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Forensic Engineering Analysis of Quadcopter Drone Personal Injury

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Abstract

A hobbyist/owner was using her remote-control model quadcopter drone for the first time when it descended and collided with a bystander. The owner believed there was a malfunction. The retaining insurance adjuster requested a review of the owner's manual and user's guide, photos and diagrams of the scene, e-mail communications, police report, and a forensic investigation of the quadcopter to determine if there was a malfunction. This paper introduces unmanned aircraft systems (UASs) for hobbyists, describes the UAS involved in this incident, outlines the planned investigation steps, and describes the sequence of events of the incident as well as resolution of the investigation. The initial activity for this case (reading manuals) prompted a question to the owner, the answer to which exposed her lack of aircraft and operating knowledge. The author convinced her that continuing the case might be embarrassing as well as costly. The planned investigation was never executed.

Keywords

Forensic engineering, unmanned aircraft system, unmanned aerial vehicle, UAS, sUAS, UAV, sUAV, remote-controlled aircraft, hobbyist, quadcopter, drone, wireless remote control, safety

Introduction

The 21st century will, in many ways, be the century of the unmanned aircraft[1]. Drones are a hot item. Although some may consider drones weapons of war, a threat to personal privacy, a leap forward in video technology, or hazardous toys, they are much more useful than the confines of these limitations — and will soon affect our everyday lives in a host of ways[2].

The growing phenomenon of unmanned aerial vehicles (UAVs) for hobbyists began in 2008 with the Top Gun RC Airplane Contest[3]. Presently, sales of hobbyist and commercial unmanned aircraft systems (UASs) are predicted to increase from 2.7 million units in 2016 to 7 million units by 2020, as estimated by the FAA[1]. A more aggressive estimate, revealed in January 2016 from technology market intelligence firm ABI Research, predicts that UAS sales to the consumer market will surpass 90 million units and generate $4.6 billion in revenue by 2025[4].

UAS usage by hobbyists and commercial entities presents a risk to safety that is addressed by the Federal Aviation Administration (FAA). In 2012, the FAA enacted an exemption process for commercial use of drones in Section 333 of the FAA Modernization and Reform Act of 2012[5]. The FAA released its first regulations on hobbyist use of drones in "The Small UAS Rule," FAA sUAS Part 107 of June 2016[6]. For both hobbyist and commercial use of small UASs, maximum altitude is confined to 400 feet, and flight is constrained to be within the operator's line of site[1,5,6]. It is important for forensic engineers to note that forensic use of UASs are covered by Section 333, falling outside of the Part 107 rules for hobbyist drones.

New commercial applications are developing rapidly, despite local regulations being in a state of flux. Some new applications are package delivery, agricultural and safety inspections, industrial and consumer photography, humanitarian aid, first responder assistance, and surveillance[2].

There is much work left to do to keep the public safe as the UAS market continues to grow at a rapid rate[1]. UAS operators are required to register their aircraft with the FAA[2], and the UAS owner manual for the subject device strongly suggests obtaining training. Owner's manuals may spell out federal regulations and rules of safe operation, but there

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are no requirements for training or licenses for UAS hobbyists as of the date of this paper. Since there is no requirement to report hobbyist UAS crashes to any civil aviation authority, there are no reliable statistics on drone crashes. However, online searches for "quadcopter crashes" turn up multiple articles about injuries and property damage.

This paper reports an analysis of an injury due to a crash of a small (under 55 pounds[5]) UAS (sUAS) quadcopter drone operated by a novice hobbyist, who claimed an aircraft malfunction had taken place.

Background

Early one midsummer's evening with plenty of daylight remaining, under partly cloudy skies and mid-70s temperature (according to historical meteorological data collected approximately eight miles from the site of the incident), a novice owner of a new quadcopter drone took it to a city park for its maiden flight. She set it up on a playground basketball court, started it up, and caused it to lift off. Soon thereafter, she lost control of the aircraft, which flew away from the basketball court, through some trees, out of the park, and descended — striking an unsuspecting bystander. The operator and victim visited a nearby police outpost and reported the incident. Fortunately, the bystander reported no serious injuries. Nonetheless, the bystander later sued the owner/operator of the quadcopter drone.

The operator notified her insurance agent and retained an attorney, saying that the drone malfunctioned and "dropped onto the claimant." The insurance agent contracted with the author through an expert witness agency.

Small Unmanned Aircraft Systems for Hobbyists

Drones are essentially flying robots[7]. A "small" drone, weighing less than 55 pounds[5], is sometimes referred to as an sUAV. As one might guess, warfare was the earliest use of drones, dating back to air balloons carrying explosives in 1849[7]. Radio-controlled aircraft were used in World War II as aerial torpedoes and during the Cold War, both as target-drones and for data collection[7]. Earliest civilian and hobbyist UAVs were fixed-wing remote control aircraft[3]. Quadcopters, also called rotorcraft, appeared later and have become widely available to hobbyists since the early 2010s[7].

Quadcopters use two pairs of spinning rotors. Two rotors spin clockwise, and two rotors spin counter-clockwise. Computer algorithms translate joystick commands to adjust altitude, speed, or direction into wireless signals that control the rotor spin rates. The combination of four rotor spin rates achieves control of the craft[7].

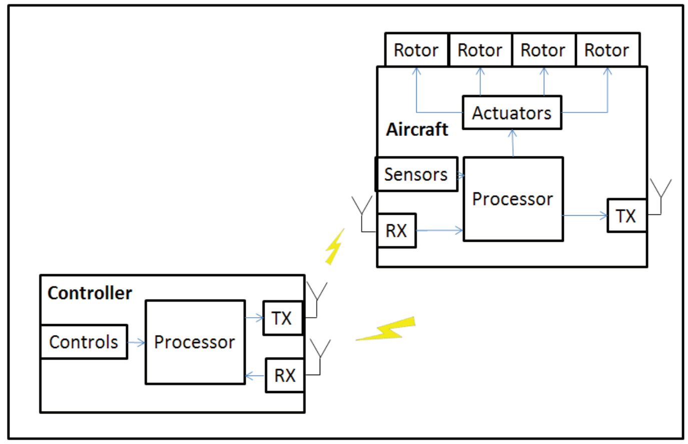

Figure 1
Block diagram of aircraft and controller.

Figure 1 is a simplified block diagram of a quadcopter aircraft and its remote controller. The processor on the controller takes its input from the joystick, other manual operator controls, and from received feedback from the aircraft. As output, the processor transmits an encoded radio signal to the aircraft. The aircraft has its own processor. The encoded radio signal from the controller is input to the aircraft's processor. The processor also receives input from sensors. Sensor information may include altitude, GPS coordinates, magnetic compass readings, wind speed and direction, battery status, and more. With this information, the processor outputs electrical signals controlling four rotor actuators that achieve flight. Simultaneously, the processor transmits an encoded radio signal back to the controller. The encoded return signal includes flight status data, which closes a feedback loop establishing stable control.

Figure 2 helps to illustrate how uplift, downfall, yaw, pitch, and roll are controlled by rotor speeds[8]. Equal thrust from all four rotors with a magnitude equal to the aircraft weight results in a stable altitude and hovering in place. Increasing the throttle increases the rotor speed, which, in turn, increases upward force or thrust, causing the aircraft to gain altitude or uplift. Decreasing the throttle decreases rotor speed and thrust, producing downfall. ("Throttle" in the context of a UAV refers to the operator control inputs and circuitry regulating the rotation rate of the electric motors.)

Yaw is a rotation about the vertical axis through an aircraft's center of gravity. Quadcopter yaw is accomplished

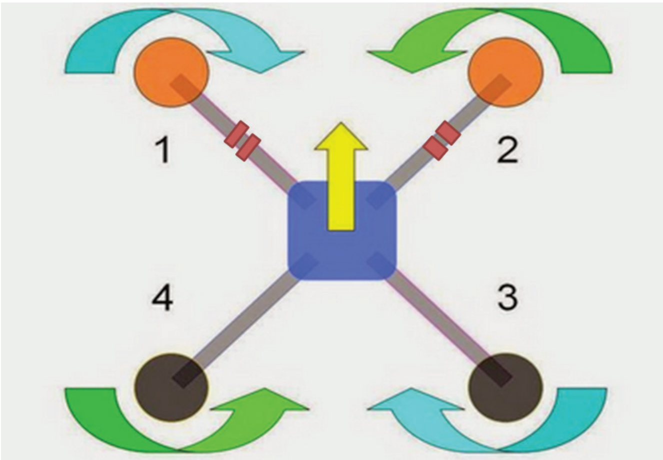

Figure 2
Rotor direction diagram for generic quadcopter[8].

by increasing the rotation speed of rotors rotating in the same direction with respect to rotors rotating in the opposite direction. In **Figure 2**, increasing the thrust of rotors 1 and 3 with respect to rotors 2 and 4 causes counterclockwise yaw; increase thrust of 2 and 4 with respect to 1 and 3 causes clockwise yaw.

On the subject quadcopter, the forward direction is indicated by contrasting color bands on two of the fuselage arms. In **Figure 2**, the red bands on the arms of rotors 1 and 2 indicate the forward direction is that of the yellow arrow. It is important for the operator to be aware of the quadcopter's orientation and forward direction. The "forward" command on the controller applies to the direction indicated by the color bands. In nearly all cases, it is recommended to orient the quadcopter so that forward is away from the operator, to avoid confusing the operator. This drone characteristic differs from radio-controlled cars and fixed-wing aircraft, which cannot be readily operated "in reverse," necessitating the use of the controls "backward" when returning to the point of origin.

Pitch means to tilt the nose of an aircraft down or up, rotating about a lateral axis. Roll means to tilt it from side to side, about a longitudinal axis. To simplify the description of pitch and roll, temporarily redefine forward as the direction of rotor 1 in **Figure 2**. If forward is the direction of rotor 1, increasing the thrust of rotor 3 with respect to the other rotors causes the quadcopter to pitch forward. Increasing the thrust of rotor 1 with respect to the other rotors causes the quadcopter to pitch backward. Increasing the thrust of rotor 4 with respect to the other rotors causes the quadcopter to roll to the right. Increasing the thrust of rotor 2 with respect to the other rotors causes the quadcopter to roll to the left.

Modern quadcopters make concern for individual rotor speeds unnecessary. The operator commands rudder and throttle through the joystick and trigger-activated buttons on a radio control (RC) unit in what is intended to be an intuitive manner, and the processor's software translates the commands into throttle control of the four rotors.

The UAS in Question

The sUAS involved in this incident comprises the aircraft with a gimbal-mounted camera mounted beneath its fuselage, the remote controller, and the application software.

Application software must be downloaded onto a separately purchased tablet or mobile phone and onto a personal computer. Two sets of hard-copy documentation are shipped with the product: a Quick Start Guide and a full User's Manual. Both the guide and manual are available online as PDF files.

Quick Start Guide

The Quick Start Guide includes:

- Disclaimers and warnings.
- A pre-flight checklist including rules of safe flying.
- Cautions regarding battery charging and usage.
- A pictorial listing of product package contents.
- Illustrated summary instructions for controls.

A point important to this case is that there is no mention of a flight data recorder anywhere in the Quick Start Guide. Assembly steps include:

- The attaching of landing gear, propellers, gimbal and camera to the aircraft.
- The charging and installing of batteries.

Flight instructions steps are:

- Power on the transmitter.
- Establish the (IEEE 802-11 b/g) radio link between controller and aircraft.
- Power on the aircraft.

- Calibrate the compass.
- Record "Home."
- Make a short test flight.

The UAS in question makes use of GPS when six or more GPS satellites are available. The aircraft saves its GPS location as "Home" 10 seconds after it is powered up. The recorded Home may be used to automatically command the aircraft to return to its launching pad. This return routine may be configured to occur automatically as a failsafe reaction to loss of RC signal. The Quick Start Guide describes the return and failsafe routines in narrative form, graphically, and by flow chart. The return routine may not work without good GPS connectivity, and it does not attempt object avoidance. In lieu of object avoidance, the routine begins by uplifting the aircraft to a default return altitude of 65 feet above the initial operating point. This return altitude may be changed within the application software.

The Quick Start Guide describes the aircraft's power management system, which, among other duties, monitors battery voltage. The low-voltage response of the system is described as having two levels of protection.

- The first level response displays a warning sequence of beeps and LED flashes on the remote controller.
- The second immediately forces an orderly landing with limited control still available to the operator.

The Quick Start Guide's appendix includes:

- A table of LED Flight Indicator states and audio signal sequences to the operator.
- Aircraft specifications.
- Camera specifications.

Rules of Safe Flying

Here are key rules from the Quick Start Guide:

- Obtain some flight training before using the product for the first time.
- Check condition of all parts of the product, especially propellers and motors installation, for firmness and propeller directions.
- Make sure transmitter and aircraft batteries are fully charged.
- The transmitter to aircraft link is via IEEE 802-11 b/g. Avoid interference with other wireless equipment.
- Power sequence should always be first to power on the controller, and second to power on the aircraft. The landing sequence should be to first power off aircraft and second to power off the controller.
- Keep the aircraft 3 meters away in any direction from the operator, other people, obstacles, power lines, and sources of magnetic interference.

Online User Manual

The online user manual lists a gimbal-mounted camera with Wi-Fi video downlink, flight battery with built-in power management system, and remote-control flight controller as key features. In general, the Online User Manual has more detailed instructions, explanations, and diagrams than the Quick Start Guide.

Another point important to this case is that a so-called "beginner mode" is described in the Online User Manual but not in the Quick Start Guide. The quadcopter kit is shipped in beginner mode by default. In beginner mode, flight is restricted to within a cylinder of radius 30 meters and altitude of 30 meters (about 98 feet) from the initial operating point. In beginner mode, the aircraft is designed not to fly beyond this cylindrical boundary, but to halt and hover by means of GPS feedback when reaching any of the boundary edges. It is explicitly stated in the Online User Manual that the return routine will not work if GPS lock is lost — a fact that may be inferred from the Quick Start Guide but is not explicitly stated.

There is a flight data recorder built into the aircraft, and a battery life recorder built into the aircraft battery and power management unit. It is important to emphasize that this information, given in the Online User Manual but omitted from the Quick Start Guide, turned out to be crucial to the sequence of events of this case.

Investigation Plan

Planned External Examination and Non-Destructive Internal Examination of Crashed Aircraft and Remote Controller

Note: These steps were obviated when the drone owner dropped the case.

1. Inspect condition of aircraft and controller batteries for residual odor, deformation in shape or color change, which may have resulted from high temperature or leakage.

2. Inspect motors and brushes for evidence of shorting, which could occur from operation in rain, fog, or high humidity.

3. Inspect propeller locations and tightness.

4. Inspect landing gear installation integrity.

5. As far as possible without damaging the aircraft and controller, dismantle and inspect interior for loose wires, bad solder joints, or other visible faults.

6. Measure residual charge on aircraft and remote controller batteries.

7. Observe results of "Battery Life Test" directly on the aircraft battery package.

8. Charge the aircraft and remote controller batteries (possibly a "destructive" step). Throughout the charging process, observe the battery LED signaling sequences and compare to sequences described in the Quick Start Guide.

9. Observe the remote controller's switch settings. Check that it is set for FCC rules for North America (as opposed to European CE rules).

10. With charged batteries installed, test that aircraft and remote controller are wirelessly linked.

11. Connect the aircraft to a computer running the downloaded application software to access information from the flight data recorder and battery data recorder (possibly a "destructive" step). Expected information includes telemetry and other detailed flight data, and a battery log of charging and discharging history going back to initial factory testing. Observe all recorded events, looking for control sequences and the resulting flight pattern as well as looking for any mechanical or electronic anomalies.

12. Following instructions in the full owner manual, identify the status of the aircraft and controller calibration state, and determine if it is still valid.

13. Follow the prescribed power-up sequence for the aircraft and remote controller. Observe and record the sequence of beeps and LED patterns, comparing to expected sequences according to the manual.

14. Test that the aircraft compass module was not compromised by proximity to magnets, including (but not limited to) speaker magnets inside motor vehicles. A straightforward screening test would be to bring the system to an open area away from large metal objects, power lines, or other magnetic interferers, and compare aircraft compass readings to readings from a compass.

Planned External Examination and Non-Destructive Internal Examination of Exemplar Aircraft and Remote Controller

1. Inspect aircraft and remote controller externally and internally.

2. Charge aircraft and controller batteries.

3. Connect the aircraft to a computer running the application software to access information from the flight data recorder and battery data recorder. Expected information includes telemetry and other detailed flight data, and a battery log of charging and discharging history going back to initial factory testing. Observe all events but especially confirm expected history of either a brand new kit or the absence of any failure or derogatory log entries.

4. Perform all specified pre-flight checks.

5. Check power-on sequence of beeps and LED patterns.

6. Calibrate the known-good aircraft and controller according to instructions: Trigger calibration by exercising mode control switch, from GPS to ATTI (attitude) modes.

NOTE: In ATTI mode, control is set for equal thrust from all four rotors with a magnitude equal to the aircraft weight. With no wind, the aircraft would hover in place, but wind will change both altitude and position in ATTI mode. In GPS mode, a servo loop making use of GPS attempts to maintain a constant altitude and position.

Repeat calibration while stressing or slightly breaking rules of the calibration procedure and observe calibration response. Attempt to force a calibration failure, and follow that up with a proper calibration.

7. Perform short up/hover/down flight tests staying well within rules. On subsequent tests, attempt to push the limits of the rules.

8. Observe operation of GPS mode successfully holding the aircraft's position in wind.

9. Repeat flight test with low battery level and observe first level automatic response (LED warnings) and second level automatic response (automatic altitude drops and landing sequence).

10. Exercise the quick start manual's "Return-to-Home" fail-safe flow chart on the exemplar aircraft. Look for bad flow chart cases. Try with the subject controller as well as the exemplar controller. Try with borderline low batteries. Stress the envelope of corner cases by devising a test list that exercises combinations of parameters set to slightly beyond their specified minima and maxima. Use these as well as full online manual's instructions as of the date of the crash.

Planned Stress-Testing of Aircraft and Controller

As mentioned, the client contracted the author to determine whether a malfunction had occurred. Accordingly, the author planned to go beyond a perfunctory inspection and functional test, and to seek out deep, hard-to-find, intermittent faults. If no faults were found in the initial tests, the next step would have been to test for intermittent hardware faults on the crashed aircraft and the potential for hardware design faults or algorithmic faults on the known-good aircraft.

The stress-test plan was to conduct "constrained random tests" by crafting a computer-controlled electrical and possibly mechanical test harness to randomly "throw" switches and controls without the aircraft being in flight. Possible methods to eliminate motion during tests included:

- Modify or replace the rotor blades.
- Mechanically fasten the aircraft to a flat surface.

Constrained random sequences are a well-known approach to testing integrated circuits and software[9]. The randomness of this approach is accomplished by repeatedly and randomly exercising all switches while also varying the time interval between transitions. The constraint of the approach is to only avoid switch combinations and sequences that are specifically disallowed in the documentation. If a combination or sequence is not forbidden, then it is allowed, and should be tested — even if it not a reasonable combination or sequence.

A major characteristic of the constrained random testing approach is to apply any — and ideally all — control sequences and timings that are not specifically disallowed in the manual, even though some of the sequences or timings seem not to follow common-sense.

Note that this approach should have been followed by system design and verification engineers during the product development phase. When this process is neglected, hardware and software bugs may go undetected and find their way into finished products. A goal of product design is to be robust against non-common-sense operation of controls. The device may shut down in self defense, but should not permanently damage itself.

Possibly Destructive Tests

The second part of the planned investigation was to disassemble (possibly destructively) the kit that was involved in the incident side-by-side with a new kit shipped in its original packaging, visually inspecting and comparing each aircraft structure and mechanical/electrical content. The inspection would focus on identifying loose wires, bad solder joints, cracked circuit boards, and loose mechanical connections (among other things) that could be visibly identified as different between the two aircraft.

Planned On-Site Tests

The weather bureau archive for the date and time of the incident, taken less than eight miles from the incident, reported partly cloudy skies at 70°F with little wind. Counsel for the drone manufacturer might have argued that environmental conditions, such as electromagnetic interference, were more of a factor in the crash than any defect found by testing. In anticipation, a visit to the site was planned for the same day of the week and same time of day of the incident — to measure the presence of radio or magnetic interference and accessibility of GPS satellite signals.

Timeline of the Investigation

Immediately upon signing the expert agreement and before receiving any documentation, the author provided questions to the operator through the retaining party. They were intended only to get a feel for the incident as a starting point. Many questions were obviated by conversations with the retaining party and reading the manual and other provided documentation. The following questions illustrate the author's general troubleshooting approach:

1. How many times was the aircraft successfully flown by you or others without problems?

2. Regarding the aircraft battery:

   a. Do you always begin a flight with a fully charged aircraft battery, or is it allowable for the aircraft battery to be partially discharged at the beginning of a flight?

   b. Have you ever allowed the aircraft battery to run out during a flight?

   c. What happens when the aircraft battery runs low during a flight?

3. Regarding the battery in the controller module:

   a. Do you always begin a flight with a fully charged controller battery, or is it allowable for the controller battery to be partially discharged at the beginning of a flight?

   b. Have you ever allowed the controller battery to run out during a flight?

   c. What happens when the controller battery runs low during a flight?

4. Regarding the last flight before the flight when the incident occurred, did you notice any symptoms? For instance:

   a. Did the aircraft start to work badly or sound funny?

   b. Did the aircraft become difficult to control?

   c. After you landed it, did the aircraft smell funny, or did it feel hotter than usual?

5. On the day of the flight when the incident occurred, what was the weather like — rainy/sunny, windy, temperature?

6. At the start of the flight when the incident occurred, were the batteries full, partial or low for:

   a. Aircraft battery?

   b. Controller battery?

7. During its final flight:

   a. Did the aircraft start to malfunction, sound funny?

   b. Did it become difficult to control?

8. During its final flight: Did you fly the aircraft farther from you than usual, or did you keep it within its usual distance?

9. What happened as it fell?

   a. Propellers stopped, and it fell right down?

   b. Propellers continued to rotate but aircraft went out of control and fell?

   c. Something else?

10. After it fell, when you picked up the aircraft, did it smell funny, or did it feel hotter than usual?

The independent investigating party retained by the client, who specified that an electrical engineering expert was needed to determine whether a malfunction occurred, suggested the following procedure:

1. Read all the documents provided.

2. Obtain answers to any remaining questions.

3. Draw up a time and expenses estimate based upon the intended investigation procedure.

4. Do not purchase anything until authorized.

The aircraft operator's attorney provided these statements from the aircraft operator to the retaining party:

- It was the first time the operator had flown the aircraft.

- The operator told her attorney that the aircraft went out of control and hit a bystander in the head.

- The operator and the injured bystander walked to a nearby police outpost and filed a report.

- No medical care was given, requested, or offered.

- The operator's attorney told the retaining party that the operator was a busy professional and had no time to speak with the retaining party or answer further questions.

- The operator said that she had reviewed the Quick Start Guide in detail but only briefed the user's manual.

The client's planned interaction with the operator and her attorney incorporated the following actions:

- Contact the operator and set up a meeting at her home.

- Measure and photograph all aspects of the drone and the box it was in.

- Obtain the size and weight of the aircraft.

- Photograph any instruction manuals.

- Photograph the operator's original receipt for date of purchase.

- Identify warning labels.

- Request the name and contact information of the operator's friend that was present at the time of the incident as a possible witness.

- Take a recorded statement from the operator and the operator's friend of what happened.

- Determine the approximate location of the operator and operator's friend, as well as the location of the struck party.

- Travel to the playground and photograph of the incident location.

- Photograph the operator holding the drone, and their height and weight for handling purposes of the drone.

Documentation provided by the client included:

- Photographs:

  o Ground-level photos of the scene.

  o Satellite aerial views of the incident location, some marked by the operator.

  o Dimensional and weight measurement photos of the kit contents from multiple angles.

  o Packaging photos.

  o Warning message photos.

- E-mail messages between the operator's attorney and the retaining client showing the provided questions and answers by the operator.

- The police report.

- The retaining client's report.

- The two manuals.

Conclusions

The following considerations were made and actions taken after reading the documents. In the first and only flight by the operator, she violated safety and operating rules and suggestions within the manuals. The operator did not obtain flight training from a professional or practice flying on an online flight simulator, as advised in the full manual and the quick start. The operator removed the camera from the aircraft for the flight in question, which violated the specific instructions of the full manual (but not the quick start guide) that the camera should always be mounted on the aircraft, and that the mounted camera is necessary for stable flight.

The public park in the center of a city where the incident-related flight took place was unsuitable for flying, and the operator should not have attempted to fly the aircraft at that location. The presence of people, trees, and powerlines rendered the site unsuitable for safe flying, according to both the quick start and full manuals. Both manuals say not to operate near other people, near power lines that may cause magnetic interference, or near tall buildings which may compromise GPS operation.

Even considering the unsuitability of the flight location, the potential of a malfunction remained. Any malfunction discovered would have to be significant enough to outweigh the contributions by the actions of the operator. The operator's response that she only "briefed" the user's manual also implies she may not have been aware of the flight data recorders.

The author contacted the retaining client, requesting to ask the owner/operator if she was aware of the existence of flight and battery data recorders, stating that one of the first planned investigative actions was to review the flight data. The full planned investigation and testing would be expensive, and — even if hardware or software faults were found — the opposing side may point out all the violations of rules and guidelines as major contributing factors to the incident. Therefore, no further inspection or testing would be completed until approved by the owner/operator. Within two days, the client responded that the drone operator decided to drop the investigation and settle the matter immediately.

As Fred H. Taylor aptly put it[10],

"This study demonstrates how the [forensic engineer] may protect the client from making a serious or costly mistake through unsubstantiated litigation. One of the services the [forensic engineer] must provide is to evaluate and challenge a situation as early as possible so the client knows how valid his or her position is before pursuing a claim or litigation."

References

1. D. Lenz, "Navigating Quickly Crowding Skies," *PE Magazine*, p. 8, Dec. 2016.

2. T. Foster, "10 Ways Drones Are Changing Your World," *Consumer Reports*, pp. 45-51, Jan. 2017.

3. W. Kalif, "Timeline of Radio Control," Storm the Castle.com, 2016. [Online]: Available: http://www.stormthecastle.com/model-airplanes/timeline-of-radio-control.htm. [Accessed 15 May 2018].

4. P. C. Miller, "Consumer drone sales expected to skyrocket in coming decade," UAS Magazine, 21 January 2016. [Online]: Available: http://www.uasmagazine.com/articles/1403/consumer%E2%80%90drone%E2%80%90sales%E2%80%90expected%E2%80%90to%E2%80%90skyrocket%E2%80%90in%E2%80%90coming%E2%80%90decade. [Accessed 15 May 2018].

5. Federal Aviation Administration, Washington DC, "Subtitle B—Unmanned Aircraft Systems," 29 August 2017. [Online]: Available: https://www.faa.gov/uas/media/Sec_331_336_UAS.pdf. [Accessed 15 May 2018].

6. Federal Aviation Administration, Washington, DC, "FAA sUAS PART 107: THE SMALL UAS RULE," 29 August 2017. [Online]: Available: https://www.faa.gov/uas/media/faa-uas-part107-flyer.pdf. [Accessed 15 May 2018].

7. Quadcopter Arena, "The History of Drones and Quadcopters," QuadcopterArena.com, 2018. [Online]: Available: https://quadcopterarena.com/the-history-of-drones-and-quadcopters/. [Accessed 15 May 2018].

8. "Fly your Way! An Ultimate resource for Quadcopters and Drones," Quadcopterflyers.com, 2017. [Online]: Available: http://www.quadcopterflyers.com/2015/02/quadcopters-yaw-roll-and-pitch-defined.html. [Accessed 15 May 2018].

9. D. Shleifman and V. Besyakov, "Constrained Random Test Environment for SoC Verification using VERA," in *SNUG*, Boston, 2002.

10. F. H. Taylor, "Environmental Systems Failures," in *Forensic Engineering*, New York, Elsevier Science Publishing Co., Inc, 1989, p. 256.