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Develop a UAV Platform for Automated Bridge Inspection

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16. Abstract Inspecting the health of bridges is important to maintain the operation of a road network while protecting public users' safety. However, routinely inspecting numerous bridges in a state over a long time period by human is a labor-intense and costly task, or a dangerous task in some environments such as inspecting the underneath of a bridge spanning across a rushing river. This project seeks to develop an automated bridge inspection technology that can make the inspection process safer, more efficient and convenient. The focus of this research is to study the technical foundation of an Unmanned Aerial Vehicle (UAV) system capable of remotely inspecting bridges with sensors without interfering with road operation. The applicability of this technique will be validated by a prototype UAV system with field testing.

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List of Abbreviations

Global Positioning System (GPS)
Mid-America Transportation Center (MATC)
Nebraska Transportation Center (NTC)
Proportional-Integral-Derivative (PID)
Unmanned Aerial Vehicle (UAV)

Disclaimer

Abstract

Inspecting the health of bridges is important to maintain the operation of a road network while protecting public users' safety. However, routinely inspecting numerous bridges in a state over a long time period by humans is a labor-intense and costly task, or a dangerous task in some environments, such as inspecting the underneath of a bridge spanning across a rushing river. This project seeks to develop an automated bridge inspection technology that can make the inspection process safer, more efficient and convenient. The focus of this research is to study the technical foundation of an Unmanned Aerial Vehicle (UAV) system capable of remotely inspecting bridges with sensors without interfering with road operation. The applicability of this technique will be validated by a prototype UAV system with field testing.

Chapter 1 Introduction

As the number of road users grows and infrastructure continues to advance in age, monitoring bridge health is an increasingly pertinent problem. Tragedies like the Minnesota bridge collapse of 2007 can occur unexpectedly and have devastating consequences in terms of loss of life and economic impacts, such as bringing the surrounding transportation network to a virtual standstill. Therefore, bridge engineers need reliable and efficient tools to evaluate the structural health of bridges in order to maintain the safe operation of road networks [1,2,3,4].

Monitoring bridge structures is a potentially tough problem to tackle in many cases. First, collecting data on hard-to-access regions of a bridge is difficult. For example, a regular inspection of the underneath of a bridge spanning across a 1,000 ft chasm or a rushing river is not a simple task, and can be dangerous to all involved. Second, routinely inspecting a large number of bridges in a state manually by civil engineers is also a labor-intensive and time-consuming task.

We propose a feasible, safe, and efficient solution by developing an autonomous bridge inspection system. Our goal is to be able to autonomously collect inspection data of bridges using non-invasive sensor technologies mounted on a relocatable robotic platform; to be able to detect and find patterns that could possibly tell us information about the structure’s integrity, therefore keeping track of a bridge’s health over time.

Chapter 2 Project Overview

An autonomous system capable of automatically monitoring and inspecting bridges with minimum labor involvement is to be researched. The prototype system consists of a mobile robot called an Unmanned Aerial Vehicle (UAV), a control unit to control the robot from a base station, a set of sensors on the robot, a signal communication module, an onboard computer chip, and data analysis algorithms running at a base station.

The autonomous system will monitor in-service bridges by following navigation paths designed by control algorithms or human operators, use sensors on the copters to collect data that record changes in a bridge over time, and transmit the data over a wireless network back to a base station. The data analysis algorithms at the base station will process the data to assess bridge health. Figure 2.1 illustrates the research ideas.

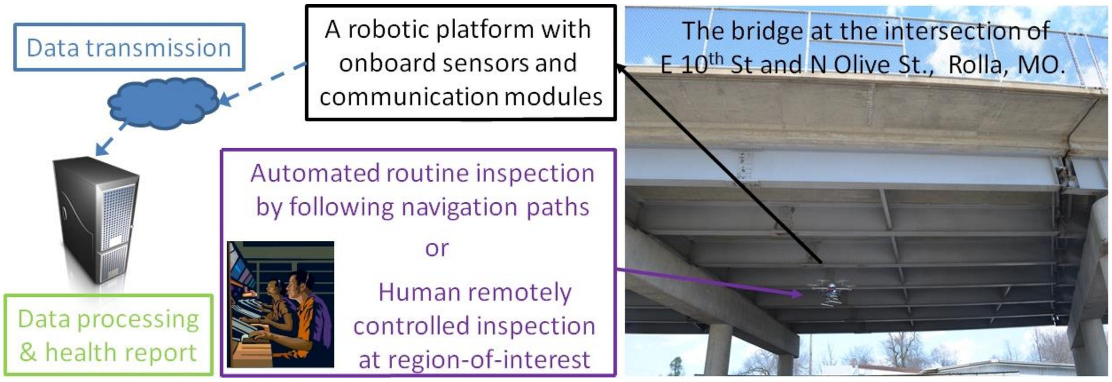


Figure 2.1 Bridge inspection by a UAV with onboard sensors

Chapter 3 Prototype UAV Systems

We built multicopters as our relocatable robotic platform capable of carrying onboard sensors. The multicopter gets its name from its appearance. The radio-controlled mini-helicopter has multiple propellers to lift it into the sky and is loaded with an assortment of cameras, sensors, and other technologies that help it maneuver and hover, making it ideal for reaching otherwise challenging locations around a bridge structure, such as the underneath. The PI's group has created several versions of the machine, including a quadcopter (four propellers) and a hexacopter (six propellers), as shown in figure 3.1. The multicopters are outfitted with the necessary equipment while being kept light enough to maneuver proficiently. The multicopter as our mobile platform will be able to freely move around a bridge and collect data without interfering with daily transportation operations.

Figure 3.1 Left: quadcopter; right: hexacopter

We embedded sensors and data transmission modules in the quadcopter to collect data and transmit data and commands between the quadcopter and ground station. Sensor data, including live videos, are transmitted back to the ground station by our signal transmission module for data processing or human-piloted navigation. In this one-year project, our goal is to build the proof-of-concept system with GPS, an accelerator, a gyroscope, and video camera sensors. In the future, we plan to collaborate with civil engineers and radar scientists to incorporate more sensors on the quadcopter, such as the heavier GPR module.

Chapter 4 Multicopter Control

While multicopters have been utilized commonly for several years now, it was not until recently that they have gained high-performance automatic navigation capabilities. Newer multicopter flight control computers have seen the addition of GPS, 3-axis magnetometers (compass), and range-finding sensors. Together, these sensors give the multicopter enough information to accurately determine where it is on the earth.

Not only can the multicopter determine where it is on the globe, but it can also use this information to navigate to specific locations as well. It accomplishes this by calculating the bearing to a set of coordinates in a 3-D space (called a waypoint) from where it is currently located. Then, it uses a simple control algorithm called a PID controller to fly directly to the point in a straight line. Once the mutlicopter is at the waypoint, it can perform tasks such as an automatic landing, or it can simply fly to the next waypoint. By stringing together many waypoints, we can stitch together a grid which allows the multicopter to fly in such a way as to give the camera carried as payload a clear view of the object to be observed.

One issue with this type of navigation is that it is fully reliant on the availability of GPS to determine the position of the craft. A GPS fix is obtained on a high frequency signal that comes from satellites orbiting the earth. Because it is a high frequency signal, it has very little penetration power. Thus, GPS is available in an outdoor environment; however, in an environment with obstacles we may not have a consistent or accurate GPS signal. In the project, we first experimented using external sensors to control the multicopter and then tested the multicopter in the field.

4.1 Multicopter Control with External Sensors

One external sensor system we tested was an array of infrared cameras we used to demonstrate control of the multicopter in the absence of GPS. The goal of this experiment was to use computer vision to accurately place the multicopter at a specified location within the 3-D space using the infrared cameras to track the current position of the multicopter. This would allow us to accurately mimic the function of GPS, even if it were unavailable.

While using GPS confines the sensor solution to the multicopter and requires no equipment on the ground or even off the multicopter, the infrared computer vision system does require some external components. A description of the required components is as follows:

- Infrared camera array
    - Four total cameras were placed around the inside of a cage inside our lab.
- Testing “cage”
    - A 16ft x 16 ft x 8ft string-weave cage which surrounded the flight test area. The camera array was pointed into this cage.
- Camera hub
    - The array of cameras was plugged into a central hub, which finally connected to the computer. This hub also synchronized the cameras.
- Vision markers installed on the multicopter
    - Because the infrared cameras need exact targets to locate within the cage, specially colored spherical markers were used to identify specific parts of the multicopter. These were attached to the multicopter using thin wooden rods and small amounts of hot glue.
- PC running computer vision software

- The PC ran the computer vision software, which was written in Microsoft Visual C++ using the OpenCV computer vision libraries.
- The software consisted of three parts:
    - The first part of the software estimated the position and heading of the multicopter. The heading of the aircraft describes the pan-tilt-yaw angles of the craft in the 3-D space.
    - The second part of the software used a PID controller to apply control corrections to steer the multicopter in the direction of the desired position.
    - Finally, the control corrections were sent to the multicopter using custom developed software which emulated a human remote controlling the copter.

Using this computer vision software, we were able to reliably identify and correct the position of the multicopter within the cage. Below is a snapshot of the computer vision stabilization software in the process of stabilizing the multicopter inside the cage.

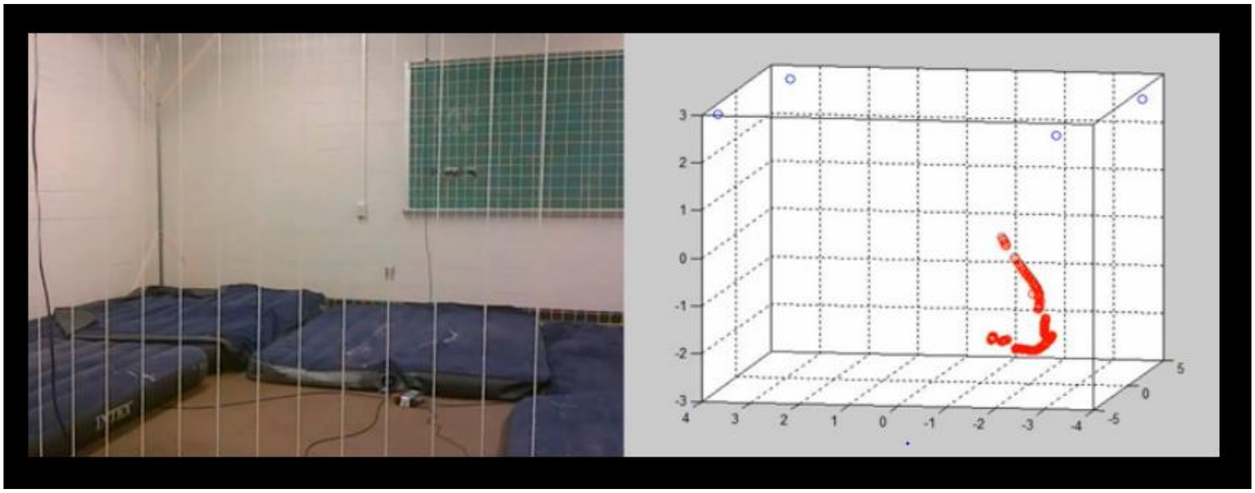


Figure 4.1 This snapshot shows a miniature multicopter being tracked in the cage. On the left, live video is shown from an external video camera. On the right, a snapshot is shown from the computer vision attitude estimation program. The ‘J’ shaped line represents the multicopter’s real position within the cage.

4.2 GPS Assisted Multicopter

While the infrared computer vision experiments revealed that we could use the multicopter with no GPS availability, we still needed to test the multicopter under control of GPS. We chose to utilize an existing GPS-enabled quadrotor to allow us to better obtain results given the small time frame. We purchased an Arducopter quadcrotor kit, which contained everything required to build a GPS-enabled multicopter using the Arducopter APM hardware platform.

We first experimented using the multicopter without GPS augmentation, simply to verify that all the video systems worked. In this configuration, we used the stock Arducopter carrying a standard FPV (first person video) system. The FPV system utilized a simple camera and radio transmitter to transmit video information back to a receiver on the ground. In this case, the receiver was attached to a video capture card, and then to a high powered desktop PC running Matlab and Visual C++. Matlab was used to acquire live video streams and on top of Visual C++, we developed our image processing software. For these tests, the goal of the image processing software was to simply identify the form of people within the image and track them as they walked below the flying multicopter.

The figure below represents a snapshot of the live video feed from the multicopter. The rectangles in the figure are the outline of the software-identified human form.

Figure 4.2 In this snapshot, the image on the left represents the computer parsed image with rectangles around the human forms. The right side of the image contains the matching video from a handheld camera. The multicopter is visible hovering just above and in front of the subjects.

4.3 GPS Augmented Multicopter Experiments

After we verified that the multicopter would be suitable for carrying computer vision equipment, we begin experimenting with using the multicopter in GPS augmented mode. In this configuration, the multicopter is flown directly from the GPS with little or no input from the operator. The multicopter even regulates altitude automatically using the altitude feedback provided by the GPS receiver. There are two main modes of operation while using the multicopter with GPS augmentation. In the first mode, called “loiter,” the multicopter will simply cling to its current location in 3-D space. This mode is useful to keep the multicopter hovering above a target at a fixed location and altitude. The second mode involves combining loiter mode with a navigation aspect; instead of flying in one single space, the position hold target is consistently moved such that the multicopter is guided along a path of waypoints. The navigation mode of the GPS augmented flight controls provides the most autonomous experience, since it can be trigged via a single switch on the operator’s transmitter.

The first experiments in using the GPS augmented modes were promising. The aircraft loitered with a low degree of “wobble” and did a good job of keeping its position, even in strong winds. Unfortunately, the same cannot be said for the navigation modes. While navigation mode did work well several times, we were unable to achieve consistent success. In one trial, the multicopter performed almost flawlessly, while in another (with higher winds) the multicopter continued to descend from altitude as it tried to fly toward the next waypoint until it eventually struck ground. It is suspected that the reason for these inconsistent results has to do with the limited information available to the multicopter about its location in 3-D space, leading the onboard flight control electronics to become confused and cease to fly the aircraft correctly. In the future, we plan to investigate the failure recovery algorithms in the autonomous control.

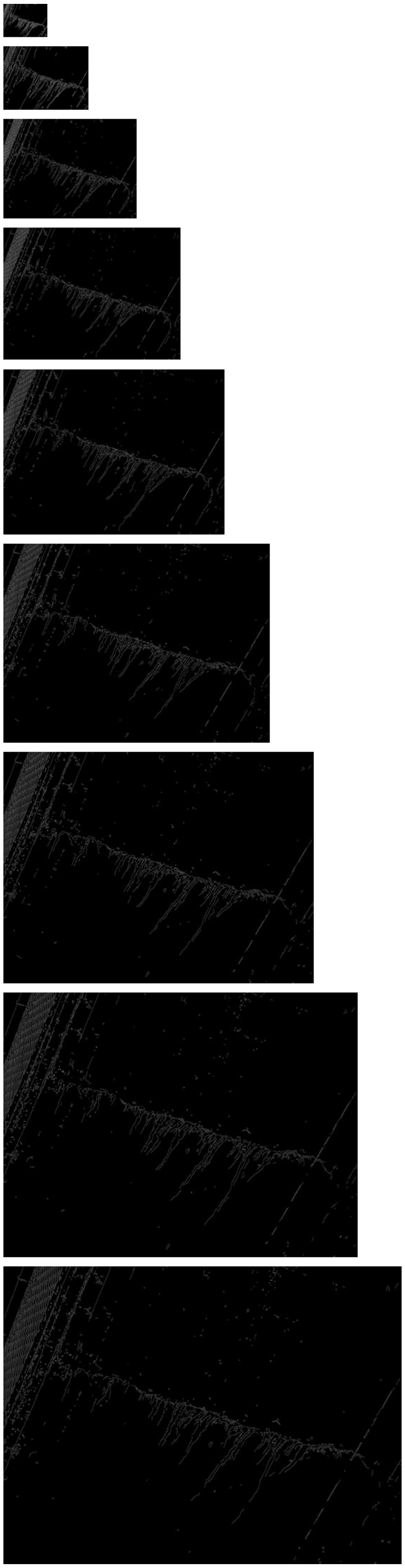
Chapter 5 Analyze Image Data Collected from the Quadcopter.

Based on this prototype UAV system, we used image data as a case study on bridge health inspection. We developed image processing techniques to analyze the images to detect and locate cracks on the structure surface.

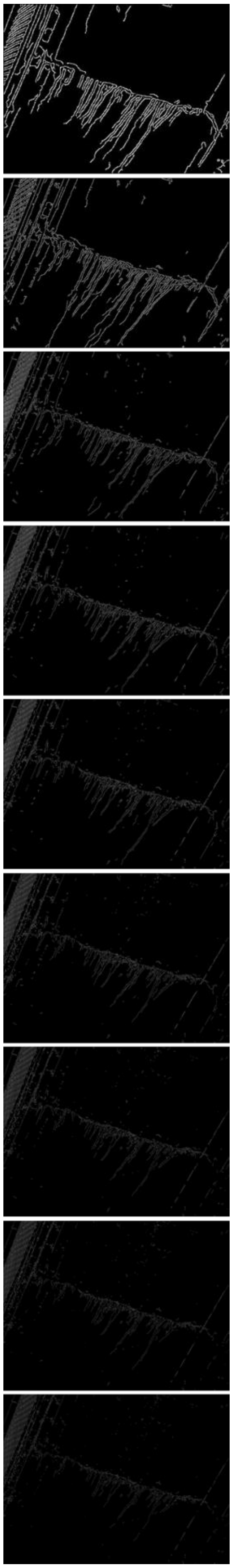
Edge detection has been widely developed in different computer vision systems in the past. Traditional edge detection methods like the Prewitt detector [5], Canny detector [6], Sobel detector [7] and other crack detection algorithms [8, 9] are designed to robustly detect edges/cracks. One problem of these traditional edge detection algorithms is that it is hard to choose the threshold of the detector when the scale of image is unknown, which is proportional to the distance between the structure surface and camera onboard.

To conquer the problem involving parameters setting we designed a Gaussian image pyramid method to enhance the response from the crack, but reduce response from other regions. As shown in figure 5.1, the original bridge surface image [fig. 5.1 (d)] is resized to different scales to build the image pyramid [fig. 5.1 (a)], then we apply the Canny filter to each scaled images to generate responses on the different scales [fig. 5.1 (b)]. We resize the filtered images to same scale [fig. 5.1 (c)]. Finally we generate the mean of these filtered images as the final result [fig. 5.1 (e)].

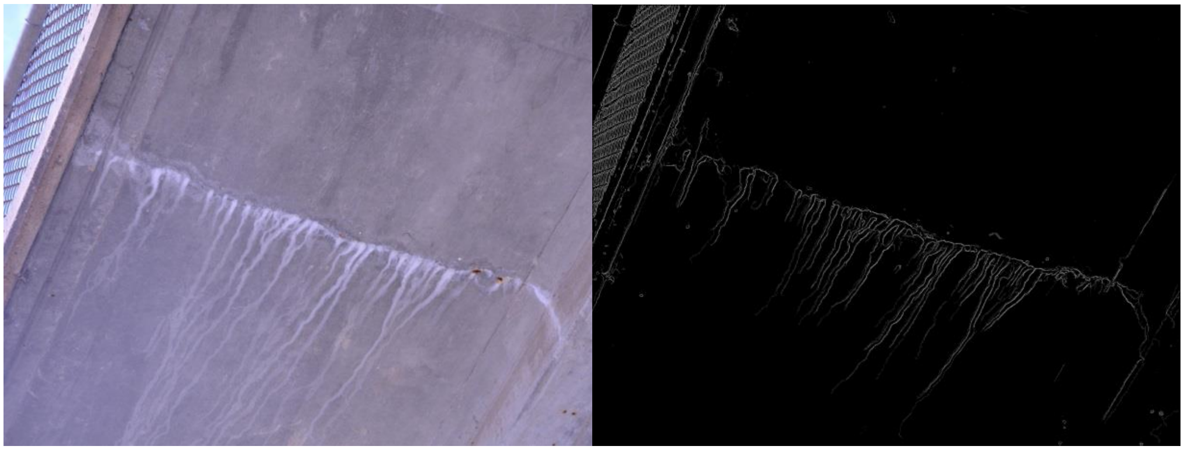
(a) image pyramid



(b) filtered image pyramid



(c) resized images



(d) bridge surface Image (e) result by proposed method

Figure 5.1 Crack detection by applying edge detection to an image pyramid

More qualitative examples of the crack detection on images captured underneath the bridge are shown in figure 5.2. In addition to the surface underneath bridges, we also tested the algorithm on other civil infrastructures such as the exterior surface of a building (fig. 5.3) and some pavement in the campus of Missouri S&T (fig. 5.4). The initial exploration of the crack detection shows its effectiveness and future work will be to quantitatively evaluate the severity of cracks on civil infrastructures.

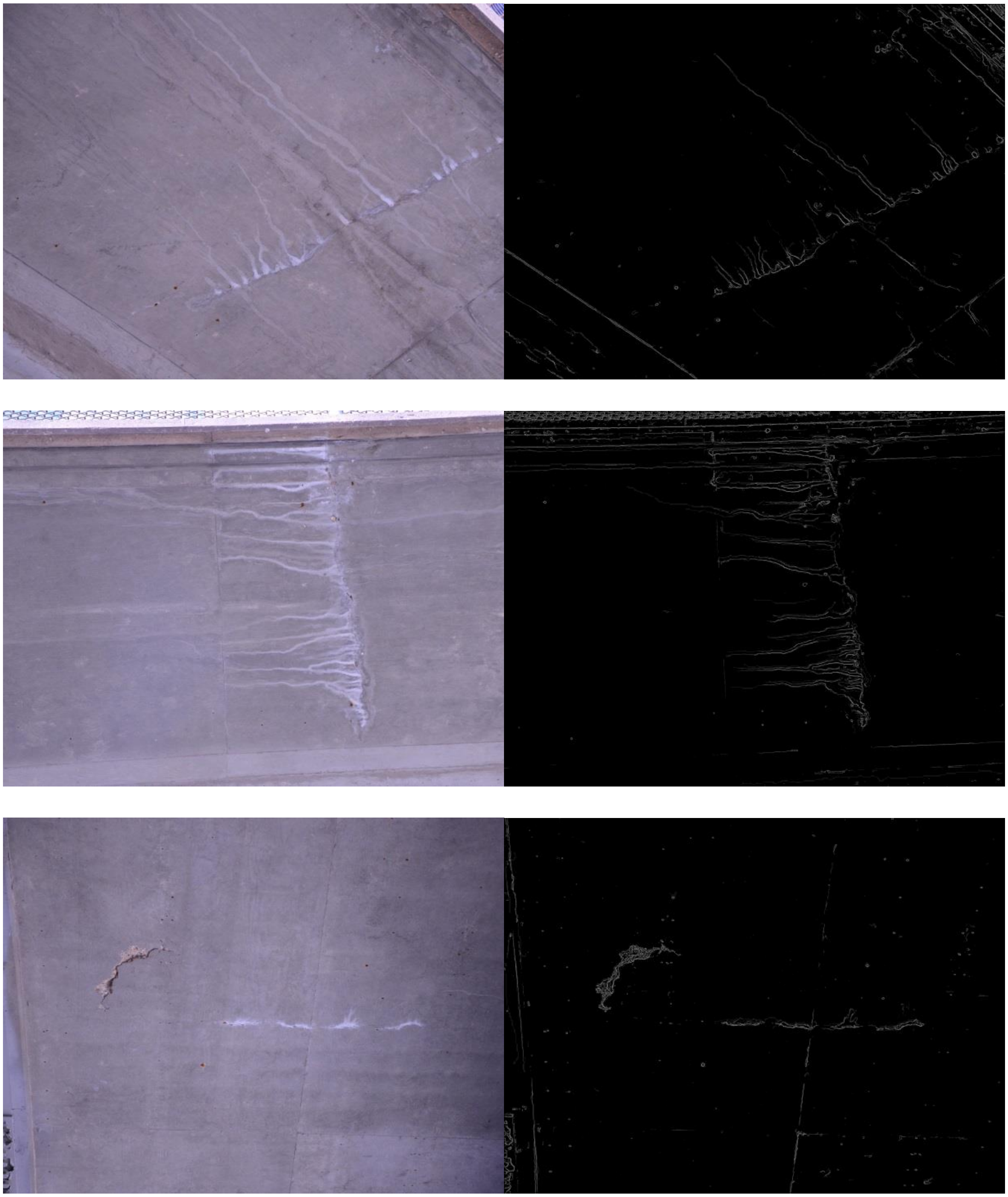


Figure 5.2 Crack detection on images captured underneath the bridge

Figure 5.3 Crack detection on images captured on the exterior surface of a 3-story building

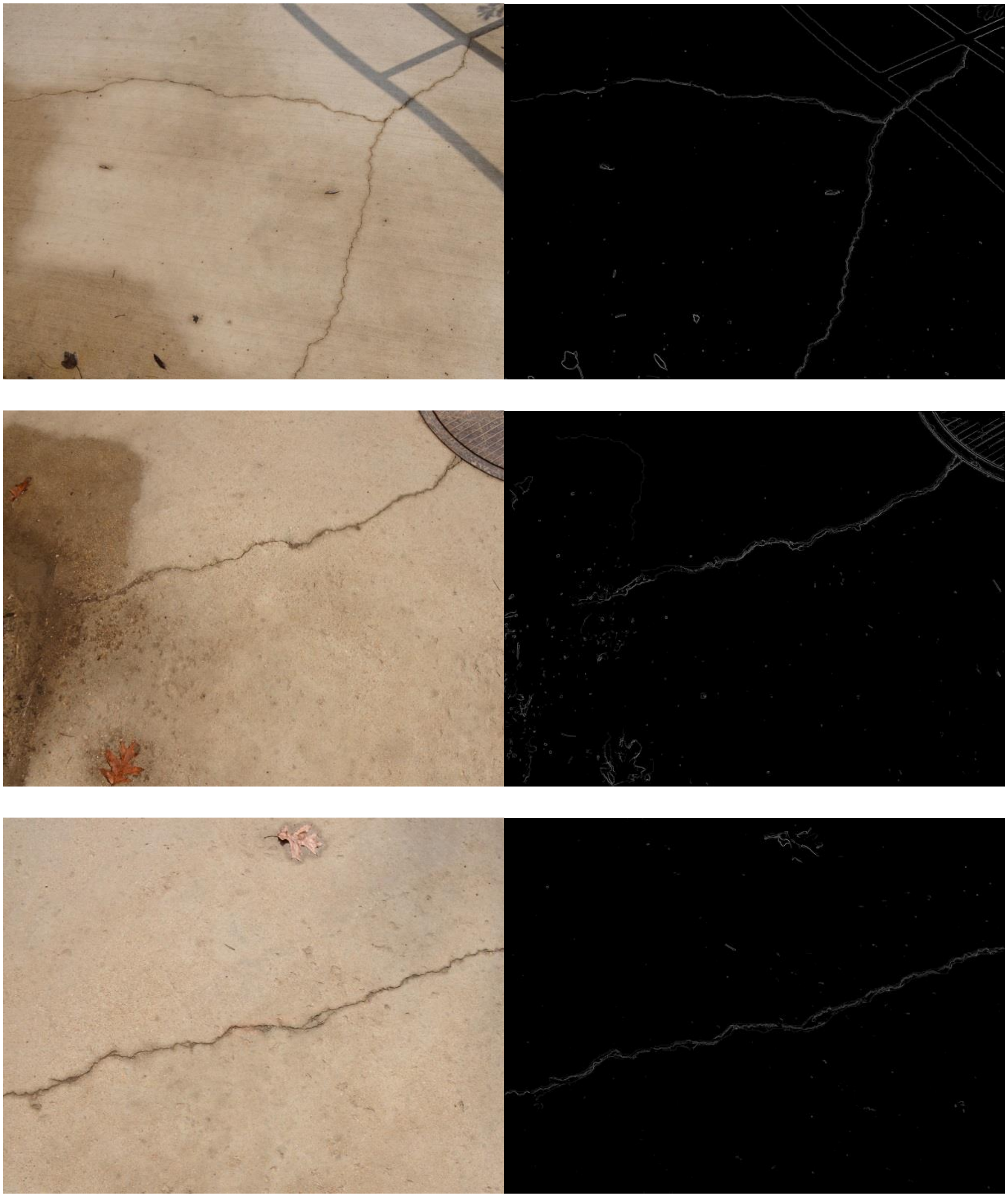


Figure 5.4 Crack detection on images captured on a pavement

Chapter 6 Conclusion

This project developed prototype UAV systems with heterogeneous sensors for the purpose of autonomously inspecting and monitoring bridges. The prototype system will serve as a basis for the PI to use as he collaborates with bridge health experts and sensor scientists to design innovative technologies on the autonomous inspection and monitoring of bridges by robots, therefore improving the sustainability of the transportation infrastructure.

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