Regular Article

The Use of Unmanned Aerial Vehicles for Sloped Roof Inspections – Considerations and Constraints

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Abstract

Building roof inspections should be performed periodically to ensure repairs and replacements are done in a timely manner. These inspections get neglected on sloped roofs due to two factors: the inefficiency of manual visual inspections, and the difficulty of accessing sloped roofs. Walking a roof to inspect each tile is time consuming. As roof slope increases so does this difficulty, increasing the time needed for an inspection. Additionally, there is an inherent safety risk involved. Falls from roofs tend to cause serious and expensive injuries. These two factors, safety and efficiency, motivated this study, the purpose of which was to determine whether Unmanned Aerial Vehicles (UAVs) can be used to perform sloped roof inspections efficiently, thus eliminating the safety risk involved in manual inspections. The metric for determining whether this is possible was that there is a UAV available on the market that (1) produces images in sufficient quality to make maintenance decisions, (2) can be flown efficiently enough so that the inspection process can be done in less than two hours for a building with a roof of about 30,000 sqft, (3) can be controlled safely by amateur pilots, and (4) is reasonably priced. The study was done in three phases. Phase 1 addressed the choice of UAV. Phase 2 explored image quality and UAV flying. Phase 3 developed the optimal approach. The study found that an economic UAV can be used in a way that makes manual inspections unnecessary. Still images and manual UAV control were sufficient and large roofs could be done in well under two hours using a three-step approach with images taken at various heights. This study has therefore identified an economical and effective technology-based alternative process for sloped roof inspection using UAVs that eliminates the risk of working at height.

Keywords: drones; quadcopter; roof inspection; roof safety; UAV

INTRODUCTION

An organization (the Client) that has a large number of buildings around the world with sloped roofs has asked the authors to develop a new and more automated process for inspecting the roofs of their buildings. The Client has found that such inspections are done too infrequently and with too many accidents. There is also concern about consistency in assessing the results of the inspections, as they are done locally by the facility manager responsible for the building. Finally, there is no record kept of the imagery taken during the inspection. Only the facility manager who did the inspection sees the condition of the roof. The Client's facility management (FM) workforce is aging, which tends to reduce inspection frequency. Even among the Client's younger FM workforce, there are individuals who have a fear of heights which can reduce frequency. The issue with the aging FM workforce is not unique to the Client but is global. The average age of members of the International Facility Management Association (IFMA) is more than 50 years old (Lockwood, 2016). This increases the risk of falling due to lessened physical strength and balance, as well as increasing the impact of a fall. However, all age groups are exposed to risk when they get on a roof simply due to gravity, and anyone can have physical limitations such as weight or disability that increase the risk of climbing on a roof. Such falls generate significant cost. The average cost of falls in the construction industry is shown in Table 1 (OSHA, 2012).

As an alternative to having facility managers do roof inspections, the Client sometimes resorts to using specialist consultants. While this practice does reduce Client liability in case of accident, and potentially reduces the actual risk of accidents since the consultants are better trained for this specific work, it does create significant cost that the Client would like to reduce.

The Use of UAVs in the U.S.

Unmanned Aerial Vehicles (UAVs, or drones or quadcopters) are establishing themselves as useful tools for infrastructure inspections, especially for inaccessible areas, for example because of height or extent of the area needing inspection or surveying. The authors' research question was: Can UAVs be used for sloped roof inspections effectively and economically? If this is the case, then there would need to be a UAV available on the market that produces images in sufficient quality to make maintenance decisions, that can be flown efficiently enough so that the inspection process can be done in less than two hours for a building with a roof of about 30,000 sqft, that can be

TABLE 1.—Average Cost of Falls from Height

Fall from elevation (roofers):	$106,000
Fall from elevation (carpenters):	$97,000
Fall from elevation (other occupations):	< $50,000
Fall from ladder/scaffold (roofers):	$68,000
Fall from ladder/scaffold (carpenters):	$62,000

controlled safely by amateur pilots, and that is reasonably priced.

UAVs have a camera that can be used to inspect a roof as the UAV flies over it. The camera can take either still images or video. These can be stored and used for later evaluation, or the facility manager can inspect the roof live as the UAV is flying using a smart phone or tablet connected to the UAV's hand-held control panel. The Client ultimately wants to evaluate recorded inspection images of groups of buildings together in a management team. This evaluation can feed into the Client's budgeting cycle.

The U.S. Federal Aviation Administration (FAA) has certain rules and constraints in place for UAVs. While hobby pilots do not need a license to fly a UAV, if the UAV is being used in a commercial setting (this includes using it as part of the pilot's job) a license is required. This is given by the FAA upon taking an exam. One of the authors took this exam successfully after approximately 8 hours of studying training videos that are available online. Two other people known to the authors subsequently passed the exam successfully using the same materials in about the same time. The other author did not attempt the test. The test costs $150 and the license must be renewed every two years. The test must be taken at an FAA-approved knowledge testing center.

Some of the FAA constraints involve the location of the UAV and the process of flying it. Flying within five miles of an airport requires FAA approval. The UAV must be kept within 400 feet of the ground or within 400 feet of the structure being surveyed. The UAV may not be flown over non-participating people, must yield to manned aircraft, and be kept within line of sight without the use of binoculars. The UAV may not be flown faster than 100 miles per hour or from a moving vehicle and may only be flown during daylight hours. Other constraints involve the pilot, who must be at least 16 years old, read, write, speak, and understand English. The pilot must have sufficient physical and mental condition to safely operate the UAV. Additionally, the UAV may not weigh more than 55 pounds and must be registered with the FAA if it weighs more than 0.55 pounds. If it is involved in an incident that causes serious injury, loss of consciousness, or property damage of at least $500, this must be reported to the FAA within 10 days. These regulations can change though, and it is recommended that a pilot stay informed at all times (FAA, 2018).

Concerns have been raised by parts of the U.S. government that data from DJI UAVs might be transmitted to the Chinese government (New York Times, 2017). DJI is the dominant UAV manufacturer, and is a Chinese-owned company. This data could include images and locations of sensitive civil and military infrastructure. In the latter half of 2017 both the Immigrations and Customs Enforcement bureau and the U.S. Army sent internal memos warning against this risk, and in the case of the U.S. Army, prohibiting the use of DJI products (SUAS, 2017; U.S. ICE, 2017). The Australian Defense Force also issued a temporary ban on DJI products (The Australian, 2017). DJI is disputing these claims.

LITERATURE REVIEW

A review of relevant literature did not show previous studies directly relevant to the goals of this study. Much of the UAV literature focused on using them to inspect infrastructure: pipelines, roads, railways, canals, rivers, or the environment in general. The work of Máthé and Buşoniu (2015) may prove useful to the authors in a potential next phase of this project: the investigation of programmed flight and the value of the various UAV options (for example, cameras) for roof inspections. Allen (2017) from the University of Missouri is using UAVs to inspect water towers. This effort is more closely related to roof inspections but lacks the level of close proximity that roof inspections require. The ability to safely control the UAV in close proximity to the object being inspected is critical for effective roof inspections.

PHASE ONE – CHOICE OF UAV

The Chinese company DJI is the dominant UAV manufacturer, with a market share of about 70%. The authors chose to test DJI UAVs to reduce the risk of performance issues due to product flaws that could be more likely with less-established companies. Three types of DJI drones were tested: the entry-level Mavic, the mid-level Phantom, and the professional-level Inspire. All three come in different models with varying details. The parameters of interest were cost, ease of use (including portability), and image quality. All three models were flown and used for a roof inspection, both by the authors and by expert users in the presence of the authors.

The Mavic costs about $1000, the Phantom between about $1500 and $2500 depending on model, and the Inspire from $3000 without camera to about $20,000 with various high-end camera options. Prices are, however, dropping and refurbished models are starting to become available on the second-hand market.

The Phantom and Inspire are both relatively large devices compared to the Mavic, and both come with a fairly bulky hard case. The Mavic is small and folds together to make a very portable device that easily fits in the hand and can be carried in a soft case about the size of a small camera bag. The Mavic has stabilization controls similar in quality to the Inspire, whereas the Phantom is noticeably less stable in flight. This is a major advantage of the Mavic over the Phantom for use by relatively unskilled pilots. Stabilization controls allow the UAV to hover in place, even in windy conditions. This is of great importance during a roof inspection, both due to the impact on image quality if the UAV is moving erratically, and the risk of wind pushing the UAV into the roof at the close proximity needed for the images.

All three models have 12-megapixel still cameras, and no difference in image quality was seen during testing. The various video modes are generally similar on all three too. The Inspire has numerous options for mounting cameras, including the use of infrared cameras, however these did not justify the higher price, since the image quality of the standard DJI camera was sufficient.

In consideration of these factors, the Mavic Pro was chosen for the testing in Phases 2 and 3 of the study.

Battery Life

Once the choice of UAV was made, the battery life was tested to determine its impact on the inspection process. Mavic batteries were found to need between 70 and 80 minutes to charge, which would cause a significant interruption of the inspection. Extra batteries can be bought, but this adds cost to a process that is mainly about efficiency. The Mavic battery life is around 27 minutes during the summer and fall temperatures in which the testing was done. This was measured from a fully charged battery until the UAV landed on its own. This happens at a somewhat inconsistent point, according to the battery charge indicator on the UAV controller, but was generally at just under 10% remaining battery charge. However, at about 30% remaining battery charge the UAV starts to signal (acoustically and visually) that the battery is getting low and that the pilot should land the UAV soon. The inspection of sloped roofs for this project was done at close range and the UAV could have safely been flown longer, but the warning signals coming from the UAV's controller are distracting which compromises the pilot's ability to focus on inspecting the roof safely. While in practice it was possible to continue flying the UAV until the remaining battery charge was in the high-teen percentages, the need to maintain a reserve charge effectively reduces the useable battery life to about 20 minutes. The batteries were also tested during the winter at 20° Fahrenheit. At this colder temperature, battery life was reduced to about 19 minutes, a loss of approximately a third of the battery capacity. With the need to retain a backup charge, this effectively reduces the useable capacity of the batteries to 15 minutes during cold weather. Based on this, at least three batteries were deemed necessary to perform a sloped roof inspection without interruption, potentially more if the inspection is done in cold weather.

Issues with Camera Mount Fragility

An issue was found with the Mavic's camera mount that might influence the purchase decision. The camera on the Mavic hangs on a gimbal in front of the UAV and is therefore exposed to damage if the UAV crashes. The risk of accident is high for new pilots, and several crashes occurred during the research. In one case, the gimbal mounting plate snapped, in another the mounting plate was bent and the gimbal itself was damaged requiring replacement. In both cases the camera itself was not damaged. The gimbal plate is made of a fragile cast metal ("pot metal"). This plate might have been designed as a deliberate weak spot to avoid damage to the camera itself. It is possible to replace the plate at home with some technical skills (the authors succeeded in doing it twice), but the process is unnecessarily awkward and time-consuming because of the cable routing to the camera. The Mavic was clearly not designed to be repaired by an average owner, yet with a minor change of cable routing the job could be done simply and quickly. Given the probability of crashing the Mavic in the application in question, this is seen as a significant issue. Illustration 1 shows the mounting plate's weak spot.

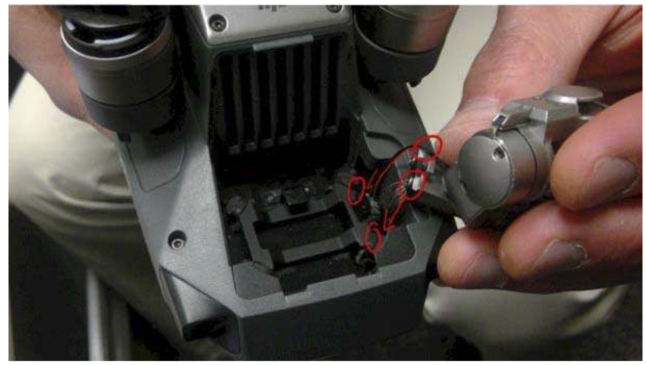

ILLUSTRATION 1.—Gimbal Mounting Plate Breaking Point

The Mavic has a protective clear-plastic bubble that can be mounted over the camera and gimbal. In most situations this does not have an impact on the quality of the images, but under certain conditions the sun can cause a glare through the bubble. The authors found it best to use the bubble during practice to reduce risk, but to remove it when taking images, since it was not possible to see the glare until the images were being analyzed on the computer afterwards. This could necessitate returning to the building to take additional images.

This camera mount fragility is enough to cast doubt on the choice of the Mavic if the organization doing the roof inspections does not have the skills to replace the mount and does not want to pay for shipping the UAV to DJI for repair each time. There is a new UAV maker (Parrot) on the market that has its camera mounted inside a protective housing. This will be the subject of future research. In general, the Mavic UAV does not seem to have been designed for do-it-yourself repairs, but the Parrot UAV is. The Parrot has a modular design, with plug-and-play components and instructional videos.

PHASE TWO – IMAGE QUALITY AND FLYING THE UAV

This phase of the research was to determine whether a UAV could give the needed image quality and whether it

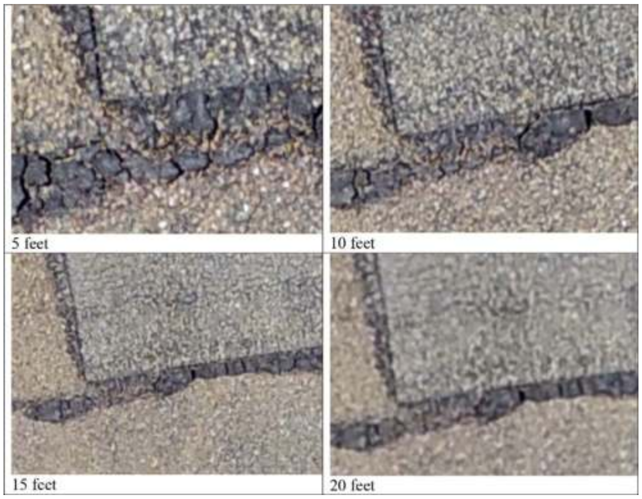

ILLUSTRATION 2.—Zoomed Image Quality at Different Heights

could realistically be flown for roof inspections by non-specialists. The authors had no previous experience with UAVs, so started the process by meeting with the Center for Unmanned Aircraft Systems (C-UAS) which is comprised of faculty and students from Civil and Environmental Engineering (CEEN) and Chemical Engineering (CE) at Brigham Young University. C-UAS has mainly used UAVs for damage assessment after earthquakes and landmass changes due to earth movement such as landslides. From the UAV images, 3D models are created to help assess the impact of these large-scale events. While the goal of this center was somewhat related to this research effort, there were differences in the desired output product.

Image Quality

The authors worked with the C-UAS to have them fly their UAV over a Client building and take images to see if they would work for roof inspections. During the first flight, both still images and videos were taken. After reviewing the images, it was determined that the UAV was flown too high to achieve an image quality suitable for roof inspections. The authors attribute this to the past experience of the UAV pilot, which was creating large scale imagery of landslides, etc., where the big picture was more important than fine details.

To determine the optimal flight elevation, a second test flight was performed, taking hovering still images at 5, 10, 15, 20, 25, and 30 feet above the roof. A sample of the images can be found in Illustration 2. Table 2 gives a summary of the image usability at the different heights. It was determined that the optimal flight elevation should be between 10-15 feet above the roof. If the UAV was flown below this elevation, the image quality was excellent – better than required – but more images were needed for the inspection. Above 15 feet elevation, the image quality was not sufficient for the roof inspection.

After the videos and still images were downloaded to a computer, it was found that one can zoom in (using standard PC or Mac capability) on the still images to

TABLE 2.—Comparison of Inspection Heights

Altitude from Roof	Image Quality	UAV Pass Density	Comments
5 Feet	Excellent	High	More detail than necessary
10 Feet	Excellent	High	Good balance between quality and UAV pass density
15 Feet	Good	Medium	Good balance between quality and UAV pass density
20 Feet	Fair	Medium	Image quality is not sufficient for the roof inspection
25 Feet	Poor	Low	Good for property overview
30 Feet	Poor	Low	Good for property overview

compensate for flying at a higher elevation. This could not be done with video. The Mavic used in this project has a 2x zooming capability (a software, not optical zoom). This was found to accurately compensate for flying the UAV twice as high. Flying at 15 feet without zoom and flying at 30 feet with 2x zoom gave essentially equal image quality. Zooming on the computer of an image taken at higher altitude without zoom gives the same effect. This gives the pilot some flexibility in flight height during the inspection. However, the image quality deteriorates faster when zooming on the computer with an image taken using the 2x zoom than with one taken without using zoom. Flying between 10-15 feet provides the best image for zooming on the computer, without the risk of flying closer to the object (say, at 5 feet).

After the elevation test, a flight was conducted passing over the roof at a lower elevation (10-15 feet) than the first flight. The image quality here was much better than the original imagery. Only still images were taken. As the UAV was flown over the building, an image was taken automatically every two seconds of the flight. This is the shortest interval possible with the Mavic. Flight speed was controlled manually by the pilot. The entire roof was covered. An attempt was made to take these individual images and combine them (“stitch” them together) to make a single composite image for the entire roof, as it was felt this was necessary for a quality inspection. This requires specialized software, which is available in both PC and online formats. An online stitching software (AutoStitch) was used with the images taken in this first low-elevation flight, with unsatisfactory results likely due to insufficient overlap of the images. Without stitching the images together, it was difficult to know which part of the roof an individual image came from, which greatly limited the usefulness of the images in spite of their optical quality. To increase image overlap, the UAV would need to be flown more slowly if using a two-second image interval. According to a commercially experienced pilot known to the authors, approximately 80% image overlap would be needed to form a high-quality composite image due to the uniformity of the images of the roof shingles.

Flying the UAV

It was found that while an older novice can become reasonably comfortable with the basic mechanics of flying a good quality UAV in less than an hour, the pilot must use great care and concentration to avoid accidents. It is unrealistic to try to control the camera and observe real-time images at the same time until the pilot has more experience. After approximately 10 hours of flight time, novice pilots start to develop some basic reaction skills that allow them to start thinking of the inspection project first of all, and flying the UAV as a secondary concern. Even so, depth perception at height remained a challenge, and the authors found that it was prudent to use a second person (a "spotter") that walks around the building maintaining a direct line of sight to the UAV and objects that the UAV could hit (trees, roof walls, power lines, etc.) and gives instructions to the pilot. This "triangulation" using two people is highly recommended.

The outcome of Phase Two was that it is possible to get inspection-quality still images of a roof using a common UAV with a stock camera. Video recording is not necessary to get inspection-quality imagery, and if anything, is inferior to still images because of the loss of resolution. Inexperienced pilots can learn to fly the UAV for roof inspections in a matter of hours if a spotter is used to guide the pilot. The experienced pilot in this phase of the study needed about 30 minutes for an approximately 30,000 sqft roof. At this speed, there was not enough overlapping of the images to successfully stitch them together. However, even if the stitching had been successful, the fine image details would have been lost, making the stitched image of little value.

PHASE THREE – THE OPTIMAL APPROACH

This phase of the research was to determine the optimal approach to performing a sloped roof inspection with a UAV, given that it was generally found to be suitable. Four approaches were considered: image stitching, video recording, streaming, and individual still images.

Image Stitching

Image stitching software can be used to create map-like composites out of a group of still images. This software requires significant overlap in the still images (potentially up to 80%). It is difficult to manually fly the UAV over a roof slowly enough while taking pictures often enough to achieve this overlap density, at the same time keeping the flight paths parallel during the several passes over the roof that are needed. Flight path control software (DroneDeploy) was tested and functioned well, overcoming the issues of manual control in creating images that can be stitched. With the flight path control software, the user specifies the amount of image overlap desired and the flight path control software flies the UAV at the correct speed to achieve this.

An initial attempt at using stitching software (AutoStitch) was made during Phase Two, but the image overlap was insufficient, so the quality of a composite image could not be assessed. A second stitching test, using images taken with DroneDeploy, was successful in that the software was able to combine the images, however the fine detail was lost at the image boundaries. It appears that the image stitching extrapolates and interprets the edges of the images as it combines them and creates something similar to reality, but not reality. This significantly reduces the usefulness of the stitched image for detecting roof defects, since it is not showing true detail everywhere. Stitching was therefore rejected from further consideration.

Video Recording

While flight path control software could be used for video recording to ensure the entire roof is covered, it is not recommended for sloped roofs due to the need to adjust the UAV's height during the flight. Because a video cannot be zoomed on the computer, the UAV needs to be kept closer to the roof when recording video than when taking still images to ensure enough detail is captured. Often the flight height needed at the edge of the roof for video will be below the ridge of the roof, requiring the UAV to be raised as the upper sections of the roof are being filmed. Manual control is therefore better for video flights.

The main advantage of video recording over still images is that you have a complete record of the state of the roof. However, the video images are lower quality than still images. Since the purpose of inspecting a sloped roof is to find details, this overview nature of a video is a serious drawback. Additional disadvantages are the difficulty in finding flaws (even obvious ones) without watching the entire video, that one tends to "get lost" on the roof while watching the video, and finally the large file size (6 GB in this case). Video recording was rejected in favor of continuing with still images.

Streaming

Streaming would entail flying a pattern over the roof and sending the camera output to an expert to observe live, using a tool like Skype. The UAV pilot would not need to know much about roofs, which could be an advantage when many roofs need to be inspected. The facility manager could stay in one location and allow someone to travel to the buildings to be inspected.

While streaming has the advantage of allowing an expert to view the roof without physically being there, the transmission depends heavily on the Internet connection, adding potential quality losses to the inherent quality disadvantage of video compared to still images. Additionally, there is no record of the inspection, as it is done live. This is a significant disadvantage if the decision makers want visual evidence to support their decision to replace or repair a roof. It would be possible, as a variant, to "stream" smaller still images as they are being taken, but then one might as well just take still images and send them to the expert with email. There is no net advantage in using a live Skype-type link during the inspection. While one could argue that the expert would guide the UAV pilot to spots of interest, in practice it proved to be cumbersome and slow. This option was rejected. The one qualified to assess the roof should be present at the building.

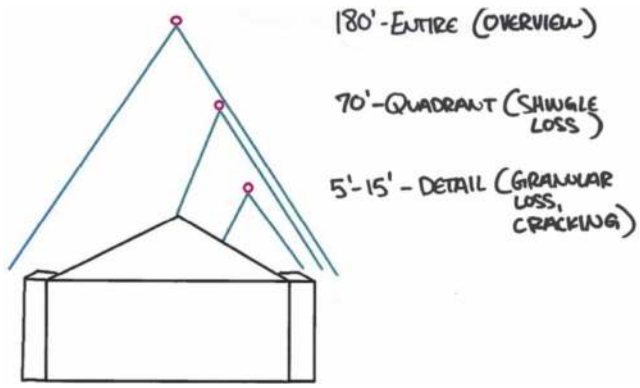

ILLUSTRATION 3.—Vertical Approach to Still Images

Individual Still Images

There are two basic approaches to inspecting a sloped roof with individual still images. The first approach would be to fly the roof (either manually or automatically) and take somewhat overlapping images of the entire roof from 10-15 feet above the roof surface. This will be called the "horizontal" approach. The second approach has three-stages and will be called the "vertical" approach. The horizontal approach is essentially the same as the image stitching approach described above, except the images are viewed individually without trying to create a composite.

The vertical approach is to start at an elevation sufficient to see the entire roof. This was approximately 180 feet for the buildings in this study. This allows the pilot to look for areas of interest that could use closer inspection. While this can be done live while looking at the UAV control panel, it was better to download this image to a computer to inspect it. This allows the pilot to zoom in with the screen to see something more closely. This step orients the pilot to the entire roof. The next step is to move down to about 70 feet and take "quadrant" pictures, dividing the roof into 4-6 sections (for a 30,000 sqft roof). This gives the pilot a much better look at potential problem areas. It might not be necessary to download the quadrant picture to the computer to analyze it. Often, it can be seen directly on the control panel screen that there is a problem. For problems seen from the quadrant height, the pilot flies the UAV down closer to take detailed pictures of that area. These pictures might be taken from between 5-15 feet depending on the detail desired. After completing the quadrant, the pilot flies the UAV back up to 70 feet and moves to the next quadrant to repeat the process. This allows one to keep better track of which areas of the roof have the defects. If one is using a tablet computer, it is possible to draw a circle directly on the image marking areas of interest. A graphical representation of this three-stage approach can be seen in Illustration 3. The horizontal approach could be described as a shotgun approach, whereas the vertical approach is more targeted and efficient.

The horizontal approach is less efficient than the vertical approach. Due to the zooming capability, once the images have been downloaded, there is no significant advantage to having pictures of the entire roof taken from 10-15 feet. It was found that if the entire roof was pictured at the 10-15 foot level, it was hard to keep track of which part of the roof was being shown. It is possible to get a good overview of the general condition of the roof by zooming in on the quadrant-height images, supplemented by the detail-height images. The vertical still image approach is the preferred method. It is the most efficient method to manage, and can be expanded to give more detail by dividing the roof into more sections if the quadrant height is reduced from 70 feet. Examples of image quality using this approach can be seen in Illustrations 4 and 5.

ILLUSTRATION 4.—Initial Image at 180 Feet to See Defect Zones

CONCLUSION

The recommended process for inspecting sloped roofs with a UAV is to use individual still images, following the vertical (zooming) approach. It can be done quickly in comparison to the other options, provides evidence of the inspection in a manageable format (small individual photos), and reduces the risk of flying into obstacles. Using a horizontal approach (flying across the roof) increases this risk due to the difficulty of judging relative depths at height and distance. It also generates so many images that one can get lost when reviewing the images. Using the vertical approach lowers the skill threshold for a pilot to do an inspection. An inspection of a 30,000 sqft roof can be done in well under two hours with a UAV using this approach. A physical inspection of a sloped roof that size will generally take at least two hours.

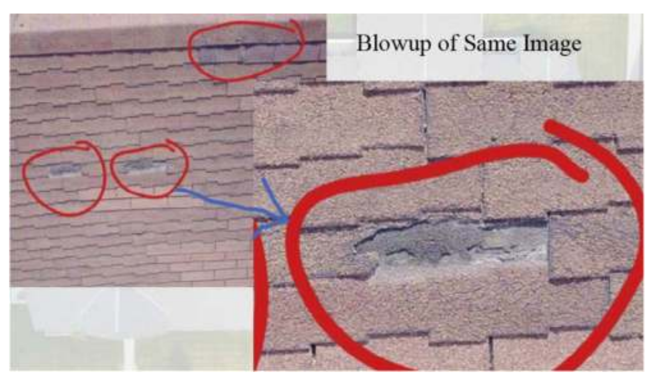

ILLUSTRATION 5.—Zooming Capability on Details

Using UAVs to inspect sloped roofs is effective and reduces the risk of falls, as well as the damage that occurs to a roof when someone walks on it. UAVs represent an economical way to inspect roofs. The UAV chosen was the DJI Mavic Pro. This UAV can be bought for approximately $1000. In some areas of the U.S., this is the cost of a single roof inspection if a contractor specialist is used.

Future research will examine flat roofed buildings, which have different constraints, both in terms of access and of what one can generally see with a visual inspection, programmed flight, and the use of various camera options.

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