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16. ABSTRACT

This report provides summary details of integrating monochrome and Thermal Infrared (IR) imaging cameras, 3D Ground Penetrating Radar (3D-GPR), and Global Navigation Satellite System (GNSS)/Inertial Navigation System (INS) systems into a multi-sensing vehicle for high-speed collection of pavement condition data for use in Nondestructive Testing (NDT).

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Advanced Highway Maintenance and Construction Technology Research Center

Department of Mechanical and Aerospace Engineering
University of California at Davis

Research to Integrate Color and Thermal Imaging IR Cameras with Caltrans 3D-GPR and GNSS/INS System

Kin Yen &
Ty A. Lasky: Principal Investigator

Report Number: CA20-3608
AHMCT Research Report: UCD-ARR-20-04-30-01
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April 24, 2020

California Department of Transportation

Division of Research, Innovation and System Information

Executive Summary

Background, Problem, Need, and Purpose of Research

The Strategic Highway Research Program recognized the utility of Thermal Infrared (IR) imaging for early identification of shallow-seated pavement and bridge deck deterioration [1]. Early detection of such deterioration allows repair and rehabilitation before such significant degradation can occur, saving maintenance time and money. This research and integrated and installed a thermal IR system on the California Department of Transportation's (Caltrans') existing 3D Ground Penetrating Radar (GPR) vehicle, allowing synchronized georeferenced visual and thermal IR imaging of pavement and deck surfaces concurrent with 3D GPR subsurface imaging.

The primary goal of this research was to significantly improve Caltrans' ability to inspect pavement and bridge decks through use of thermal IR sensing and data processing by providing an integrated vehicle sensing platform which can collect data while the vehicle is moving at highway speeds, eliminating the need to close lanes or slow traffic.

Overview of the Research Work and Implementation Methodology

To achieve the project goal, the following work was performed:

1. Literature review.
2. Camera requirements development.
3. COTS camera and system search and purchase recommendations.
4. System integration electronics and wiring design.
5. Camera mount design, fabrication, and installation.

Major Results and Recommendations

This research enabled Caltrans to perform thermal IR and 3D-GPR data collection from a moving vehicle, keeping workers off the pavement. There is currently no other Department of Transportation with the unique combined capability of mobile 3D GPR and thermal IR imaging. This research should help accomplish multiple Caltrans Strategic Goals: it helps the Safety and Health goal by reducing worker and traveler injuries and fatalities; it helps the Stewardship and Efficiency goal by reducing delivery time and cost; it helps the System Performance goal by facilitating smooth traffic flow, eliminating the need for lane closures, and reducing inconvenience to travelers; and it contributes to the Organizational Excellence goal by continuing Caltrans' national leadership in the application of Nondestructive Evaluation methods for highway infrastructure.

Future research and development work includes developing a Standard Operating Procedure (SOP) and software automation to support consistent application of thermal IR data collection and processing for improved infrastructure inspection and maintenance.

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List of Acronyms and Abbreviations

Acronym	Definition
3D-GPR	3 Dimensional Ground Penetrating Radar
AC	Alternating Current
AHMCT	Advanced Highway Maintenance and Construction Technology
B/W	Black and White
CAD	Computer-Aided Design
Caltrans	California Department of Transportation
COTS	Commercial Off–The-Shelf
DC	Direct Current
DHCP	Dynamic Host Configuration Protocol
DMI	Distance Measurement Instrument
DOE	Division of Equipment (Caltrans)
DOT	Department of Transportation
DRISI	Caltrans Division of Research, Innovation and System Information
FHWA	Federal Highway Administration
FOV	Field of View
FPS	Frames per Second
GNSS	Global Navigation Satellite System
GPIO	General Purpose Input Output
GUI	Graphical User Interface
HDMI	High-Definition Multimedia Interface

Acronym	Definition
IMU	Inertial Measurement Unit
IP	Internet Protocol
IR	Infrared
MWIR	Mid-wavelength Infrared
NDE	Nondestructive Evaluation
NDT	Nondestructive Testing
NETD	Noise Equivalent Temperature Difference
NUC	Next Unit of Computing
PCS	POS Computer System
PM	Project Manager
POS	Position and Orientation System
RAM	Random-Access Memory
SDK	Software Development Kit
SHRP2	The second Strategic Highway Research Program
SOP	Standard Operating Procedure
SSD	Solid State Drive
TRB	Transportation Research Board
USB	Universal Serial Bus

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Chapter 1: Introduction

Background and Problem

Researchers, the Federal Highway Administration (FHWA), and the Transportation Research Board (TRB) have performed various investigations on Nondestructive Evaluation (NDE) methods for concrete and pavement subsurface damage and deterioration [2]–[8]. Ground Penetrating Radar (3D-GPR, also GPR) and thermal Infrared (IR) imaging NDE technologies provide the means for rapid, nondestructive, and accurate condition assessment and performance monitoring of concrete bridge decks and pavement. Both NDE methods will significantly reduce the resources and expenditures needed for testing, renewal, and repair. Aside from reducing the duration of traffic interruption during field operation, the more dense measurements yield a more accurate characterization of the concrete and pavement subsurface condition, a better prediction of the deterioration progression, and a better assessment of the rehabilitation needs.

Figure 1.1 shows a sample graphic of the pavement intralayer GPR response, which provides an indicator for overlay stripping or delamination. Figure 2.2 shows a sample of a processed thermal image of a bridge deck where the color difference (red shade) can indicate delamination.

Figure 1.1: A sample graphic of the pavement intralayer GPR response, which provides an indicator for overlay stripping or delamination

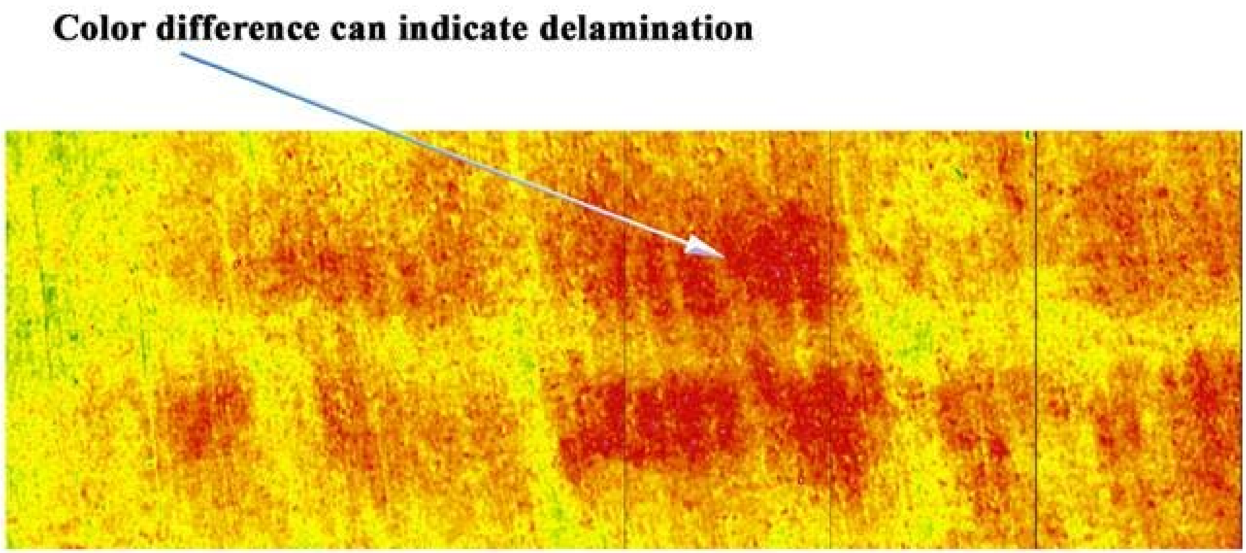

Figure 1.2: A sample of a processed thermal image of a bridge deck where the color difference (red shade) can indicate delamination [1]

The California Department of Transportation (Caltrans) Geophysics and Geology Branch has received four Strategic Highway Research Program (SHRP2) grants that incorporate implementation of 3D-GPR and thermal IR imaging NDE technologies for Caltrans. Working with the Caltrans Division of Equipment (DOE), the Geophysics and Geology Branch integrated a commercial off-the-shelf (COTS) 3D-GPR system with a precision COTS Global Navigation Satellite System/Inertial Measurement Unit (GNSS/IMU) position and orientation system (visible in Figure 1.3). UC Davis' Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center assisted Caltrans in the software and electronics integration between the 3D-GPR and the Applanix GNSS/IMU position and orientation system.

The SHRP2 grants provide limited funds for procurement of thermal IR imaging camera hardware for the Caltrans 3D-GPR vehicle. However, the SHRP2 grants are insufficient for design and integration of the IR camera with the 3D-GPR vehicle and the GNSS/IMU positioning system. Therefore, this research project was approved and funded by the Caltrans Division of Research, Innovation and System Information (DRISI) to help accomplish the objectives discussed below.

Objectives

3D-GPR and IR imaging have ranked high in the SHRP2 NDE evaluations and have been applied separately by several agencies as tools for concrete surface condition assessment. However, there is limited reported work describing the combined use of the results of these two methods [5]. 3D-GPR and thermal IR imaging have complementary strengths that can reduce their individual limitations. GPR is equally effective on bare concrete decks and on decks with concrete and bituminous overlays. Thermal IR imaging is effective for imaging the debonding of concrete decks and overlays but may have limitations detecting rebar-level delamination if the rebar is deep. While very effective for non-overlaid decks, thermal IR's effectiveness can be reduced in the presence of overlays. In previous studies, users were on foot using a hand-held thermal IR imaging camera, and they could not safely capture inside lanes without a lane closure.

Figure 1.3: The Caltrans NDE vehicle

Caltrans Geophysics and Geology Branch expressed a need for a safer, more effective, high-speed, and efficient way to collect 3D-GPR and thermal IR image data as well as black and white (B/W) images for visual references. For imaging of tunnel linings under SHRP2 Product R06G and for support of Structures Maintenance, visual and thermal IR imaging would maximize the effectiveness of the technology and significantly reduce data acquisition costs. The goal of the Caltrans Geophysics and Geology Branch was to enable the Caltrans 3D-GPR and IR imaging collection vehicle to collect IR images, visual images, and 3D-GPR data in a single pass at highway speed while operators are kept safe inside the protection of a vehicle and removed from direct exposure to highway traffic.

Scope

This research examined and identified innovative IR and visual image cameras, selected the most optimal candidates, and integrated them into the existing Caltrans 3D-GPR vehicle. The designs and implementation methods were established, focusing particularly on the incorporation of commercially-available and customizable equipment. The equipment incorporated the features identified in collaboration with the Caltrans Geophysics and Geology Branch.

This research improves the quality of assessing the condition of pavement and concrete surfaces. Such comprehensive and accurate assessments can reduce the cost, duration, and frequency of detailed regular and follow-up inspections. In addition, data collected from the Nondestructive Testing (NDT) of pavement and concrete surfaces can complement other information to better understand life-cycle costs, deterioration mechanisms, and the effectiveness of preservation techniques at various stages of the infrastructure lifecycle. The integrated system will lead to earlier fault detection, lower rehabilitation cost, and higher level of service.

Research Methodology

The AHMCT Research Center examined and identified innovative IR and color or B/W cameras based on previous research results, recommended the best candidates, and supported integration of these cameras into the existing Caltrans 3D-GPR vehicle. The designs and implementation methods incorporated commercially-available and customizable equipment and software. This task was performed collaboratively with the Caltrans Geophysics and Geology Branch. AHMCT provided the equipment specifications for Caltrans Geophysics and Geology Branch to perform the hardware and software procurement. AHMCT purchased COTS camera and related systems in support of evaluation and recommendation development. Caltrans purchased actual cameras, enclosures, and systems to be integrated with the 3D-GPR vehicle. AHMCT performed the system integration. The integrated vehicle was field tested by Caltrans.

A Project Panel (panel) was established early in the project. Meetings were held with the Project Manager (PM) and the panel on an as-needed basis. AHMCT and the panel worked collaboratively during the research project to best guide the work.

The hardware and software components needed for successful integration were identified based on the literature review. To achieve the goals of this project, the following tasks were performed:

1. Literature review and camera requirements development.
2. COTS camera and system search and purchase recommendations.
3. System integration electronics and wiring design.
4. Camera mount design.
5. Project documentation and management.

Research Results and Benefits

This research outcome should improve the quality of assessing the condition of pavement and concrete surfaces. Such comprehensive and accurate assessments could reduce the cost and frequency of detailed regular and follow-up inspections. In addition, data collected from the NDT of pavement and concrete surfaces should complement other information to support future, improved understandings of life-cycle costs, deterioration mechanisms, and the effectiveness of testing and preservation techniques at various stages of the structures lifecycle. These improvements would lead to earlier detection, lower rehabilitation cost, and a higher level of service.

This research will reduce the need for lane closures and improve safety and efficiency of testing and maintenance processes. Through the current SHRP2 grants, Caltrans Geophysics and Geology Branch actively engages with other Departments of Transportation (DOTs) and researchers. The FHWA and other state DOTs will be interested in this leading research.

Chapter 2: Literature Search and Camera Requirements

A literature search related to NDE using thermal IR imaging was conducted to determine the state of the art in the application of IR imaging for pavement and bridge deck distress detection. One goal of this task was to enhance Caltrans Geophysics and Geology Branch's understanding of this evolving research area. Based on the literature review of NDE, AHMCT developed requirements for thermal IR and color or monochrome cameras. These requirements were reviewed with the project panel and updated based upon their feedback.

IR Camera Requirements

There has been extensive research in the use of IR thermography for bridge and pavement distress [4]detection [4]–[34]. Previous research typically used handheld thermal imaging equipment. Hiasa and Matsumoto [4], [15]–[17], [35], [36] have performed extensive research on using IR thermal imaging cameras in mobile high-speed applications instead of a handheld thermal imaging camera on a tripod. Their findings show that there are four key specifications for an IR camera to be used in detecting pavement and bridge deck distress: image resolution, temperature sensitivity, sensor integration time, and frame rate. Other important specifications include inter-changeable lenses and external image trigger support for geo-referencing of the data. Table 2.1 shows the key IR camera specifications.

The selected IR camera was the FLIR A6701 Mid-Wavelength Infrared (MWIR) camera with a 17 mm lens (Figure 2.1). The FLIR A6750 MWIR and A8580 MWIR cameras also met the requirements but at considerably higher cost. These FLIR camera models have an integrated cryocooler which lowers the sensor temperature to cryogenic level. Thermal imaging cameras with a cooled detector are more expensive but offer some advantages over thermal imaging cameras with an uncooled detector. The reduction in sensor temperature reduces thermally-induced noise, the Noise Equivalent Temperature Difference (NETD), and integration time.[1] Detailed FLIR A7601 MWIR camera specifications are available on FLIR's website.[2] Figure 2.1 shows the top view of the FLIR A7601

[1] FLIR: Cooled or uncooled (https://www.flir.com/discover/rd-science/cooled-or-uncooled)
[2] FLIR Science-grade A6700 MWIR INSB camera (https://www.flir.com/products/a6700-mwir/)

camera. The camera has an Ethernet port for data communication, a 24-volt power input, and a BNC connector for frame synchronization input.

Table 2.1: IR camera requirements (specifications)

Feature	Description	Requirement
Image sensor resolution	IR sensor resolution.	≥ 640x480 pixel
NETD	Measure for how well a thermal imaging detector is able to distinguish between very small differences in thermal radiation in the image.	< 20 milli-Kelvin (mK)
Integration time	Low integration time enables the capture of every pixel from a scene simultaneously, which is crucial to measuring temperatures of fast-moving objects. It is similar to shutter speed for a color camera.	≤ 480 ns
Maximum frame rate	Maximum number of IR data frames that can be captured per second.	15 frame per second (fps) or higher
Lens focal length	The lens focal length controls the camera field of view (FOV). When mounted on top of a van, IR camera FOV should cover the width of a lane.	17 mm

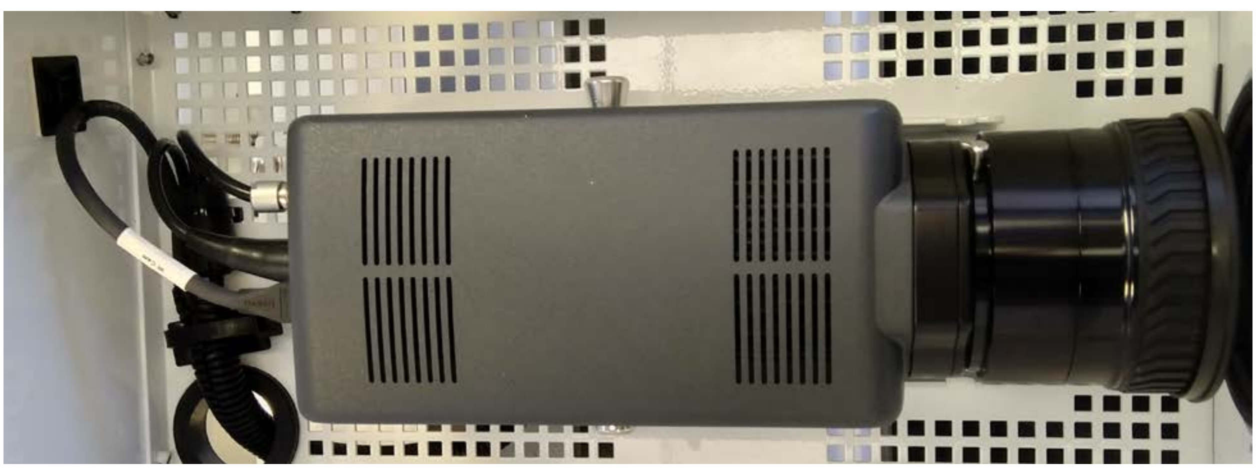

Figure 2.1: FLIR A7401 MWIR with 17 mm lens (top view)

Figure 2.2 shows a side view of the FLIR A6701 camera mounted on top of the van alongside the monochrome camera (with grey enclosure housing). This was a temporary mount for testing, verifying, and determining the optimal mounting angle and its FOV. The figure also shows the GNSS antenna (mounted on the roof) and the Distance Measurement Instrument (DMI) connected to the Applanix GNSS/IMU system and GeoScope (mounted on the left rear wheel of the van).

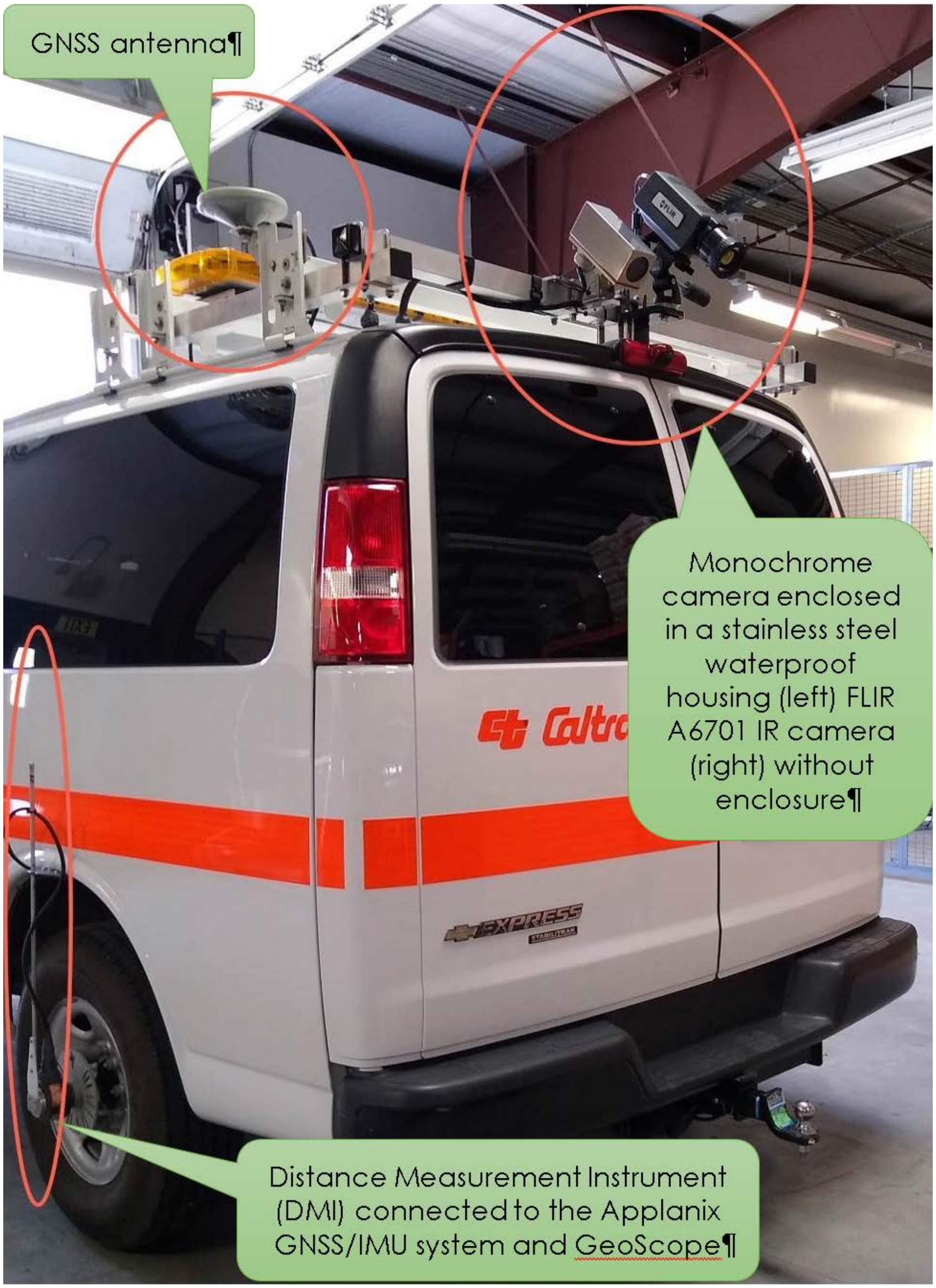

Figure 2.2: FLIR A7401 MWIR with 17 mm lens evaluation setup

IR Camera Enclosure

Mid-State Instruments, an authorized FLIR distributor, designed and fabricated an enclosure specifically for the FLIR IR camera. The enclosure, shown in Figures 2.3 and 2.4, has an opening to provide air-cooling for the camera as well as an integrated window through which IR light could pass. Mid-State Instruments' enclosure was selected for the IR camera.

Figure 2.3: Mid-State Instruments FLIR IR camera enclosure (exterior view)

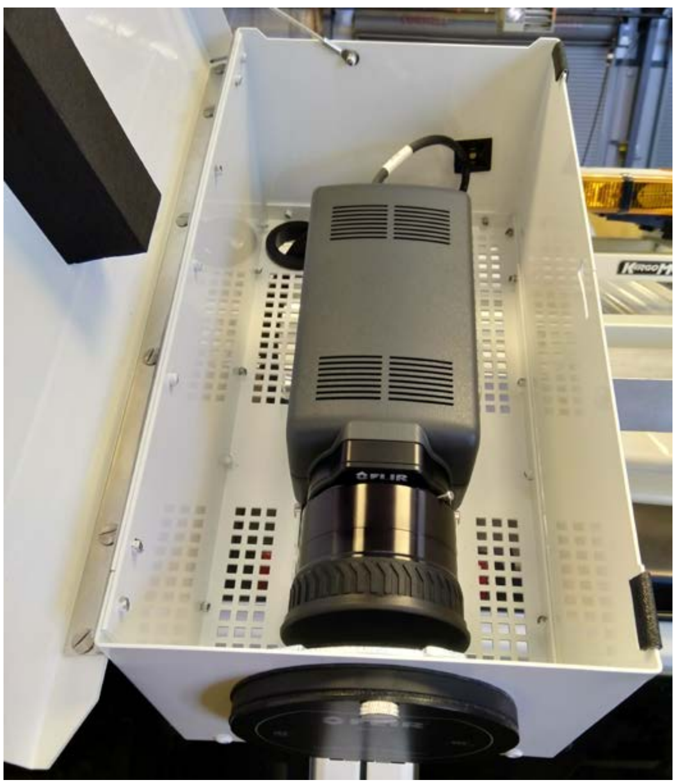

Figure 2.4: Mid-State Instruments FLIR IR camera enclosure (interior view)

Visible Light Camera Requirements

A visible light camera is useful to provide context and visual reference in identifying underground anomalies. In particular, it helps to identify and discriminate IR and GPR response between shallow-seated anomalies and surface defects that may contribute to the signal. The FLIR Blackfly S BFS-U3-51S5P-C camera was selected for integration to the GPR van. The FLIR BFS-U3-51S5P-C camera has a Universal Serial Bus (USB) 3.0 data interface, a Sony IMX250MZR image sensor, a maximum capture frame rate of 75 Hz, and trigger input and output interface. Detailed FLIR BFS-U3-51S5P-C specifications are available at FLIR's website (https://www.flir.com/products/blackfly-s-usb3/?model=BFS-U3-51S5P-C).

The Sony IMX250MZR is a global shutter, 5-megapixel monochrome polarization image sensor and has a 4-directional on-chip polarizer. The 4-directional polarizer is formed on the photodiode of the image sensor chip. This image sensor can also capture polarization information that cannot be detected by a normal image sensor. This polarization sensor can be used in many applications in the field, such as inspection when visibility and sensing are difficult.[3]

To match the FOV of the FLIR A6701 IR camera, a Fujinon HF12XA-5M 12.4-mm lens was chosen for the FLIR BFS-U3-51S5P-C camera as shown in Figure 2.5. Figure 2.5 also shows a 6-pin, 4.5-meter General Purpose Input Output (GPIO) cable (grey in color) with Hirose HR10 Circular Connector (FLIR P/N: ACC-01-3009) connected at the top of the camera. The GPIO cable provides power as well as input/output camera triggering connections. The USB 3.0 data port is connected to a 5-meter black USB3 Type-A to Micro-B (locking) cable (FLIR P/N: ACC-01-2302).

Monochrome Camera Enclosure

An APG Vision model 30S-AD camera enclosure with the 30S-PT1 mount, shown in Figure 2.6, was chosen for the monochrome camera based on its small size and robust stainless steel housing. APG Vision graciously provided the Computer-Aided Design (CAD) model files for their model 30S-AD camera enclosure with the 30S-PT1 mount[4] for ease of CAD design integration.

3 Sony Image Sensor (https://www.sony-semicon.co.jp/e/products/IS/polarization/technology.html)

4 APG Vision model 30S-AD camera (http://www.apgvision.com/product-category/food-environments/30s/)

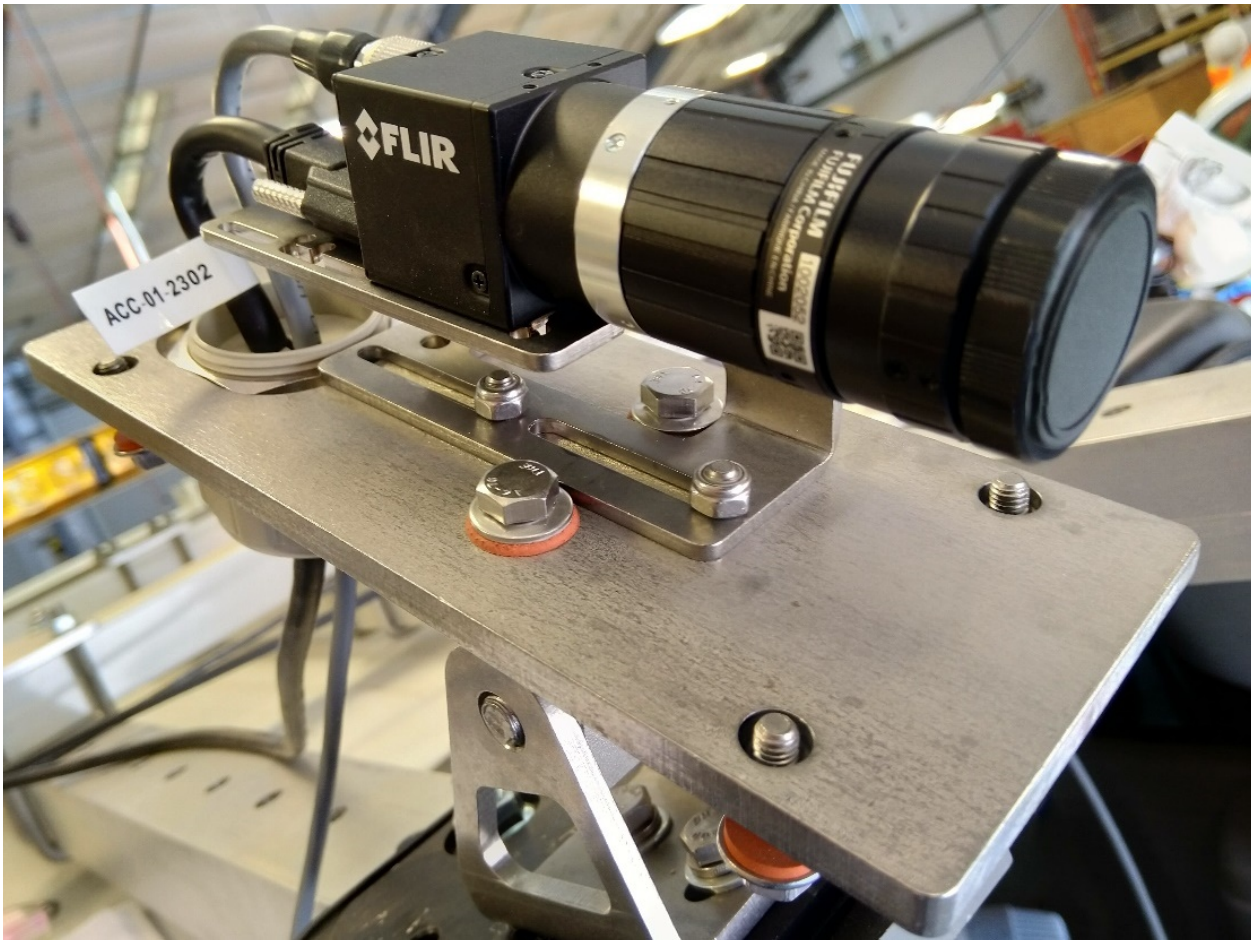

Figure 2.5: FLIR monochrome camera mounted inside the APG Vision model 30S-AD camera enclosure (the enclosure lid moved)

Figure 2.6: APG Vision model 30S-AD camera enclosure with the 30S-PT1 mount

Chapter 3:
COTS Purchase Recommendations

Based on the camera requirements developed in Task 1 and agreed upon by the panel, AHMCT searched for COTS cameras, data capture software, and related systems that are within current Caltrans budget constraints. This included thermal IR cameras, color or monochrome cameras, data capture software, data synchronization hardware, and power systems. AHMCT provided Caltrans with purchase recommendations, including specifications for procurement. Caltrans and AHMCT have procured all necessary COTS equipment and supplies.

Cameras and Control Software

The IR camera and monochrome camera recommendation along with their enclosure are provided in the previous chapter. FLIR provides ResearchIR software to record data from the FLIR A6701 IR camera. Moreover, ResearchIR provides camera control, image analysis, thermal analysis, data export, and measurements on real-time and recorded data. A FLIR software development kit (SDK) is also available for their IR camera to support custom software development. The ResearchIR Graphical User Interface (GUI) is shown on the right side of the monitor in Figure 3.1. ResearchIR has been used and evaluated initially for data collection and analysis for pavement distress.

FLIR also provides a free Spinnaker SDK with image capture software with all of their machine vision camera products, including the Blackfly S BFS-U3-51S5P-C monochrome camera. The Spinnaker SDK image capture software application GUI is shown on the left side in the monitor in Figure 3.1. The Spinnaker SDK also allows users to configure, control, view, and record data from the FLIR Blackfly S BFS-U3-51S5P-C monochrome camera. It has been used and evaluated initially for the monochrome camera data capture and control.

Computer, Keyboard, and Monitors

An Intel Next Unit of Computing (NUC) 8 minicomputer NUC8i7HVK was selected to provide operator control interface and record data. It has two Ethernet network interfaces. One network interface is connected to the Applanix PCS and GeoScope via an Ethernet switch. The second network interface is connected directly to the FLIR A6701 IR camera. The WiFi and Bluetooth wireless are normally disabled except during Microsoft Windows 10 operating system and software updates. Both the WiFi and Bluetooth wireless would interface with the 3D-GPR operation. The computer has 32-GB Random-Access Memory (RAM) and two Intel 660p Series M.2 2280 2TB PCI-Express 3.0 x4

Solid State Drive (SSD) installed internally. The first SSD is used for the Windows operating system and data storage, and the second SSD is used for data storage. Depending on the SSD write speed and data recording rate, data may be required to stream into two different SSDs to ensure that the data stream does not exceed the SSD maximum write speed.

A Perixx Periboard-522 wired trackball mechanical keyboard was recommended and installed for the operator. It has a build-in 2.17-inch trackball with pointing and scrolling feature (Figure 3.1). Based on previous AHMCT and Caltrans experience, a trackball or a touchpad is easier to use in a moving vehicle vs. a mouse, and the trackball is preferred by the end users.

The HP Elite Display E273Q monitor, which is on the Caltrans IT approved hardware list, is one of the biggest and highest-resolution displays that can fit between the GPR van's front seats. Thus, it was recommended, procured, and installed using the space between the driver and front passenger seats. The high-resolution display enables the operator to monitor simultaneously the proper functioning of the sensors and data collection status without moving applications from background to foreground. Figure 3.1 shows the 3D GPR van operator user interface (HP E273Q monitor and keyboard). The monitor and keyboard are secured using a RAM Mount system. The display shows the ResearchIR GUI (on the right) and Spinnaker SDK GUI (on the left).

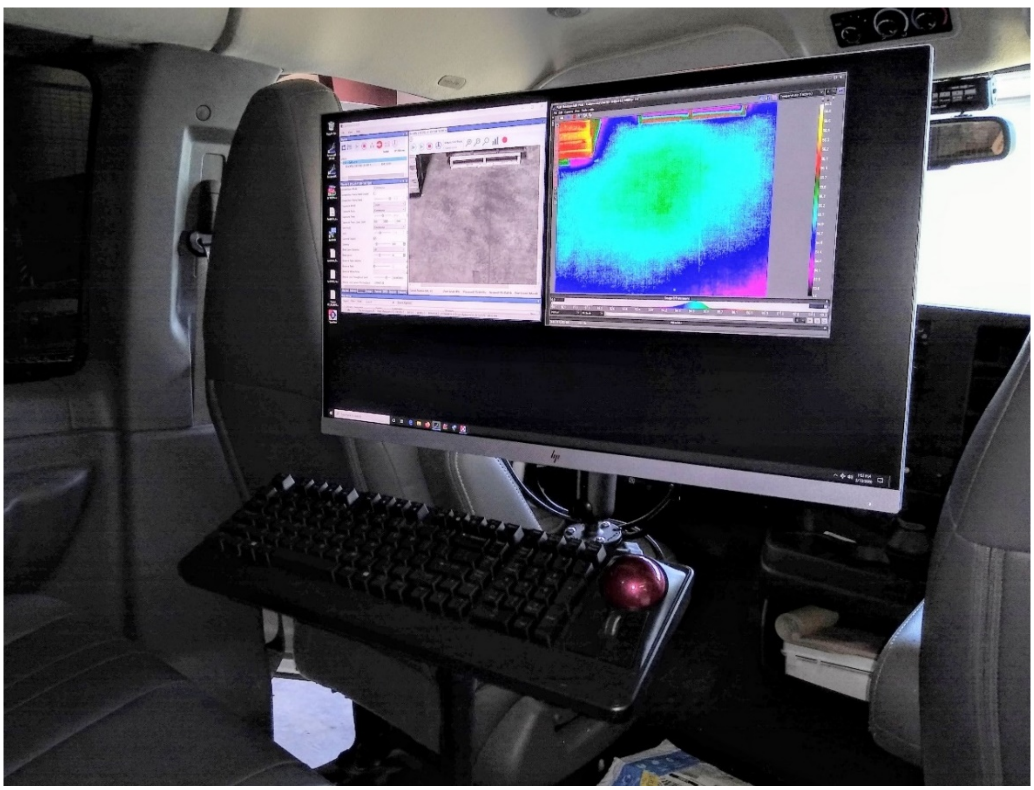

Figure 3.1: Operator's user interface

As shown in Figure 3.2, an additional 7” 1080p monitor was installed for the driver to view the driving path history in order to establish the proper offset from the previous data recording path in order to provide complete data collection coverage.

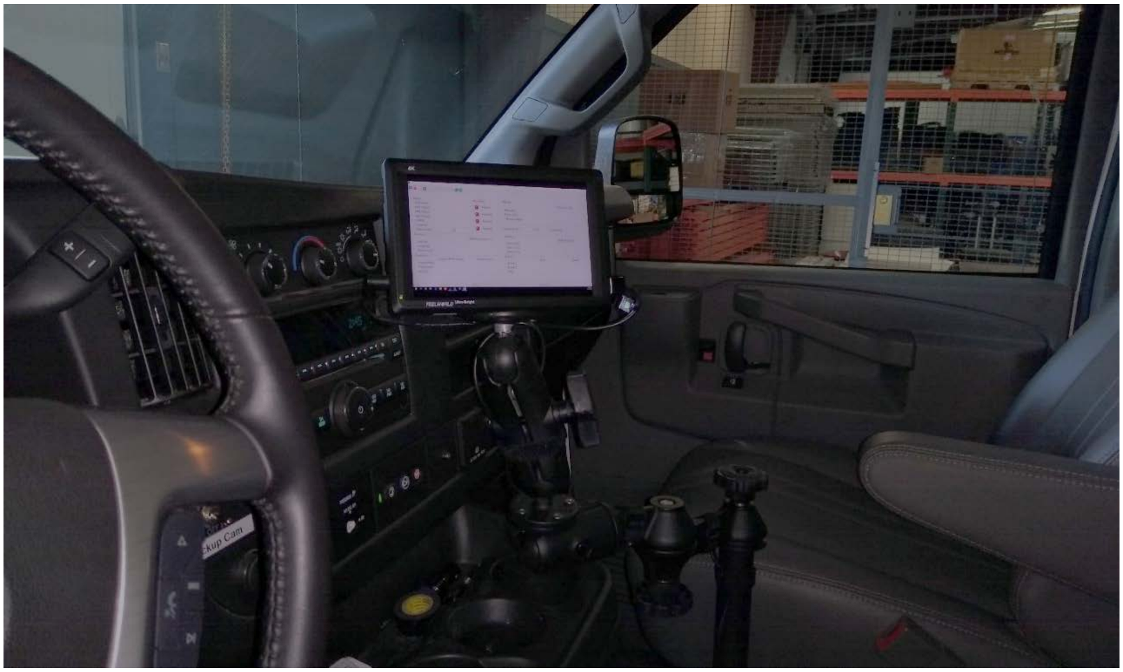

Figure 3.2: 7” 1080p driver guidance display

Ethernet Switch

A Caltrans-approved Cisco IE1000-4T1T-LM 4-port managed industrial Ethernet switch was installed. This switch requires a 12-volt direct current (DC) power source. The Ethernet switch, which is connected to the Ethernet port of the computer, GeoScope, and the Applanix PCS, enables the computer to control and collect data from the GeoScope and Applanix PCS.

Rack-Mount Equipment

A 19” open-frame rack was chosen to securely mount and house the computer and electronics. The open frame allows easy access and cable routing. The open-frame design also eliminated the need to add air-cooling fans. The 19” rack was rigidly mounted on top of the equipment storage drawer unit because the IMU was mounted inside the rack. A 6061 aluminum 90-degree angle (round edge, 1/4" thick, 4" high x 3" wide, shown in Figures 3.3 and 3.4) was added across the top of the equipment storage drawer unit to reinforce and stiffen its top surface. Figure 3.3 shows the 19” rack with various 3D GPR electronic components including: inverter (bottom), GeoScope MK IV computer for 3D GPR data acquisition, Intel NUC computer (labeled PC), Applanix Position and Orientation (POS) Computer System (PCS), IMU (top), and alternating current (AC) power supplies located behind the GeoScope.

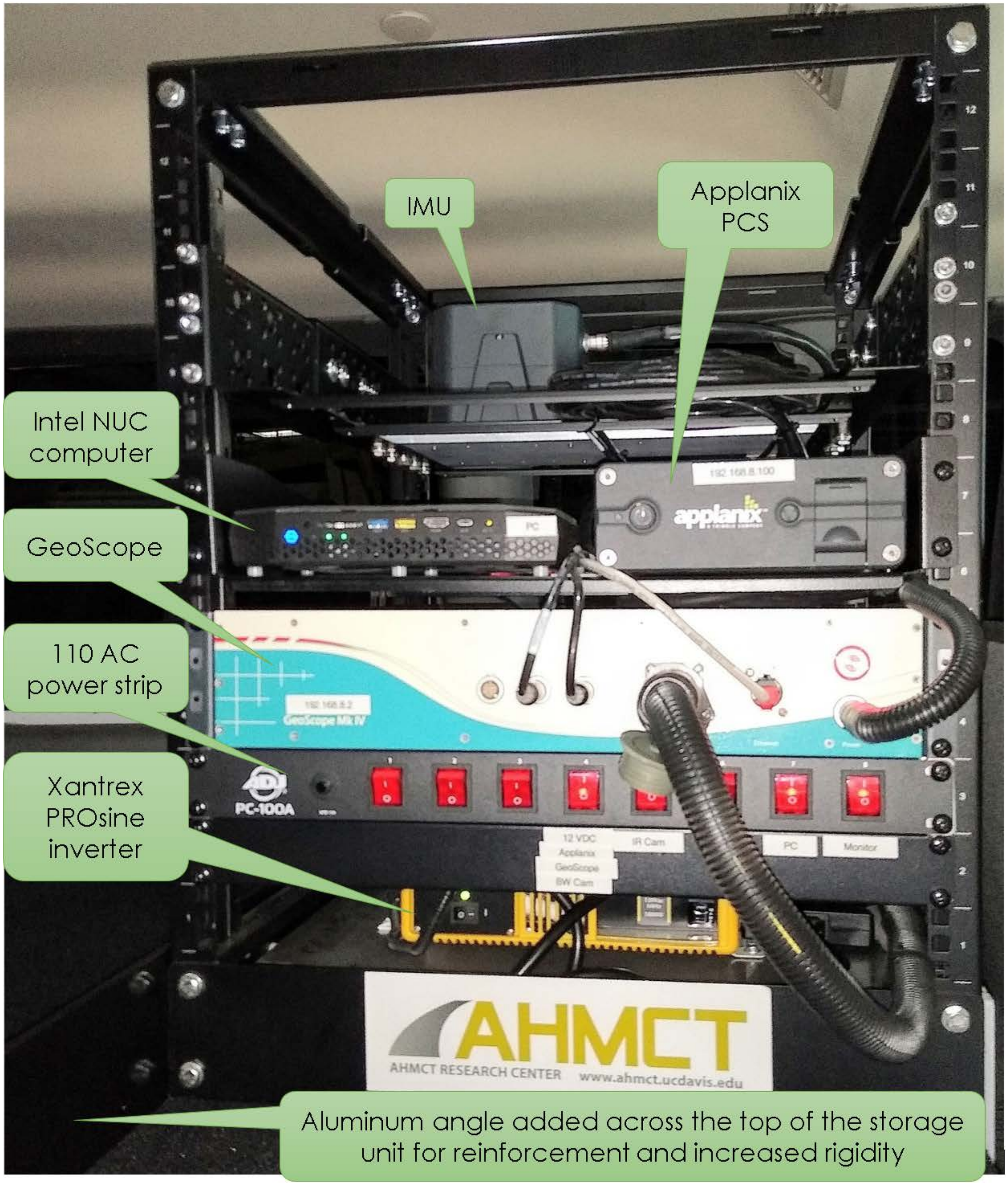

Figure 3.3: 19” open-frame equipment rack with all components installed (front view)

Equipment Storage

A large equipment storage space is required to securely store and transport the 3D-GPR antennas, antenna mounts, and installation tools. A three-drawer unit designed by [TruckVault (https://truckvault.com/)](https://truckvault.com/) for use in vans was selected. Figure 3.4 shows the lockable storage system mounted at the rear of the 3D GPR van. The top drawer stores the ground-coupled 3D GPR antenna with tools and accessories. The lower-left drawer stores the air-coupled GPR antenna supported by custom-made foam. The lower-right drawer stores the air-coupled GPR antenna mounts. The drawers have custom-designed holders to prevent components from moving during transport.

Figure 3.4: TruckVault three-drawer equipment storage unit

Chapter 4: System Integration Electronics And Wiring Design

AHMCT developed the needed electronics and wiring designs for integration of the recommended cameras and systems with the existing Caltrans 3D-GPR system and its GNSS/IMU position and orientation system. This include power connections, data connections, and camera triggering with associated geotagging of images to precise locations. Figure 4.1 shows the 3D-GPR system wiring diagram.

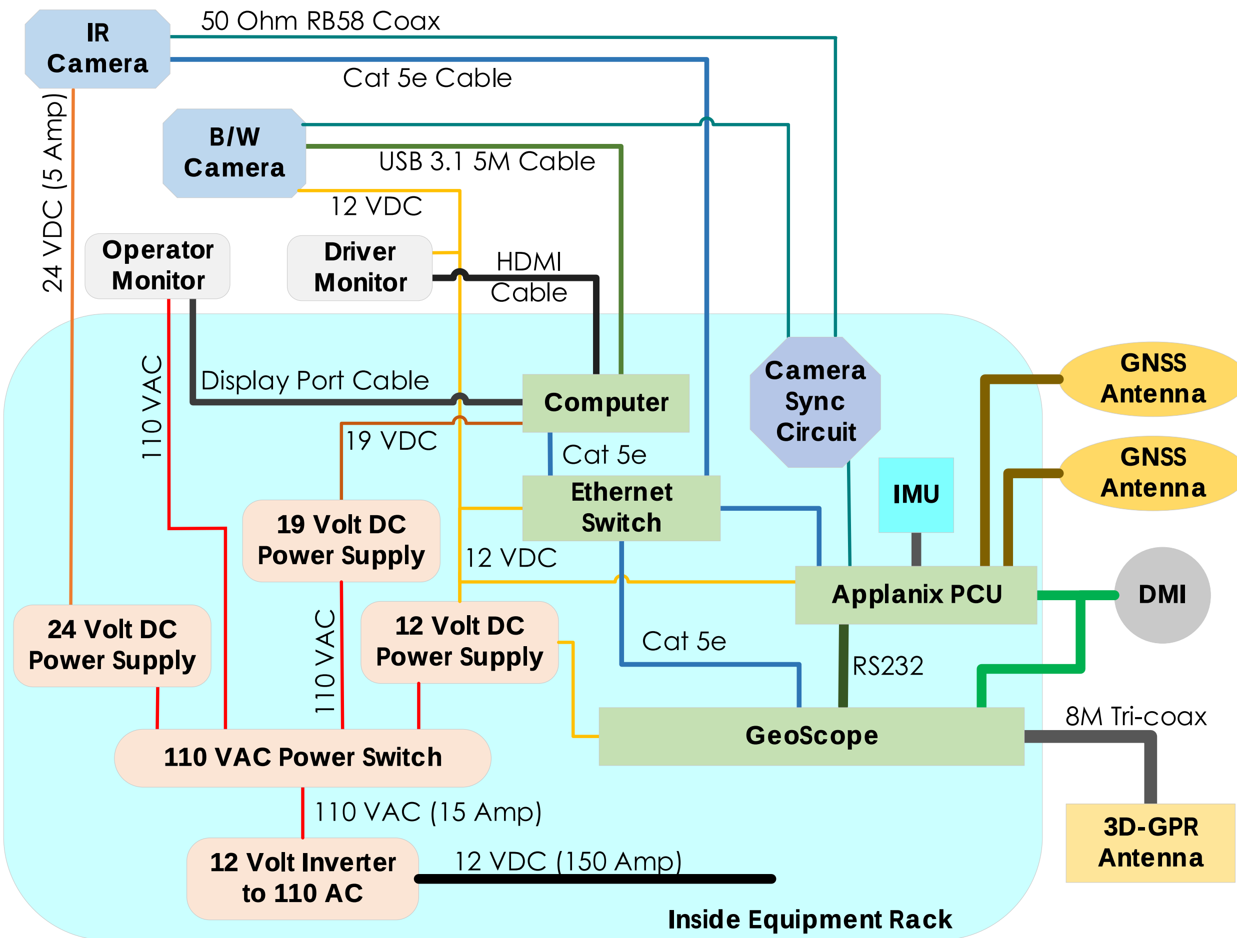

Figure 4.1: 3D-GPR system wiring diagram

Power Connections

The 3D-GPR van 12-volt DC main power is connected to a Xantrex PROsine™ 1800-watt inverter that converts 12-volt DC to 110-volt AC. The Xantrex inverter, shown in Figure 3.3, is connected to a remote control unit that is mounted on the wall panel next to the operator's seat on the driver's side of the van. The remote control unit can turn the inverter on and off and display the input DC voltage and current.

The 110-volt AC power is distributed to other power supplies through an ADJ power strip (PC-100A). The PC-100A power strip, shown in Figure 3.3, is a 19-inch rack-mountable 8-channel AC power strip with 15-amp breaker and eight on/off toggle switches for each AC outlet. The power strip can be unplugged from the inverter and plugged into an AC outlet for shore power. In this case, the operator may perform testing, evaluation, demonstration, and data transfer without having the vehicle engine running when indoors.

AC outlet #4 of the power strip is connected to a 110-volt AC-to-12-volt DC power supply. This 12-volt DC supply provides power to the Applanix PCS, GeoScope, Ethernet switch, driver monitor, and B/W camera. AC outlet #5 is connected to the IR camera 24-volt DC power supply. AC outlet #7 is connected to the I9-volt DC power supply for the Intel NUC computer, and AC outlet #8 is directly connected to the operator's monitor. The user can turn each outlet on or off using the correspond switch as shown in Figure 3.3.

FLIR A6701 IR Camera Connections

The FLIR A6701 camera is powered by the 24-volt DC power supply that was provided with the IR camera purchase. Its Ethernet data port is connected to the Intel NUC computer's Ethernet port #2.

Monochrome Camera Connections

The FLIR Blackfly S camera is powered by a 12-volt DC power supply provided with the GeoScope purchase. Its USB 3.0 data port is connected to the Intel NUC computer's USB 3.0 data port.

GeoScope Connections

The GeoScope is powered by a 12-volt DC power supply provided with the GeoScope purchase. It is connected via a tri-coax cable to either the air-coupled antenna mounted in front of the vehicle or to the ground-coupled antenna trailer at the rear. Its serial input is connected to the Applanix PCS serial port #1. The DMI data port is connected to the DMI supplied with the Applanix LV220 system. The Applanix DMI cable is split to connect to both GeoScope and Applanix PCS DMI input ports.

Applanix PCS Connections

The Applanix PCS is powered by a 12-volt DC power supply provided with the GeoScope purchase. The Applanix IMU input port is connected to the IMU with a 1-meter IMU cable. The Applanix LV220 system is supplied with very long IMU cable in its standard configuration. The Applanix PCS Ethernet port is connected to the Cisco Ethernet switch.

Intel NUC Computer Connections

The Intel NUC computer is powered by a 19-volt DC power supply. Its Ethernet port #1 is connected to the Cisco Ethernet switch. Its second Ethernet port is connected to the FLIR A6701 IR camera directly with a 25-foot Category 5e outdoor-rated shielded Ethernet cable. One of computer's USB 3.0 ports is connected directly to the FLIR Blackfly S BFS-U3-51S5P-C camera with a USB 3, 5-meter, Type-A-to-Micro-B (locking) cable (FLIR P/N: ACC-01-2302). The driver monitor is connected to one of the computer's mini Display Port with a 15-foot mini Display Port-to-High-Definition Multimedia Interface (HDMI) cable, and the operator monitor is connected to the computer's other mini Display Port with a 15-foot mini Display Port-to-Display Port cable. The keyboard is connected to one of the computer's USB 3.0 ports via a USB 3.0 hub.

Internet Protocol (IP) Address Assignment

Each device's Ethernet port must has a unique IP address in order to communicate with other devices. Table 4.1 lists the final IP address assignment.

Table 4.1: IP address used by each device

Devices	IP address assigned
Intel NUC PC Ethernet port #1	192.168.8.10
Intel NUC PC Ethernet port #2	192.168.10.10
Intel NUC PC Wi-Fi (normally disabled)	Dynamic Host Configuration Protocol (DHCP)
Applanix PCS	192.168.8.100
GeoScope	192.168.8.2
FLIR A6701 MWIR	No IP address assigned

Chapter 5:
Camera Mount Design

Mounting location and orientation support integration with the existing Caltrans 3D-GPR system and its GNSS/IMU position and orientation system based on previous NDE research results. AHMCT performed bench testing of components to verify their functionality and evaluate various camera mount location and orientation options. To minimize obstruction of the van's warning lights for any driver behind the van, the cameras were mounted as close to the roof as possible without interfering with opening and closing the rear doors. Tests determined that the optimal mounting angle is 35 degrees down from horizontal.

In addition, AHMCT performed hardware integration with the 3D-GPR vehicle. AHMCT designed, fabricated, and installed camera mounts. Previously, Caltrans DOE installed a Kargo Master Crossbar roof rack with warning light and GNSS antennas using custom mount brackets on the roof of the van. The camera mounts were integrated to the existing Kargo Master Crossbar roof rack.

The camera mount design aimed to

- Use COTS parts as much as possible.
- Have maximum adjustability for future configuration changes.
- Provide rigidity to reduce vibration.
- Have a low profile to not extend beyond certified vehicle height, have all openings covered to reduce wind noise, and minimize blockage of the flashing warning light from the rear.

SOLIDWORKS CAD models and assembly drawings were created for the roof rack and camera mounts. Use of CAD reduced interference conflicts and documented the design for future modification.

IR Camera Mount Design

Two 2" x 2" aluminum tubes were mounted to the Kargo roof rack vertical support to provide support for a 2" x 4" aluminum tube across the rear of the van roof as shown in Figure 5.1. A 3-foot 1.5" x 3" T-slotted framing rail was mounted to the 2" x 4" and Kargo roof rack crossbeams using 3/8" U-bolt with a custom-made ¼" thick aluminum plate. A McMaster.com 3136N221 T-slotted framing rail 90-degree locking pivot was mounted to the end of the 1.5" x 3" T-slotted framing rail as shown in Figures 5.1 and 5.2. The 90-degree pivot plates were secured to the IR camera enclosure.

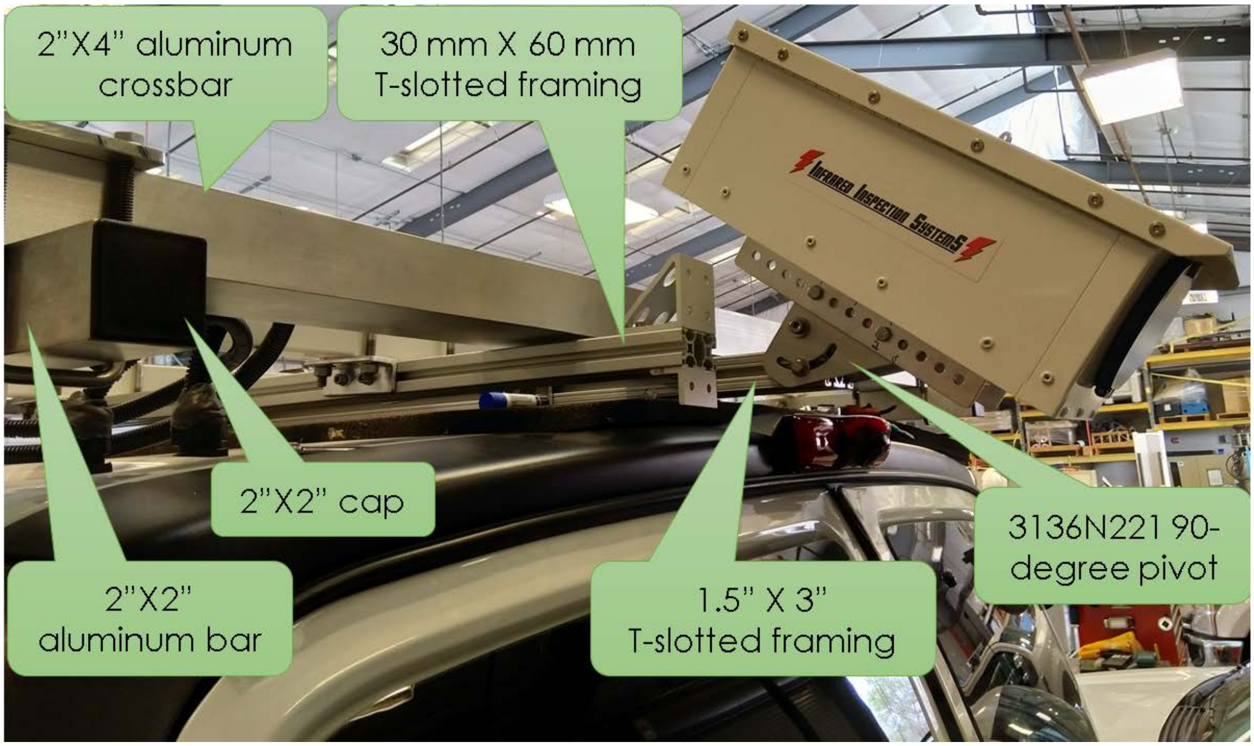

Figure 5.1: IR camera mount

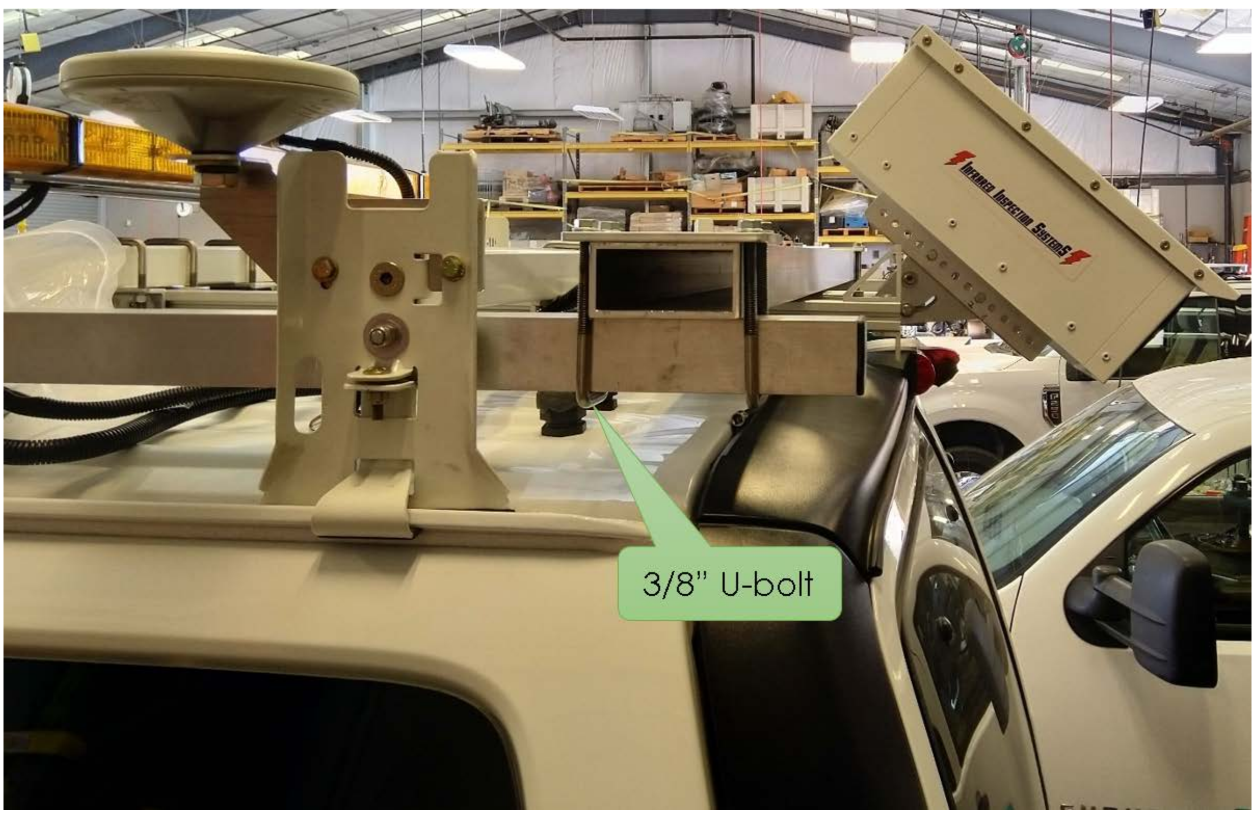

Figure 5.2: IR camera mount (side view)

Black and White (B/W) Camera Mount Design

A 3-foot 30 mm X 60 mm T-slotted framing rail was mounted to the 2" x 4" and Kargo roof rack crossbeams using 3/8" U-bolt with a custom-made ¼"-thick aluminum plate. A ½"-thick custom-designed aluminum plate was mounted at the end of the 30 mm x 60 mm T-slotted framing rail as shown in Figure 5.3. The monochrome camera housing and pivot mount were secured to the ½"-thick custom-designed aluminum plate.

Figure 5.3: Camera mounts (rear view)

Chapter 6: Deployment and Implementation

Due to the limited scope and resources for this research, only the first phase of the hardware integration of all the sensors was completed. Follow-up phases are required to complement this research and development for eventual full deployment of the IR imaging system.

Problems and Issues that Affected Product Deployment and Operation

The main goal of this project was to substantially improve pavement and bridge deck inspection capability through the integration of thermal IR data collection and processing with visual imaging and 3D GPR. More research is still needed to:

1. Develop a Standard Operating Procedure (SOP) to support Caltrans' consistent application of this important technology as well as document the corresponding benefits of improved infrastructure diagnostics and maintenance. The SOP will form the implementation plan.
2. Provide custom software for thermal IR data processing.

Recommended Solutions to Noted Problems and Issues

1. Develop SOP to support Caltrans' consistent use of thermal IR technology for early detection of pavement and bridge deck defects.
2. Develop custom software for thermal IR data processing. Software integration and data processing automation will improve processing speed, efficiency, and consistency.

Issues Expected to Affect Full Implementation

1. Lack of SOP.
2. Lack of software automation. Currently, users have to review each thermal image manually to identify possible anomalies (defects in the pavement). This manual task is time consuming and labor intensive. Software automation, possibly using machine learning technologies, could reduce time and labor to post-process the data and identify possible anomalies for users to review for quality control and quality assurance.

Other Considerations for Reaching Full Product Deployment & Optimal Operation

Equipment Issues

1. Lack of integrated software for full-suite data collection. Currently, data acquisition requires running and monitoring four separate software applications simultaneously (GPR, visual camera, thermal IR camera, and GNSS).

Operational Issues

The primary goal of this research was to significantly improve Caltrans' ability to inspect pavement and bridge decks through appropriate use of thermal IR sensing and data processing by providing: (1) SOPs for collecting and processing georeferenced thermal IR data and (2) recommendations for data interpretation and presentation to maximize the speed and minimize the time and cost of identifying pavement and bridge deck degradation and defects.

More research is needed to provide integration of the technology within Caltrans inspection practices through identification of software solutions and the development of standardized processes and procedures. Future research will be needed to:

1. Develop a software solution and SOP for
    a. Acquisition of georeferenced thermal IR data.
    b. Processing of data to enhance, isolate, and visualize thermal anomalies.
    c. Processing, interpretation, and presentation of inspection results.
2. Investigate the development of custom software to meet this need.
3. Develop recommended SOPs for collecting georeferenced thermal IR data.
4. Develop recommended SOPs for processing thermal IR data to
    a. Optimize the identification of thermal anomalies associated with pavement and bridge deck defects.
    b. Isolate anomalies from thermal noise for better interpretation and presentation.
5. Provide recommendations for data interpretation and presentation to
    a. Discriminate thermal anomalies from noise.
    b. Integrate thermal IR and 3D GPR datasets.

c. Maximize positive identification of pavement/deck defects.

Policy Issues

The researchers encourage Caltrans to contemplate the development and implementation of safety procedures to be used while operating the van. Data collection, processing, sharing, and storage methodologies may need to be discussed and coordinated with Caltrans Division of Information Technology.

Full deployment will entail closer collaboration with Materials Engineering and Testing Services, Structures Maintenance & Investigations, and the Division of Maintenance Pavement Program. Appropriate roles, responsibilities and resourcing will need to be developed to integrate these tools into inspection practice. Full deployment may impact future reorganization plans within the Division of Engineering Services.

Chapter 7: Summary, Conclusions and Proposed Future Research

This research has fulfilled the stated objectives of this project given its limited scope based and resources. Due to the limited personnel available from Caltrans DOE, the AHMCT researcher has performed all the hardware fabrication and installation, which differed from the original research plan in which DOE personnel would have performed some of the hardware fabrications and installations. This diverted some of the researcher's effort from originally proposed tasks, as agreed upon with the customer and project manager.

The key deliverables of this project are:

- Literature search and camera requirements.
- COTS camera and system search, including purchase recommendations.
- System integration electronics and wiring design.
- Camera mount design.
- Project final report with system design, installation details, and documentation.

SHRP2 recognized the utility of thermal IR for early identification of shallow-seated deterioration in pavements and bridge decks. Early detection would allow for repair and rehabilitation ahead of significant degradation, saving maintenance time and money. Through this research, Caltrans has now installed a thermal IR system on its 3D GPR vehicle, allowing georeferenced visual and thermal IR imaging of pavement and deck surfaces concurrent with 3D GPR imaging of the subsurface.

This research directly supports Caltrans' Strategic Goal of Stewardship and Efficiency as it supports consistent application of thermal IR data collection and processing for improved infrastructure inspection and maintenance. The research also supports Safety and Health as it allows thermal IR data collection from a moving vehicle, keeping workers off the pavement. The research supports System Performance as data collection will be at highway speed, eliminating traffic impacts, and will enable improved inspection and maintenance of critical infrastructure, including bridge decks. Finally, currently no other DOT possesses the unique, combined capability of mobile 3D GPR and thermal IR imaging. Thus, this research particularly contributes to the Caltrans Organizational Excellence strategic goal by continuing and enhancing Caltrans' national leadership in the application of NDE methods for highway infrastructure.

Future work

Suggested future research and development work includes:

1. Developing SOP and software for
    a. Acquisition of georeferenced thermal IR data.
    b. Processing of data to enhance, isolate, and visualize thermal anomalies.
    c. Interpretation and presentation of results.
2. Investigating the development of custom software to meet the aforementioned needs.
3. Developing recommended SOPs for collecting georeferenced thermal IR data.
4. Developing recommended SOPs for processing thermal IR data to
    a. Optimize identification of thermal anomalies associated with pavement and bridge deck defects.
    b. Isolate anomalies from thermal noise for interpretation and presentation.
5. Providing recommendations for data interpretation and presentation to
    a. Discriminate thermal anomalies from noise.
    b. Integrate thermal IR and 3D GPR datasets.
    c. Maximize positive identification of pavement/deck defects.

References

[1] "NDE Technology," Nov. 03, 2015. https://fhwaapps.fhwa.dot.gov/ndep/DisplayTechnology.aspx?tech_id=14 (accessed Apr. 20, 2020).
[2] T. M. Ahlborn and C. N. Brooks, "Evaluation of bridge decks using non-destructive evaluation (NDE) at near highway speeds for effective asset management.," Michigan Technological University, 2015.
[3] N. Gucunski and National Research Council, *Nondestructive testing to identify concrete bridge deck deterioration*. Transportation Research Board, 2013.
[4] S. Hiasa, "Investigation of infrared thermography for subsurface damage detection of concrete structures," Ph.D. Dissertation, Department of Civil, Environmental, and Construction Engineering, University of Central Florida, 2016.
[5] K. R. Maser, "Integration of ground penetrating radar and infrared thermography for bridge deck condition evaluation," *Proc. NDTCE*, vol. 9, 2009.
[6] K. Vaghefi, H. Melo e Silva, D. Harris, and R. Ahlborn, "Application of thermal IR imagery for concrete bridge inspection," presented at the PCI National Bridge Conference, PCI/NBC, Salt Lake City: UT (USA), 2011, pp. 1–12.
[7] G. Washer, R. Fenwick, S. Nelson, and R. Rumbayan, "Guidelines for thermographic inspection of concrete bridge components in shaded conditions," *Transp. Res. Rec.*, vol. 2360, no. 1, pp. 13–20, 2013.
[8] G. Washer, M. Trial, A. Jungnitsch, and S. Nelson, "Field testing of hand-held infrared thermography, phase II TPF-5 (247) interim report," Missouri Dept. of Transportation, Division of Construction and Materials, 2015.
[9] C. Maierhofer *et al.*, "Application of impulse-thermography for non-destructive assessment of concrete structures," *Cem. Concr. Compos.*, vol. 28, no. 4, pp. 393–401, 2006.
[10] J. R. Brown and H. Hamilton, "Quantitative infrared thermography inspection for FRP applied to concrete using single pixel analysis," *Constr. Build. Mater.*, vol. 38, pp. 1292–1302, 2013.
[11] C.-C. Cheng, T.-M. Cheng, and C.-H. Chiang, "Defect detection of concrete structures using both infrared thermography and elastic waves," *Autom. Constr.*, vol. 18, no. 1, pp. 87–92, 2008.
[12] G. G. Clemena and W. T. McKeel, "Detection of delamination in bridge decks with infrared thermography," *Gerardo G Clemena Wallace T McKeel JR Transp. Res. Rec.*, no. 664, pp. 180–182, 1978.

[13] S. S. de Freitas, V. P. de Freitas, and E. Barreira, “Detection of façade plaster detachments using infrared thermography–A nondestructive technique,” *Constr. Build. Mater.*, vol. 70, pp. 80–87, 2014.
[14] U. Galietti, V. Luprano, S. Nenna, L. Spagnolo, and A. Tundo, “Non-destructive defect characterization of concrete structures reinforced by means of FRP,” *Infrared Phys. Technol.*, vol. 49, no. 3, pp. 218–223, 2007.
[15] S. Hiasa, F. N. Catbas, M. Matsumoto, and K. Mitani, “Testing of dynamic infrared thermography application for subsurface damage detection in concrete structures,” presented at the International symposium on non-destructive testing in civil engineering (NDTCE 2015). Bundesanstalt für Materialforschung und–prüfung (BAM), Berlin, 2015.
[16] S. Hiasa, N. Catbas, M. Matsumoto, and K. Mitani, *Monitoring concrete bridge decks using infrared thermography with high speed vehicles*, vol. 3. 2016.
[17] S. Hiasa, F. N. Catbas, M. Matsumoto, and K. Mitani, “Considerations and issues in the utilization of infrared thermography for concrete bridge inspection at normal driving speeds,” *J. Bridge Eng.*, vol. 22, no. 11, p. 04017101, Nov. 2017, doi: 10.1061/(ASCE)BE.1943-5592.0001124.
[18] M. Ishikawa, H. Hatta, and S. Utsunomiya, “Effects of heating duration on pulse phase thermographic non-destructive testing,” *Infrared Phys. Technol.*, vol. 61, pp. 216–223, 2013.
[19] M. Janků, I. Březina, and J. Grošek, “Use of infrared thermography to detect defects on concrete bridges,” *Struct. Phys. Asp. Constr. Eng.*, vol. 190, pp. 62–69, Jan. 2017, doi: 10.1016/j.proeng.2017.05.308.
[20] S.-H. Kee, T. Oh, J. S. Popovics, R. W. Arndt, and J. Zhu, “Nondestructive bridge deck testing with air-coupled impact-echo and infrared thermography,” *J. Bridge Eng.*, vol. 17, no. 6, pp. 928–939, 2011.
[21] W. Lai, S. Kou, C. Poon, W. Tsang, and C. Lai, “Characterization of the deterioration of externally bonded CFRP-concrete composites using quantitative infrared thermography,” *Cem. Concr. Compos.*, vol. 32, no. 9, pp. 740–746, 2010.
[22] S. Chase, Y. Adu-Gyamfi, and P. Tunuguntla, “Bridge deck sub-surface defect detection using time-lapse thermography,” presented at the TRB 94th Annual Meeting, 2015.
[23] T. Omar and M. L. Nehdi, “Clustering-based threshold model for condition assessment of concrete bridge decks using infrared thermography,” presented at the International Congress and Exhibition, "Sustainable Civil Infrastructures: Innovative Infrastructure Geotechnology", 2017, pp. 242–253.
[24] “Comparison of infrared cameras for bridge deck scanning: - Vol.1 Laboratory test,” NEXCO-West USA, Inc., Dec. 2014. [Online]. Available: https://www.w-nexco-usa.com/assets/documents/Vol.1%20Laboratory%20Test.pdf.
[25] “Comparison of infrared cameras for concrete bridge deck scanning: Vol.2, Field test at Haymarket Bridge,” NEXCO-West USA, Inc., Dec. 2014.

[Online]. Available: https://w-nexco-usa.com/assets/documents/Vol.2%20On-Site%20Test.pdf.
[26] W. Roddis, "Concrete bridge deck assessment using thermography and radar," M.S. Thesis, Department of Civil Engineering, Massachusetts Institute of Technology, 1977.
[27] G. Washer, R. Fenwick, N. Bolleni, and S. Alampalli, "Development of hand-held thermographic inspection technologies," *Mater. Eval.*, vol. 66, no. 3, 2008.
[28] C. Meola, "Infrared thermography of masonry structures," *Infrared Phys. Technol.*, vol. 49, no. 3, pp. 228–233, 2007.
[29] X. P. Maldague, "Introduction to NDT by active infrared thermography," *Mater. Eval.*, vol. 60, no. 9, pp. 1060–1073, 2002.
[30] T. Dawood, Z. Zhu, and T. Zayed, "Machine vision-based model for spalling detection and quantification in subway networks," *Autom. Constr.*, vol. 81, pp. 149–160, 2017.
[31] A. Watase, R. Birgul, S. Hiasa, M. Matsumoto, K. Mitani, and F. N. Catbas, "Practical identification of favorable time windows for infrared thermography for concrete bridge evaluation," *Constr. Build. Mater.*, vol. 101, pp. 1016–1030, 2015.
[32] C. Maierhofer, A. Brink, M. Röllig, and H. Wiggenhauser, "Quantitative impulse-thermography as non-destructive testing method in civil engineering–Experimental results and numerical simulations," *Constr. Build. Mater.*, vol. 19, no. 10, pp. 731–737, 2005.
[33] I. Abdel-Qader, S. Yohali, O. Abudayyeh, and S. Yehia, "Segmentation of thermal images for non-destructive evaluation of bridge decks," *Ndt E Int.*, vol. 41, no. 5, pp. 395–405, 2008.
[34] C. Maierhofer, A. Brink, M. Röllig, and H. Wiggenhauser, "Transient thermography for structural investigation of concrete and composites in the near surface region," *Infrared Phys. Technol.*, vol. 43, no. 3–5, pp. 271–278, 2002.
[35] S. Hiasa and N. Catbas, *Efficient Bridge Deck Inspection and Assessment Framework Utilizing Image-based Non-destructive Evaluation Methods*. 2017.
[36] "Mobile Infrared Scanning — A High-Tech, Accurate Alternative to Traditional Bridge Inspection Methods." https://www.flir.com/discover/rd-science/mobile-infrared-scanning--a-high-tech-accurate-alternative-to-traditional-bridge-inspection-methods/ (accessed Mar. 18, 2020).