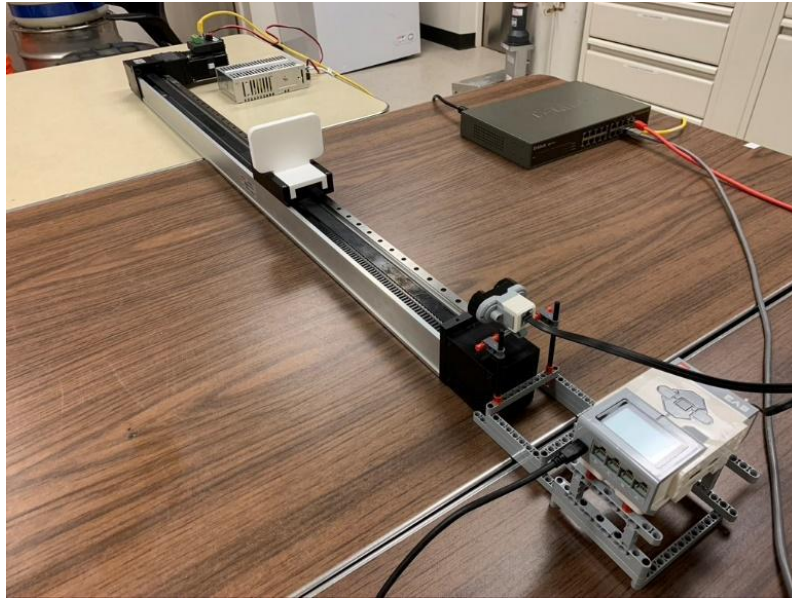


Figure 3. The ultrasonic sensor experiment apparatus.

The experiment begins with the student collecting position vs. time data. The wall is steadily moved approximately 550 mm from position 1 to position 2 on the linear slide using the LabVIEW VI while the MicroPython program simultaneously collects data. When the MicroPython program stops running, columns of time and the corresponding distance measurements are provided to the student in the output. These columns are then recorded in a spreadsheet.

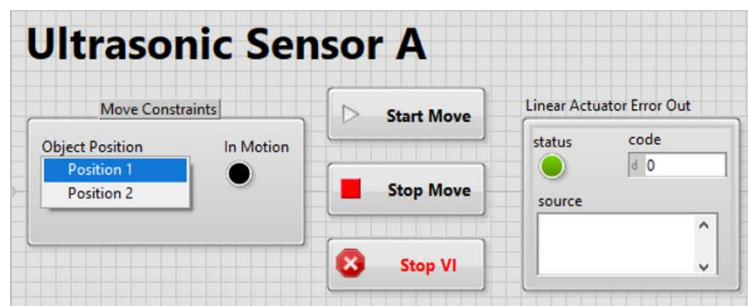


Figure 4. Front panel of the LabVIEW VI for part A of the ultrasonic sensor experiment.

Once the data are in a spreadsheet, the velocity of the wall is determined by plotting the distance measurements with respect to time. With the knowledge that velocity is equal to distance as a function of time, the student is able to ascertain the wall's velocity from the slope of a generated trendline in a plot. The Microsoft Excel LINEST function is used to provide the uncertainty in the slope of the linear trendline. These steps are repeated for parts B and C using their respective LabVIEW VIs. A sample of the produced plots for parts A–C are shown in Figures 5–7, respectively.

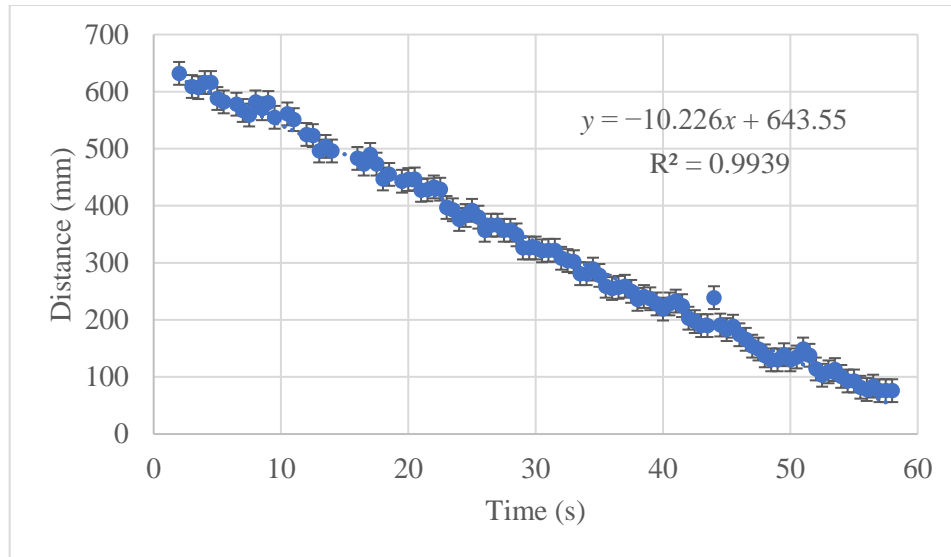


Figure 5. Results from part A of the ultrasonic sensor experiment. Vertical error bars are shown to 2σ to account for the distance measurement uncertainty.

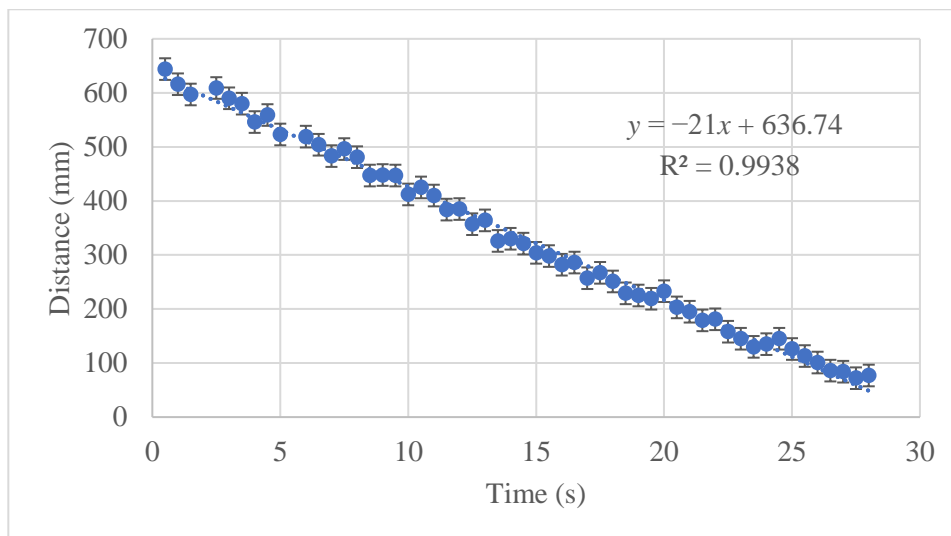


Figure 6. Results from part B of the ultrasonic sensor experiment. Vertical error bars are shown to 2σ to account for the distance measurement uncertainty.

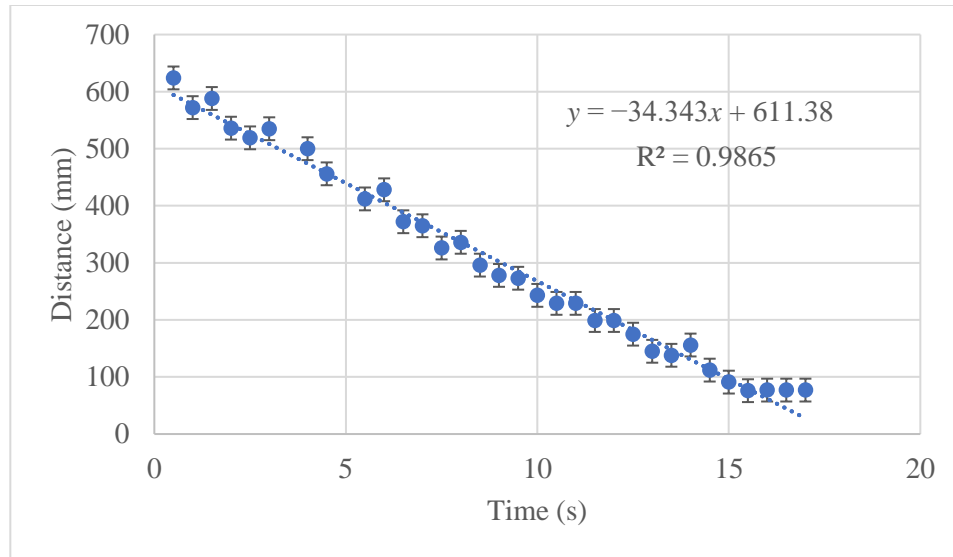


Figure 7. Results from part C of the ultrasonic sensor experiment. Vertical error bars are shown to 2σ to account for the distance measurement uncertainty.

Table 2. Collected data from a run-through of the ultrasonic sensor experiment. Uncertainties are shown to 2σ [6].

Experiment part	Calculated velocity (mm/s)	Expected velocity (mm/s)
A	-10.2 ± 0.16	-10.6 ± 0.25
B	-21.0 ± 0.46	-21.6 ± 0.63
C	-34.3 ± 1.46	-33.0 ± 1.36

Several discussion questions are provided to the student at the end of the experiment as a postlaboratory assignment, as shown in the following list. For reference, the results of a run-through of the ultrasonic sensor experiment are shown in Table 2.

- What does the slope of the line in each plot represent? What does the R^2 value imply?
 - The slope of the line is the velocity of the wall as it traveled toward the ultrasonic sensor, and the R^2 value shows the student that the data closely align with the linear relationship of distance over time.
- Are the calculated velocities statistically equivalent to the expected velocities given by the TA?
 - As shown in Table 2, the experimentally determined velocity values are within 2σ of the actual value, indicating they are statistically equivalent. After the laboratory, the TA will provide the student with the velocity of the object in each part of the experiment. The uncertainty of the ultrasonic sensor was reported to be ± 1 cm [3].
- How could an ultrasonic sensor be programmed to alert a facility when there is movement in a restricted area?
 - This sensor can be used for this capability by implementing conditional statements in the MicroPython program that check whether an object is within a predefined boundary. For instance, if the sensor detects that an

object is 100 cm away with a predefined boundary of 150 cm, the program can alert the user that there has been a security breach and that there may be an unwanted presence in a secure area.

5. Infrared Sensors for Remote Object Measurements

A question at the end of the ultrasonic sensor experiment asks students how an ultrasonic sensor could be used in a security or surveillance application. This question serves as the basis of the culmination of the physical security experiments series. If the velocity of an object is determined, how can its magnitude be used to acquire other quantifiable data? In the infrared sensor experiment, the student will use a known velocity to measure the length of a moving object and the details of its shape.

Infrared sensors function similarly to that of ultrasonic devices in security and surveillance scenarios. Infrared sensors operate by sending an infrared signal toward an object, measuring the reflection of its signal [2]. Whereas ultrasonic sensors can more generally determine that motion is occurring in a large area, infrared sensors must be closer to the object of interest. A scenario presented to the student is an unattended monitoring system supplemented with an infrared sensor placed at a key measurement point (KMP) between two material balance areas (MBAs). This tool could help automatically verify material inventory by tracking movement from one MBA to another. If itemized forms of nuclear material, such as storage tanks or containers, were transported between the two MBAs on a conveyor belt of a known speed, the length and number of the objects being transported could be determined based on the total amount of time that the infrared sensor detects each object. Even without a conveyor belt with a known speed, an ultrasonic sensor could be used to determine the speed of the objects as they are moved between MBAs before being used for object measurement.

The infrared sensor experiment aligns well with the scenario of the KMP between two item MBAs. In this experiment, an irregularly shaped, comb-like object was designed for the linear slide. For the purposes of this experiment, the object was called the *comb wall*. When executing the laboratory, the comb wall would pass by the infrared sensor at a known velocity, which was determined in Part A of the ultrasonic sensor experiment. The infrared sensor was placed 2 mm away from the comb wall. The apparatus is shown in Figure 8. This experiment operates using a single infrared sensor to give a 1D measurement of the object based on the device's proximity readings. If possible, a grid of infrared sensors would give a more-encompassing 2D measurement of objects passing through the KMP to estimate the length and height of the passing objects; however, this experiment only uses a single infrared sensor for simplicity.

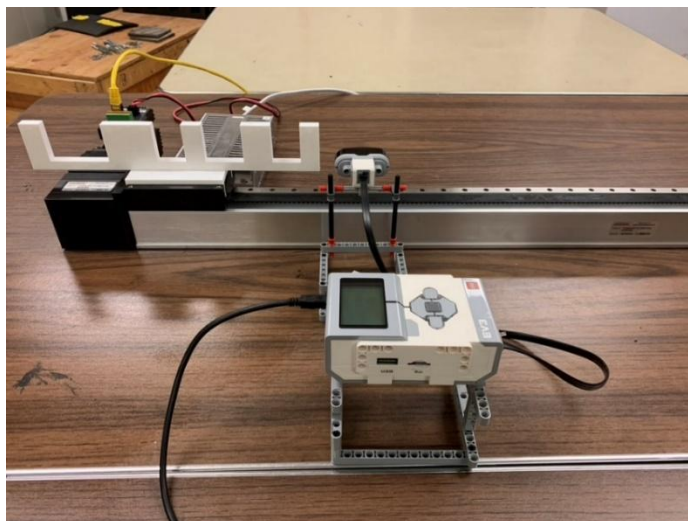


Figure 8. The infrared sensor experiment apparatus.

By completing this experiment, the student can recognize the importance of material reflectivity as they learned in the light sensor experiment. Because infrared sensors operate by detecting reflected light, the type and color of the material of the transported items affects the performance of the infrared sensor. Thus, the comb wall was designed to be white to reflect light back more effectively to the infrared sensor. Another trial of the experiment is performed by the student using a black comb-like object. This shows the operational difference in how the infrared sensor responds to a change in color. Because the black object absorbs more of the infrared light, less light returns to the sensor, resulting in skewed measurements.

In this experiment, the student will develop a MicroPython program to collect data from the infrared sensor with the aid of an instructional video. To begin, a “time_step” variable is set to define how often to retrieve a distance value from the infrared sensor in units of milliseconds. In the ultrasonic sensor experiment, the time step was held constant throughout each of the three parts. For this experiment, however, the time step is the variable changed in parts A–C to show the student how results are affected by the frequency with which measurements are taken.

The experiment begins with the student ensuring the correct starting position of the comb wall. Using the LabVIEW VI interface shown in Figure 9, the student selects “Position 1” in the object position drop-down menu for the linear slide to position the comb wall at its starting point on the left-hand side of the infrared sensor. The wall is moved from position 1 to position 2 with the same velocity as in part A of the ultrasonic sensor experiment. The MicroPython program is simultaneously running in Visual Studio Code to collect data. When the student’s program stops running, columns of time and the corresponding distance measurements are generated. The student recorded the results in a spreadsheet that was prepared before beginning the experiment. These steps are repeated for parts B and C with time step values of 200 ms and 100 ms, respectively.

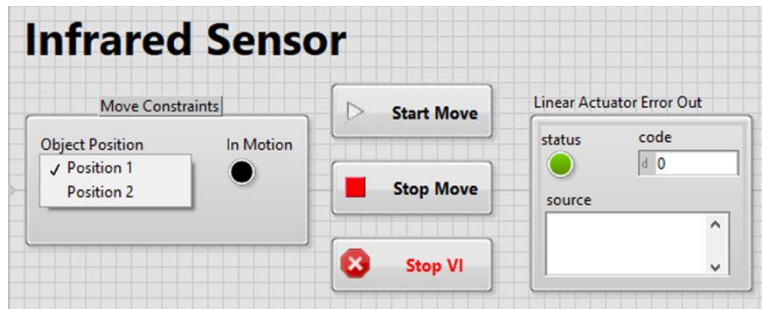


Figure 9. Front panel of the LabVIEW VI for the infrared sensor experiment.

The length of the comb wall and its constituents are determined based on the Boolean values of each distance measurement. Boolean values are used for expressions that have a yes or no answer, where an outcome of “true” is typically assigned a value of 1 and an outcome of “false” is typically assigned a value of 0. If a constituent of the comb wall reflects light to the sensor at a certain time, then the distance measurement for that time will be 0, the Boolean value will be “true,” and a value of 1 will be assigned. Alternatively, if there is a gap between the comb wall’s teeth, the distance measurement will be greater than 0, the Boolean value will be “false,” and a value of 0 will be assigned. This distance threshold can be adjusted based on the application, such as if the infrared sensor needs to be positioned further away from the moving object. In the spreadsheet, a new column will be created for the values of 0 and 1. In each cell, an IF function is used to identify whether a constituent of the comb wall is present or absent for certain periods of time. Once this column is created and values of 0 and 1 are assigned to each distance measurement, a scatter plot of assigned values with respect to time shows the overall shape of the moving object; this plot is shown in Figures 10–12. Visual shifts occur along the x-axis in these plots because of the difference in time for when the MicroPython program was initiated with respect to when the comb wall began its travel; however, this issue has no effect on the results. Looking at Figures 10–12, there is also a noticeable change in the shape of each constituent. As the time step is decreased, the infrared sensor retrieves distance measurements much more frequently. Therefore, the shape of each constituent becomes less trapezoidal and more rectangular because the infrared sensor detects the presence of the start and end of each constituent sooner.

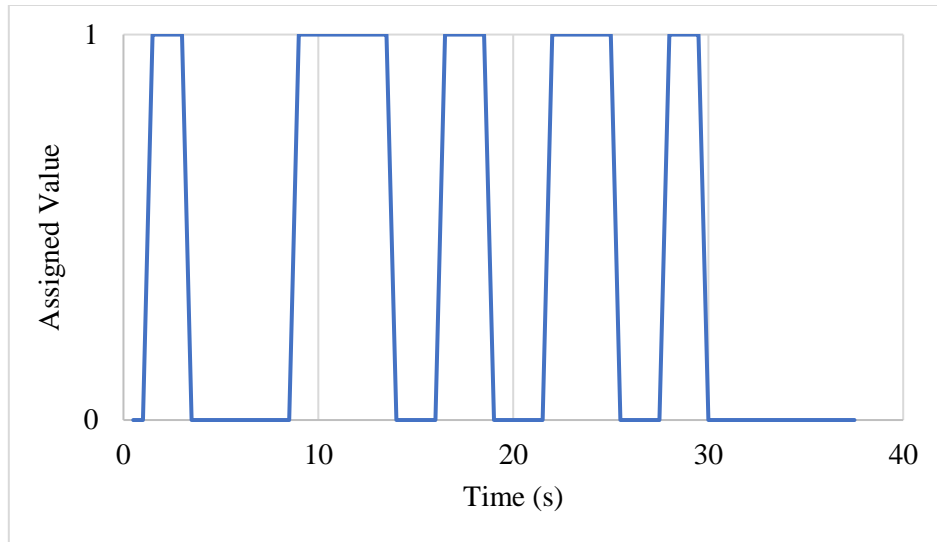


Figure 10. Example plot showing the overall shape of the comb wall using a time step of 500 ms.

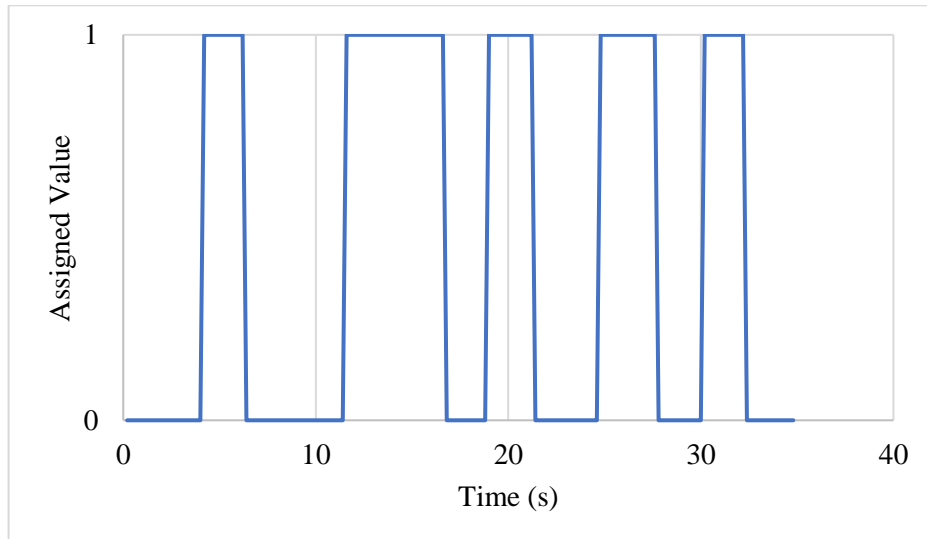


Figure 11. Example plot showing the overall shape of the comb wall using a time step of 200 ms.

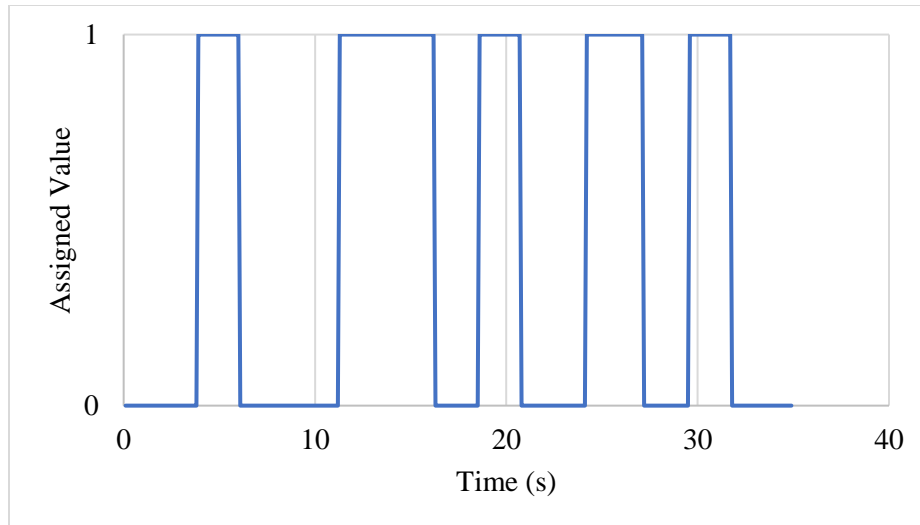


Figure 12. Example plot showing the overall shape of the comb wall using a time step of 100 ms.

Next, the student is directed to determine the length of each constituent. This task is accomplished by multiplying the amount of time that each constituent was detected by the velocity of the linear slide as determined in part A of the ultrasonic sensor experiment. This calculation results in an estimate of the length of the constituent, and it is then repeated for the remaining four regions of interest (ROIs). The student is also advised to propagate the error from the velocity found in the ultrasonic sensor experiment. The students will compare their calculations with the actual width of each ROI. They will be instructed to discuss any discrepancies between their results and the expected measurements, as well as how they would improve their measurements in the future.

Table 3. Collected data from a run-through of the infrared sensor experiment. Uncertainties are shown to 2σ .

ROI	Actual measurement (mm)	Estimated measurement for part A: 500 ms time step (mm)	Estimated measurement for part B: 200 ms time step (mm)	Estimated measurement for part C: 100 ms time step (mm)
1	20.19 ± 0.04	14.49 ± 0.53	19.32 ± 0.70	20.29 ± 0.74
2	30.19 ± 0.04	24.15 ± 0.88	28.98 ± 1.05	28.98 ± 1.05
3	20.25 ± 0.04	19.32 ± 0.70	19.32 ± 0.70	20.29 ± 0.74
4	50.10 ± 0.04	43.47 ± 1.58	46.37 ± 1.68	47.33 ± 1.72
5	20.04 ± 0.04	19.32 ± 0.70	19.32 ± 0.70	19.32 ± 0.70

Several questions are asked to the student as a postlaboratory assignment, as shown in the following list. For reference, the results of a run-through of the infrared sensor experiment are shown in Table 3.

- How are the results affected by the change in the time step value?

- The majority of the constituents had an improvement in the estimation of their length as the time step was decreased. This result is expected because the infrared sensor retrieved distance measurements much more frequently as the time step decreased. Therefore, the calculated results became more accurate because the increased number of steps meant that the infrared sensor made measurements closer together.
- Is there a disadvantage associated with decreasing the time step?
 - There are going to be limitations with respect to how often any sensor can retrieve data. This limitation is a result of a dead time that affects sensors similarly to that of radiation detectors. Much like the limit to how quickly a person can contract their muscle after a previous contraction, the dead time is the amount of time in which some sort of event cannot be completed or recorded. Eventually, the time step will reach this limit, and the sensor will not be able to retrieve data at that frequency.
- How do the estimated measurements compare with the actual measurements?
 - Three of the ROIs eventually had estimated measurements that were statistically equivalent to the actual measurements with the time step of 100 ms in part C. This measurement can be improved by continuing to decrease the time step until the actual and estimated measurements are within 2σ for all ROIs.

The same procedures can be used to complete an additional version of this experiment with a black comb wall. This structure is shown in Figure 13, has the same dimensions as the white comb wall, and is placed the same distance away from the infrared sensor. The purpose of this supplementary portion of the experiment is to demonstrate material reflectivity and how it affects data collection for physical protection systems.



Figure 13. The black comb wall used for a supplementary portion of the infrared sensor experiment.

Table 4. A sample of raw data from the white and black comb wall versions of the infrared sensor experiment using a time step of 500 ms. This sample corresponds to the first constituent of the comb wall.

Time (s)	Proximity with white comb wall (cm)	Proximity with black comb wall (cm)
0.5	61	100
1	51	100
1.5	38	100
2	27	100
2.5	21	100
3	16	100
3.5	12	100
4	4	74
4.5	0	20
5	0	16
5.5	0	16
6	0	19
6.5	0	47

A sample of the raw data collected by the infrared sensor using both the white and black comb walls is shown in Table 4. A comparison of the two columns of data shows that the infrared sensor registered the black comb wall further away from the sensor than the white comb wall. The reason for this phenomenon is that the reflectivity of the black material is substantially lower than that of the white material. This lower reflectivity causes more infrared light from the infrared sensor to be absorbed by the comb wall as heat. Because this light becomes lost from the system, it is unable to be reflected to the sensor. The infrared sensor then confuses the lost infrared light as light that is being reflected off an object that is farther away than it is, resulting in the measurements not approaching 0 mm. Despite the lack of physical contact between the sensor and the comb wall, the distance measurements reach 0 mm with the white comb wall because of the material's high reflectivity and actual separation distance of 2 mm. Lastly, another notable observation is that the proximity measurements decrease gradually with the white wall. This decrease is because infrared signals are emitted in all directions, so as the wall approaches the sensor, the emitted infrared signals are gradually reflected to the sensor. This results in a gradual decrease in proximity measurements for that wall. The black wall, however, absorbs the emitted infrared signals as it approaches the sensor. This absorption results in the black wall being able to sneak up on the sensor because it does not contribute to a gradual decrease in proximity measurements. The culmination of the physical security experiments results in the student experiencing firsthand how the light reflectivity of various materials will affect measurements when using light-emitting sensors. With this experience, students will be able to recognize scenarios in which the material type, velocity, and dimensions of an object will all need to be considered.

6. Conclusion

A remote laboratory was developed to provide nuclear security education and training to students and professionals. Beginning with the remote laboratory for radiation detection education, a series of physical security experiments was developed to provide a nuclear security component to the remote laboratory. The experiments explored fundamental concepts for understanding how sensors are used in a facility's physical protection system. Using custom-made components, a rotary table, and a linear slide, the concepts of light reflectivity, motion sensing, and remote object measurement were taught in a distance-learning laboratory setting. After completing the experiments, the student will have gained an understanding of how material properties affect the measurements taken by light-emitting sensors, as well as how motion sensing can complement the function of an infrared sensor.

7. References

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