SANDIA REPORT
SAND2020-9029
Printed August 2020

Sandia National Laboratories

Optical Engine Lockout System Design and Operation

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ABSTRACT

Engine run days in the Diesel Combustion and Fuel Effects Lab are hectic. The long mental lists that must be kept by engine operators, paired with the tight time constraints between experiments, can cause operational issues that may be dangerous to personnel and/or cause damage to test equipment. Until now, a paper sign has been used to warn operators not to motor the engine when a foreign object has been placed inside of it. Unfortunately, this simple administrative control has failed in the past, motivating this effort to develop an improved system. The lockout system described in this document introduces an engineering control that, when activated, actually prevents the engine from being motored. The new system consists of a primary and a secondary control panel. Prior to an operator placing a foreign object into the cylinder, they press a button on the secondary control panel near the engine. This breaks the interlock circuit for the engine dynamometer and activates LEDs on both control panels to notify operators that a foreign object is present within the engine cylinder. Once the work is done and all foreign objects have been removed from the combustion chamber, two operators must be present to disable the system by simultaneously pressing the buttons on the primary and secondary control panels. Requiring a second operator to disable the system increases accountability and reduces the likelihood of potentially costly mistakes.

ACKNOWLEDGEMENTS

I would like to thank Dr. Charles Mueller and Dr. Drummond Biles for taking time out of their busy schedules to provide me with guidance and to review my writing. Their advice and insights throughout this project greatly facilitated the design process, and improved my ability to problem-solve as an engineer. It was a pleasure working with them both.

I would also like to thank Sandia, the SULI program, and Dr. Christopher Shaddix for organizing and extending this internship opportunity to me. Their efforts to provide a quality internship program amid a global pandemic is truly impressive and is greatly appreciated.

FUNDING

Funding for the research and development of this project came from the Department of Energy's Science Undergraduate Laboratory Internships (SULI) program, facilitated by Sandia's Program Administrator, Dr. Christopher Shaddix.

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EXECUTIVE SUMMARY

The purpose of the optical engine lockout system is to notify operators and prevent engine operation when foreign objects, such as calibration tools, are present within the cylinder. The system consists of two indication/control panels connected to the existing engine interlock circuit. The primary control panel is located near the engine controls, while the secondary control panel is located near the engine itself. The lockout system is activated when the operator presses the button on the secondary control panel. Upon activation, the engine interlock circuit is broken, disabling the dynamometer that is used to run the engine. Deactivating the lockout system requires two operators, and is accomplished by pressing the buttons on both control panels simultaneously.

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
DPDT	Double Pole Double Throw
IC	Integrated Circuit
LED	Light Emitting Diode
NPN	Negative Positive Negative
SULI	Science Undergraduate Laboratory Internships

1. SYSTEM OVERVIEW

The primary control panel (box on the left in Figure 1-1) is mounted near the optical engine controls (see Figure 1-2). It houses the Arduino microcontroller, the interlock relay, and the override system. The front side of the control panel includes LED indicators for power, interlock, and override status. Below the LED indicators is a button, used to open and close the interlock circuit. The back side houses the override switch along with ports for power input, connection to the secondary control panel, and connection to the interlock circuit.

The secondary control panel (box on the right in Figure 1-1) is mounted near the engine itself (see Figure 1-2), and includes the same button and LED indicators as the primary panel. The back side of the panel houses a single port which connects it to the primary control panel.

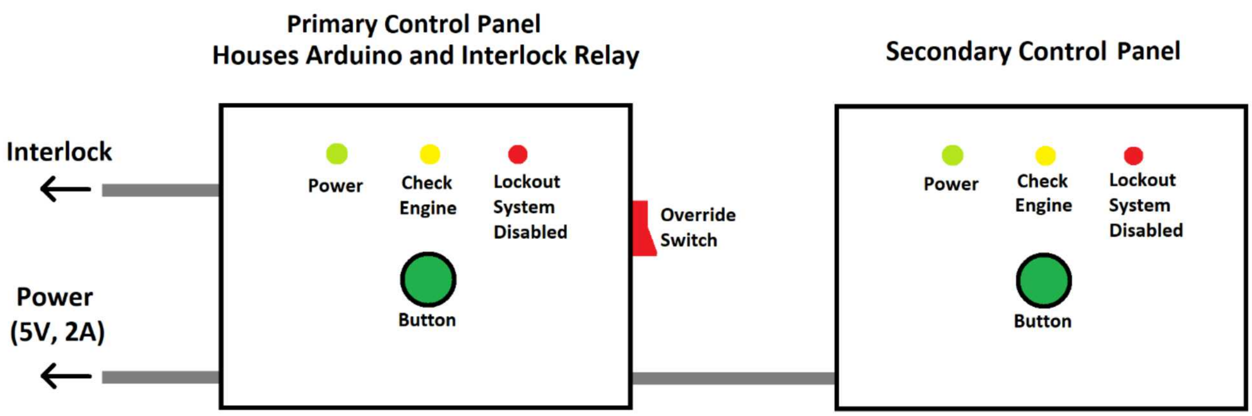

Figure 1-1. Lockout System Diagram

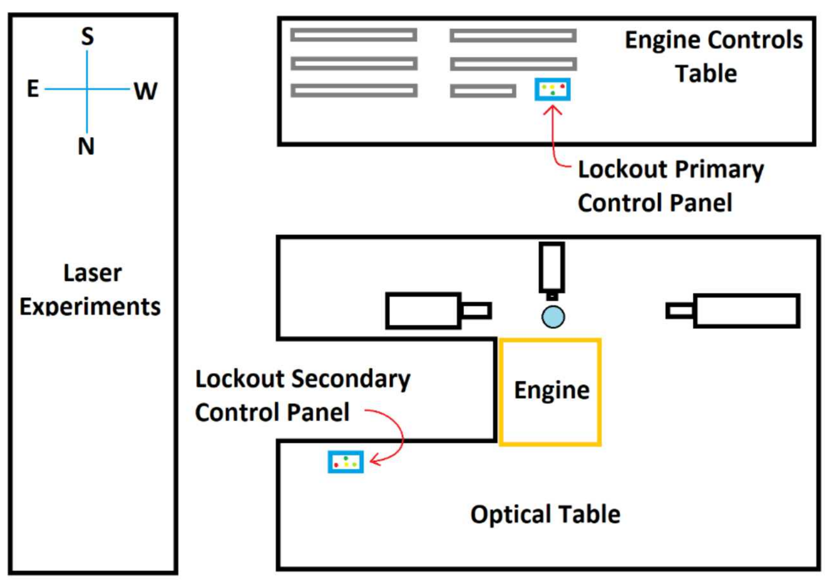

Figure 1-2. Lockout System Control Panel Locations

2. COMPONENT LIST

The components used to create this system were sourced from various manufacturers through McMaster-Carr (www.mcmaster.com) and Digi-Key (www.digikey.com). A list of all of the necessary components is tabulated below.

Table 2-1. Parts Sourced from McMaster-Carr

Description	Part #	Qty.
Plastic 22 mm Panel-Mount Switch	6749K34	2
Wall Power Adapter 5V, 2A, 2.1mm tip	70235K129	1
2.1mm Barrel Connector	8320N115	1
18-8 Stainless Steel Hex Nut	91841A115	1 pack
Passivated 18-8 Stainless Steel Pan Head Phillips Screw	91772A102	1 pack
Stranded Wire 22 Gauge, 25 Feet Long	8054T13	1

Table 2-2. Parts Sourced from Digi-Key

Description	Part #	Qty.
Arduino Nano with Headers	ABX00033	1
Buzzer (Audio Piezo Transducer 1-30V)	PT-3110P-05Q	1
BOX ALUM BLACK 6.02"L X 3.27"W	1590WP1FLBK	1
BOX STEEL BLUE 6"L X 6"W	1458C4B	1
Breadboard	PRT-12070	1
0.1 uF Capacitor	C322C104K5R5TA7301	2
10 uF Capacitor	C324C106K3R5TA	1
15 pin Headers	PPPC151LFBN-RC	2
Mini-Con-X Male Plug	6282-6PG-3DC	3
Mini-Con-X Female Receptacle	7282-6SG-300	3
Resettable, Low Frequency Oscillator (LTC6991)	LTC6991IS6#TRMPBF	1
LED Green Diffused	SSL-LX5093GD	2
LED Yellow Diffused	SSL-LX5093YD	2
LED Red Diffused	SSL-LX5093ID	2
330 Ohm Resistor (1/4 W, <5%)	CF14JT330R	6
2.4 kOhm Resistor (1/4 W, <5%)	CF14JT2K40	1
10 kOhm Resistor (1/4 W, <5%)	CF14JT10K0	2
75 kOhm Resistor (1/4 W, <5%)	MFR-25FBF52-75K	1
280 kOhm Resistor (1/4 W, <5%)	MFR-25FBF52-280K	1
500 kOhm Resistor (1/4 W, <5%)	HHV-25JR-52-500K	1

Description	Part #	Qty.
681 kOhm Resistor (1/4 W, <5%)	MFR-25FBF52-681K	1
1 MOhm Resistor (1/4 W, <5%)	MFR-25FBF52-1M	1
Nylon Spacers	9913-250	16
Normally Open Solid State Relay	CMX60D5	1
SMT to DIP Adapter	PA0180	1
DPDT Rocker Switch	R5CBLKREDEF0	1
NPN Transistor	PN2222ATA	1
6-Wire Oil Resistant Cable	CF211-05-03-02	30 ft

3. CIRCUIT

This section covers internal component function and interconnection. The lockout system is controlled by an Arduino Nano microcontroller along with button and switch inputs from the operators. All of the logic components are housed within the Primary Control Panel, while the Secondary Control Panel simply houses the status indicator lights and control button. A complete circuit diagram is shown in Figure 3-1.

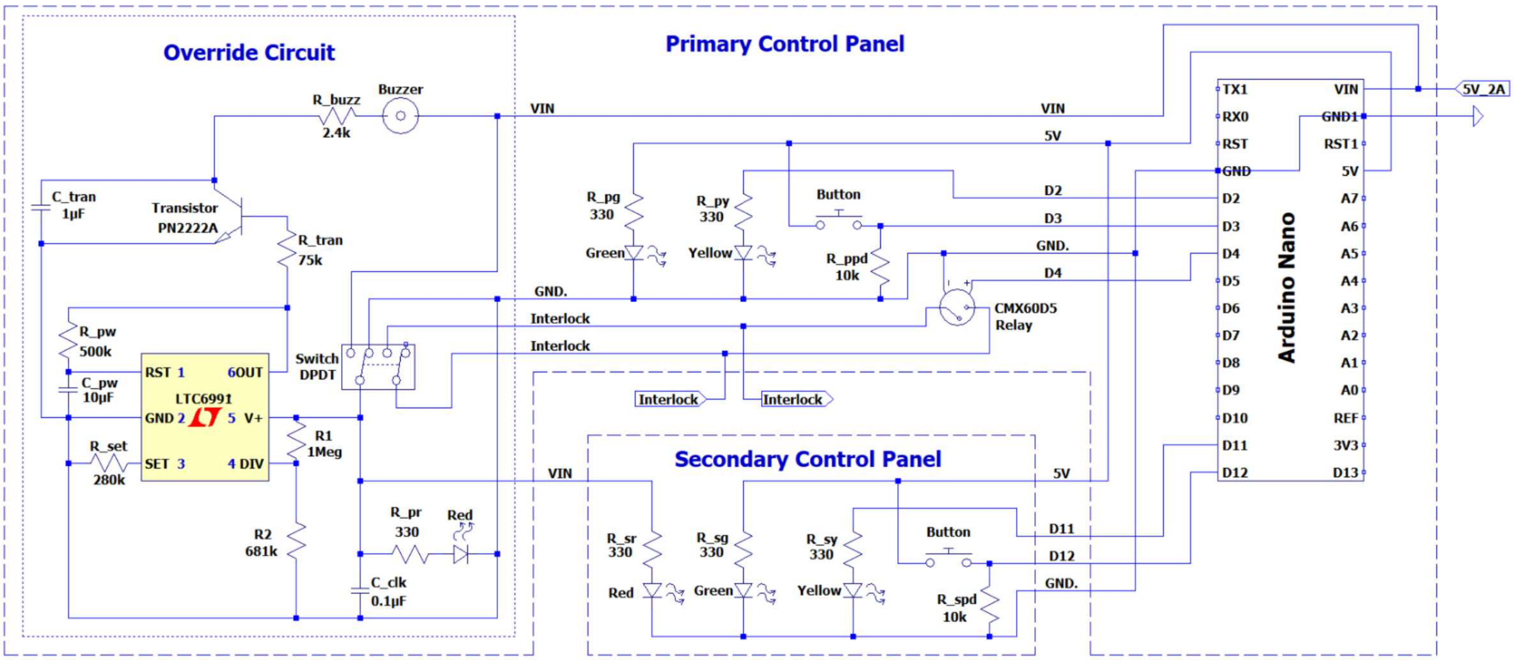

Figure 3-1. Circuit Diagram

3.1. Primary Control Panel

The primary control panel, located near the engine controls, houses the Arduino Nano, the interlock relay, a button, 3 LEDs and the override circuit.

3.2. LEDs

The green LED is a power indicator. Whenever the Arduino is powered on and outputs voltage through its 5V pin, the green LED will be on. The yellow LED indicates the status of the interlock. It is controlled by one of the microcontroller's logic pins. The red LED is an override status indicator. When the system is in override mode, the red LED will be on. The red LED is wired directly between the voltage input (VIN) and ground, and will function properly even if the Arduino is disconnected.

3.3. Button

The button is used to indirectly open and close the interlock circuit. It is wired between the Arduino's voltage output pin (5V) and one of the logic pins. When the button is not pressed, the logic pin is connected to GND through the 10kΩ pull-down resistor, and the Arduino reads a "LOW" signal. When the button is pressed, the logic pin is momentarily connected to the 5V pin, and reads a "HIGH" signal.

3.4. Relay

The relay is used to directly open and close the interlock circuit. The particular model used here is a CMX60D5 produced by Sensata. It is solid state, is normally open and is isolated from the Arduino circuit thanks to an internal optoisolator. [1] An Arduino logic pin is used to control the relay. When a 5V "HIGH" signal is established across the relay's CONTROL pins, the relay LOAD pins form a closed circuit. When a 0V "LOW" signal is established across the relay's CONTROL pins, the LOAD pins remain open circuit.

3.5. Override Circuit

While the override circuit is housed in the primary control panel along with the Arduino, the two are otherwise not connected in any meaningful way. The override circuit is designed to be isolated from the rest of the system so that it may function even if the rest of the lockout system fails completely.

3.6. DPDT Switch

The switch is used to simultaneously close the interlock circuit and activate the override notification system. A double pole double throw (DPDT) switch was chosen to isolate the interlock circuit from the lockout system. When the switch is moved to the "on" position, the red LEDs illuminate, and the LTC6991 integrated circuit (IC) is powered on.

3.7. LTC6991 Timer and Buzzer Circuit

The LTC6991 is a resistor-programmable low frequency oscillator produced by Analog Devices. It has a period range of 1ms to 9.5 hours, and can be reset in order to modulate pulse width. Details on how to program this IC can be found on its datasheet.[2] The resistors and capacitors chosen in this case set the period to 1,503 seconds (~25 min), and the pulse width to roughly 5 seconds. This pulse is used to switch on an NPN transistor (PN2222ATA by ON Semiconductor), which in turn passes current from the main voltage input, through a 1 kHz buzzer. Along with the red LED indicator, the recurring 5 second tone is used to remind the operators that the override system is active, and that the lockout system interlock will not be able to protect the engine.

3.8. Secondary Control Panel

The secondary control panel, located next to the optical engine, serves to notify operators of the lockout system status and to open and close the interlock. It shares the same button and LED layout as the Primary Control Panel, but only has one cable exiting its back face. This cable connects it to the power line and Arduino logic pins held within the Primary Control Panel. The LEDs and button serve the same functions as they do in the Primary Control Panel. The Secondary Control Panel exists in order to ensure that two people must be present to disable the lockout system, therefore increasing accountability.

4. OPERATION AND PROCEDURE

4.1. Standard Operation

When the system is powered off, the interlock circuit is kept open by default. After powering the system on, the green "Power" light will turn on and the yellow "Check Engine" light will start blinking slowly, indicating that the interlock circuit is open. In order to close the interlock circuit, the operators must simultaneously press the button on the primary control panel and the button on the secondary control panel for at least two seconds. If successful, the yellow "Check Engine" lights on both control panels will blink ten times quickly, and then turn off. The microcontroller will then send power to the relay in the primary control panel, and the relay will close the interlock circuit. To open the interlock circuit, the operator must press the secondary control panel button (close to the engine) for two seconds. The "Check Engine" lights will blink ten times quickly to indicate the successful detection of the button push and the relay will open the interlock circuit. The "Check Engine" lights will then continue to blink slowly to remind the operators that the lockout is active.

4.2. Standard Operating Procedure

1. Before placing an item into the engine cylinder, press and hold the button on the Secondary Control Panel (near the engine) for at least two seconds. Release the button when the "Check Engine" light begins to blink quickly. This indicates that the interlock circuit will be broken. After ten fast blinks, the "Check Engine" lights will continue to blink slowly until the lockout state is cleared as described in Step 4 below.
2. Proceed with in-engine cleaning/calibration tasks.
3. Before raising the cylinder liner for the last time prior to running the engine, double check that all foreign objects have been removed from the cylinder.
4. To close the interlock circuit, first ask a colleague to confirm that all foreign objects have been removed from the cylinder, reminding them that they are accountable for ensuring the safe operation of the engine. If the engine is confirmed to be safe to operate, have them press and hold the button on the Primary Control Panel. At the same time, press and hold the button on the Secondary Control Panel. After two seconds of the buttons being pressed simultaneously, the "Check Engine" lights will blink ten times fast, before turning off.

Note: A 10 second cool down period begins when the lockout system opens or closes the interlock. The lockout system buttons will not function during the cool down period. This feature is meant to avoid inadvertent opening or closing of the interlock in the case that the operators hold the buttons for too long.

4.3. Override Operation

In the case of a lockout system failure, the override switch located on the back of the Primary Control Panel can be flipped to manually close the interlock circuit. When the switch is flipped, the red "Lockout System Disabled" light will turn on, and a 1 kHz buzzer will sound for 5 seconds every 20-25 minutes, reminding the operators that the override system is active. When the red light is on, the other indicator lights should be disregarded, and the engine cylinder should be checked before operation of the dyno. Once the issue with the lockout system is resolved, the switch can be flipped back to its original position to set the lockout system back to regular operation mode.

4.4. Override Operation Procedure

In a case where the lockout system is malfunctioning in some way, but an engine run must be conducted, the operators should adhere to the following procedure.

1. Flip the override switch, located on the back face of the Primary Control Panel (near the engine controls), to the “on” position. A lit red LED and five-second tone will indicate that the override system is active, and the interlock circuit is closed. The five-second tone will repeat every 20-25 minutes to remind the operators that the engine is unprotected by the lockout system.
2. Take special care to use the “Parts Inside Engine, Do Not Run (At Least Think First)” signs to indicate when foreign objects are present within the engine cylinder.
3. After cleaning or calibration tasks but before running the engine, take special care to ensure that all foreign objects have been removed from the engine cylinder before raising the cylinder liner. Also remove the “Parts Inside Engine, Do Not Run (At Least Think First)” signs.
4. Repair the lockout system as soon as possible.
5. Upon successful repair, flip the override switch back to its original position, and test the system by performing a dry run of the standard operating procedure.

5. CONCLUSION

By implementing the system described in this paper, the lab transitions one of its safety mechanisms from an administrative control to an engineering control. The previous procedure involved posting two warning signs before placing objects within the engine cylinder, then remembering to take down the signs when the items were removed. This method was inconvenient, unreliable, and did not provide robust protection. In contrast, the Optical Engine Lockout System is easily activated, requires two people to deactivate (increasing accountability), and connects directly to the existing engine interlock system, meaning the engine will not run while a lockout condition is in effect. Additionally, the Lockout System can be overridden if any of its internal components fail. In this case, engine operators can cautiously proceed with their experiments with little downtime, returning to the previous safety procedure until the Lockout System is fixed. In conclusion, the new system is safer, more convenient, and will not negatively affect the progress of an experiment in the case of failure.

6. RECOMMENDATION FOR FUTURE IMPROVEMENT

When it comes to preventing engine operation while items are present within the cylinder, the current version of the Lockout System only accomplishes a partial shift from administrative control to engineering control. Operators must still follow a procedure in order to benefit from the system's safety features. An ideal system would be fully automatic and would break the interlock circuit at an appropriate time without any conscious input from the operator. A possible solution is to use one of the cylinder liner hydraulic control buttons to activate the lockout notification system and break the engine interlock circuit. This can be accomplished in a few ways. One example would be to create a separate interlock circuit between the Arduino and a button cover with electrical contacts. This interlock circuit would be closed when the button cover is closed, and would be broken when the button cover is open. Arduino logic pins could be used to detect the state of the button cover. When an operator uses the hydraulic control button, say to open the cylinder liner and access the engine, the Arduino could be programmed to activate the notification system and break the engine interlock. This system would likely require an extra wire to be run between the two control panels, so it is recommended that the initial system be built with six-wire cable instead of five-wire cable to accommodate this change should it be implemented in the future.

REFERENCES

[1] Sensata Technologies, CMX Series PCB Mount Datasheet, <https://www.sensata.com/sites/default/files/media/documents/2018-04-30/ourproducts_cmx-series-dc-pcb-mount_datasheet.pdf> (Accessed July 30, 2020).

[2] Analog Devices, LTC6991 TimerBlox: Resettable, Low Frequency Oscillator, <https://www.analog.com/media/en/technical-documentation/data-sheets/LTC6991.pdf> (Accessed July 30, 2020)

APPENDIX A. ARDUINO CODE

```
/*  Optical Engine Lockout System
    Revision 2
    Author: Vittorio Martinet

    Changes:
    Revision 2:
      Modified code to work with pins specified in the wiring diagram
      Changed variable names for clarity
      Add more comments
      Add deactivation cool-down so system isn't reactivated accidently by holding down the
buttons for too long

    Revision 1:
      Added Comments
      Simplified Code
      Added "long press" functionality
*/

//User Defined Variables
unsigned long blinkTimer = 1300; //ms   //rate at which the interlock indicator blinks
int unlockBlinks = 10;                  //how many time the interlock indicator light blinks
after activation/deactivation
int longPressTime = 1500; //ms          //how long the user has to press the button to
activate/deactivate lockout
int cooldownDuration = 10000;           //ms //how long button inputs are ignored after
activation/deactivation

//Other Variable Initialization
bool interlockClosed = true;
bool lightStatus = false;
unsigned long longPressStart = 0;
unsigned long time_initial = 0;
unsigned long cooldownTimer = 0;
bool cooldownStatus = false;

//Pin Assignments (Using Arduino Nano)
int engineLED = 11;
int engineButton = 12;
int controlsLED = 2;
int controlsButton = 3;
int interlockRelay = 4;

//Logic Input/Output Pin Setup:
void setup() {
  pinMode(engineLED, OUTPUT);
  digitalWrite(engineLED, LOW);
  pinMode(controlsLED, OUTPUT);
  digitalWrite(controlsLED, LOW);
  pinMode(interlockRelay, OUTPUT);
  digitalWrite(interlockRelay, HIGH);
  pinMode(engineButton, INPUT);
  pinMode(controlsButton, INPUT);
}

//Standard Operation Loop
void loop() {
  //Light Control
  if (interlockClosed) {
    blinks();
  } else {
    noBlinks();
  }

  if (!cooldownStatus) {
    //Lockout Activation Condition Check
    if (!interlockClosed && longPressEngine()) {
      //Lockout Activation
      quickBlinks();
```

```
      cooldownStatus = true;
      cooldownTimer = millis();
      digitalWrite(interlockRelay, HIGH);
      interlockClosed = true;
    }

    //Lockout Deactivation Condition Check
    if (interlockClosed && longPressBoth()) {
      //Lockout Deactivation
      quickBlinks();
      cooldownStatus = true;
      cooldownTimer = millis();
      digitalWrite(interlockRelay, LOW);
      interlockClosed = false;
    }
  }

  //Cooldown Timer
  if (cooldownStatus && (cooldownTimer >= cooldownDuration)) {
    cooldownStatus = false;
    cooldownTimer = 0;
  }
}

//Blink Timing Control for Interlock Indicator LED
void blinks() {
  if ((lightStatus) && (millis() - time_initial >= blinkTimer)) {
    time_initial = millis();
    digitalWrite(controlsLED, LOW);
    digitalWrite(engineLED, LOW);
    lightStatus = false;
  } else if ((!lightStatus) && (millis() - time_initial >= blinkTimer)) {
    time_initial = millis();
    digitalWrite(controlsLED, HIGH);
    digitalWrite(engineLED, HIGH);
    lightStatus = true;
  }
}

//Lockout Activation/Deactivation Quickblink Loop
void quickBlinks() {
  for (int i = 1; i <= unlockBlinks; i += 1) {
    digitalWrite(engineLED, HIGH);
    digitalWrite(controlsLED, HIGH);
    delay(100);
    digitalWrite(engineLED, LOW);
    digitalWrite(controlsLED, LOW);
    delay(100);
  }

}

//LED Turn-Off when Interlock is Closed
void noBlinks() {
  if (digitalRead(engineLED == HIGH)) {
    digitalWrite(engineLED, LOW);
  }
  if (digitalRead(controlsLED == HIGH)) {
    digitalWrite(controlsLED, LOW);
  }
}

//Long-Press Detection for Engine Button Only
bool longPressEngine() {
  if ((digitalRead(engineButton) == HIGH) && (digitalRead(controlsButton) == LOW)) {
    longPressStart = millis();
    while (millis() - longPressStart < longPressTime) {
      if (digitalRead(engineButton) == LOW) {
        return false;
      }
    }
```

```
    return true;
  }
  return false;
}

//Long-Press Detection for Both Buttons Simultaneously
bool longPressBoth() {
  if ((digitalRead(engineButton) == HIGH) && (digitalRead(controlsButton) == HIGH)) {
    longPressStart = millis();
    while (millis() - longPressStart < longPressTime) {
      if ((digitalRead(engineButton) == LOW) || (digitalRead(controlsButton) == LOW)) {
        return false;
      }
    }
    return true;
  }
  return false;
}
```

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