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WHO PAYS WHEN DRONES CRASH?

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Who Pays When Drones Crash?

Henry H. Perritt, Jr.

I. <u>A (Hypothetical) Lawsuit</u>

A. The Plaintiff's Story

Traynor Birmingham, a promising young college athlete, was riding his Honda motorcycle in the middle lane of I-75 on a sunny Thursday in May. He was alongside Mary Carol when she suddenly swerved and hit his motorcycle, causing him to lose control and strike a nearby bridge abutment. The force of the motorcycle against the abutment severed his left leg above the knee. Only the quick action by other motorists and the quick response by paramedics prevented him from bleeding to death. He has undergone several surgical procedures to shape the stump of his leg so it will fit in a prosthesis without too much pain and hours of rehabilitation to learn how to walk again. He remains as active as he can, but any thoughts of a career as a professional football player are over. He has mastered the prosthesis but he still experiences pain and emotional distress occasionally when the device needs adjustment or skin breakdown necessitates his moving about on crutches, exposing him to pity and underestimation of his abilities.

Defendant Spencer Hagan was flying a small unmanned aircraft, popularly known as a "drone," on the day of the accident. The drone fell directly on the windshield of the Toyota Camry being driven by Mary Carol. The drone did not penetrate the windshield, but was deflected down to the pavement, where it was crushed by a following vehicle. Startled, Carol swerved her car into the plaintiff.

Evidence will show that Hagan flew the drone carelessly and recklessly in a number of regards. First, he selected this particular model drone and continued to use it even though it had a reputation for erratic behavior. He violated the FAA rules for small commercial drone flight, contained in part 107 of the Federal Aviation Regulations by failing to conduct a sufficient preflight investigation to determine that the drone would fly correctly and safely on the occasion of the accident. He was also flying the drone at a height and position from which a failure in the drone's navigation control system, such as occurred on the occasion of the accident, was likely to cause the drone to fall on the expressway where it would endanger the occupants of the motor vehicles.

B. The Operator's Story

Spencer Hagan is an extremely careful pilot. Struck with an enthusiasm for aviation when he was in high school, he majored in Professional Flight Management at Auburn University and earned his commercial pilot's license. Auburn is a leader in civilian drone studies and Hagan took all the drone courses that he could find. When the FAA issued general regulations for commercial drone flight in 2016, Hagan was among the first to qualify as a remote pilot with a small unmanned aircraft rating, earning 98% on the FAA's test. After passing the test, he regularly practiced with new models of drones and offered to teach others best practices for flying them safely. He virtually memorized the manufacturer's flight manual, which will be evident from his testimony.

On the day of the accident, Hagan had briefed his customer, a general contractor erecting a new shopping center, on the rules for a drone survey of the site. Though he was not required to do so, he made sure that the contractor had room for a visual observer. His individual observer, Bradford Cannon, also had his remote pilot certificate and several hundred hours of experience in flying drones. Hagan checked the weather carefully and determined that the winds were light and forecast to remain so, that only high clouds could be expected, and that no precipitation was due.

The purpose of the mission was to survey the construction site, more particularly to get aerial imagery from which a detailed grid could be developed to show how much earth needed to be removed and added on different portions of the site to produce a level surface suitable for a foundation. The process of leveling is known in the construction on the street as making cuts and fills. The way this was to be accomplished involved, first, installing supplementary surveying software on the drone, and then, launching it and flying it along the boundary of the area to be surveyed. Once these preliminary steps were complete, the operator would activate the survey software, and the survey software, working in conjunction with the navigation and attitude control systems that came with the drone, would cause the drone to fly a series of closely spaced flights along one dimension of the field and take a still photograph at one or two second intervals as it flew. Each photograph would be accompanied by a sonar image of the ground below, which would enable the exact height of different parts of the image to be determined.

After the flight, the images could be uploaded to the surveying service's web servers, which would stitch them together and produce a comprehensive topographical map of the area. Spencer and Bradford had practiced using the surveying software and were completely familiar with its functions, knew how to set its options, and also had practiced recovering from emergency situations.

The drone vendor had aggressively advertised the availability of surveying software and sold its drones packaged with the surveying software as a bundle.

The printed documentation for the drone comprised a four-page fold out. Purchasers were referred to the vendor's website for more detailed documentation. The online documentation was poorly translated into English from Chinese, with many grammatical errors and awkward phrasing that obscured its meaning. It had the equivalent of three pages of material on emergencies, which combined battery exhaustion, failure to obtain a GPS lock before launching, and failure to calibrate the compass before launching. There was nothing in the manual or on the website about use of the surveying software increasing the likelihood of a fly-away.

The vendor provided email, chat, and telephone support, but on several occasions Spencer experienced great difficulty in getting technical support when had questions about installing new software. Emails and text messages went unanswered or prompted Spencer to make a phone call. Telephone hold-times often exceeded one hour and often resulted in disconnections before a support agent picked up. On the few occasions when Spencer talked to a support person, he could not get beyond rote recitation of instructions to reinstall the software and reboot the drone. Before he flew the mission that resulted in the accident, he persisted until he talked to a support agent and requested information about anomalies and operation of the drone with the survey software. He was told that the vendor knew of no problems.

On the occasion of the accident, Spencer and Bradford conferred and agreed that they would define the perimeter of the flight path by flying the drone slightly outside the actual legal boundary of the construction area. They did a preflight inspection according to the drone's downloaded manual, confirmed the absence of damage, looseness, or maladjustments to physical components, confirmed that all systems were functioning properly, double checked the settings for safety protocols such as return to home, land-immediately, and the geo-fencing for height and horizontal limits. All settings were well within the parameters allowed by Part 107 of the Federal Aviation Regulations.

They then launched the drone along the agreed-upon boundary. Spencer sought and received Bradford's confirmation that they were ready to trigger the automatic performance of the mission. Spencer tapped the requisite icon for the flight software and the drone began the flight by climbing to 200 feet above the survey site and flying the outbound portion of its first flight leg. When it reached the boundary at which it should have turned around and begun to fly the second leg back, it instead continued, accelerated, and began to climb. Spencer provided the necessary control inputs to terminate execution of the surveying software and to regain manual control. His commands had no effect. He tried multiple ways to activate the return to home feature. No effect. Finally, he activated the combination of control inputs that was supposed to stop the engines immediately and cause the drone to fall directly downward. No effect. The drone was, by then, nearly out of sight, and the indication on Spencer's console was that the radio signal comprising the control link was weakening.

C. The Vendor's Story

To claim that the defendant's design and manufacture of the drone caused this tragic accident requires stretching imagination beyond the breaking point. First, the defendant was entirely without fault in the design of the drone and all of its subsystems. There's actually very little to distinguish the drone's technologically from at least a half-dozen other models with which it competes. It is an electrically powered quadcopter with a battery life of about 30 minutes, capable of a maximum speed of 30 knots. It has automatic control systems that permit it to hover over one spot on the ground automatically, regardless of wind condition, automatically take off and land, fly a pre-programmed path defined by the operator, circle or orbit a chosen object, and to return to home either at the command of the operator or when its on board systems detect a loss of radio control link or impending battery exhaustion, represented by depletion of 75% of the total charge.

The defendant does little more than assemble off-the-shelf components designed and produced by other entities and readily available in the marketplace for drones and model aircraft. This is true of the battery, the navigation control board, the power control board, the motors, the rotor blades, the body, the radio control receiver and transmitter on both the drone and the operator console, and the gimbal, camera, and transmitter for sending video imagery to the drone operator or a separate photographer on the ground. Any shortcoming in the design or performance of these components is the fault not of defendant, but of the vendors of these components.

The defendant seeks to enhance its competitive position in the marketplace not by any unique capabilities or features of its product, but by creative advertising and product support that enables inexperienced purchasers to get good results.

Second, and most important, any failure in the drone or its subsystems was not the legal cause of the accident. The accident occurred because Mr. Birmingham was riding alongside Ms. Carol's vehicle, in her blind spot, for an unnecessarily long time. He should have known that if she changed lanes, she would not see him and very well might hit him.

Ms. Carol is an unskilled driver. She suffers considerable anxiety whenever she's driving on the expressway. The impact of the drone on her windshield, while no doubt startling, created no danger to her. Her automobile immediately deflected the drone down and away from the car, where it represented no further threat. Nevertheless, Ms. Carol wildly wrenched her steering wheel and accelerated, causing her to strike Mr. Birmingham's motorcycle. She had failed to keep a proper lookout for nearby vehicles and thus was unaware of his presence.

The accident also would not have occurred had Mr. Hagan flown the drone in a prudent and careful manner, in accordance with the standards usually followed by skilled commercial drone operators. He unaccountably manipulated the controls so as to cause the drone to fly outside the boundaries of the property he was surveying, and at the same time failed to fly at sufficient height to avoid objects on the ground. He failed to follow the detailed preflight inspection procedures set forth in the operating manual. If he had followed them, he would have discovered any anomalies in the drone's automatic flight control systems and, if he had followed the instructions in the manual, he would have postponed the flight until he had corrected the anomalies.

D. The Moral of the Story

The three different stories about the same accident illustrate what every good trial lawyer knows: the best way to be successful at trial is to take the facts that already exist and weave them into a story that follows principles for a good narrative.[2] A "good" narrative is measured by its tendency to persuade the fact finder to understand the facts in a way that benefits one litigant as opposed to the others.[3]

The little stories related above show the plaintiff giving an account in which he is blameless while the defendants are heedless of the risks to him. They also illustrate how each defendant then seeks to shift responsibility to other defendants and back to the plaintiff. Those basic precepts and principles of storytelling in the legal context will not change when drones crash and lawsuits result.

II. Introduction

In his 1942 short story, "Runaround," Isaac Asimov set forth three "laws" for robots:

1. A robot may not injure a human being, or, through inaction, allow a human being to come to harm.

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[2] *See*, Henry H. Perritt, Jr., *Technologies of Storytelling: New Models for Movies*, 10 VA. SPORTS & ENT. L.J. 106 (2010) (illustrating Scribean principles); Kate Wright, The Five S's of Screenwriting: Principles Of Storytelling, MOVIE OUTLINE, http://www.movieoutline.com/articles/storytelling-principles-for-screenwriting.html#.WCecL2-ZU7c.email.

[3] *See*, PHILIP N. MEYER, STORYTELLING FOR LAWYERS (2014).

2. A robot must obey the orders given it by human beings except where such orders would conflict with the First Law.
3. A robot must protect its own existence as long as such protection does not conflict with the First or Second Law.

Later, Asimov introduced a more basic law, sometimes numbered fourth, sometimes zeroth, which outranked the others:

0. A robot may not harm humanity, or, by inaction, allow humanity to come to harm.[4]

Asimov was addressing the terms under which robots might participate in everyday life. His purpose was to entertain by imagining a future that did not exist.[5]

Now, Asimov's future exists in small robots' colloquially called "drones" buzzing about by the hundreds of thousands and automobile manufacturers' jockeying for who will be the first to market a driverless car. American railroads have reluctantly committed $ 7 billion to automate the control of railroad trains.

These automated systems have caused few accidents to date,[6] but more will come. When they do, the courts will have to sort out who pays for the cost of the accident. The law has worked out a detailed set of doctrines to adjudicate products liability, and its basic outlines are clear: an actor is liable for the injuries caused by its defective products. No longer is an accident likely to have resulted from the separation of a massive connecting rod on a 300-ton steam locomotive. Now, an accident is more likely to occur because of a glitch in the execution of computer code in an integrated circuit chip about the size of a fingernail. Design defects are less likely to involve the collapse of a bridge, and more like to involve the flyaway of a 2-pound drone into parts unknown, as it is escapes control by its master.

This article argues that lawyers, policymakers, and entrepreneurs must readjust their thinking to focus on new ways in which errant technology causes injury. The functioning of new technologies in the real world is inherently uncertain and unpredictable. Post-sale technical support of products play an important role in ensuring safe operation. Vendors should face the consequences of inadequate technical support because their product cannot be operated safely without continuing and competent support.

The article recognizes that a policy bargain must be struck: law should get out of the way so that society gets the benefit of new robots without waiting for regulators to guess the future. The law

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[4] *Do We Need Asimov's Laws?*, MIT TECH. REV., (May 16, 2014), https://www.technologyreview.com/s/527336/do-we-need-asimovs-laws/ (quoting Asimov and reviewing skeptics of need for his "laws").

[5] F. Patrick Hubbard, *Regulation Of And Liability For Risks Of Physical Injury From "Sophisticated Robots*," WE ROBOTS 6, n.17 (April 21, 2012) (for presentation as a work-in-progress at We Robot Conference), http://robots.law.miami.edu/wp-content/uploads/2012/01/Hubbard_Sophisticated-Robots-Draft-1.pdf (quoting Asimov to motivate an analysis rules for liability for robot mishaps).

[6] One of the most publicized examples of such an accident involved a Tesla automobile. The fatal accident apparently resulted from driver inattention to an auto pilot blindspot that caused him to ignore a semi-trailer truck making an illegal turn in front of the car and smashing into the truck at full highway speed.

should also hold designers and vendors accountable for supporting new uses and covering the cost of accidents. Sale does not relieve manufacturers and distributors of their legal duty.

The growing importance of robotics shifts the responsibility for avoiding product defects away from mechanical and aeronautical engineers and places it on software engineers. The products the engineers design are less tangible then mechanical objects, but their characteristics nevertheless result from conscious design choices. The design choices implicate risk, because they may increase or decrease the vulnerability of a subsystem to programming bugs, or because it affects risk associated with environmental conditions.

Assuring the reliability of these products involves testing. In that respect, the shift toward robotics makes no difference in designing to manage risk. Indeed, the growing number of products liability claims involving pharmaceuticals represents a greater shift in emphasis, from the mechanical and electronic world to the world of biochemistry. Nevertheless, pharmaceutical product liability litigation has less to do with the different nature of the design and manufacturing processes than with mass marketing of products that are consumed, eliminating much of the tangible evidence available when machines cause injury.

Personal injury lawyers, especially those specializing in mass-tort cases, long have had to understand enough of the physics of accidents to deploy appropriate expert and fact witnesses to prove what went wrong in an accident.[7] In a more robotic world lawyer understanding must encompass the behavior of electrons and radio waves in the physical world as well as the behavior of large mechanical objects. A bug in the execution of a computer program is likely to be more important in evaluating causation than the forces that produce a skid on pavement. Robotics requires, not so much a change in legal doctrine, as a change in factual investigation and evidence presentation, including careful review of error logs, forensic testing, and evaluating of the software engineering design process.

This article starts with hypothetical opening arguments by the opposing parties in a lawsuit that has resulted from a drone accident. It then explains the likely issues when drone automation runs amok, presenting the leading edge of issues that will occur in every transportation mode as robotics plays a greater role in the lives of professional pilots, engineers, drivers, and masters. That section explains why drones are a good way to begin thinking about how the law will sort out legal responsibility for mishaps. Collectively, robotics in the different modes illustrate different aspects of the legal challenge. Cockpit automation,[8] well advanced, illustrates the evolution of human operators from operators to automation monitors. Positive Train Control ("PTC")[9] in the railroad industry illustrates the interdependency of different subsystems with different legacies, vendors, and purposes. Automation of ocean-going ships illustrates how the market, free of regulatory constraints will adopt robotic technology for transportation. The balance between robot and remote-pilot-operator responsibilities represents the logical extension

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[7] *See*, Loren Peck, *How Sound is the Science? Applying Daubert to Biomechanical Experts' Injury Causation Opinions*, 73 WASH. & LEE L. REV. 1063, 1090-96 (2016) (explaining engineering calculations typically used in accident reconstruction).
[8] *See*, § III.A.1.
[9] *See*, § III.B.

of what has been happening with cockpit automation to drones.[10] Eventually the balance and the law's allocation of accountability will be extended to road vehicle systems.[11]

The article then moves to a major section reviewing the basic doctrines in tort law for allocating liability when several actors' conduct has played a role in causing injury, reviewing cases drawn from the several different transportation modes involving plaintiff contingents against operators, designers, and manufacturers. Next, a short section explains why, contrary to the views of many participants in the market, making a collaborator an independent contractor instead of an employee or a partner does little to change the outcome of lawsuits. This analysis identifies the kinds of fault likely to be involved and reviews the economics that will determine how many lawsuits were filed and how vigorously they are pursued.

The cases analyzed in the article illustrate controversies about automation in all transportation modes: maritime, automotive, aviation, and rail. The existence of the cases reinforces the intuition that, as drones proliferate, litigation over accidents involving automation is not far off.

III. <u>Automation's Progress in the Different Transportation Modes</u>

Automation of all modes of transportation is occurring rapidly. Hardly a day passes without a news story about self-driving cars.[12] The aviation industry is under a mandate to equip all of its aircraft with ADS-B technology by 2020, which enables every aircraft to transmit its position to other aircraft and the air traffic control system every second.[13] Amazon is aggressively pushing for a low-level automated air navigation system that will permit small drones to deliver merchandise.[14] The railroads are well along on a Congressionally-mandated, nationwide, positive train control (PTC) system, which permits passenger and freight trains, signals and switches, maintenance personnel, and dispatchers to exchange data on a real-time basis to avoid collisions and derailments.[15]

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[10] *See*, § III.A.2.
[11] *See*, § III.C.
[12] *See, e.g,* Mike Isaac*, Uber Defies California Regulators with Self-Driving Car Service*, N.Y. TIMES (Dec. 16, 2016), http://www.nytimes.com/2016/12/16/technology/uber-defies-california-regulators-with-self-driving-car-service.html?_r=0/; Adrienne Lafrance, *Self-Driving Cards Could Save 300,000 Lives Per Decade in America*, THE ATLANTIC, Sep. 29, 2015, https://www.theatlantic.com/technology/archive/2015/09/self-driving-cars-could-save-300000-lives-per-decade-in-america/407956/, Tim Adams, *Self-driving cars: from 2020 you will become a permanent backseat driver*, THE GUARDIAN, Sep. 13, 2015, https://www.theguardian.com/technology/2015/sep/13/self-driving-cars-bmw-google-2020-driving, Alex Davies, *Uber's self-driving crash proves we need self-driving cars*, WIRED, Mar. 25, 2017, https://www.wired.com/2017/03/uber-self-driving-crash-tempe-arizona/.
[13] *ADS-B Frequently Asked Questions*, FED. AVIATION ADMIN., https://www.faa.gov/nextgen/programs/adsb/faq/ (last modified Feb. 07, 2017).
[14] *Amazon Prime Air*, AMAZON, https://www.amazon.com/Amazon-Prime-Air/b?ie=UTF8&node=8037720011 (last visited Mar. 2, 2017).
[15] *Positive Train Control*, U.S. DEP'T TRASNP., FED. RAILROAD ADMIN., www.fra.gov/ptc (last visited Mar. 2, 2017).

None of these systems will function perfectly. Mishaps will occur, causing damage to property and loss of life. When these accidents do happen, the high-level of automation will pose new challenges for tort law in deciding whether to blame man or machine. If the machine is to blame, how does the law translate that culpability into meaningful judgments?

Automation of all of the modes involves the same underlying technologies,[16] but drones provide the best context for exploring the legal framework for assigning liability. All of these vehicle automation systems use the same basic components: GPS systems for determining position, inertial measurement units for determining attitude and supplementing position information, computerized automatic control systems to apply control inputs to stabilize direction and pace of movement, computerized navigation systems to determine course, and radio links to transmit telemetry from the vehicle to a control station on the ground and to transmit control commands from the control station to the vehicle. The functioning of each of these subsystems is similar, regardless of the type of vehicle in which it is installed.

Three factors differ, however, depending on the mode: the maturity of the vehicle-specific technologies, the degree to which autonomous or remotely controlled vehicles are actually in service, and the centralization of control over the vehicles. Which mode provides the best model for considering common issues depends upon these differences. Drones stand out, compared with automobiles, trucks, and railroads. Drones are actually in service, while few cars and trucks are operating autonomously on ordinary roads. Only a few miles of railroad have operational PTC.

Drone operational responsibility is diffused geographically and organizationally because smaller entities are involved in drone design, manufacture, and operations than in the corresponding activities for other modes. This diffusion of responsibility makes controversies over liability for a mishap more visible than is likely in larger, more integrated organizations such as Tesla or Union Pacific.[17]

Traditional aviation case law is the starting point for drone accident analysis. Traditional aviation has well-developed tort doctrines for allocating responsibility among multiple actors: pilots, air traffic control specialists, manufacturers, and automated system designers.

A. Aviation

1. Cockpit Automation

The aviation industry and the FAA recognize that aviation technology is shifting responsibility for managing flight. Increasingly, pilots spend less time operating the aircraft and more time

[16] Cross pollination among the modes will be the norm. The designs for each mode will be better and safer if the engineers making the design decisions are well-informed about automation of all the modes. A concept that has proven itself in the real world of the rail industry, for example, might be the right starting point for designing a subsystem to perform a similar function in a semi-trailer truck or a drone.

[17] Railroads also do not provide the best context for analysis because almost every everything that might be said to cause an accident is under the control of the railroad. The railroads have, for the most part, set up wholly-owned subsidiaries to design and deploy PTC technology. *See* FED. R.R. ADMIN., POSITIVE TRAIN CONTROL IMPLEMENTATION STATUS, ISSUES, AND IMPACTS 16 (2012) (describing PTC 220 LLC, consortium of NS, CSX, UP, and BNSF, which bought radio frequency spectrum for PTC).

monitoring the operation of robots that actually fly the aircraft, autopilots chief among them.[18] Increasingly, airplane and helicopter pilots are becoming system monitors rather than manual operators of the aircraft. As this occurs manual flying skills atrophy, and lack of proficiency in programming and controlling autopilots represent an increasing accident threat.[19]

Autopilots, long common in commercial airplanes, are beginning to penetrate recreational general aviation and rotary wing operations. At the same time, the FAA's management of the national airspace system is evolving under a policy concept known as "Next Generation." The FAA seeks to lessen reliance on ground based radio navigation facilities and radar and ground-based air traffic controllers, and to increase reliance on GPS signals for defining airborne routes and for aircraft-to-aircraft data exchange to keep traffic separated so as to reduce the likelihood of collisions. A significant step in the implementation of Next Generation is the FAA's mandate that all aircraft be equipped with ADS-B Out systems by 2020. ADS-B Out systems broadcast a data block containing the aircraft altitude, position, direction of flight, and speed whenever it receives a "ping" from another ADS-B Out equipped aircraft or from a ground station (which might be a conventional air traffic control radar station).

Separate ADS-B In subsystems permit pilots to see on their navigational video displays all of the ADS-B Out equipped aircraft in the vicinity, with indications of whether they represent potential collision hazards. The ADS-B data can be fed into autopilots and all-encompassing flight control systems to enable various kinds of automatic collision avoidance maneuvers. Rarely do these systems take control over the aircraft; instead, they advise pilots of necessary collision avoidance actions.

As the ADS-B Out mandate is implemented, aircraft designers are installing other features such as terrain proximity warning systems and flight-envelope limits, some of which take over control of the aircraft, or otherwise limit a pilot's ability to provide unsafe control inputs.

2. Drones

Drones, more formally called "small unmanned aircraft," are remotely controlled air vehicles. The most popular ones weigh less than 55 pounds and have multiple rotors driven by electric motors which are powered by LiPo batteries.[20] The attitude of the aircraft is controlled by varying the electrical current provided to the different motors, thereby changing the RPM of that rotor and thus the thrust it generates. Controlling the thrust of the different rotors permits the vehicle to tilt and thus to turn, and to fly forward, backward, sideways, to climb and to descend. Like all rotorcraft, drones are capable of taking off and landing vertically.

No human operator has the perceptive acuity or the reaction times to manage the differential thrust of the motors quickly and accurately enough, so a high degree of automation is necessary for these vehicles to be flyable at all. Pressure altimeters (barometric altimeters), magnetometers

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[18] *See* MATTHEW E. HAMPTON, U.S. DEP'T TRANSP., FED. AVIATION ADMIN., OFFICE OF INSPECTOR GEN., FAA REPORT NO. AV-2016-013, ENHANCED FAA OVERSIGHT COULD REDUCE HAZARDS ASSOCIATED WITH INCREASED USE OF FLIGHT DECK AUTOMATION, (Jan 7, 2016).
[19] *See id*. at 1.
[20] *See* HENRY H. PERRITT, JR. & ELIOT O. SPRAGUE, DOMESTICATING DRONES: THE TECHNOLOGY, ECONOMICS, AND LAW OF UNMANNED AIRCRAFT SYSTEMS ch. 3 § 3.2, ch. 5 § 5.2.3 (2017) [hereinafter DOMESTICATING DRONES].

(electric compasses), and accelerometers packaged into inertial measurement units ("IMUs") permit on-board flight control systems to know the drone's attitude spatially and the precise nature of its movement from millisecond-to-millisecond. Automatic control algorithms provide the electrical current changes necessary to conform the drone's actual behavior to a desired behavior. Combining data about attitude with GPS signals allow the onboard systems to navigate, to fly the drone from point to point.[21]

The operator, using a small console, does not control specific electrical inputs; rather, he, like the modern aircraft pilot is essentially a system monitor, telling the onboard automation where he wants the drone to go and how fast and how high.

Virtually all drones have algorithms that give the drone the capability to execute emergency maneuvers autonomously. Most common, and found on virtually every small drone on the market, are autonomous hover, land immediately, and return to home.

B. Rail Robots

The railroad industry has the longest history with sophisticated robotics. In 1927, the New York Central Railroad deployed the first centralized traffic control, which had become commonplace on all railroads by the 1950s. Centralized traffic control permitted one train dispatcher to control signals and switches remotely at a distance of 200 miles, later growing to thousands of miles for multiple dispatchers located in the same place. Train dispatchers from a central location could set a signal and switch to divert a train onto a passing track so that another train could pass. Sensors associated with switch, signal, and track circuit sent telemetry back to the dispatcher so that he could determine the track configuration and the position of trains. The signals sent by the dispatcher conferred movement authority, eliminating the need for written train orders and telegraph operators whose job was to control movements onto railroad tracks at the end of every block.[22]

The Interstate Commerce Commission ("ICC") required automatic train control for high -speed passenger trains as early as the 1920s, which caused brakes to be applied automatically to a locomotive that passed a restricting signal without acknowledgment by the engineer.

The nation's railroads are required by statute to install a positive train control ("PTC") system by 2017.[23] PTC combines GPS, track circuit, and geographic data from train locomotives, transceivers, and antennas. In doing so, it maintains real-time awareness of the position of every locomotive and track maintenance vehicle and the condition of every traffic control device such as a signal or a switch. System logic within PTC employs algorithms that detect hazardous train operations, such as proximity of one train to another on the same track, crew violation of signal indication, excessive speed that might cause derailments and other noncompliant vehicle operations.[24]

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[21] *See id*. ch. 3 § 3.10.3.3.

[22] *See generally*, U.S. CONG., OFFICE OF TECH. ASSESSMENT, PB-254738, CHRONOLOGY OF TRAIN CONTROL DEVELOPMENT, Appx. E, https://www.princeton.edu/~ota/disk3/1976/7614/761414.PDF.

[23] *See* Positive Train Control Systems, 75 Fed. Reg. 2598 (Jan. 15, 2010) (to be codified at 49 C.F.R. pts. 229, 234, 235, & 236).

[24] Limiting train speed through a particular switch is one example.

A wayside[25] data communications subsystem communicates signal indications, switch position information, dragging-equipment detectors, landslide detectors, and hotbox detector readings from wayside sensors to nearby locomotives. It also communicates track occupancy telemetry from track-circuit sensors to signal subsystems, train dispatchers and nearby locomotives. Finally, it sends locomotive telemetry including GPS-based position information to wayside systems, other locomotives, and the dispatcher does the same thing for light engines and maintenance-of-way vehicles that might not trigger truck circuits.[26] It includes, but goes far beyond the functionality of aviation's ADS-B.

The tasks to be performed in train dispatching roughly correspond to the tasks performed by air traffic control. Both involve clearances to spatially defined blocks and instructions and clearances given by personnel (e.g., railroad dispatchers and air traffic controllers) on the ground. Both train dispatching and air traffic control make use of fixed navigational facilities not involving voice communication, namely wayside signals for railroads and VORTAC[27] and ILS[28] signals for aviation.

There are, however, differences between the two systems. Remotely controlled wayside signals can communicate movement authority to railroad engineers; aviation navigation facilities cannot engage in this kind of communication.

Still, Visual Flight Rules (VFR) in aviation roughly resemble restricted speed in railroading since both are concerned with line of sight to avoid collisions. ADS-B in NextGen aviation resembles PTC in that both involve telemetry sent by vehicles as to their position and speed. Both aviation and railroad modernization are proceeding by overlaying new technologies on legacy systems: ADS-B and GPS-based routes on top of ground-based radar and radio systems in the case of aviation; PTC on top of existing signaling and centralized traffic control systems for railroads; and overlaying data communication on top of voice for both.

C. Automated Automobiles

> And trust me, my fellow lawyers, there are going to be a whole lot of car wrecks in Tennessee in the years to come. How do I know this? Simple. Two words: driverless cars.
>
> . . .
>
> Within the next several years, driverless cars will be smashing into each other all over the Volunteer State, and at that point there will be a whole new wave of car wreck cases against sleeping occupants, driverless car manufacturers, or both.

---

[25] "Wayside" refers to something, such as a signal, that stands near, but not on, a railroad track.
[26] *See generally* FED. R.R. ADMIN., POSITIVE TRAIN CONTROL IMPLEMENTATION STATUS, ISSUES, AND IMPACTS (2012); NTSB Safety Recommendation, R-12-25 and -26 at 2 (May 10, 2012) https://www.ntsb.gov/safety/safety-recs/recletters/R-12-025-026.pdf (finding the absence of positive train control was contributing factor in collision between BNSF freight train and MOW equipment)
[27] Very high frequency Omni Range and Tactical distance measuring: a technology to allow a flying aircraft to determine the range and distance to a ground station.
[28] Instrument Landing System: a technology that allows the pilot of a descending aircraft to maintain his path on a specific approach angle to the runway.

> . . .
>
> And so while Randy Kinnard, you and I, may not have any workers' comp or medical malpractice cases in the coming years, we'll have a whole bunch of car wreck lawsuits! At that point we lawyers will be in the driver's seat.[29]

A variety of automatic safety features on automobiles and trucks long have been on the market. These features have been consolidated into the systems that permit a motor vehicle largely to drive itself such as maintaining its position in traffic lanes, maintaining a safe distance from other vehicles, automatically braking to avoid obstacles, and correcting for operator steering or braking errors that might cause skids or rollovers. The technology has reached a point where ordinary cars are capable of driving themselves for considerable distances without human input. The law already is hospitable to the technology.[30]

The regulator of highway vehicles, the National Highway Traffic Safety Administration (NHTSA), is generally supportive of the technology's potential to reduce accidents and to allow for safely increasing traffic density and therefore enlarging the capacity of the nation's roads and highways. Research and testing is underway to determine the best regulatory approach to ensure safety. This includes expanding data on the actual behavior of existing vehicles, testing new autonomous functionality, and conducting statistical fault analysis to justify mandated reliability and performance standards. NHTSA and the automotive industry have adopted a classification system for grading the degree of autonomy, ranging from one to four. Level one vehicles are largely driven by a human operator aided by systems capable of performing some discrete functions automatically, such as mediating brake applications to prevent skidding, a capability commonly known as an automatic braking system. At the other end of the rating system, level four vehicles are capable of operating and navigating without human driver input from origin to destination.

Debate is growing on how loss should be allocated when self-driving vehicles are involved in accidents.[31]

D. Self-Navigating Ships

Ships, whether designed for carrying cargo or passengers, have employed progressively more automation over the last century. Autopilots are commonplace, as are navigation systems that combine input from GPS signals, internal measurement units ("IMUs") and celestial

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[29] Bill Haltom, *But Seriously Folks: The Solution to Tort Reform*, 51 TENN. B. J. 34 (2015) (tongue-in-cheek article by former state bar association president and tort lawyer on all the litigation that will result from driverless cars).

[30] *See* Spencer Peck et al, *The SDVs Are Coming! An Examination of Minnesota Laws in Preparation for Self-Driving Vehicles*, 16 MINN. J.L. SCI. & TECH. 843 (2015) (reviewing state law and concluding that self-driving cars are already legal in most states).

[31] *See, e.g.,* Jessica S. Brodsky, *Autonomous Vehicle Regulation: How an Uncertain Legal Landscape May Hit the Brakes on Self-Driving Cars*, 31 BERKELEY TECH. L.J. 851, 859-867 (2016) (analyzing common law negligence and products liability doctrine, concluding that they are unsuitable for driverless cars, and recommending federal statute); *See also* Katelyn Sheinberg, *Embracing the Imminent: Proposed Legislation for Automated Cars in Pennsylvania*, 15 U. PITT. J. TECH. L. & POL'Y 265, 272 (2015) (advocating state legislation imposing strict liability on manufacturers of driverless cars).

observations by the crew. Ocean-going vessels have propulsion systems that employ sophisticated power management and fuel control systems. The typical propulsion system for a large container or cruise ship comprises diesel engines that drive generators. The generators, in turn, provide electricity to turn the motors connected to the shafts and screws.[32] On cruise ships, about half of the electrical power is used, not for propulsion, but for the "hotel operations" such as lighting, heating, air-conditioning, and cooking.

The technology has reached a point where self-navigating seagoing vessels are entirely feasible.[33] The barriers to actual commercial deployment lie more in the regulatory and terrorism prevention regimes than in the engineering one. The singular characteristic of this industry is that navigation on the high seas is not within the regulatory power of any sovereign state.[34] Thus, an operator believing that a level of autonomy in ship operations will serve the operator's interests is free to deploy it without colliding with any regulatory probation.

E. Architectural Similarities

Whether in aviation, locomotive, automotive, or maritime, all robotic systems share characteristics that will change the way the law addresses responsibilities for defects. These characteristics will also change the way lawyers litigate accident claims. Automation strategies must sense the state of the environment and produce particular vehicle behavior that mitigates risk. Collisions with other vehicles and objects fixed to the ground must be avoided. That requires good sensors and smart autopilots. All modes depend on radio control and thus are vulnerable to phenomena that impede radio waves. All depend on an appropriate human/machine interface. For the law to assess legal liability, it must understand what can go wrong. Understanding what can go wrong requires understanding the underlying technologies.

The purpose of the following section is to illustrate the various ways that the specific technologies that are important to robotics can fail. The technologies are the same regardless of mode; it is only their implementation that varies from mode to mode.[35]

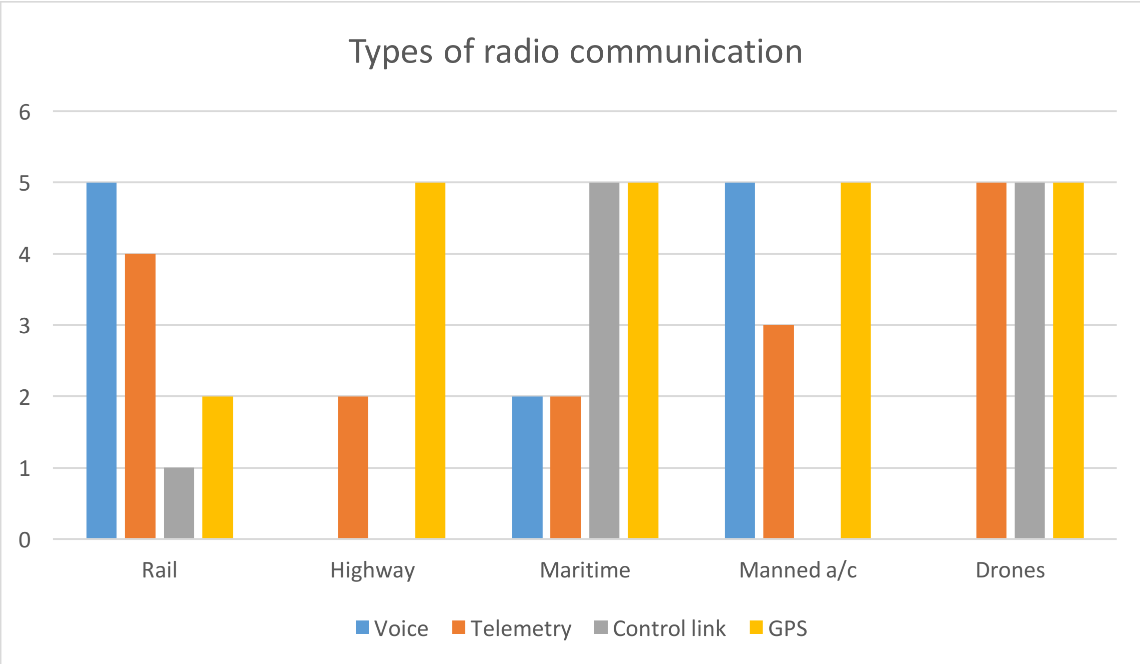
1. Radio and Its Weaknesses

The robotic technologies for all of the modes use radio communication for some of their

[32] The shaft on a ship propulsion system delivers power from the engine to the screw. The screw is a propeller designed to deliver thrust under water when it turns.
[33] *See* Jane Wakefield, *Rolls-Royce imagines a future of unmanned ships*, BBC (Mar. 5, 2014) http://www.bbc.com/news/technology-26438661; *Is 2017 the breakthrough year for unmanned vessels?*, SHIP-TECHNOLOGY.COM, http://www.ship-technology.com/features/featureis-2017-the-breakthrough-year-for-unmanned-vessels-5692723/ (reporting on demonstration programs to prove suitability of existing technology).
[34] See *The International Regulation of Shipping*, INTERNATIONAL CHAMBER OF SHIPPING, http://www.ics-shipping.org/shipping-facts/safety-and-regulation/the-regulation-of-international-shipping (explaining that nation states apply international standards).
[35] "Failure," does not signify only that a device or a segment of computer code and has failed to perform its intended task function, but it may also signify that the wrong device or the wrong computer algorithm was selected. The transmitter and receiver on a 10 meter licensed radio link may work perfectly in transmitting and receiving signals, while the 10-meter frequency band is demonstrably inferior to the 1.2 GHz band for drone control links because of the greater likelihood of interference on the 10-meter band.

functionality. Failure of radio communication is especially likely to cause accidents, so the following sections stress the behavior and vulnerabilities of the different radio technologies.

The following table shows each type of radio communication used by the different modes and its relative importance.[36]



The importance of voice and control-link radio communication varies inversely with the presence of an onboard operator. If the vehicle is entirely remote-controlled, the control link is of great importance, and voice communication is irrelevant because there is no one with which to communicate on the vehicle.

On the microdrone systems marketed in 2017, control links are implemented by spread spectrum modulation[37] of frequencies in the unlicensed 2.4 GHz band,[38] with some vendors selecting the

[36] The importance dimension is not quantitative, but qualitative and suggestive.
[37] Spread-spectrum modulation is a system for splitting information into tiny slices of content that are transmitted separately on each of a hundred or more frequencies in a band of RF spectrum. *See* K. H. Torvmark, *Frequency Hopping Systems*, TEX. INSTRUMENTS, Application Note AN014, http://www.ti.com/lit/an/swra077/swra077.pdf (last visited Mar. 5, 2017) (explaining spread- spectrum modulation). *See generally* Methods, Apparatuses, and Sys. for Asynchronous Spread-Spectrum Commc'ns, U.S. Patent No. 7,990,874 (issued Aug. 2, 2011) (reviewing history and characteristics of spread spectrum technologies). Wi-Fi uses spread spectrum modulation. Syed Masud Mahmud, *Spread Spectrum and Wi-Fi Basics*, WAYNE ST. U. http://ece.eng.wayne.edu/~smahmud/ECECourses/ECE5620/Notes/Wi-Fi-Lecture.pdf (last visited Mar. 5, 2017) (explaining how Wi-Fi uses spread-spectrum modulation).
[38] *Phantom 3 Professional Specs*, DJI, http://www.dji.com/product/phantom-3/spec (last visited Mar. 2, 2017).

5.7 GHz band instead.[39] Sometimes the control link piggybacks on top of a Wi-Fi connection;[40] in other cases it uses coding and modulation schemes similar to those used by Wi-Fi but independent of it.[41] The range of control link signals is limited to a half-mile or so.[42]

Interference from the other strong sources of RF[43] energy, such as high tension power lines or broadcast radio and television antennas can disrupt the control link, as can congestion on the relevant frequency band from other Wi-Fi users. Heavy cellphone usage would be unlikely to interfere because the frequencies are different.[44] Dense materials such as structures and hills attenuate these frequencies and can result in loss of the control link when they come between the DROP[45] and the drone.

GPS operates by means of a receiver and associated processing software that triangulate RF signals received from a multiplicity of GPS satellites. The receiver is passive; it is not a transmitter, and no handshake is involved with the GPS satellite. All the receiver needs to do is to be able to see and hear the requisite number of satellites. The satellites transmit on two frequencies: 1575.42 MHz (L1) and 1227.60 MHz (L2).[46] Typical drone GPS implementations require anywhere from 6 to 12 satellite signals to perform the necessary computations.[47] When this occurs, a state known as "GPS lock" exists. The frequencies involved suffer significant attenuation from physical objects such as foliage, structures, and precipitation, and so it is not unusual for the requisite signals to be unavailable or intermittent in particular circumstances.

a) Synchronization, GPS and Otherwise

Synchronization must exist between transmitter and receiver for any radio communication to

[39] Craigi, *Basics of Radio Frequencies for FPV Quadcopter Drones*, DRONEFLYERS (Nov. 17, 2014), http://www.droneflyers.com/2014/11/basics-radio-frequencies-fpv-quadcopter-drones/ (reviewing frequencies used by popular drones).
[40] *The Complete Drone Data Platform*, 3DR, http://3drobotics.com (last visited Mar. 2, 2017).
[41] A drone vendor could design and deploy its own control link hardware that would use some or all of the 802.11 standard without relying on off-the-shelf WiFi products.
[42] *Phantom 3 Professional Specs*, *supra* note 38; DJI MAVIC SPECS, https://www.dji.com/mavic/info (claiming control link range or 4.3 miles, and video transmission range of 80 meters horizontally and 50 meters vertically).
[43] Radio frequency.
[44] U.S. cellphones operate on the 800 MHz and 1.9 GHz frequency bands; WiFi operates in the 2.4 and 5.8 GHz bands. *Cellular Frequencies and Bands in use Today*, CRITERION CELLULAR, http://www.criterioncellular.com/tutorials/bandsandfrequencies.html (last visited Mar. 2, 2017) (summarizing cellphone frequencies); *wifi radio frequency channels*, RF WIRELESS WORLD, http://www.rfwireless-world.com/Terminology/wifi-radio-frequency-channels.html.
[45] DRoneOPerator.
[46] *GPS signals*, WIKIPEDIA (Jan. 31, 2017, 4:45 AM), https://en.wikipedia.org/wiki/GPS_signals.
[47] Tom Clark, *How a GPS Receiver Gets a Lock*, GPSINFORMATION.NET, http://gpsinformation.net/main/gpslock.htm (last visited Mar. 2, 2017) (explanation by amateur radio operator of how a device gets a GPS lock). The author holds a remote pilot certificate from the FAA and his small business owns registered drones. In his extensive experience flying these drones, none of them get a GPS lock until they have acquired signals from 6 to 12 satellites.web2.westlaw.com

occur.[48]

Loss of synchronization of GPS systems is quite common in drones, but less so in manned aircraft and highway applications. The GPS receiver requires signals from a certain number of satellites, typically 6 to 12, in order to compute its position. When the requisite number of signals become unavailable, it loses the capability to perform its function. If GPS link and position is reestablished sometime later, there will be a gap in the drone's memory about where it has been. This may or may not create a risk, depending on when the GPS link is lost and how soon it is reestablished.

Redundancy is the most common way to mitigate lost synchronization. When multiple channels exist, the likelihood that synchronization will be lost on all of them at the same time is low. Different frequencies, different modulation schemes, and different methods increase the power of redundancy. For example, relying on data about position and attitude from an IMU unit does not require radio communication at all, and thus overlaying a GPS-based navigation and control with an IMU system increases reliability of control and navigation considerably. This is not typically done in low-cost vehicles because low-cost accelerometers, the heart of an IMU, drift rapidly.

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[48] The simplest form of synchronization is for the transmitter and receiver to be tuned to the same frequency and for the receiver to be listening when the transmitter is transmitting. Radio nets are long-standing ways of achieving this kind of communication. A group of stations wishing to exchange traffic for a particular purpose agree to meet on a particular frequency at a particular time. Both frequency and time synchronization are involved.

More sophisticated automated multiplexing schemes place much greater demands on synchronization. In spread-spectrum-frequently-hopping systems, for example, the receiver must coordinate the frequency it is listening on with the frequency the transmitter transmitting on at each microsecond. If it gets behind or ahead, it will not receive any relevant information from the transmitter.

Even at the most rudimentary level of digital communications, synchronization is necessary. The transmitter and receiver must know which bit occupies each position in an eight-bit byte. Typically, low-level synchronization is achieved in transmitter and receivers close to each other (as by being inside a single computer) by using closely coordinated or common clock signals. The more widely separated the sending and receiving stations, the more difficult it is to do clock-based synchronization.

Some synchronization algorithms depend on a synchronization header—a particular pattern of bits or a particular type of signal that signifies the beginning of a packet or transmission. The receiver must be able to identify the header as such and know what to do next. Some synchronization schemes are implemented for packet communications; others are oriented toward bit streams comprising communications session events, such as one station's transmission.

Fading or interference can cause the receiver to miss critical synchronization information, in which case it loses synchronization and must have some strategy for reestablishing it. In the most primitive implementations, they only solution is to terminate the communications session altogether and attempt to reestablishing it. More sophisticated systems maintain the link, while the receiver looks for another synchronization point such as a "begin packet" header. During any period of lost synchronization, the communications channel is not transmitting any information. This may have serious consequences. If an operator transmits a control command during a period of lost synchronization, the vehicle doesn't know about it.

b) Interference, Including Multi-Path

The millions of radio signals present everywhere would produce a cacophony of interference unless some method exists for separating them. The most basic method separates them in the first instance by frequency, a technique made easier because antennas strongly receive only those signals on or near their resonant frequencies. Antenna resonance occurs when the length of the antenna is the same of a small fraction of the wavelength of the signal. Then, receiver "tuning" circuits separate the subset of signals received by the antenna. When two signals exist on exactly the same frequency, at exactly the same time, and they are exactly equal in strength, no receiver can pick out the information from one and ignore the information from the other.

Preventing this kind of common-channel interference requires assigning different frequencies to transmitters located near each other. The task is made easier by regulatory control over transmitter power and geographic location of transmitter antennas. This is always done by the FCC, which increasingly relies on private sector frequency coordinators for different services and different parts of the country.[49] A single designer of a system of multiple transmitters and antennas can present a total package to the frequency coordinator, such as in the railroad industry.

S*pread spectrum frequency hopping* is a form of rapid fire frequency division multiplexing in which a signal is sliced up into very small components and distributed across 100 or more frequencies. Multiple stations using the same block of frequencies can transmit at the same time because the statistical likelihood of a collision between any one transmission and any other is low, and because the amount of data lost when a collision does occur is so small that common error-correction protocols can reconstruct the lost data. Spread spectrum modulation is required for Wi-Fi communication in 2.4 GHz band.

Interference on common frequencies can be prevented by *time division multiplexing*, a human protocol or technology-enforced scheme in which only one transmitter transmits at a time. This occurs in hundred-year old simplex voice communications such as that employed in air traffic control, and railroad train dispatching. Stations communicating with each other signify that is the other station's turn to transmit by saying "over" or implying it by the content of the transmission. Newer, computerized, and much faster forms of time division multiplexing are commonplace in cellular telephone and virtually all transportation data systems. Packet-based data communications used over the Internet are an example of time division multiplexing over a single channel.

Another form of interference occurs when the same station's signals following multiple paths to the receiver interfere with each other. This is known as *multipath interference* which is common on VHF and higher frequencies, whose signals bounce off buildings and terrain features like mountains. A receiver might receive the signal from one path and simultaneously receive the signal from another path so that the signals are exactly out of phase and therefore completely cancel each other. This obviously is a problem. The possible paths change when the transmitter or receiver or both are mobile. The movement alters the possible paths for the signal as they

[49] *See*, *Frequency Coordinators*, FED. COMM. COMMISSION, http://wireless.fcc.gov/services/index.htm?job=licensing_3&id=industrial_business (last updated June 1, 2016) (listing of frequency coordinators).

move around. One common solution to reduce but not to eliminate this problem is to have a redundant system of multiple antennas spaced a few inches or a few feet apart on both transmitter and receiver to reduce the chance of multipath interference occurring on every pair of antennas.[50]

Interference can also be reduced by *space division multiplexing*, causing signals travel only in one direction from the transmitter, thus being available only to receiving antennas located in that direction. This means of interference reduction is available to all radio designers who can use directional antennas at both ends. It is commonplace in cell phone site design.

It does not, however, work very well for aviation, motor vehicle, and maritime applications. The vehicle with which communications is desired may be at any azimuth from the transmitting site. It does however work for railroad communication, where a train or a maintenance way vehicle almost certainly will be on or alongside the track. Antennas for wayside stations and for many base stations involve communications with activities occurring on one or a few lines of railroad, and the antennas may be directed along the tracks.

c) *Fading*

Fading is a rapid shift in signal strength. Depending on the reason for the fade, a signal that is quite readable may become so weak that it is unreadable in a matter of a few seconds. Fade is common in HF communications, where minute by minute fluctuations in the height and characteristics of different layers of the ionosphere occur[51] and somewhat less frequent at higher frequencies in the UHF or microwave range, [52]where the term "rain fade" evokes its cause. Changes in receiver antenna orientation can cause signals to fade, as can multi-path interference.

2. Blocks

All of the systems use blocks. Conceptually, a block is a defined space reserved exclusively for an occupant. A block system avoids collisions by ensuring that no vehicle enters another vehicle's block. Block systems for traffic control originated in the rail industry, but aviation uses them as well. Railroad blocks are defined as segments of mainline track between particular mileposts or traffic control facilities. Air traffic control blocks are defined as particular altitudes and headings between waypoints for IFR traffic. Base leg, final approach, and the runway itself define blocks utilized by ATC for visual approaches at controlled airfields. Smaller blocks allow for more traffic, while greater speeds require bigger blocks.

a) *Borrowing Concepts From Communication*

This article focuses on automation of transportation. Some of the strategies for protecting against collision imitate strategies long used in radio and wired communication, especially computer-network communications, to avoid collision. Just as a human pilot can look outside for another aircraft or a fixed object that might pose a potential threat, a human radio operator can listen to a channel before transmitting to see if anyone else is using it. Listening to the channel before transmitting can be done by a machine as well as by a human operator. Sensors and automated

[50] Separations of a few inches work when the wavelength is no more than a few inches.
[51] The fluctuations occur because of changes in ionization from solar radiation, for example due to solar flares.
[52] UHF is usually unaffected by the Ionosphere, because its shorter wavelengths are not refracted there.

collision avoidance systems can look outside as well.

Machines, on the other hand, have to use other strategies to protect against collision; they lack the instincts that permit human pilots simply to touch a control and fly around a collision threat. They must explicitly calculate collision-avoidance paths. Prevention of radio interference long has involved means for separating different signals. The first techniques assigned transmitters to particular frequencies and limited their power. This is analogous to separating air traffic by assigning different altitudes and flight stage lengths. Frequency assignment allows a receiver to discriminate among all the signals it receives; a transmitter and receiver on the same frequency constitute a discrete channel, the rough equivalent of a block in the other modes. Limiting the power defines the range of a particular transmitter in spatial terms. Separate frequency channels within the same range constituted the earliest block protection in radio technology. It does not matter whether a machine effects the separation of a human operator effects it. The result is the same.

Now, with highly directional antennas, radio spectrum can be subdivided into point-to-point spatial regions, not entirely unlike airways or GPS-defined routes in the international airspace.

All of these techniques come into play in husbanding radio spectrum for automated transportation systems, but some of them are more applicable to collision avoidance by vehicles. Particularly relevant is carrier-sense-multiple-access ("CSMA"), the technique used by Ethernet for computer networks and by most digital radio modes to avoid collisions between electronic signals on the same channel. CSMA requires a device to listen to a channel to see if it is occupied before it sends a packet of information. If it is occupied, it waits for a statistically determined time interval and then listens again. It also detects interference once it has started transmitting and backs off before trying again for a similar interval.[53]

b) Neighborhood Access for MicroDrones (NAMID)[54]

The NAMID system for managing airspace for drones delivering packages, discussed in section III.G, illustrates the utility of the CSMA model and further illustrates block protection in the automated transportation realm.[55] It uses a combination of external surveillance by radar, satellites, and cell towers, and peer-to-peer telemetry exchange to track drone positions. Then, it relies on onboard collision avoidance and geofencing to control navigation by consulting Internet linked databases of weather and wind, airspace constraints, and three dimensional maps of terrain and human-made structures. Human oversight and flight planning are involved, but not moment-to-moment vehicle control by remote pilots.

NAMID utilizes a network of allowable routes from one point to any other point within, say, five miles, developed from detailed data about ground features available from Google maps and a wide range of mapping competitors. Basic algorithms in the system do not simply draw a straight

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[53] *See*, *Introduction, Carrier Sense Multi-Access/Collision Detection (CSMA/CD)*, CISCO, http://www.cisco.com/en/US/tech/tk389/tk214/tk125/tsd_technology_support_sub-protocol_home.html.
[54] *This section is excerpted from* DOMESTICATING DRONES, *supra* note 20, ch. 3.
[55] The NAMID system described in this section is very similar to the system proposed by Amazon in two white papers released in August, 2015; although the following subsections provide more detail on the architecture and its traffic–separation rules. NASA's UTM project is developing concepts similar to those described for NAMID. *Unmanned Aircraft System (UAS) Traffic Management (UTM)*, NAT'L AERONAUTICS & SPACE ADMIN., http://utm.arc.nasa.gov/index.shtml.

line between origin and destination pairs; they figure out how to use the existing infrastructure of streets, sidewalks, and expressways. They update their routing strategies based on minute-to-minute information about congestion, construction, and street closures, information available from databases associated with consumer-level GPS navigation systems.

Layered on top of this basic infrastructure map are traffic separation rules. A microdrone tasked to fly to a particular destination would broadcast its intentions. Other nearby microdrones would respond with a data block disclosing their positions, routes of flight, and intentions. These autonomous communications exchanges would reference the routes defined in the infrastructure map.

If a particular segment of the route desired by the first microdrone is occupied, it would wait or seek another route. A first-come-first-served rule of thumb is built in. For example, a microdrone delivering a package to the apartment complex at 930 Evanston Street would request access to the segment between the intersection of Bode Road/ Evanston Street and the driveway into the complex. If that segment is already occupied by another microdrone, it would hold at the intersection until the segment is clear.

Each microdrone is equipped with a transceiver capable of communicating with NAMID, constantly exchanging information about geographic position from onboard GPS, magnetometer, altimeter, and accelerometers. When a microdrone plans to enter a NAMID neighborhood, it would broadcast an inquiry message, similar to the message broadcast by a wireless-network-equipped computer wishing to connect to a WiFi network, a cellphone seeking a handoff to a new cell tower, or an office computer connecting for the first time to a wired LAN.

The NAMID protocol would cause any other NAMID station within range to acknowledge receipt of the inquiry, and a handshake (establishment of a communications link between the two) would result. The new microdrone would then be connected to that NAMID network and become a node in that network.

Thereafter, each NAMID node in a network would broadcast its position and destination in packets. All nodes would process these packets and determine which microdrones were on the same route. Collision avoidance architecture is peer-to-peer; no ground stations would be required for collision avoidance.

NAMID blocks could be particular segments between two intersections, or pathways to individual residences in a housing complex. GPS permits blocks to be arbitrarily defined, but they must be known to every vehicle participating in the system.

The blocks can be fixed, or they can move with the vehicle, as in some advanced forms of railroad dispatching and in IFR approach-control operations.

Capacity depends upon the size of the blocks; larger blocks mean less capacity, while smaller ones mean greater capacity. A block would have both a vertical and a horizontal dimension. For example, one block in a neighborhood might be the airspace between 50 and 90 feet over Carol Lane between its intersection with Green Bay Road and the intersection of Park Place; another block might be the airspace between 110 feet and 150 feet over the same segment of road. Grid systems in the form of maps already exist for neighborhoods, but NAMID also must have altitude separation.

Some blocks would be defined on an ad hoc basis, such as those accommodating descents for landing at a particular destination (e.g. the front porch of a residence). Entry into an arrival block from a predefined en route block would be indicated by the transmission of a message alerting the other microdrones in the vicinity to expect pathway coordinates for the landing profile. Once they receive it, the landing segment block would be like any other block in terms of the exclusive right of the first entrant to occupy it.

Higher-level blocks would have larger lateral boundaries and be reserved for the en route portions of flights, while lower-level blocks would be smaller to accommodate arrivals and departures, and to transition from the en route blocks.

Microdrones flying in NAMID would constantly broadcast their locations, thus allowing other drones to know when a block is occupied. They also would listen to other drones broadcasting their locations. If another drone is already in a block, a second drone would not enter.

Once a block is free, a drone could enter it and have exclusive authority to remain in the block, potentially limited by time. Time limits for block occupancy might be fixed, or they might depend on the size of the block, defined, for example, by a certain direction multiplied by the length of the block. The latter approach would give flexibility to blocks of varying sizes, which in turn would depend upon the capacity needs for that particular portion of the network. A largely rural area with one farmhouse per square mile would have blocks a mile long. Limiting access to that block by only one drone at a time would not impose significant cost; the likelihood of other drones waiting for access is small. On the other hand, recalling that only one drone can occupy a block at one time, the blocks in a residential apartment complex would need to be quite small, probably the size of segments of sidewalk extending from the projected sidewall of one building to its opposite side wall.

Traffic separation by limiting vehicle access to blocks of space, long managed by human dispatchers or controllers can also be implemented by computerized navigation systems.

F. Human and Machine Relationships

Some systems dispense with the human operator altogether and perform both the sensing and the response functions autonomously. Others, like most aircraft, rely on a human pilot for most of the sensing because of a perception that human senses are better than machine sensing, at least for routine navigation. On the other hand, ADS-B Out is purely oriented toward enhancing pilot sensing. Increasingly, these systems constrain what the pilot may do. The Airbus envelope enforcement protocols are an example of constraining pilot input. The railroad system mainly overrides unsafe operator control inputs, although it also enhances sensing.

Human beings other than pilots and engineers long have played a role in both aviation and railroad navigation and traffic separation. An air traffic controller is like a railroad dispatcher. Both give vehicles under their authority clearance to enter certain blocks of space. In the distant past both depended on positon reports: in the case of aircraft, position reports were communicated by radio; in the case of trains, position reports were communicated by telegraph or telephone “OS” reports from operators in stations every few miles. Now, air traffic controllers mostly depend on computerized radar depictions for aviation, and railroad dispatchers track occupancy indications on centralized traffic control boards.

In many cases, designers believe that human perception is better than robotic perception for certain navigation and collision avoidance tasks. In such cases, the role of automation is to enhance the human operator's perception. For example, ADS-B Out provides visual imagery for potential conflicts to onboard pilots. In other cases, regulation requires that the operator maintain a watch (as in highway operation), be able to see a certain distance (as in aviation's Visual Flight Rules), or keep the drone within his line of sight (as under Part 107 of the FARs). The optimal relationship between human perception and robotic perception is constantly changing as robotic perceptive apparatus improves.

Autonomous robot operations have been introduced to all modes of transportation because robotic systems can perform some functions better than human operators. For example, a small, electrically powered quadcopter cannot fly at all without substantial autonomy in its attitude and electrical control systems; human operators simply cannot change the current for the different motors rapidly enough to keep the drone upright and to move it along its three axes. So even the most basic thousand-dollar quadcopter has capabilities in its autopilot that would amaze most pilots. Similarly, the automobile industry has gradually embraced vehicle autonomy as it has come to realize that affordable systems can handle common emergencies, such as skids, better than most human drivers. And policymakers have forced the railroad industry to accept PTC in light of highly publicized fatal accidents involving human operators who ignored or misunderstood signals.

Autonomy" and "*robotics*" are terms that can be misleading. A common view is that the term "robot" signifies a completely autonomous agent with broad spectrum intelligence. But that is inaccurate. Autonomy exists in varying degrees, and a subsystem may be a robot, while the larger system of which it is a part is controlled by human operator. According to this more sophisticated understanding, even the simplest automatic control system with feedback is a robot, capable of operating autonomously within a limited sphere of responsibility.

Almost any drone on the market uses a combination of autonomy and human direction to fly its intended mission. As the regulatory environment begins to permit drones to fly beyond line of sight and at night, and collision avoidance systems are improved, the balance between human control and autonomy will tip in favor of more autonomy in more major functions.

G. NAMID

Section 3.13 of *Domesticating Drones*[56] describes a Neighborhood Access for Microdrones ("NAMID") system. NAMID is a sophisticated airspace management system for logistics drones that takes autonomy and robotics beyond the level of semiautonomous, line-of-sight daytime flights by thousand-dollar quadcopters common in 2017. It is, however, entirely within the capability of existing technology, and resembles what Amazon and Google proposed in general terms in early 2016. The barriers to NAMID are more political than technological, with uncertainty about who will be responsible for its necessary infrastructure.

The fact that NAMID draws on collision-avoidance and failsafe concepts in wide use in computer networks and in train dispatching enables a broad range of alternative design challenges to establish design defects, as analyzed more completely in section XXX.

[56] DOMESTICATING DRONES, *supra* note 20, ch. 3 at § 3.13.

IV. The Legal Framework for Allocating Liability

Tort law imposes liability on anyone who breaches a duty to the plaintiff when the breach is the legal cause of the plaintiff's injury. Negligence law traditionally articulates the elements of liability as comprising (1) duty,[57] (2) breach,[58] (3) causation,[59] and (4) injury.[60] Negligence liability results when the plaintiff can prove that the interest invaded is legally protected against unintentional invasion, that that the conduct of the defendant was negligent with respect to the plaintiff or the class of persons in which she was included.[61]

Products liability law, a subspecies of negligence, combines the first two elements into product defect.[62]

Each of the following sections addresses one element of tort liability. Each section reviews the doctrine--comparing common law negligence with newer products liability law--analyzes caselaw applying the doctrine to technologies analogous to those found in drones, and explores the types of conduct by defendants that can support liability under this particular element.

A. Duty

The duty element in tort law is more extensive than in other areas of private law. Tort law imposes a duty to avoid foreseeable risks of harm to anyone within the scope of an actor's ability to cause effects. Its scope is broader than the scope of duty in contract law, which runs only to other parties to the contract and to intentional third-party beneficiaries, and broader than most aspects of property law where duties run only to others having a connection to the property. Tort duties are not unlimited, however. The Restatement (Third) of Torts explains:

> For example, a number of modern cases involve efforts to impose liability on social hosts for serving alcohol to their guests. A jury might plausibly find the social host negligent in providing alcohol to a guest who will depart in an automobile. Nevertheless, imposing liability is potentially problematic because of its impact on a substantial slice of social relations. Courts appropriately address whether such liability should be permitted as a matter of duty. Courts may also, for the same reasons, determine that modification of the ordinary duty of reasonable care is required. Thus, courts generally impose on sellers of products that are not defective at the time of sale the limited duty to warn of newly discovered risks, rather than the more general duty of reasonable care, which a jury might find includes a duty to recall and retrofit the product so as to eliminate the risk. Similarly, some courts

[57] *See infra* § IV.A.
[58] *See infra* § IV.B.
[59] *See infra* § IV.D.
[60] *See infra* § IV.C. Negligence law imposes liability for:

- Failure to exercise reasonable care,
- Factually causing,
- Physical harm,

Within the scope of "proximate causation." Restatement (Third) of Torts - Liability for Causing Physical and Emotional Harm § 6 & cmt. b.
[61] RESTATEMENT (SECOND) OF TORTS § 281 (1965).
[62] *See infra* § IV.B.3.

> have modified the general duty of reasonable care for those engaging in competitive sports to a more limited duty to refrain from recklessly dangerous conduct.[63]

The duty element in the products liability context mainly relates to the precept that actors had duties running only to those in privity with them, which was abandoned in the famous *MacPherson v. Buick Motor Co*.[64]

The center of controversy in any particular case can be shifted between the duty and breach elements, depending on how one articulates the duty. If one, for example, asks whether the designer of a drone has a duty to provide redundant GPS navigation systems, the center of controversy will involve the duty element. If, on the other hand, the same case is litigated under an assumption that the designer of a drone has a duty to avoid risks of harm arising from malfunction of the drone navigation system, the center of controversy shifts to the breach element. For organizational simplicity, this article takes the second approach and deals with most of the sources of controversy under the breach element.

B. Breach

1. Negligence

The Restatement (Second) of Torts defines negligence as "conduct which falls below the standard established by law for the protection of others against unreasonable risk of harm."[65]

The assessment of negligence begins with the defendant's perception of risk; he is judged according to a reasonable man standard, enhanced by his own special knowledge, intelligence, and judgment.[66] In assessing risk, the defendant is required to take into account matters of common knowledge, including general customs.[67]

Customs in the community are relevant to the negligence evaluation, but compliance with custom is not necessarily exculpatory.[68]

Competence is part of the assessment. Acting incompetently is acting without requisite care.[69] Section 307 imposes a duty to inspect an instrumentality and imposes negligence liability for operating it even though it is defective. Defendants are required to take into account the foreseeable risk that others will act negligently; one does not escape liability for his own conduct merely because another is at fault.[70]

The common-law balances risk against utility. Section 291 says that risk is unreasonable and an act giving rise to it is negligent, "if the risk is of such magnitude has to outweigh what the Law regards as the utility of the act of the particular manner in which it is done." Section 296 allows a wider range of risky conduct when the defendant is responding to a sudden emergency.

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[63] RESTATEMENT (THIRD) OF TORTS: PHYSICAL & EMOTIONAL HARM § 7 cmt. a (2010).
[64] MacPherson v. Buick Motor Co., 111 N.E. 1050 (N.Y. 1916).
[65] RESTATEMENT (SECOND) OF TORTS § 282.
[66] *Id.* § 289.
[67] *Id.* § 290.
[68] *Id.* § 295A
[69] *Id.* § 299.
[70] *Id.* § 302A.

Section 292 identifies the factors that influence a determination of utility: social value, the tendency of the defendant's particular course of conduct to advance that value, and the extent of the chance that the value can be adequately advanced or victims protected by another and less dangerous course of conduct."[71]

Failing to use appropriate technology is a breach of duty. The famous 1932 case *T. J. Hooper v. N. Barge Corp.*[72] held that a tug boat operator was liable for not equipping his tugboat with radio communication equipment so that the master could obtain current weather reports. *T.J. Hooper* arose in the context of changing technologies. Radio technology was just beginning to make its way into regular use by boats and ships. In the drone context, the big argument is whether "return to home" or any other capability is used by other vendors, so that it has become an industry standard.[73] Under this precedent, a drone designer would be liable for omitting common safety features, such as a return to home function triggered by a lost control link.

2. Shortcuts

Tort law provides some shortcuts for establishing negligent behavior. Several of these are embedded in products liability concepts. Others are generally available to negligence plaintiffs. Some of the shortcuts make it unnecessary for the plaintiff to prove duty and breach with respect to a particular kind of harm; others simply make it easier for a plaintiff to prove those two elements, as by shifting the burden of proof to the defendant.

a) Abnormally Dangerous

Section 519 imposes strict liability on one who carries on "an abnormally dangerous activity," with respect to the kinds of injury that make the activity abnormally dangerous.[74] The degree of care utilized in carrying on the activity is irrelevant, although the plaintiff must show injury and causation. Whether an activity is abnormally dangerous depends on the existence of a high degree of risk of harm, the likelihood that the harm that results from the activity will be great, the inability to reduce the risk with the exercise of reasonable care, the extent to which the activity is not a matter of common usage, the inappropriateness of the activity of the place where it is carried on, and the extent to which its value to the society is outweighed by its dangerous attributes.[75] Drone operations are less likely to be characterized as abnormally dangerous as their

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[71] *Id.* § 292

[72] T.J. Hooper v. N. Barge Corp., 60 F. 2d 737 (2d Cir. 1932) (Hand, J.). Because the tugs' radio receivers were not in working order, the vessel was unseaworthy. *Id*. at 740. Unseaworthiness is a product defect. It made no difference to Learned Hand that no industry custom had been established regarding the use of radio receivers. *Id.* ("Courts must in the end say what is required; there are precautions so imperative that even their universal disregard will not excuse their omission.")

[73] In some cases intellectual property may get in the way of wide adoption. Vendor A might create a new component that enhances its drone's safety and patents the technology. Vendor B is unable to use that IP to remain on top of the market's safety standards. What then?

[74] *See also* RESTATEMENT (THIRD) OF TORTS: PHYSICAL & EMOTIONAL HARM § 20 (1998).

[75] RESTATEMENT (SECOND) OF TORTS § 520 (1977). Assessing the risk/reward balance encounters questions of which part of society is the judge: a local community in which drones are perceived as undesirable, or a broader national community. [ED: additional citation OK]

use becomes more common.[76] Classification always will depend on the appropriateness of where the drone is flown,[77] and the utility of the particular mission.[78]

Section 520A imposes strict liability on the operator of an aircraft that causes damage to person or chattels on the ground. It is "a special application of section 519 and 520."[79]

The strict liability imposed by the section cannot be imposed by persons participating in the activity, such as the crew or passengers.[80] [ED: edit OK] Although the matter is not settled, the general trend among courts and commentators has been to view aviation as subject to usual negligence principles rather than special treatment as abnormally dangerous under section 520A.[81]

In *Crosby v. Cox Aircraft Co.,*[82] the Supreme Court of Washington reversed the trial court's application of section 520A and held that "aviation can no longer be designated an 'abnormally dangerous activity' requiring special rules of liability."[83] It traced the legal history of aviation and remarked on its maturation from a time when Professor Prosser wrote: "Flying was of course regarded at first as a questionable and highly dangerous enterprise, the province exclusively of venturesome fools..."[84] It saw no reason why passengers injured in a crash should have to prove negligence, while persons on the ground should benefit from strict liability.[85] It held that plaintiffs seeking damages for aircraft crashes causing ground damage must show ordinary negligence.[86] It noted, however, that they might benefit from doctrines such as *res ipsa loquitur*.[87]

b) Negligence Per Se

Proving negligence requires proving breach of a duty to the plaintiff, in that the defendant did not conform his conduct to the applicable standard of care. *Negligence per se* enables a plaintiff to prove duty and breach by showing that the defendant violated a legislative or regulatory

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[76] *Id.* § 520(c).
[77] *See Id.* § 520(d).
[78] *See Id.* § 520(f).
[79] *Id.* § 520A cmt. a.
[80] *Id.* § 520A cmt. e.
[81] *See* Michael C. Mineiro, *Assessing the Risks: Tort Liability and Risk Management in the Event of a Commercial Human Space Flight Vehicle Accident*, 74 J. AIR L. & COM. 371, 384-385 (2009); Geoffrey Christopher Rapp, *Unmanned Aerial Exposure: Civil Liability Concerns Arising From Domestic Law Enforcement Employment of Unmanned Aerial Systems*, 85 N.D. L. REV. 623, 636-638 (2009) (discussing theories of liability that might be applied in drone crash litigation).
[82] Crosby v. Cox Aircraft Co., 746 P.2d 1198 (Wash. 1987).
[83] *Id.* at 1199.
[84] *Id.*at 1200 (quoting W. Page Keeton et. al., Prosser & Keeton on Torts § 78, at 556 (5th ed. 1984).
[85] *Id.* at 1202.
[86] *Id.*
[87] *Id. See infra* § IV.B.2.c). *See generally* Theresa L. Kruk, Annotation, *Res Ipsa Loquitur in Aviation Accidents*, 25 A.L.R.4th 1237 (1983).

standard.[88] Even when *negligence per se* is not applicable, showing a governmental rule violation can shift the burden of argumentation to the defendant.

Section 874A of the Restatement Second of Torts states the negligence per se doctrine. It makes it clear that the "legislative provisions" that may give rise to common-law tort liability include regulations of administrative agencies at various levels of government. The starting point under the doctrine is that the plaintiff must be a member of the class of persons protected by the regulation.[89]

Section 288B says that when the court adopts a legislative or regulatory standard as the standard of conduct, "[t]he unexcused violation of [the standard establishes] negligence in itself." And when it is not adopted as the as the standard, it is relevant evidence bearing on the issue of negligent conduct.[90]

In the aviation context, federal aviation regulations provide a starting point for the appropriate standard of care. Part 107 establishes many standards for safety for preflight planning, altitude and distance limits, and aeronautical decision making. Although the FAA has avoided imposing traditional airworthiness and type certification standards on drones and their components, the specifications it imposes with respect to other aircraft are relevant to the standard of care. For example, a drone vendor can be challenged to justify providing an autopilot that did not meet the requirements of the FAA standard for helicopter autopilots.

Using federal standards as a reference point opens up the possibility of federal question jurisdiction in federal court, which may result in removal.[91]

Federal preemption also is a possibility. Preemption is distinct from federal question jurisdiction. The weight of the caselaw says that the FARs do not preempt state tort law in personal injury litigation, but some of the caselaw suggests that state courts are not free to substitute their own standards for those adopted by the FAA. If the plaintiff is happy with the FAA standard and being able to show that the defendant violated it, then this is not a problem. But if the plaintiff plans to argue for a more stringent standard or for a common-law standard where the FAA has been silent, then preemption is a possible barrier.[92]

c) Res Ipsa Loquitur

Res ipsa loquitur is a powerful tool for plaintiffs.[93] The phrase is Latin for "the thing speaks for itself," and the doctrine permits a plaintiff to recover for negligence without proving exactly how a defendant breached his duty of care. It also is a useful way to break the conundrum of an

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[88] *See generally* RESTATEMENT (THIRD) OF TORTS: PRODS. LIAB. § 14 (1998).
[89] RESTATEMENT (SECOND) OF TORTS § 874A (1965).
[90] *Id.* § 288B(1).
[91] Gary C. Robb, Helicopter Crash Litigation at 77-78 (2010).
[92] *See* Henry H. Perritt, Jr. & Albert J. Plawinski, *One Centimeter Over My Back Yard: Where Does Federal Preemption of State Drone Regulation Start?*, 17 N.C. J. L. & TECH. 307, 338-341 (2015) (summarizing caselaw on federal preemption in aircraft accident tort cases).
[93] *See generally* RESTATEMENT (THIRD) OF TORTS: PHYSICAL & EMOTIONAL HARM § 17 (1998). *Res ipsa* is a powerful tool for plaintiffs, because it relieves them of the need to prove the elements of negligence or to prove product defect.

indeterminate defendant.[94] Its logic is: the aircraft would not have crashed unless someone was negligent. It was disfavored in the early days of aviation, because of the belief that aircraft regularly crashed whether someone was negligent or not, but its potential availability has increased as flying has become commonplace and generally safe. Still, the cases in which it was found inapplicable far outweigh the number of cases in which it was accepted. The insuperable obstacles for most plaintiffs is that *res ipsa loquitur* requires three conditions:

> '(1) the accident must be of a kind which ordinarily does not occur in the absence of someone's negligence; (2) it must be caused by an agency or instrumentality within the exclusive control of the defendant; (3) it must not have been due to any voluntary action or contribution on the part of the plaintiff.'[95]

The second condition is the most daunting: aircraft pass through successive hands, each of which has control for a period. The designer exercises control during the design phase, the manufacturer has control during the manufacturing, fabrication, and assembly phases, and typically a retailer has exclusive control before the aircraft is sold. The owner has exclusive control after it is sold, the pilot has exclusive control while he is flying it, and the mechanic has exclusive control while maintenance is being performed.

Because of the interrelationship of design, manufacture, instruction, warnings in the flight manual, maintenance, and actual flight, it is rare that any one party has exclusive control over flight safety. It is always possible that the aircraft design was the best it could be, that pilots were warned appropriately of any risky operating quirks, and the pilot simply mishandled the aircraft, causing it to crash. But it is also possible that the pilot flew the aircraft perfectly and could not have done anything to avoid the accident if a design flaw or maintenance slip up caused a mechanical failure or a failure in the electronic systems.

Major vehicle accidents, especially airplane or helicopter crashes, usually kill the pilot and destroy much of the tangible evidence of what went wrong. When accident investigation encounters such limits, legal doctrine must provide a starting point for providing causation. *Res ipsa loquitur* is one such doctrine. Three cases illustrate application of *res ipsa loquitur* in aviation cases. In one, Stoddard v. Ling-Temco-Vought, Inc.,[96] the aircraft vanished while it was over the Pacific Ocean.

> Under normal operations and circumstances an airplane crash into the ocean does not ordinarily occur unless someone has been negligent. The happening of the accident and corresponding injury was such as in the ordinary course of things would not occur if the one having control had used proper care.[97]

A drone is unlikely to disappear after it causes an accident, so the unavailability of evidence associated with unavailability of the vehicle is unlikely in the drone context. Nevertheless,

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[94] *See infra* § IV.D.4; *see* also Ken Oliphant, *Causation in Cases of Evidential Uncertainty: Juridical Techniques and Fundamental Issues*, 91 CHI-KENT L. REV. 587, 593 (2016)

[95] Newing v. Cheatham, 540 P.2d 33, 39 (Cal. 1975) (citing Ybarra v. Apangard, 154 P.2d 687, 689 (Cal. 1944)).

[96] Stoddard v. Ling-Temco-Vought, Inc., 513 F. Supp. 314, 332 (C.D. Cal. 1980).

[97] *Id.* at 321.

analysis of *res ipsa* caselaw is helpful in the drone context, because it illustrates the role that presumptions can plan when causation is opaque.

In another, *Newing v. Cheatham*,[98] the court, having restated the doctrine, found the first condition satisfied:

> As we previously noted, the first condition for invocation of the res ipsa doctrine is satisfied if under the facts of the case, common experience indicates that the accident would not have occurred unless there had been negligence on the part of someone. In the instant case, it seems reasonably clear in light of the circumstances surrounding the crash that the accident ordinarily would not have taken place in the absence of negligence. The evidence is uncontradicted [sic] that the airplane took off from Chula Vista in clear weather with no restrictions on visibility. There is no evidence that weather conditions contributed in any way to the crash of the plane. Nor was there any evidence that the plane had collided with other aircraft while in flight. Indeed the condition of the plane after the crash was such as to eliminate an air collision. It thus fell to the ground, apparently unaffected by external factors, only a few miles from the airport whence it had departed some hours earlier. Under the circumstances of the present case, it seems reasonably clear that the accident probably would not have occurred without negligence by someone. The evidence bearing on these circumstances is not only uncontradicted [sic] but of such a nature that no issue of fact is raised as to the existence of the first condition for the application of the doctrine of res ipsa loquitur. We conclude that the first condition is established as a matter of law.[99]

It had no difficulty finding the second condition of exclusive control satisfied, because the defendant was the only pilot aboard the aircraft.[100]

Nelson v. American Airlines, Inc.,[101] involved a res ipsa loquitur claim involving a malfunctioning autopilot. The appellate court described what happened.

> According to the evidence received in a nonjury trial, . . . the autopilot overcompensated pitch trim, causing the aircraft to nose down rather than stay level. The copilot immediately disengaged the autopilot, and the pilot resumed manual control. In the cockpit the pitch change seemed slight; however the stewardess reported that some passengers were injured due to the more severe movement in the rear of the plane.[102]

The altitude hold feature of the autopilot had caused trouble before, causing replacement of one of its components.[103] After the accident, the autopilot was tested, and severe porposing occurred about 30 seconds after the altitude hold was engaged. The cause of the problem was not in evidence.

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[98] *Newing*, 540 P.2d 33 (affirming summary judgment for plaintiff).
[99] *Id.* at 40-41. (footnote and internal citations omitted).
[100] *Id.* at 41.
[101] Nelson v. American Airlines, Inc., 263 Cal. App. 2d 742 (1968).
[102] *Id.* at 744.
[103] *Id.*

The trial court granted judgment to the defendant, not because it refused to apply *res ipsa loquitur*, but because it held that the doctrine only permitted an inference of negligence, which was rebutted by defendant's evidence that it exercised due care. The appellate court disagreed with the assessment of the evidence. The evidence showed that a malfunction in the autopilot probably caused the sudden change in pitch and that the flight engineer performed a careful preflight-check. There was no evidence, however, of similar care by maintenance personnel:

> [T]here was no evidence which the trial court could reasonably have taken as excluding such possibilities as the following: negligent errors were made in installing the replacement computer; an improperly serviced component had been installed; or earlier routine maintenance had been incomplete or otherwise improper. . . . [H]ere there is simply no evidence that negligence in maintenance of the equipment did not cause some malfunction of a kind such as the flight engineer admitted might possibly escape his pre-flight test. The judgment must therefore be reversed.[104]

In *Meil v. Piper Aircraft Corp*., the court of appeals affirmed judgment in favor of the plaintiff crop duster.[105] The court held that the evidence supporting a negligence theory relating to survivability justified a *res ipsa* instruction to the jury:

> Plaintiff's remaining claims go to the crashworthiness of the plane. To recover on this ground plaintiff must show that the claimed defect enhanced the injuries received from the original crash. Defendant asserts that as to the crashworthy claims plaintiff did not prove alternative safer designs or enhanced injuries.
>
> The first claim is based on an alleged defective seat belt. Plaintiff was wearing the seat belt when the plane crashed. When the plane overturned he was suspended upside down. Plaintiff testified that he tried unsuccessfully to undo the seat belt buckle. The rescuer said that he was familiar with seat belt buckles, including the type used on the crashed plane, that he was unable to release the buckle, and finally had to cut the strap with a knife.
>
> An aeronautical expert testified that another type of buckle provided more leverage. This evidence plus that of the rescuer sufficed to justify a reasonable inference that the seat belt was defective. The record shows that plaintiff suffered extensive burns while he was trapped by the inoperative seat belt. The enhanced injuries which he received do not have to be quantified. The medical evidence of the extent of the burns was enough.
>
> The next claim relates to the fiberglass hopper which contained the insecticide. An aeronautical expert for plaintiff testified that available neopreme [sic] and stainless steel tanks would remain intact after the crash. Plaintiff was covered with the released chemical, the toxic nature of which is not contested. Rescuers of plaintiff suffered nausea and breathing problems. The doctor who examined plaintiff when he was brought to the hospital testified to the respiratory problems of plaintiff. The

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[104] *Id.* at 747.

[105] Meil v. Piper Aircraft Corp., 658 F.2d 787, 788 (10th Cir. 1981).

> evidence shows an alternative safer design and enhanced injuries and supports the denial of the motion for a directed verdict and the verdict of the jury.
>
> The next claim relates to the fuel header tank which was positioned below the feet of the pilot when he was seated in the cockpit. This tank received gasoline from the wing tanks and fed it to the engine. Evidence showed that the fire began in the engine and spread along the fuel line to the header tank. A plaintiff's witness, who was an expert aeronautical engineer, testified that the design was faulty and that another design would have prevented the engine fire from spreading. Enhancement of injuries by severe burns was established. The evidence was sufficient to sustain the actions of both the court and the jury.
>
> The first two arrivals at the accident scene were unable to extinguish the engine fire. The plane's fire extinguisher was held in place by two brackets, one of which broke in the crash, and the extinguisher was thrown loose from the plane. The bracket which broke was of much softer metal than the one which remained intact. The rescuers could not make the extinguisher work and the flames spread. An expert testified that the fire would not have spread if the bracket had not broken and rendered the extinguisher inoperative. The record sustains a finding of both faulty design and enhanced injury.[106]

The court approved a res ipsa loquitur instruction.[107]

As in *Nelson* and *Meil*, the subsystems of a drone involved in an accident are likely to survive the accident and be available for testing. In addition, a drone is more likely than a manned aircraft or a conventional water vessel to have sent data on the functioning of its systems before it is involved in an accident.[108]

The res ipsa loquitur doctrine has been restated in section 3 of the Third Restatement of Torts: Products Liability as "Circumstantial Evidence Supporting Inference of Product Defect."[109] The commentary points out that the plaintiff need not identify manufacturing or design defect as the cause and need not point to any specific defect, giving the following as an example: "[In] an aircraft . . . in new condition and while flying within its intended performance parameters, the wings suddenly and unexpectedly fall off, causing harm."[110]

3. <u>Defective Product</u>

The introduction to the Restatement (Third) of Torts: Products Liability explains that products liability is a species of tort liability that originated with section 402A of the second Restatement, which relaxed the long-standing negligence requirement for privity between actor and victim for defective products: "The major thrust of § 402A was to eliminate privity so that a user or

[106] *Id.* at 789-90 (some internal citations omitted).
[107] *Id.* at 791.
[108] See *infra* § VII.A (discussing automatic downloading of data).
[109] RESTATEMENT (THIRD) OF TORTS: PROD. LIAB. § 3 (1997); *see* Wright, *Statistical Probability* at 1336-42 (explaining that res ipsa loquitur permits liability to be imposed based on statistical probability without case-specific circumstantial evidence; urging a narrowing reinterpretation).
[110] RESTATEMENT (THIRD) OF TORTS: PROD. LIAB. § 3 cmt. b (1998).

consumer, without having to establish negligence, could bring an action against a manufacturer, as well as against any other member of a distributive chain that had sold a product containing a manufacturing defect."[111]

"Without proving negligence," signifies that products liability doctrines impose a species of strict liability, relieving the plaintiff of proving the standard of care and that it was breached. The plaintiff still must prove the other elements of injury and causation, and she must prove the conditions, such as "defective product" or "abnormally dangerous," that qualify the case for strict liability treatment.

Section 402A imposes strict liability on the vendor of a product that is defective even though the vendor has used all reasonable care in designing, manufacturing, and delivering it. A product may be defective because it contains a manufacturing defect, a design defect, or because of a failure to include appropriate instructions or warnings in conjunction with its distribution.[112]

A design defect exists when "when the foreseeable risks of harm posed by the product could have been reduced or avoided by the adoption of a reasonable alternative design by the seller or other distributor, or a predecessor in the commercial chain of distribution, and the omission of the alternative design renders the product not reasonably safe."[113]

The supplier of a component of a product is liable when the component is defective, but not when a downstream supplier incorporates a non-defective component in a way that makes the final product defective.[114]

Adequate warnings may prevent the requisite defectiveness and shield the vendor from strict liability.[115] The commentary to the section recognizes that some products—it cites certain drugs—cannot be made safe and that their delivery into commerce might be justified despite the high degree of risk they involve. Such products do not give rise to strict liability.[116]

The third Restatement of Torts has simplified the analytical framework. It brings all of the products liability doctrines together under the category of *defective product*,[117] recognizing that defects may exist in manufacture, design, or product warnings and information. It allows basic negligence principles to continue to operate in the background. The Restatement's analytical commentary finds a home for virtually all the decided cases in its simplified framework. The Restatement's authors recognized that the third Restatement effort should not only cover the law that emerges from cases decided since the second Restatement was published, but also provide an analytical framework within which lawyers can understand the cases and related statutes.

[111] *Id.* at Introduction.
[112] *Id.* § 2.
[113] *Id.* § 2(b).
[114] *Id.* § 5 (stating exception when supplier of component participates in the integration making the final product defective).
[115] RESTATEMENT (SECOND) OF TORTS § 402A cmt. j (1979).
[116] *Id*. at cmt. k.
[117] RESTATEMENT (THIRD) OF TORTS: PROD. LIAB. § 1 (1998) (imposing liability for sale or distribution of defective products).

The framework allows for liability to be established under three categories of defect: manufacturing defects, design defect, and failure to warn.[118] A plaintiff proves manufacturing defect by showing that the vendor did not manufacture the product in accordance with its design. Upon such a showing, the Restatement imposes liability "even though all possible care was exercised in the preparation and marketing of the product."[119] So, for example, if the design called for an IMU having a particular model number, and the manufacture substituted a different product number, that is a manufacturing defect. The plaintiff still must prove that the substitution was factual and legal cause of the injury.

A plaintiff may prove design defect by demonstrating a safer alternative design.[120] That design must have been known at the time of the sale of the product, and it must have been feasible. Feasibility includes consideration of cost and the market the product seeks to serve. Proving that an accurate and stable IMU is a safer alternative to GPS navigation does not satisfy the plaintiff's burden if an IMU with the requisite drift levels would cost $10,000, compared to the five-dollar cost of the installed IMU. Similarly, any alternative design proffered does not satisfy the burden if it is suitable only for a much larger or more expensive drone rather than one in the price range of a DJI Inspire.

The third category covers products that are defective because of a failure to warn.[121] The design defect and failure-to-warn categories, unlike manufacturing defect, do not impose strict liability but still require proof of fault under a negligence standard. Both contain the phrase: "is defective . . . when the foreseeable risks of harm posed by the product could have been reduced . . . and the omission . . . renders the product not reasonably safe."[122]

4. Reasonable Alternative Design

Design defects, which along with failure-to-warn are more likely than manufacturing defects to arise in connection with drone accidents, require proof of a safer alternative design. Few reported cases exist applying this standard in the aviation context because of federal preemption of state law when state law would overlap with federal aviation standards. Because federal aircraft design standards are so detailed, little room is left for state judges or juries to evaluate claims that an alternative design would have been safer.[123] In the drone context, however, the FAA has not imposed any design standards, wishing to avoid the burdens and delays associated with airworthiness and type certification of this type of aircraft.[124] Because the FAA has not acted in

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118 *Id.* § 2 (enumerating categories of defect).
119 *Id.* § 2(a); *see also id.* § 1 cmt. a (explaining that a product that fails to meet a manufacturer's design specifications is, almost by definition, defective).
120 *Id.* § 2(b).
121 *Id.* § 2(c).
122 *Id*. § 2(b) & (c); *see also id.* § 1 cmt. a (explaining that sections 2(b) and 2(c) rely on negligence test; arguing that the term "strict liability" in the design-defect and failure-to-warn contexts is misleading).
123 But see Martin v. Midwest Express Holdings, 555 F.3d 806, 812 (9th Cir. 2009) (state tort claim over defective aircraft stairs not preempted, because FAA did not regulate the design of the stairs).
124 Operation and Certification of Small Unmanned Aircraft Systems, 81 Fed. Reg. 42064, 42181-42183 (June 28, 2016) (2016) (explaining decision not to require airworthiness or type certification of small unmanned aircraft).

this area, arguments can be made that state tort law, including evaluation of alternative designs, is not preempted.[125]

The alternative design inquiry should not be limited to alternative designs for the particular mode. In other words, a plaintiff should challenge the design of a drone subsystem not only by proving safer alternative designs from the realm of drones, but also by proving safer alternative designs borrowed from the railroad or the computer networking industries. These cross-modal alternative design challenges will become richer as robotics progresses in all of the modes.

The NAMID discussion in *Domesticating Drones*,[126] for example, refers several different times to conceptual models drawn from elsewhere, particularly air traffic control for IFR flight and the railroad industry. If the designer of a drone subsystem proceeds without regard to concepts that have proven themselves in long use in those industries, the plaintiff has a much greater chance of establishing defective design of the drone subsystem.

Litigation in South Carolina over the Ford Bronco's stability provides a clear example of how the alternative design evaluation works.[127] The plaintiff was injured when his mother ran off the road and then over corrected, causing the vehicle to roll.[128] The plaintiff claimed that the vehicle was defective because of the suspension system that Ford chose: a twin I-beam system.[129] The plaintiff had evidence that Ford engineers had considered, and indeed preferred, a different system using a MacPherson strut which would have resulted in a lower center of gravity and less tendency for the tires to lose their grip on the pavement in a skid.[130] Despite multiple communications from engineers urging that their preferred system would be safer, Ford nevertheless a selected the twin I-beam system because of lower cost and because changing to the MacPherson strut system would delay market introduction of the Bronco.[131] The South Carolina Supreme Court held that there was enough evidence of a safer alternative design to go to the jury.[132] It reversed the jury's $16 million compensatory damage and $16 million punitive damage award on other grounds.[133]

The Ford case illustrates the essentiality of aggressive discovery in any products liability case. Evidence of engineer discussions about alternative designs is highly likely to exist. The reasons particular alternative designs were rejected may bear fruit for a plaintiff.

In Meil v. Piper Aircraft Corp., the court of appeals affirmed judgment in favor of the plaintiff crop duster.[134] The court held that the evidence supported strict liability for defective cable cutter blades, which failed to sever an electric transmission line the pilot hit:

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[125] Conversely, a defendant can argue that the FAA's repeated pronouncements that airworthiness and type certification of small drones is not good policy should preempt state action with respect to design standards. The FAA's forbearance involves ex ante prescription, however, not ex post liability.
[126] *See* DOMESTICATING DRONES, *supra* note 20.
[127] Branham v. Ford Motor Co., 701 S.E.2d 5 (S.C. 2010).
[128] *Id.* at 8 (summarizing facts).
[129] *Id.* at 10-11 (describing design choices).
[130] *Id.* (summarizing engineering preference for MacPherson strut).
[131] *Id.* at 11-12 (explaining why Ford chose the twin I-beam system).
[132] *Id.* at 12-13.
[133] *Id.* at 17 (summarizing reasons for reversal).
[134] Meil v. Piper Aircraft Corp., 658 F.2d 787 (10th Cir. 1981).

> An expert metallurgist testified for the plaintiff that cutter blades should have a hardness of 55-65 on the Rockwell scale of C and the blades on the crashed Piper had a hardness of only 20 on that scale. He said that the metal used by Piper was unacceptable as a cutter blade and could not cut the cable which had a hardness of 43 on the C scale. Upon contact the cutter blade would act as an impacting rather than cutting device. This testimony was consistent with that of other witnesses who said that the cable was broken and not cut. The metallurgist also testified to the availability of other harder metals which would have cut through the cable. Pilots of crop spraying planes said that they had struck and severed wires, and continued to fly. Although no pilot testified to hitting a cable similar to that present in this crash, one pilot said that from his experience, which included contact with wires, he would expect a plane outfitted with cutter blades to fly through the cable. Through various experts, none of whom were agricultural pilots, Piper introduced contrary evidence.[135]

The *Meil* case illustrates the availability of alternative designs at the most basic mechanical design level—the selection of materials. Almost any drone that crashes could have been made from a different material and such an alternative design might have reduced damage of injury resulting from a crash. The use of frangible materials for the drone's body is particularly interesting in this regard; frangible materials absorb energy when they fracture. Likewise, rotor blades can be designed from materials that fracture on impact, thus reducing the likelihood of serious cuts if they strike a person.

5. Failures in Hardware and Software

As the level of automation increases, electronic systems failures become more probable than mechanical failures. Section a explores the types of mechanical failures that may occur not withstanding higher levels of automation, while section b explores areas of possible software failure.

a) Hardware

Certain hardware design choices or manufacturing techniques give rise to risks. One source of hardware-based risk is insufficient security in the attachment of hardware components to each other such that components detach. For example, a rotor blade attachment to the motor spindle should be well secured and can cause mechanical failure if not attached properly. Mechanical failure is less likely to occur, however, as a result of a separation of a major structural components, such as a boom, in-flight. The risk associated with the attachment of landing skids is unlikely to matter much if a landing skid detaches in flight. This is so because if it detaches on landing or take off or is already detached when landing is attempted, the drone might be damaged, but the drone is unlikely to damage anything else because it is so close to the ground.

Another source of hardware-based risk are the many electrical connections that exist on a small drone: the connections between battery and power distribution board, the logic connections between the navigation control board and the power control board, the connections between the power control board and each motor, the connections between the many integrated circuit chips and the printed circuit boards to which they are attached, the interconnection of the printed

[135] *Id.* at 789-90.

circuit boards with the radio transceiver, the feed lines between the antennas and the transceiver and between the antennas and the GPS receiver. All of these connections are subject to vibration and repeated low-level shocks as the drone makes hard landings--and probably occasionally collides with the tree or a fence. Unless all of these connections are designed and manufactured to withstand vibration and shocks, the risk is high that one or more connections may be interrupted. Such an interruption, depending on the connection, may have fatal effects on the functioning of a critical system by, for example, causing a motor to shut down in flight suddenly or completely disrupting the operation of the navigational control system. Designers and manufacturers can reduce these risks by paying careful attention to where forces are concentrated in all electrical connections and designing to avoid creating stress points at these connections.

Another source of failure is the interaction of hardware and software. Some hardware decisions make it more difficult for software to function correctly. For example, the accelerometers in an inertial measurement unit may drift so quickly that the control program cannot keep up with its readings. And, electromagnetic radiation from the motors and power management logic may interfere with radio control signals and GPS signals. The placement of control-link and GPS antennas may be such that parts of the drone blocks the signal when it is oriented in certain ways vis-à-vis the GPS satellite or the control console.

Acoustic, optical, and radio sensor errors are another rich sources of anomalous vehicle behavior. No sensor models the physical world perfectly. The simplest light-beam detector in a garage door control safety device, quaintly known as a "seeing eye," can only detect the absence or presence of a visible light beam in the grossest way. A camera sensor can only detect a limited range of light intensities and a truncated version of the real world color spectrum.. A sonar sensor can detect only certain sound frequencies. A radio antenna receives signals differently depending on the antenna's physical length, total surface area, and orientation in space.

Choosing the right sensor for an application requires consideration of its specified error range. Too large an error rate renders the output of the best software logic and coding less accurate and potential dangerous.

Beyond that, hardware features the FAA identifies as "mitigating measures" in its rule for requesting waivers of specific drone operating rules represent alternative designs. Example are parachutes,[136] tethers,[137] and airbags,[138] all of which can mitigate the risk of drones falling on or crashing into people below their intended flight paths.

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[136] Henry H. Perritt, Jr. & Quinn Ford, *Making newsgathering drones safe near people* (Mar. 2016), http://www.movoaviation.com/images/Making_newsgathering_drones_safe_near_people_-_white_paper_-_perritt_and_ford.pdf. *See Mars Parachutes for Drones*, MARSPARACHUTES.COM, http://www.marsparachutes.com (last visited Mar. 11, 2017); *Skycat Parachute Launchers*, SKYCAT.PRO, http://www.skycat.pro (last visited Mar. 11, 2017); *World Class Parachute Manufacturers for Drones, UAV, Rocketry, Research!*, FRUITYCHUTES.COM, https://fruitychutes.com (last visited Mar. 11, 2017).

[137] FAA, Certificate of Waiver issued to Cable News Network, No. 107W-2016-00001A, at para. 13 (Nov. 15, 2016), https://www.faa.gov/uas/request_waiver/waivers_granted/media/107W-2016-00001A_CNN_CoW.pdf (granting waiver of prohibition against operations over people for tethered drone).

[138] Perritt & Ford, *surpa* note 136.

b) Software

Because small drones are so dependent on automation to fly at all, automation software is a fertile field for fault. The biggest foreseeable risks involve software functioning. Software that performs incorrectly can create catastrophic risks depending on the particular software routine that malfunctions. Software can malfunction because of an error in its the logic that it is executing, or in other words, because the algorithm is wrong. For example, the program enters an endless loop under some parameter values or conditions that were not anticipated by the programmer. Or, memory mismanagement results in random values erroneously being assigned to key variables.

Many of the most common and frustrating errors in software design and coding prevent the program from running at all or permit it to run but not to perform its intended function, even at a rudimentary level. The accident risk associated with these kinds of errors is small because they either prevent the drone from flying at all, or they make the software malfunction so obvious when an operator attempts to fly the drone that he will not continue the flight.

Higher levels of risk are associated with more subtle errors, like when the software designer programs for only a limited range of values. For example, the program might function correctly when the height above the ground does not exceed 400 feet, but malfunction when the vehicle is higher. Or, the relationship between the values read by the barometric altimeter and the values read by a LIDAR sensor might confuse the program at high-density altitudes, which result in lower than normal barometric pressures corresponding to a particular height above the ground read by the LIDAR. Synchronization logic for the GPS and control links may be insufficiently robust because the relevant software routines do not execute fast enough to accommodate changing propagation and signal strength as the drone moves around.

A plaintiff who claims that a designer has breached his duty of care must begin by identifying the risks that the designer should have understood and then identify those things that a prudent designer would have done to lessen the risk.[139]

A fundamental question as to each risk is whether the designer could have made a different fundamental design choice to achieve a similar function, say to rely on cell phone tower triangulation instead of GPS signals for basic navigation. Then, with respect to each element of the chosen design, the plaintiff takes each risk associated with that design and asks what a prudent designer could have done to reduce the risk. One possibility is to quantify the risk through careful fault analysis. Such a fault analysis could consist of a statistical analysis of data sensor errors in order to estimate the total error associated with a particular combination of sensors. One can then compare that total error rate with some benchmark of safety to show that the designer did or did not meet his duty of care with respect to that risk.[140] Then, depending on the risk, testing must be performed to validate the fault analysis.

The problematic programming errors are not the ones that prevent a program from compiling or executing; those will be discovered and fixed before the software is delivered. The errors most

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[139] The risks that matter, of course, are those that can be shown to bear some relationship to the accident. The risk that the camera gimbal would stop operating is irrelevant if the crash and injury resulted from loss of GPS lock.

[140] Of course, the inference to be drawn from the duty of care analysis depends on the availability of feasible alternatives to reduce the overall error rate.

likely to produce accidents are logic or execution errors that produce unanticipated result in low probability conditions. Within the normal flight envelope and normal values for every parameter programming mistakes will be evident in even the most rudimentary testing. It is those errors that rarely occur or that occur intermittently and with low frequency that pose the greatest risk.

The challenge for an accident plaintiff is to show that a system malfunctioned, because recreating the malfunction has the same elusiveness that makes it difficult for a designer to exclude a particular failure. In the vast majority of cases, plaintiffs must win or lose based on evidence that excludes other possible causes of the accident, reinforced by showing particular reliability tests the defendant should have, but did not, perform. Delivering a product that has not been subject to the requisite standard for design verification and testing is delivering a defective product.

Here is a list of common software programming mistakes:

1. Undeclared variables
2. Uninitialized variables
3. Setting a variable to an uninitialized value
4. Using a single equal sign to check equality
5. Undeclared functions
6. Extra semicolons
7. Overstepping array boundaries
8. Misusing the && and || operators[141]

These coding mistakes are likely to result in execution errors.

Two additional coding problems are insidious, because they produce symptoms randomly and sometimes not at all. Indeed, the second problem more properly might be classified as a "phenomenon" rather than an "error," because it is a product, not of anything in the code, but of the code's interaction with its environment. The first of these problems is a failure to prevent memory leaks. A memory leak occurs when the program fails to release memory that has been allocated to it but is no longer needed. The longer the program runs, the less memory available for actual use. This may cause execution to halt altogether or may cause thrashing, a process in which the operating system does not have as much memory as it needs and so it constantly swaps small amounts of data between active memory and secondary storage. Drones and DROPCONs do not have hard drives, but they do have supplementary storage such as SD cards which may be used for temporary secondary storage while the drone is flying. Memory leaks and thrashing can thus have a significant effect on the performance of such vehicles.

The small specialized computers on drones run many different computer programs in parallel. One program module listens for commands over the radio control channel, while another polls the inertial measurement unit for changes in orientation, while still another processes GPS signals to determine position, and still another computes how much electrical current to feed

[141] Alex Allain, *8 Common Programming Mistakes*, CPROGRAMMING.COM, http://www.cprogramming.com/tutorial/common.html (last visited Mar. 19, 2017).

each of the motors to keep the drone upright and responsive to operator commands. A defect can cause any of these programs to stop running while the others continue to execute normally.

Another anomaly results from some exogenous factors that disturb the sequence in which program modules are loaded into memory for execution. Any serious computer program has many functions and procedures that are not included in the main program itself. Rather they are called by the main program when they are needed. When different processes are running in parallel, as is common in drone software, something unpredictable may block or delay the loading of a particular subroutine while others continue. An interrupt from a sensor might cause this, for example.

Computer processors get data from sensors in two basic ways. One way is for the processor periodically to poll the sensor. When the sensor is polled, it sends its most recent data. Polling occurs under the control of the central processor. The other approach is for the sensor to send an interrupt to the central processor when it has new data. When it receives an interrupt, the central processor stops whatever it is doing long enough to receive and store the data. The timing of an interrupt is under the control of the sensor. When the central processor receives an interrupt just as it is beginning to load a function or a subroutine, other parts of the program, which depend on the subroutine, may proceed without it, causing anomalous results.

Logic errors are different from execution errors. A logic error produces the wrong result even though the computer program executes as intended. An execution error produces the wrong result even though the logic is right. A logic error might misrepresent the dynamic behavior of a drone by, for example, miscalculating a key variable needed for the craft to fly properly. For instance, a DJI Inspire has very different moments of inertia around its three axes, compared with a DJI Phantom because its weight is substantially greater and its shape is different. Since an automatic control system for any aircraft must model the dynamics of the aircraft using these moments of inertia so that it can calculate what movement will result from particular control inputs, a program that puts the vehicle model for a Phantom into the autopilot software for an Inspire will result in bizarre behavior.

Gyroscopic procession is another phenomenon of vehicle dynamics that confronts every aircraft designer and pilot for every powered aircraft in which the propulsion machinery spins. This is true of the gas turbines in fanjet, turboprop and piston engines in propeller driven aircraft and helicopters, and the electric motors in multirotor drones. If one tries to tilt the axle of a spinning gyroscope in one direction, the gyroscope will react in a direction 90° displaced from the applied force. Extending the same principle to a multi rotor drone, every time the drone moves about any of its three axes, gyroscopic procession occurs on all of its motors, applying torque. How much torque depends on the rpm of that particular motor, which is constantly varied to maintain the attitude. The interaction of gyroscopic precession with the forces directing flight must be part of the dynamic model of the vehicle. Logic errors easily can involve the wrong representations of gyroscopic precession.

Engineers often make approximations to simplify their analysis. Discontinuous variables are modeled as continuous ones; trigonometric functions of small angles are expressed as the angles themselves rather than as their sines, cosines, or tangents. Drag at very low speeds is expressed as a function of velocity rather than a function of velocity squared. Digital signal processing involves approximating analog signals based on choices for quantization and digitization. Lossy compression is often necessary to use available bandwidth, resulting in further approximations to data.

Moreover, aerodynamics is notorious for not being reducible to closed form analytical equations; wind tunnel testing has always been a necessary part of the design process, because, while the general behavior of an airfoil can be predicted analytically, its actual behavior always varies from the predicted value somewhat. The many types of turbulent flow associated with rotary wing propulsion are especially difficult to represent analytically. To compensate, aeronautical engineers are forced to make numerous approximations in the design of navigation and control systems and a gap between expected performance and actual behavior results. Thus, these approximations are another source of logical error. Careful scrutiny of design decisions will evaluate each of these potential sources of logical error, and predict their effect on overall vehicle operation.

In *In re Toyota Motor Corp. Unintended Acceleration Marketing, Sales Practices, and Products Liability Litigation*,[142] the district court denied summary judgment on a design defect claim growing out of an accident involving uncommanded acceleration by a Toyota. It also granted and denied motions in limine to exclude expert testimony. The district court's extensive opinion is a good snapshot of vehicle automation claim litigation, including, but not limited to the offering of safer alternative designs.

The court described what happened:

> [T]he collision at issue here occurred after the driver, Mrs. St. John, was stopped and ready to turn right at a stop sign in front of an elementary school. Before her death, Mrs. St. John testified in both a discovery and a trial deposition that when she removed her foot from the brake pedal, the Camry immediately accelerated without her depressing the accelerator pedal. She testified that application of the brakes did nothing to stop or slow the Camry, and that she struggled to control the Camry as she drove through the school yard, striking a number of obstacles in her path, including a brick column that formed part of the entryway to the school gymnasium, before ultimately coming to rest.[143]

On the admissibility of expert testimony, the court observed that the plaintiff need not identify a specific defect. Accordingly, the case law does not "'require each expert to present the complete decision tree leading from defect to collision. 'Reliable expert testimony need only be relevant, and need not establish every element that the plaintiff must prove, in order to be admissible.'"[144]

Among other things, the plaintiff claimed that a software bug could cause the throttle to go from an idle position to a full-throttle position without the driver commanding it, that memory corruption can cause sudden uncommanded acceleration, that the Camry's analog-to-digital converter was a single point of failure,[145] that fail-safe mode did not engage because the driver

[142] In re Motor Corp. Unintended Acceleration Mktg., Sales Practices, and Prods. Liab. Litig., 978 F. Supp. 2d 1053 (C.D. Cal. 2013).
[143] *Id.* at 1064.
[144] *Id.* at 1066-67 (internal citation omitted).
[145] *Id.* at 1077 (summarizing proffer of expert testimony).

did not remove her foot from brake,[146] that placement of certain tasks in particular software modules increased the likelihood of failure,[147] the availability of alternative designs that mediate conflicting accelerator and brake pedal commands,[148] and that the vendor did not follow industry computer programming coding standards.[149]

The court summarized the factors to be considered in evaluating a design defect claim involving software:

> [T]he usefulness of the product; the gravity and severity of the danger posed by the design; the likelihood of that danger; the ability to avoid the danger, i.e., the user's knowledge of the product, publicity surrounding the danger, or the efficacy of warnings, as well as common knowledge and the expectation of danger; the user's ability to avoid danger; the state of the art at the time the product is manufactured; the ability to eliminate danger without impairing the usefulness of the product or making it too expensive; and the feasibility of spreading the loss in the setting of the product's price or by purchasing insurance. . . .
>
> Alternative safe design factors include: the feasibility of an alternative design; the availability of an effective substitute for the product which meets the same need but is safer; the financial cost of the improved design; and the adverse effects from the alternative.[150]

In denying summary judgment on the design defect claim, the court explained the standard of proof and how the plaintiff could meet it:

> As to the design defect, Plaintiff has offered a plethora of expert opinion testimony regarding the development and structuring of the Camry software that supports the claim. Plaintiff offers evidence regarding the complexity of the Camry code and the failure to conform with certain coding standards in designing that code. He offers evidence that this complexity leads to an increased number of software bugs, and the inability to correct those bugs without introducing new ones. He offers evidence that these software bugs can cause memory corruption.
>
> Plaintiff's experts opine that memory corruption can lead to unpredictable results, and that it can lead to task death. They have explained how the death of Task X can affect the target throttle angle in a manner that is inconsistent with driver input.
>
> It is true that Plaintiff has failed to produce admissible evidence regarding a specific defect that could have opened the Camry's throttle from its idle position, but he has raised enough evidence to allow for a reasonable jury to infer its existence. This is particularly appropriate in light of the fact that the Camry software does nothing to track its own failures. If it did, the lack of any identification of a software failure would support Toyota's position; however, absent the ability to trace software failure, the lack of evidence of a specific type of failure is merely inconclusive.

[146] *Id.* at 1081.
[147] *Id.* at 1083-84.
[148] *Id.* at 1084.
[149] *Id.* at 1085.
[150] *Id.* at 1095-96 (internal citation omitted).

> To the extent that the risk-utility analysis implicates "alternative safe design factors," Plaintiff has offered evidence regarding at least two available alternative designs. Specifically, Plaintiff has presented evidence of the availability of an alternative brake-override system that compares the brake pedal sensor to the throttle angle rather than the accelerator pedal sensor. Plaintiff has also presented evidence regarding brake designs that would not allow depletion of vacuum available for braking assist. Under the present record, a reasonable jury could conclude that either or both of these alternative designs were desirable, feasible, and not cost-prohibitive.
>
> Toyota contends that even assuming Plaintiff could prove the existence of a defect that could cause throttle angle opening from an idle position without driver input, the Camry's software fail-safes would negate its effect. This argument assumes that the fail-safes themselves never malfunction, and that all the occurrences necessary to trigger the fail-safes occurred in the Camry immediately preceding the collision.
>
> At least two points allow for the possibility that the fail-safes would not have been triggered or may not have functioned correctly. Plaintiff's experts explain how a supposed redundancy in the accelerator and brake pedal sensors could be rendered ineffective by a single failure because their signals are all processed by the same A/D converter. Where a failure occurs in the A/D converter, it is possible that the brake echo test—a comparison that triggers the fail-safe to which Toyota points—could operate on stale data to unpredictable results. Moreover, Plaintiff's expert Barr testified that in order for brake pedal application to transition the brake switch such that the brake echo test would have the mismatching data to trigger the fail-safe, Mrs. St. John would have had to release the brake pedal for 208 to 212 ms. These points allow for the reasonable inference that the fail-safe did not operate as intended in this instance.[151]

Although the Toyota case involved automobile control systems, the extension of plaintiff and defendant arguments to the somewhat different automatic systems in the drone context is obvious.

c) Testing

The most likely breach of duty by a software programmer or electronic component designer and fabricator is failure to conduct sufficient testing.[152] Errors that occur earlier in the development of hardware or in basic software design are likely to result in the system or component not working at all, necessitating a redesign before it reaches the marketplace. This type of failure is obvious and total. Testing, on the other hand, is conceptually infinite in scope. To obtain the likelihood of failure for each risk, a prudent designer will only run the minimum number of tests to obtain a statistically valid sample. Yet, failure to perform adequate tests can give rise to

[151] *Id.* at 1101-03.

[152] The author appreciates brainstorming assistance from James Redondo, Chicago-Kent College of Law, Class of 2018.

liability because it "tends to show that a manufacturer did not exercise reasonable care in its production of the product."[153]

Test protocols specify how a system or subsystem should be tested to ensure that it meets its design goals. For example, control surfaces such as ailerons[154] can be tested under varying wind speeds in a wind tunnel by measuring the relationship between degrees of aileron deflection and the resulting moment at the wing root. Structural strength can be tested destructively by applying steadily increasing loads at the wingtip and measuring the load at which the wing-root attachment fractures. And finally, crash resistance, say of a LiPo[155] battery container, can be tested by subjecting the battery casing to various kinds of puncture loads to determine the puncture force at which the battery case is penetrated.

All of these tests can be conducted fairly quickly, given the right equipment. Other kinds of tests, however, require much more data and longer collection times. For instance, testing the fatigue tolerance of a structural component requires repeated loading and unloading of the structure until failure occurs or a crack can be detected. Testing for system reliability requires the application of enough use cycles to derive a statistically valid measure of mean time between failures. Tens of thousands of use cycles are often necessary to collect the required data.

In any test protocol, for example the fracture of a wing root in testing wing strength, failure must be defined. Additionally, the event or phenomenon whose relationship of failure is being tested must be defined; in this fatigue-tolerance example, loading and unloading the wing.

Microdrones are exceedingly unlikely to suffer structural failure in ordinary use, in the sense that the booms[156] would separate or the central bay for the electronics would collapse. Certain components, however, may experience physical failure. For example, a rotor blade could come off in flight, or a battery attachment could fail in flight, resulting in separation of the battery. Testing for these kinds of physical failures requires application of traditional techniques for measuring component attachment reliability. Additionally, the tester must determine the kinds of flight profiles or phenomena likely to cause the fault to manifest: perhaps sudden changes in torque for the rotor blade, or turbulence or other causes of abrupt, extreme acceleration in the case of the battery attachment.

The greatest concern for microdrone safety, however, is not failure of structural components; it is the reliability of safety systems. A drone with automatic take-off, automatic landing, automatic hover, geo-fencing, and automatic return to home poses little risk. The concern is the behavior of

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[153] Prather v. Abbott Labs., 960 F. Supp. 2d 700, 713 (W.D. Ky. 2013) (noting also that "careful reading of the KPLA suggests testing may be indicative of whether the manufacturer satisfied its more general duty to exercise reasonable care"). The Third Restatement does not make failure to test an independent source of liability, but it does recognize that a failure to test may allow defects that would have suggested redesign to go undetected. RESTATEMENT (THIRD) OF TORTS: PROD. LIAB. § 10 cmt. c (1998).

[154] An aileron is a hinged portion of the trailing edge of a wing that can is deflected up or down when the pilot moves the stick or yoke. The deflection increases or reduces the lift produced by the wing, enabling the aircraft to bank (i.e. roll about its longitudinal axis), and thus to turn.

[155] "Lithium Polymer" is a type of battery chemistry that produces higher specific energy than other chemistries. Specific energy is the amount of energy per unit of mass.

[156] The boom on a quadcopter is the structural component that houses the motors at a distance from the body. They are necessary to move the centers of rotation of the rotors far enough apart that the rotor blades do not contact each other.

the vehicle when one or more of these autonomous safety features fails to operate as intended. Return to home is the most basic autonomous safety feature. If it works properly, the DROP can trigger the return to home feature when he or she is about to lose control or is otherwise uneasy with drone behavior. The vehicle's onboard safety systems also can trigger the return to home feature when the battery reaches a certain level of discharge, when the drone flies outside a defined height and distance envelope, or when the control link is lost.

Understanding the potential for failure starts with understanding how the return to home feature works. Almost all microdrone return to home features start with a calculation of GPS coordinates, performed at least twice: when the drone is launched, to determine the home position, and again when return to home is triggered, to calculate present position. Calculation of a vector that connects two sets of coordinates is a straightforward application of trigonometry, but the return to home feature must rely on an algorithm to perform the calculation. The control subsystem also must be able to fly the path with some means of detecting deviation, probably requiring additional GPS-coordinate input from the GPS subsystem. Calculation of GPS coordinates depends on the availability of signals from enough GPS satellite signals to achieve "GPS lock."

Conceptually, the design of a test protocol to ensure reliability of the return to home feature is straightforward. The tester performs a large number of flights to different radii from the DROP, in different directions and different proximities to obstacles, and triggers the return to home feature at least once on each test flight. Each success and failure is recorded, along with all the flight parameters and profiles.

The challenge, and the main driver of cost and duration, is not only that many—probably thousands—of flights are necessary to collect the necessary data, but also that multiple potential causes of return to home failure exist even as a theoretical matter; never mind real-world complications. To function successfully, all of the following steps must occur: (1) the return to home feature must know the location of the vehicle when the feature is triggered; (2) the feature must know the location of home; (3) the feature must be able to calculate a path from its present position to home; (4) the feature must communicate the calculated path to a navigation system capable of causing the drone to fly the path; (5) the path must be one that the drone's thrust, climb and descent capabilities permit it to fly; (6) the path must not be interrupted by obstacles; (7) the drone's return speed must be greater than opposing wind; and (8) the remaining battery charge must be sufficient to fly the vehicle back to the launching point.

Failure can occur at each of these steps. Failure of steps (1) and (2) can result from not having GPS lock at the points when coordinates are recorded. Failure of step (3) can result from data errors in the input coordinates or a hardware fault as the algorithm is being executed. Failure of step (4) can result from a poor physical connection, data errors, or misalignment of data-structure frames. Failure of step (5) can result from the commanded path requiring altitudes, speeds, or turn rates exceeding the drone's performance capabilities. Failure of step (6) can result if the drone has flown around or above a tree, pole, or building on the outbound flight. Failure of step (7) can result if the drone flew downwind on its outbound flight, if the wind speed has increased during the flight, or if the wind speed is greater at the altitude at which the drone is flying than at the launch altitude. Failure of step (8) can result if the software mis-calculates the remaining battery charge

A comprehensive test protocol must collect failure rate data under each of these conditions, many of which must be simulated for the test. Room for argument always exists as to whether a simulation adequately models reality. Some testing, such as that for steps (3) and (5), may not require actual flight. Programmers can create "test cases" where they input several coordinates and inspect the algorithm's output. Requirements for any kind of compliance testing are controversial, even among engineers skilled on the subject matter.[157] The same room for argument exists with respect to testing drone autonomous safety systems.

The cost of all this is considerable. Suppose 1,000 flights or other test cycles for each condition are necessary to collect the data required for statistical robustness (The actual number may be much larger). Suppose a DROP, a reliability engineer, and a data analyst are necessary for each series of tests. Suppose further that the replacement cost of the test vehicle is $1,200, and that the vehicle loss rate during the tests is 10%. Finally, suppose that the duration of each test flight is 20 minutes, and that return to home can be triggered every five minutes on each flight.

Together, those assumptions result in total test-flight time of 8,333 hours.[158] Assuming personnel compensation of $30,000 annually for the DROP, $50,000 annually for the reliability engineer, and $25,000 annually for the data analyst, labor costs for the testing total $125,000.[159]

This is just one part of a comprehensive test protocol. Tests also must be designed to determine how much return-to-home capability is achievable without a GPS lock by reliance on the onboard IMU, or with onboard magnetometer and altimeter alone. An IMU can record spatial movements from the launch point and therefore enable the drone to retrace the path to return to home. A magnetometer and altimeter allow a drone to fly directly toward the launching point—assuming it knows where it is—but are incapable of compensating for wind. Current devices also drift quickly, making them more suitable for maintaining vehicle orientation than for navigation.

On the other hand, not every component has to be subjected to reliability testing if the return to home feature includes particular component designs or if off-the-shelf components have passed reliability testing with specified failure rates. A rotor blade rated at 1,000 hours will not decrease the reliability of a system in which other critical components have lives of 100 hours.

d) Reliability Standards

Autonomous return to home capability is almost certain to be included in any conceivable set of drone specifications. The specification may say something like, "the aircraft has a return to home feature that, when triggered, causes it to return to the launching point and land without user intervention."

The specifications may also define tolerances for the landing point—for example, "within two feet of the launching point."

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[157] NHTSA's recent standard for electronic stability control on busses and trucks is a good example. The final rule published in the federal register has more than a dozen pages devoted to arguments over test standards in the proposed rule. 49 C.F.R. § 571 (2015).

[158] 1,000 test cycles, divided by 4 cycles per flight, multiplied by 20 minutes per flight, multiplied by 5 scenarios (excluding tests for steps (3) and (5)).

[159] Total test time of 8,333, divided by annual work hours of 2,000, multiplied by the sum of the annual salaries for the three test professionals.

Difficulties arise, however, when reliability is addressed. It will have only limited safety benefit if the return to home system works only some of the time. Using a pure performance-based approach to reliability adds a proviso that the return to home feature must work a certain percentage of the time, say 99.5%. But why 99.5% as opposed to 85% or 92% or 99.6%? Theoretically, the most appropriate figure should be based on a balancing of the magnitude of the cost of a failure weighed against the cost of compliance. But, that requires data and there is currently not much data for microdrone return to home feature functionality. There is even less on the cost of drone accidents.

One can build a failure rate estimate by careful fault analysis of the components of the system. Similarly, one can begin quantifying the cost of improving the failure based on the cost of adding an additional or more reliable component to the system. Redundancy almost always improves reliability, and it is not difficult to determine the cost of a backup system. Backup systems reduce endurance, however, because of additional power consumption and weight.

In the aviation industry, reliability engineering requires: (1) inventorying every fault that can occur in every aircraft component, (2) quantifying the probability of that fault occurring, and (3) assessing the risk of failure. An example would be the failure of a pitch link on a helicopter rotor blade. The probability of failure depends on the design of the link and the properties of its material components. The consequences of failure would be catastrophic: asymmetric lift between the two rotor blades would likely cause the rotor blade to separate from the rotor hub.

In a microdrone, a fault might occur in the power supply to one rotor because the soldered connection of one of the motor leads to the power distribution board has failed, resulting in an open circuit to that motor. The probability of that occurring is relatively high because wire connections consisting of only the solder itself are brittle and weak. The consequences would not likely be catastrophic in a multirotor design, because the thrust of the rotors still in operation could be increased to ensure stable flight or at least a controlled landing.

A capacitor on an integrated semiconductor circuit board might fail, rendering a micro-drone's GPS navigation system inoperative. The consequences of an inoperative GPS navigation system depend upon how else the drone could navigate in that particular flight regime.

Fault analysis also recognizes that multiple faults can occur at more or less the same time. Rigorous fault analysis must consider all of the possible fault permutations.

The results can be quantified by use of a fault tree, in which generally accepted probability analysis multiplies and adds the probabilities to determine the joint probability of various combinations of multiple faults.

When faults have been identified, their probabilities estimated, and their consequences assessed, designers and regulators decide what should be done to reduce the risk of failure. One possibility is to redesign the failing component to reduce the probability of failure. Depending on the way in which the failure such as that of the pitch link occurred, the component could be redesigned to be made of stronger material or of larger dimension. Alternatively, designers could attach the link to the pitch horn of the blade or to the upper swashplate in a different way.

In the case of the broken solder connection, assembly procedures could be modified to require that the wire be mechanically connected before it is soldered. This could be achieved by wrapping the wire around or hooking it through a terminal, or by twisting two wires together before the connection is soldered.

If redesign is not likely to be cost-effective, redundancy is another possible corrective action. Each rotor blade could be equipped with two pitch links, either one of them strong enough to adjust the pitch of the rotor blade throughout its operating range. Two power connections for each leg of the electrical circuit could be provided for each motor.

Another mitigating strategy is to revise component specifications so as to narrow operating limits in terms of speed, temperature, or turbulence.

Engineering science permits the designers of physical components to determine their strength and other properties and thus to determine the conditions under which they will break, bend or suffer fatigue likely to lead to eventual fractures.

But, under real-world conditions things often behave differently than theory predicts. Data on actual behavior is essential for good failure analysis and it often is unavailable in sufficient quantities to make rigorous fault analysis feasible before an aircraft enters operation. For example, a power lead from a microdrone motor might pop loose from a poorly soldered connection once, but how often will that happen? Usually, full fault analysis is not possible until after an aircraft system is in service for many months or years. Before that, averages of test results can be used, but averages such as mean time between failure (MTBF) are not enough. Failures often exhibit wide deviations around the average, and a particular fault may have such a catastrophic consequence that it would be insufficiently protective of safety to focus on the average circumstances under which it will occur, rather than conditions that might cause it to occur at the 10%, 5%, or 1% probability level.

Especially likely points of failure involve the three different RF links involved in drone missions: the control link, the GPS link, and the Internet connection.[160] Control link failure is the most basic of these, but when that happens, well-functioning autonomous safety protocols can resolve the situation safely. Almost all of the autonomous safety modes depend upon GPS lock. Complete loss of control requires the loss of the control link and GPS lock. Live Internet connectivity is not essential for safe flight, but it is necessary to provide live telemetry to customers and vendors, and to provide moving map displays to DROP and photographer.

6. Duty to Provide Adequate Product Support

a) Foundation of Duty

An important aspect of drone sales is that product support is necessary to realize the potential of the product. Indeed, the “product" comprises a combination of hardware, software, documentation and post-sale product support. It is rare that a drone works out of the box exactly as advertised and in accordance with all of the detailed documentation. There are simply too many things that can change between the time the advertisement and documentation are written and published and the time when the drone is delivered. In addition, frequent firmware and other software updates are inevitable. Bugs in the computer code are discovered and must be fixed. Likewise, new features are added.

Product support is necessary to deal with these realities. It must be reasonably available,

[160] *See supra* § III.E.1 (summarizing relevant radio technology and its modes of failure).

available in the language of the purchaser, delivered by people knowledgeable about the product, and reasonably adaptable to the customer's actual problems.

When this kind of product support is not available, the product is defective and the strict liability of Section 402A is implicated. Some support for a duty to provide adequate product support can be found in the numerous cases holding aircraft manufacturers liable for failure to warn operators of defects and risks discovered after design, manufacture, and sale.[161]

Just as failure to warn can make a product defective,[162] it can lead to a negligence claim, even if the product is not defective.[163] Liability for negligent failure to warn arises when "(1) the defendant knows or has reason to know: (a) of that risk; and (b) that those encountering the risk will be unaware of it; and (2) a warning might be effective in reducing the risk of harm."[164] In addition, "[e]ven if the defendant adequately warns of the risk that the defendant's conduct creates, the defendant can fail to exercise reasonable care by failing to adopt further precautions to protect against the risk if it is foreseeable that despite the warning some risk of harm remains."[165]

The Third Restatement of Torts recognizes that a mere warning may be insufficient; the supplier may be obligated to train. "In a limited number of cases, the relationship between the defendant and the plaintiff suggests that the defendant in order to exercise reasonable care must properly instruct the plaintiff as to how to proceed safely."[166] At least one case has accepted the proposition that the duty to warn extends to providing post-sale product support under federal aviation regulations.[167]

The duty to warn should extend to the drone industry. The drone industry, just like the airline industry, involves a high-technology product that may have hidden bugs or anomalies not apparent from brief user instructions and warnings. The supplier is in the best position to know of the anomalies, and its duty to instruct includes adequate product support. Burdening or hindering access to product support represents a breach of the duty. Failing to provide reasonably competent product support specialists who are able to communicate in the language of the buyers also constitutes a breach.

Effective representation by counsel who pursue this theory will go beyond a plaintiff's testimony about product support waiting times and inadequate product support and will request discovery of the vendor's records as to how its product support works.

The obligation to provide adequate product support also arises from distribution of firmware and software updates and the law of product recalls, which is considered in Section VII.B. A plaintiff pursuing a claim based on inadequate product support would argue that the distribution of a

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[161] *See* Sonja A. Soehnel, Annotation, *Products liability: personal injury or death allegedly caused by defect in aircraft or its parts, supplies, or equipment*, 97 A.L.R.3d 627 § 4 (1980).
[162] RESTATEMENT (THIRD) OF TORTS: PROD. LIAB. § 2 (1998).
[163] RESTATEMENT (THIRD) OF TORTS: PHYSICAL & EMOTIONAL HARM § 18 (2010).
[164] *Id.* § 18(a).
[165] *Id.* § 18(b).
[166] *Id.* § 18 cmt. d.
[167] Burroughs v. Precision Airmotive Corp., 93 Cal. Rptr. 2d 124, 138 (Ct. App. 2000) (holding that successor had duty to provide service bulletins and other service information, imposed by federal law; state standards for duty to warn were preempted).

firmware or software update is a limited product recall. Typically, notices of such updates tell users not to continue operating the drone until the update has been accomplished, and some implementations of flight software will not let the motors start unless the update has been installed.

It is not uncommon for updates to install incorrectly, or when installed, to render certain product features inoperative. When that occurs, a user's only recourse is to contact the vendor's product support for assistance in solving the problem

When product support is inadequate for this purpose, the user may do any of three things. First, he may essentially scrap the drone and write off his investment. Second, he may fly the drone despite the defect introduced by the software update. Finally, he may roll back the drone operating system to its status before the update was attempted, thus rendering inoperative whatever performance or safety enhancements the update contained. The second and third of these options introduce safety risks. Of course, the fact that the operator did not choose the first option increases the degree of responsibility for any accident caused by the operator.

It must be conceded, however, that case law and secondary authority explicitly supporting a duty to provide product support are thin. This article argues that a duty to provide product support should exist and that such a requirement is consistent with the widely-accepted duty to warn.

b) Duty to Train

The duty to warn extends, in appropriate circumstances, to a duty to train.[168] Post-sale product support is one relatively inexpensive way to train users.

Glorvigen v. Cirrus Design Corporation arose from the fatal crash by a new owner of a Cirrus aircraft.[169] The evidence showed that the pilot took off in marginal VFR,[170] entered IMC,[171] and stalled the aircraft while trying to make a 180-degree turn back to VMC.[172] The next of kin of the pilot and his passenger sued Cirrus and its training contractor for failure to provide transition training on the aircraft's autopilot as promised. The evidence showed that proficiency with the autopilot would have enabled a non-instrument rated pilot like the deceased to exit IMC safely. The jury awarded $12 million to the passenger's estate and $7.4 million to the pilot's next of kin. It allocated 37.5% of the fault to Cirrus, 37.5% to UNDAF, and 25% to the pilot.[173] The intermediate appellate court reversed. It agreed that Cirrus has a duty to warn:

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[168] Hendrix v. Phillips Petroleum Co., 453 P.2d 486, 496-97 (Kan. 1969) (holding that manufacturer of L.P. gas had a duty to instruct a distribution or to ascertain that he has been instructed in the use and handling of the product); *cf. Burroughs*, 93 Cal. Rptr. 2d at 138 (holding that successor had duty to provide service bulletins and other service information, imposed by federal law; state standards for duty to warn were preempted).

[169] Glorvigen v. Cirrus Design Corp., 796 N.W.2d 541, 543-44 (Minn. Ct. App. 2011), aff'd 816 N.W.2d 572, 583-84 (Minn. 2012).

[170] Visual Flight Rules—conditions, according to the Federal Aviation Regulations, good enough to permit pilots to see and avoid other aircraft and obstructions.

[171] Instrument Meteorological Conditions—conditions worse than VFR, in which flight is legal only according to an instrument flight plan and detailed clearances from air traffic control operators.

[172] Visual Meteorological Conditions—conditions in which VFR flight is permissible.

[173] *Glorvigen*, 796 N.W.2d at 548.

> In general, a supplier has a duty to warn end users of a dangerous product if it is reasonably foreseeable that an injury could occur in its use." Gray v. Badger Mining Corp., 676 N.W.2d 268, 274 (Minn. 2004). The duty to warn includes providing adequate instructions for the safe use of the product. Id. "[W]here the manufacturer or the seller of a product has actual or constructive knowledge of danger to users, the seller or manufacturer has a duty to give warning of such dangers." Frey v. Montgomery Ward & Co., 258 N.W.2d 782, 788 (Minn. 1977). "To be legally adequate, the warning should (1) attract the attention of those that the product could harm; (2) explain the mechanism and mode of injury; and (3) provide instructions on ways to safely use the product to avoid injury." Gray, 676 N.W.2d at 274. The adequacy of a warning must be evaluated in light of the knowledge and expertise of those who may be reasonably expected to use the product. Dahlbeck v. DICO Co., 355 N.W.2d 157, 163 (Minn. App. 1984), review denied (Minn. Feb. 6, 1985).[174]

The duty to warn, however, did not extend to a duty to provide transition flight training for a new model of aircraft.

The Minnesota Supreme Court has endorsed the broad statement of principles contained in the Restatement (Second) of Torts § 388 (1965) with respect to suppliers of goods. Gray, 676 N.W.2d at 274. According to section 388:

> One who supplies directly or through a third person a chattel for another to use is subject to liability to those whom the supplier should expect to use the chattel with the consent of the other or to be endangered by its probable use, for physical harm caused by the use of the chattel in the manner for which and by a person for whose use it is supplied, if the supplier
>
> (a) knows or has reason to know that the chattel is or is likely to be dangerous for the use for which it is supplied, and
>
> (b) has no reason to believe that those for whose use the chattel is supplied will realize its dangerous condition, and
>
> (c) fails to exercise reasonable care to inform them of its dangerous condition or of the facts which make it likely to be dangerous.
>
> Restatement (Second) of Torts § 388.[175]

The court rejected the plaintiffs' theory that Cirrus had a duty to train the pilot to an adequate level of proficiency because it found no support in the case law for extending the duty to warn so far. The duty extended only to putting a purchaser of an aircraft on notice as to particular dangers in its use, and providing adequate information on how to avoid the danger.[176] Cirrus did that by providing an autopilot supplement in its flight manual and written material on how to exit IMC with the autopilot during the transition training.

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[174] *Id.* at 550.
[175] *Id.* at 550-51.
[176] *Id.* at 551-52.

It also found the claims barred by the educational malpractice doctrine, a common law defense recognized in Minnesota.[177]

Glorvigen can be distinguished in the drone context. A drone-accident plaintiff would not argue that the drone vendor should have trained all the operators of its products to a particular level of proficiency; she would argue that inadequate levels of product support made even the most skillful and proficient pilot likely to lose control of the drone.

C. Injury

Despite wide variation in the standards for establishing breach of duty and causation, virtually every jurisdiction and the Restatement accept the proposition that negligence and product-defect liability result only when the plaintiff can prove physical injury or damage, not for economic loss.[178] This is known as the "economic loss" rule. Its rationale is that allowing tort liability for economic losses generally turns every breach of contract case into a tort case in which punitive damages and other damages far in excess of what is available for breach of contract would be available. The classic measure of damages for breach of contract is "benefit of the bargain." Consequential damages are not generally available for breach of contract unless it can be shown that the parties specifically contemplated them.

D. Causation

All schemes for imposing negligence liability require causation,[179] though some commentators criticize the utility of the concept.[180] Legal causation does not, however, require that the accused conduct be both necessary *and* sufficient to cause the injury. There are three principal views on legal causation. As Professor Wright and his collaborators explain, the most stringent view of causation ("strict necessity") requires that the result would never occur in the absence of the accused conduct.[181] The weakest view (the "NESS[182] criterion") requires only that the accused conduct be part of a set of conditions that was sufficient for the result.[183] An intermediate view ("but for") requires that the accused conduct be necessary for the result, given all the other conditions.[184] Accidents, especially those involving sophisticated technology, often produce situations in which causation is inherently uncertain,[185] and some in which causation is over-determined. For example, what should the law do when a victim is shot in the head by two

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177 *Id.* at 555.
178 See Giddings & Lewis, Inc. v. Industrial Risk Insurers, 348 S.W.3d 729, 733 (Ky. 2011) (explaining economic loss rule); RESTATEMENT (THIRD) OF TORTS: PROD. LIAB. § 21 (1998).
179 *See* Richard W. Wright et al., *Causation, Liability and Apportionment: Comparative Interdisciplinary Perspectives*, 91 CHI.-KENT L. REV. 445, 445 (2016) [hereinafter Wright, Introduction].
180 *See* Richard W. Wright & Ingeborg Puppe, *Causation: Linguistic, Philosophical, Legal and Economic*, 91 CHI.-KENT L. REV. 461, 494-97 (2016) (explaining Calabresi view that causation theories operate ex post and thus interfere with efficient deterrence and dispute resolution).
181 *Id.* at 473-81 (2016) (explaining and criticizing strict necessity approach).
182 "[N]ecessary for the sufficiency of a sufficient set." Wright, Introduction, *supra* note 179, at 447.
183 Wright & Puppe, *supra* note 180, at 481-89 (explaining and arguing for acceptance of NESS criterion).
184 Wright, Introduction, *supra* note 179, at 446.
185 *Id.* at 449.

different assailants and either bullet would have been fatal by itself?[186] Some commentators and courts have sought to escape the difficulties with the three traditional causation formulas by focusing on the probability that a particular actor's conduct would cause the type of injury that resulted, regardless of whether it actually did.[187] Allocating liability in uncertain circumstances is the particular concern of this article, which focuses on the possibilities beginning in Section IV.D.1.

The number of factual permutations contributes to the variety in legal approaches to concurrent causation. One possibility is that Actor #1 breaches her duty in a way that would have caused injury, but something else causes injury first and interrupts the chain of causation. For example, suppose a small drone navigation system has a defect in its navigation software that will cause it to lose attitude orientation when the temperature of the drone exceeds 100°F. The operator of the drone flies it in a part of the country where the temperature regularly exceeds 100°F.

Before the defective drone is flown in such temperatures, however, the operator fails to do a sufficient preflight inspection and the defective drone takes off with a cracked rotor blade. The rotor blade fractures in flight, causing a crash resulting in a total loss. The navigation software designer was at fault under several potential legal theories ranging from negligence for delivering a defective product to delivery of an inherently dangerous product into commerce, but the designer has no liability at all because its fault did not cause the accident.

On the other hand, consider the same basic facts except this time the drone begins behaving anomalously in 105°F weather and the rotor blade fractures along the crack because of the resulting loads on the aircraft. A crash would not have occurred but for the rotor blade fracture *and* the navigation system malfunction. Both the operator's failure to inspect the drone and the designer's mistake in the navigation software caused the accident here.

Tort law takes one of two basic approaches in this circumstance. The traditional common law concept of "joint and several liability" holds both the operator and the software designer liable for the full damages. The plaintiff could decide to sue both of them or sue only one or the other. By statute, in almost every state, the losing defendant could seek contribution from the absent defendant if damages are awarded.

The newer approach allows the plaintiff to sue whichever causal agent she wants. The other causal agents do not become indispensable parties, but she can recover no more from any defendant then his proportionate contribution to the accident, as determined by the fact finder.[188] On the facts of the hypothetical it's essentially arbitrary whether the broken rotor blade was 80% responsible, only 10% responsible, or somewhere in between. Establishing the relative percentages of liability would be entirely up to the fact finder, although that decision would likely be informed by factual and expert testimony about how much damage would have resulted from the software malfunction without the rotor blade fracture.

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[186] Florence G'Sell, *Causation, Counterfactuals and Probabilities in Philosophy and Legal Thinking*, 91 CHI.-KENT L. REV. 503, 509 (2016) (posing hypothetical); *id.* at 512 (explaining that but-for criterion results in conclusion that neither assailant "caused" the injury).
[187] *Id.* at 520-21 (explaining "probabilistic" approach: "[I]n the probabilistic perspective, a condition is the cause of some result if it increased the probability that the result would occur.")
[188] As the discussion of the Montana and Florida statutes, *see infra* § IV.D.4, shows, different states establish different thresholds for proportionate liability.

The traditional joint and several liability rule may seem unreasonable in holding each tortfeasor responsible for the entire amount of the damages, but several economic and moral arguments support it. One argument approaches the rule from the injured plaintiff's perspective. If the plaintiff was injured through no fault of her own, she should not have to bear the loss; the parties who caused the loss should pay for it. If several parties were responsible for the plaintiff's loss, and only some of them have sufficient resources to compensate the plaintiff for her injuries, she should be able to recover a judgment for the full amount; otherwise she will be undercompensated.

The second argument is that the law should discourage irresponsible behavior. If one irresponsible actor partially escapes legal responsibility because someone else acted irresponsibly as well, the incentive to act responsibly is weakened. At the limit, if many people act irresponsibly under circumstances where the aggregate injury is great but the contribution of each is small, no one bears much responsibility.[189]

1. Apportioning Fault Between Man and Machine

Drones, like helicopters, airplanes, trains, and self-driving cars, require interaction between human operators and increasingly autonomous machines. *Penn Maritime, Inc. v. Rhodes Electronic Services, Inc.*[190] involved a claim that a defect in a tugboat's autopilot caused the tug to push its barge into another. The case illustrates the need for a plaintiff to rule out operator error as the cause of an accident involving an autopilot. After a bench trial, the district court found it at least equally probable that the tug captain's failure to operate the autopilot correctly caused the accident.[191] The autopilot had intermittently malfunctioned and allegedly did so again after the captain re-engaged it after a period of hand steering in the Delaware River.[192] Some, but not all, post-accident testing showed that the autopilot steered the vessel incorrectly when re-engaged.[193] Servicing showed that certain settings on the autopilot were incorrect. After they were corrected, the autopilot performed normally.[194]

The tug's owner sued the supplier and installer of the autopilot (Rhodes) for breach of contract and warranty, and for products liability. It brought similar claims against Navico, the autopilot's manufacturer. The tug owner also sued the operator of the other barge for negligence. Rhodes filed a third party complaint against the manufacturer of the tug, alleging that excessive vibrations resulting from faulty design of the tugboat caused the autopilot to malfunction.[195]

The evidence did not establish who was responsible for the erroneous autopilot settings and, in any event, did not establish that the settings could have caused the accident.[196] The court reviewed the ways in which the autopilot could be re-engaged after a period of hand steering and concluded that failure to reset the autopilot's heading separately from the hand steering heading

[189] This is the case with much pollution injury.
[190] Penn Mar., Inc. v. Rhodes Elec. Servs., Inc., 41 F. Supp. 3d 507 (E.D. La. 2014).
[191] *Id.* at 509.
[192] *Id.* at 513-14.
[193] *Id.*
[194] *Id.* at 514.
[195] *Id.* at 514-15.
[196] *Id.* at 518-19.

could cause the autopilot to veer the vessel off course when it was re-engaged.[197] The captain testified that he operated the autopilot correctly,[198] but the court explained that his testimony was not credible: He was under pressure to remember facts in a certain way, his demeanor at trial was "shaky," he demonstrated familiarity with only the most basic features of the autopilot, and gave contradictory testimony about how he operated it. [199]

The tug's operator also claimed products liability under the abnormally dangerous doctrine of Restatement (Second) of Torts sec. 402A.[200] But, its failure to rule out operator error defeated the inference of causation necessary to make this a viable theory.[201]

Ferguson v. Bombardier Services Corporation, arose from a crash of a Sherpa C-23B+.[202] After one hour of flight, the aircraft encountered strong turbulence, which caused the aircraft initially to pitch up and, after a pitch correction, to enter a dive that impacted the ground, killing 18 passengers and 3 crew members—all members of the Virginia National Guard. The court summarized the conflicting theories about what happened:

> The appellants allege that two design defects and a manufacturing defect, all in the autopilot system, conspired to cause the aircraft to crash following the gust of wind. They contend that the autopilot system went into 'torque limiting mode' improperly and that the autopilot should have been equipped with an annunciator in order to warn the pilot when it went into torque limiting mode. They also contend that the autopilot system was improperly installed, leading to a cable jam that prevented the aircraft from recovering once it began its dive. The appellees argue the aircraft was improperly loaded, such that the center of gravity was beyond the limit allowed for the safe operation of the aircraft. According to the cockpit voice recorder, moments before the turbulence one of the pilots left the cockpit and walked to the rear of the aircraft; the appellees contend that the pilot's movement allowed the aircraft to become more unstable, causing the aircraft to crash following the gust of wind.[203]

The plaintiff's expert, who was prepared to testify that the autopilot was defective, allowing oscillations in pitch to develop, admitted during a *Daubert* hearing that improper loading would have produced the same oscillations. His testimony therefore was excluded.[204] The testimony of another expert, that the FARs required the autopilot to be equipped with an annunciator that would have shown it to be in torque limiting mode, was excluded after the plaintiff was unable to identify any such regulation.[205] The appellate court found no errors and affirmed.[206]

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[197] *Id.* at 521-22.
[198] *Id.* at 522.
[199] *Id.* at 522-24.
[200] Id. at 523 (describing claims).
[201] *Id.* at 524.
[202] Ferguson v. Bombardier Servs. Corp., 244 F. App'x 944, 947 (11th Cir. 2007).
[203] *Id.* at 947.
[204] *Id.* at 948.
[205] *Id.*
[206] *Id.* at 952.

Penn Maritime illustrates an evidentiary phenomenon likely to exist in the drone context, but not in the manned aircraft context: the survival of the human operator and his availability to give testimony. Most accidents, even those involving vehicle system defects, can be prevented or their consequences mitigated by skillful operator action. When the operator is available, he can offer explanation as to the cause of the accident, which would be unavailable if he had died in the accident. The operator's availability may result in shifting the evidentiary record toward vendor liability. It may also, however, result in the opposite effect as a result of effective cross-examination of the operator, as in the *Penn Maritime* case.

Sometimes multiple human actors are involved.[207] *Simon v. United States* arose after air traffic control cleared an airplane for a published approach, where the requisite navigational facilities did not exist.[208]

The court summarized the negligence theories:

> Relying on a chart published by the Federal Aviation Administration in Washington, D.C., the pilot sought clearance to complete a Simplified Directional Facility (SDF) approach due to the poor weather conditions. FAA air traffic controllers based at Indianapolis cleared the approach despite the fact that the instrumentation required for the landing at Somerset Airport had not been operational for several years. While attempting to land, the plane struck a radio tower and crashed.
>
> Plaintiffs alleged (1) negligence in the publication at Washington of a chart incorrectly showing that a long-inactive instrument landing approach at the airport was active; and (2) the negligence of Indiana-based air traffic controllers in clearing the pilot for an approach that was out of service, neglecting to monitor the radar during the flight's landing approach, failing to alert the pilot that he was in peril of striking an obstacle, and failing to respond to the pilot's last-minute radio communications.[209]

The aviation and maritime accident cases discussed in the preceding paragraphs are unusual in their focus on system error; aviation accident litigation almost always involves the possibility of pilot error as one of the causes of the accident. Because of this possibility, a DROP should take certain precautions when he knows the drone will crash instead of continuing on its path. This would come into play when a drone is about to collide and none of its emergency mechanisms kick in. The operator can prevent it from continuing and plowing through a crowd of people by stopping the motors, causing it to fall out of the sky, and turning off its propellers to minimize harm to the crowd.

Drone accident litigation also is likely to involve another kind of human factor: fault by the victim. Assumption of the risk would arise as a defense if the victim intruded into an area where drones were operating and the public had been excluded. The last clear chance doctrine would

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[207] *See* Universal Aviation Underwriters v. United States, 496 F. Supp. 639, 648 (D. Colo. 1980) (finding air traffic controller negligent for failing to consult television display of radar information which shows the aircraft were on collision course).
[208] Simon v. U.S., 805 N.E.2d 798, 800-01 (Ind. 2004).
[209] *Id.*

arise if a drone was obviously behaving erratically, and the victim failed to get out of the way when she had the opportunity.

2. Independent Contractors

The rule for allocating responsibility between employers and their agents is a special case of concurrent liability. In the paradigmatic case, the actor was the agent and not the principal. The doctrine of *respondeat superior*, however, imposes vicarious liability on the principal for his agent's actions.

Employers of independent contractors are not liable for the negligence of the independent contractor,[210] subject to exceptions for abnormally dangerous activities[211] and for peculiar risks.[212] Employers may be liable, however, for negligence in selecting the contractor,[213] for failure to inspect the contractor's work,[214] negligence and exercising control retained by the employer,[215] and negligence in giving directions.[216]

3. Multiple Vendors

Modern high-technology consumer products are rarely designed and manufactured by only one vendor; often, layers of subsystems, each designed and manufactured by a different supplier are finally assembled by the entity whose brand appears on the finished product. This trend complicates any process for apportioning liability. Did the final assembler breach its duty or was it the designer of the accelerometer package, which was integrated into a different manufacturer's inertial measurement unit, which was integrated into yet another vendor's navigation control subsystem, which was integrated into the final product assembled by yet another enterprise.

The answer is that all of these parties can be held liable. Each designer and manufacturer of the finished product or its sub-components is subject to product liability claims with respect to hardware and software. All have a duty to the end user. Section 5 of the Restatement (Third) of Torts holds component sellers and distributors liable for harm caused by products into which those components are integrated when the component is defective or when the component by itself is not defective, but the component supplier participates in the integration of the component into the final product and that integration makes the final product defective.[217]

Downstream vendors do not escape liability by showing that the defect was in the components they assembled or sold, and was not caused by any independent action on their part.[218] The

[210] RESTATEMENT (SECOND) OF TORTS § 409 (1979); RESTATEMENT (THIRD) OF TORTS: PHYSICAL & EMOTIONAL HARM § 57 (2010).
[211] RESTATEMENT (THIRD) OF TORTS: PHYSICAL & EMOTIONAL HARM § 58 (2010).
[212] *Id.* § 59.
[213] *Id.* § 411.
[214] *Id.* § 412.
[215] *Id.* § 414.
[216] *Id.* § 410. *See generally id.* § 55 cmt. a (bases of direct liability).
[217] RESTATEMENT (THIRD) OF TORTS: PROD. LIAB. § 5 (1998).
[218] *Id.* § 1 cmt. e.

analysis for each of the vendors is the same; the factual specifics of their hardware and software choices are different.

In re Aircraft Crash Litigation Frederick, Md.[219] illustrates the detailed factual inquiry necessary to sort out products liability claims against multiple suppliers in air crashes. The court summarized the cause of the accident and the opposing contentions by the parties:

> The Air Force's analysis of possible causes of the crash led it to conclude that
>
> > for undetermined reasons, the aircraft pitch trim moved to the full nose down position. The aircraft then rapidly pitched over, most likely upon release of the auto-pilot, and induced sufficient negative 'G' forces to cause [its AC] generators to trip off line, resulting in the loss of all AC electrical power. The pitch trim could not then be moved electrically. This condition, while unusual, can be controlled [manually, by use of the trim wheel] if prompt corrective action is taken; however, if corrective action is delayed approximately 8 seconds, the aircraft pitch angle will be greater than 30 degrees nose-down and the airspeed in excess of 350 knots indicated airspeed. Under these conditions, the aircraft cannot be controlled until the pitch trim is moved toward neutral. While it is evident that recovery was delayed, the reason for the delay is unknown. The aircraft became uncontrollable and entered a steep descent. During the rapid descent, an explosion occurred at approximately 1300 feet above ground level followed immediately by catastrophic failure, and complete break-up of the aircraft.
>
> AF Investigation Report at 'Synopsis' and Tab 3.3. It is not disputed that rapid pitch-over of the aircraft could and did result in loss of AC electrical power so that the pitch trim could not be corrected electrically. It is also not disputed that after approximately eight seconds of full nose-down pitch, the aircraft pitch angle and airspeed would be such as to make manual recovery of the aircraft impossible.
>
> B. The Parties' Contentions Concerning the Accident's Cause
>
> The parties to the instant Motions differ markedly in their theories of the cause of the aircraft's pitch-over and succeeding events leading to loss of the airplane. Plaintiffs contend that the aircraft's sudden pitch-over was the result of a 'flight control system malfunction,' most probably in the autopilot. They claim that the aircraft's automatic flight control system was designed to be capable on its own (i.e., without a command from the flight crew) of moving the pitch trim to the full nose down position while the autopilot is in altitude hold mode. They contend that the flight control system was defective in that the autopilot was 'failure prone' and because 'single point failures in the system [that] caused uncommanded trim inputs which threatened the safe operation of the plane were commonplace.' Plaintiffs' contend that the design of the aircraft's autopilot was defective in several respects.

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[219] *In re* Aircraft Crash Litig. Federic, Md., 752 F. Supp. 1326 (S.D. Ohio 1990).

> Plaintiffs allege that the aircraft was defectively designed such that the combination of unanticipated trim malfunction leading to full nose-down attitude and complete loss of electrical power . . . led to a 'failure mode' from which a reasonably qualified pilot such as Captain Emilio could not recover the aircraft . . . .
>
> Defendants contend that the aircraft's pitch-over was caused when Mrs. Emilio, seated in the left pilot's seat, inadvertently activated the trim stabilizer switch located on the left pilot's control wheel, and that the failure to correct the pitch-over in the time period before the situation became irremediable was due to human error attributable to Captain Emilio .[220]

The court held that the claims of negligent flight testing were barred by the 'Boyle defense' for contractors who follow government specifications.[221] It found that the rate-of-trim movement, tripping off of the electrical generators under negative G forces, and the placement of the manual trim wheel were all approved by the Air Force.[222] Among other things, the Air Force rejected specific Lear suggestions to improve the safety of the autopilot:

> It is undisputed that Lear made two design suggestions which directly relate to enhancing the safety features of the autopilot, and that the Air Force rejected those suggestions. Plaintiffs contend that the autopilot was defective, in part, because it used a vacuum tube system instead of a solid-state system. In 1958, Lear recommended that the autopilot's yaw axis components be transistorized to improve the autopilot's reliability and hence the KC-135A's lateral stability when the autopilot was engaged. The Air Force rejected this proposal to transistorize the autopilot. Plaintiffs also contend that the autopilot should have been accompanied by additional warning lights and aural signals to alert the crew to autopilot malfunction. Lear's recommendation that such additional warning and monitoring systems be included was likewise rejected by the Air Force as unnecessarily complicating the autopilot's design.[223]

In order to fix responsibility for particular design decisions involving the cockpit layout and the autopilot (and therefore to decide whether the *Boyle* defense applied), the court exhaustively reviewed the history of the EC-135N aircraft involved in the crash.[224] The Air Force procured the autopilot separately and provided it to the airframe designer and manufacturer, having earlier written specifications for it.[225] Subsequent testing and discussions among Boeing, Lear, and the Air Force resulted in design changes.[226]

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[220] *Id*, at 1333 (describing plaintiff allegations).
[221] *Id.* at 1350.
[222] *Id.* at 1351.
[223] *Id.* at 1357-1358.
[224] *Id.* at 1343-1345.
[225] *Id.* at 1345.
[226] *Id.* at 1346-1347. Appendices to the opinion detail some of the crucial testimony before the court.

The *Aircraft Crash Litigation* case illustrates an effort to sort out responsibility among multiple suppliers.

4. Indeterminate Causation

Legal commentators have wrestled with two examples involving indeterminate causation, which is defined as the uncertainty as to who should bear liability when multiple actors may have caused an injury. In the first classic example, two factories discharge pollutants into a river and the fish in the river die. Each factory's effluent was sufficient to kill the fish. As a practical matter, the individual responsibility of each factory cannot be established.[227] This is an example of over-determined causation. An older example involves two fires set by two independent actors. The fires merge and burn down the plaintiff's house. Either fire would have been sufficient by itself, so neither can be said to have been the "but-for" cause of the victim's loss.[228]

The drone analogy involves a vehicle with two defects introduced by distinct subsystem suppliers. The first would be a GPS navigation system that lost a GPS signal whenever the drone flew near an object, and the second would be an attitude control system that caused the drone to tumble and become uncontrollable whenever it lost its GPS signal. Either defect was sufficient to cause the drone to crash.

The second classic example involves two hunters shooting at a duck and one accidentally hits and kills a human victim. It is certain that one of them killed the victim, but forensic investigation cannot determine which one (this would be the case if they shot shotgun pellets rather than rifle bullets). Who is liable?[229] This type of uncertainty is more common in the drone context. Was it the return-to-home logic in the flight control system or the GPS receiver that caused the flyaway and the crash?

Traditionally, "[a]t common law, 'if the concurrent negligence of two or more persons causes an injury to a third person, they are jointly and severally liable and the injured person may sue them jointly or severally and recover against one or all.'"[230] Allocation of liability among all those responsible was left to the separate law of contribution:

> The right of contribution is established by statute, while the right to indemnity invokes equitable principles. Contribution and indemnity are similar in that the essential purpose of both is to shift one's losses to another. The objective of contribution is to allocate liability among all responsible parties. Contribution distributes loss among joint tortfeasors by requiring each tortfeasor to pay his or her proportionate share based upon his or her proportion of the negligence which proximately caused the plaintiff's injuries. Conversely, indemnity "shifts the entire

[227] *See* Michael Faure, *Attribution of Liability: An Economic Analysis of Various Cases*, 91 CHI.-KENT L. REV. 603, 606 (2016) (describing example).
[228] Samuel Ferey & Pierre Dehez, *Overdetermined Causation Cases, Contribution and Shapely Value*, 91 CHI.-KENT L. REV. 637, 637-638 (describing example).
[229] *See* Faure, *supra* note 227, at 607 (describing example).
[230] Metro Aviation, Inc. v. United States, 305 P.3d 832, 837 (Mont. 2013) (quoting Black v. Martin, 292 P. 577, 580 (Mont. 1930)) (answering certified question; prohibiting indemnity claim among joint tortfeasors).

> loss from the one who has been required to pay it to the one who should bear the loss."[231]

Traditionally, a plaintiff did not have to sue everyone who might have been responsible. "It has long been the rule that it is not necessary for all joint tortfeasors to be named as defendants in a single lawsuit."[232] Transitioning to a proportionate-several liability regime did not change this.[233] A defendant who was held fully liable had a remedy in a subsequent contribution action,[234] or the defendant might implead others with potential joint liability.[235]

Now, the traditional all-or-nothing approach to negligence liability has largely been replaced by comparative fault concepts. "If the plaintiff has been contributorily negligent in failing to take reasonable precautions, the plaintiff's recovery in a strict-liability claim under §§ 20–23 for physical or emotional harm is reduced in accordance with the share of comparative responsibility assigned to the plaintiff."[236] This comparative fault concept applied to allocating responsibility between the plaintiff and a single defendant has been extended to allocate responsibility among multiple defendants.

The third Restatement significantly expands the second Restatement's treatment of the interrelation of foreseeability of harm, proximate causation, and multiple causes.[237] The third Restatement consistently recognizes the national trend away from common-law joint and several liability. It offers four alternative approaches, each of which enjoys substantial support in state statutory law:

- Joint and several liability, with modifications
- Proportionate several liability
- Proportionate several liability with a floor or threshold
- Joint and several liability with reallocation of uncollectible judgments

Hart v. Cessna Aircraft illustrates the interrelationship between liability actions involving fewer than all joint defendants and subsequent contribution actions.[238] In *Hart*, a plane crashed because the aircraft had no deicing equipment. The widow of a passenger killed in the light-airplane crash unsuccessfully sued the pilot. She then sued the manufacturer of the aircraft, Cessna. Cessna, then, impleaded the pilot, who had won the first lawsuit, seeking contribution. The Minnesota Supreme Court considered whether the contribution action was barred by the judgment in the first action.[239]

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[231] 305 *Id.* at 834.
[232] Clay v. AIG Aero. Ins. Servs., 61 F. Supp. 3d 1255, 1267 (M.D. Fla. 2014) (denying motion to dismiss for failure to join other mechanics as indispensable parties).
[233] *Id.*
[234] *Id.*
[235] *Id.* (noting possibility of impleader).
[236] RESTATEMENT (THIRD) OF TORTS: PHYSICAL & EMOTIONAL HARM § 25 (2010).
[237] *See Id.* § 29-36.
[238] Hart v. Cessna Aircraft Co., 276 N.W.2d 166 (Minn. 1979).
[239] *Id.* at 167 (summarizing litigation and stating issue).

The court held that an obligation to contribute depends on underlying liability. Thus, the pilot could not be held liable in the contribution action. But, the court recognized an equitable dilemma and sought to craft an equitable solution:

> [C]ontribution is an equitable action, and the rules governing its use should promote the fair and just treatment of the parties. . . . In the instant case, if Cessna is found negligent and cannot claim contribution from Vogt, it may be required to pay more than its share of the plaintiff's loss. Although we do not want to impose liability on the previously successful defendant, Vogt, we do not want the second defendant, Cessna, to bear the entire burden of the plaintiff's loss if he can show that Vogt's negligence contributed to that loss.
>
> We believe there is an equitable solution to this apparent dilemma. The plaintiff does have, and should have, the right to control his own lawsuit—to sue or not to sue whomever he chooses. However, if there are two or more possible defendants and plaintiff elects to sue them piecemeal, it is he who should bear any risk imposed by using that procedure.[240]

The court held that Vogt was not liable to the plaintiff or to Cessna based on claim preclusion.[241] Cessna, however, was liable only for the percentage of fault the jury apportioned to it, assuming that was less than 50%.[242]

It is a growing trend in tort law to apportion liability according to relative causation.[243] At common law, apportionment was not possible; joint tortfeasors were jointly and severally liable for the entire judgment.[244] The effect of this doctrine was blunted, however, by the possibility of the tortfeasors recovering against each other for contribution.[245] Contribution did not take into account relative causation, however. An intervening cause simply negated liability of the tortfeasor whose fault preceded the intervention.[246] Now, the rise of comparative responsibility has blunted the force of traditional rules about superseding and intervening causes.[247]

Professor Wright summarizes:

> [W]hen there are multiple legally responsible causes of a specific injury, the issue arises as to how to apportion the liability among the multiple responsible causes,

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[240] *Id.* at 169-170.
[241] *Id.*
[242] *Id.* at 169-170.
[243] *See* Mario J. Rizzo & Frank S. Arnold, *Causal Apportionment in the Law of Torts: An Economic Theory*, 80 COLUM. L. REV. 1399 (1980). *See generally* Richard W. Wright, *The Grounds and Extent of Legal Responsibility*, 40 SAN DIEGO L. REV. 1425 (2003); Richard W. Wright, *Liability for Possible Wrongs: Causation, Statistical Probability, and the Burden of Proof*, 41 LOY. L.A. L. REV. 1295 (2008) [hereinafter Wright, Statistical Probability].
[244] Rizzo & Arnold, *supra* note 243, at 1400.
[245] *See id.* at 1400-01; RESTATEMENT (THIRD) OF TORTS: PHYSICAL & EMOTIONAL HARM § 34 cmt. c (2010) (explaining historical evolution from reliance on contribution to comparative assessment of responsibility).
[246] *See* Rizzo & Arnold, *supra* note 243, at 1401.
[247] RESTATEMENT (THIRD) OF TORTS: PHYSICAL & EMOTIONAL HARM § 34 cmt. c (2010).

> which may include a negligent plaintiff as well as one or more defendants. Under a "joint and several" (or "solidary") liability rule, which is the general rule in almost all legal systems, the plaintiff can recover the entirety of her damages, after proportionate reduction based on her percentage of comparative responsibility if she was contributorily negligent, from any one of the legally responsible defendants (tortfeasors). Any tortfeasor who pays the plaintiff can seek contribution from the other tortfeasors based on their respective percentages of comparative responsibility for any payment to the plaintiff in excess of the paying tortfeasor's percentage of comparative responsibility. Under a "several" or "proportionate several liability" rule, which exists in many states in the United States for varying parts of the plaintiff's damages due to so-called "tort reform," the plaintiff may only recover from each tortfeasor a portion of her damages equal to that tortfeasor's percentage of comparative responsibility. Comparative responsibility is usually based on comparative fault, although it may also take into account relative causal contribution if that is measurable.[248]

Metro Aviation, Inc. v. United States[249] illustrates the proportionate-several liability approach in the context of a settlement under a proportionate-several liability statute. Metro Aviation, which owned and operated a plane that fatally crashed, settled with the estates of the two passengers and then sued the United States for indemnity and contribution, seeking to recover the amounts it had paid in settlement.[250] The Federal Tort Claims Act referred to state law for determination of liability.[251]

The Montana statute at issue restated the general rule that each defendant was jointly and severally liable, with a right of contribution against other persons who were negligent. Defendants found to be less than 50% responsible, however, were responsible only for the percentage of liability attributable to them.[252]

The Montana Supreme Court held that a potential defendant who settles in advance of trial or without filing a lawsuit may not bring an independent contribution action.[253] Thus, because Metro Aviation was potentially liable for some fault, they could not seek indemnity from the FAA.[254]

To make sense of proportionate-several liability statutes like this, one must understand the political campaign that led to their enactment. The insurance industry persuaded many state legislators that the tort liability system was broken because it often imposed high financial

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[248] Wright, Introduction, *supra* note 179, at 453.
[249] Metro Aviation, Inc. v. United States, 2013 MT 193, 305 P.3d 832 (Mont. 2013).
[250] *Id.* at 833-34.
[251] *Id.*
[252] *Id.* at 834-35.
[253] *Id.* at 836-37.
[254] *Id.* at 838.

responsibility on entities that were only marginally responsible for accidents but had deep pockets.[255] Thus, 50% responsibility thresholds were established.

In some cases, the problem is that the plaintiff can prove that someone in a small group of actors was responsible for his injury, but he cannot prove which one.[256] Joint-and-several liability doctrine permits holding all defendants liable even though no fault is apportioned. Then the court must apportion liability even though fault is not apportioned? In such cases, the courts typically shift the burden of proof to the defendants, holding each liable unless each defendant can prove he did not cause the injury.[257]

The Seventh Circuit reviewed the conflicting approaches to apportioning liability and collecting judgments in *Schadel v. Iowa Interstate R.R*.[258] The problem is complicated when some of the defendants settle, as in *Schadel*.[259] It framed the issue as follows:

> Specifically, we must decide whether a non-settling railroad should be held liable for all damages suffered by its employee, reduced by an amount attributable to the employee's comparative negligence and a settlement with a third party, or alternatively, if the railroad should be responsible only for its proportionate share of damages, taking into account the comparative fault of the employee and that of a settling third-party defendant. The district court allowed the jury to find the total damages suffered by the plaintiff, without regard to the settlement; it then reduced those damages by 50%, the amount representing the plaintiff's negligence; and finally, using an Illinois standard, it applied a set-off against the balance owed by the railroad. While our reasons are not identical to those offered by the district court, we conclude that the result was correct, and we therefore affirm the judgment.[260]

The differences among state law, not only for liability allocation, but also for other liability issues, makes choice of law controversies a regular feature of aviation accident litigation. In *In re Colorado Springs Air Crash,* the issue was "whether the remaining defendants' share of liability [should] be reduced by the government's proportionate share of liability, or by the actual amount paid in settlement."[261] Resolution of the issue depended on whether proportionate-several liability or the traditional joint and several liability was the rule. This presented a choice of law issue. Illinois and Washington followed the traditional joint and several rule; Colorado followed the proportionate-several rule.[262] The court applied Illinois law, in part because it encourages

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[255] *See* Richard W. Wright, *The Logic and Fairness of Joint and Several Liability*, 23 MEM. ST. U. L. REV. 45, 50, 63-65, 81-82 (1992).
[256] *See* Wright, Statistical Probability, *supra* note 243, at 1299 (discussing Summers v. Tice, 199 P.2d 1 (Cal. 1948) (involving uncertainty as to which shotgun fired a shotgun pellet)).
[257] *Id.*
[258] Schadel v. Iowa Interstate R.R., Ltd., 381 F.3d 671, 671, 675-76 (7th Cir. 2004).
[259] *Id.* at 677-79.
[260] *Id.* at 673.
[261] *In re* Colo. Springs Air Crash, 867 F. Supp. 630, 630 (N.D. Ill. 1994).
[262] *Id.* at 632-33.

settlements by making the settling party potentially liable for more than its pro-rata share if it does not settle.[263]

Brewer v. Dodson Aviation involved products liability actions against the manufacturer of a dry air vacuum pump, the company that overhauled it, and the company that installed it.[264] The litigation ensued from the loss of control and in-flight breakup of a Beechcraft aircraft, allegedly resulting from the failure of the vacuum pump that drove its critical instrument displays.[265] Determining liability and allocating responsibility required resolution of choice of law issues related to joint and several versus proportionate-several liability, the statute of limitations, and substantive products liability issues (consumer expectations, the existence of a negligent design claim, and assumption of the risk as a bar to liability).[266] The court wrote:

> In Ohio, a defendant may be jointly and severally liable for all compensatory damages that represent economic loss in a tort action if the defendant was more than fifty percent at fault. Ohio Rev. Code Ann. §§ 2307.22–23. In Washington, product liability defendants are jointly and severally liable for the sum of their proportionate shares of the claimant's total damages if the claimant was not at fault. RCW § 4.22.070(1)(b); RCW § 4.22.015. Thus, there is an actual conflict between Ohio's and Washington's joint and several liability rules.[267]

Litigants and legislators will continue to argue over the rules for apportioning liability in indeterminate causation cases because the different approaches embody different policy choices.

V. <u>Special Characteristics of Drones</u>

In the drone accident realm, the rules for products liability and for apportioning liability among multiple tortfeasors are well-settled. Although the legal rules vary from state to state, the alternatives are well crystallized and sufficiently flexible to accommodate the facts of almost any drone accident case. The novelty of drone accident cases relates to the lower risks of serious injury or damage, more demanding proof of facts, and the fact that more data is needed to prove them.

A. Limited Damages

In some ways, conventional aviation accident litigation is a useful guide for drone accident litigation because both categories of tort liability involve aircraft. But, the dramatically different size and weight of drones as compared to helicopters and airplanes, the fact that drones do not carry people, and the fact that most small drones do not carry flammable fuel means that the damage associated with the most likely drone accidents is minimal compared to the damage associated with most commercial aircraft accidents. Manned aircraft carry people whose survivors are likely to sue if the aircraft disappears. This is not the case with drones.

Indeed, one has to have a fairly vivid imagination to come up with a scenario in which an

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[263] *Id.* at 636.
[264] Brewer v. Dodson Aviation, 447 F. Supp. 2d 1166, 1172-74, 1181 (W.D. Wash. 2006).
[265] *Id.* at 1172.
[266] *Id.* at 1177.
[267] *Id.* at 1178 (internal quotation marks omitted).

accident involving a small drone could result in a fatality. If a drone falls directly onto the heads of a crowd, it is unlikely to do more than bruise a few people, although it might cause a concussion or a skull fracture if it hits someone directly on the head while falling at an appreciable speed. If a drone were to be flown at high speed into someone horizontally, that could result in serious head, torso, or extremity injuries, but the scenario leading to that is unlikely barring a deliberate attack. Movie or television production might be an exception, when an actor or a drone is out of position.

A drone falling on an automobile might break the windshield, depending on the collision speed. If it does, impact on the driver could be fatal, either directly or because it causes the driver to lose control of the vehicle.

The morbidity and mortality associated with mid-air collisions involving drones and commercial aircraft is likely to be higher. If a drone impacts the rotor of a helicopter, especially the tail rotor, it could make the helicopter uncontrollable and result in a fatal crash.[268]

It also is reasonable to think of drone strikes as analogous to bird strikes, which are a serious threat to helicopter operations and, less so, to fixed wing operations. Fixed wing aircraft usually fly higher than birds, except for the landing or take off phases of flight. The probability of a bird strike causing serious injury is approximately five per hundred thousand (an accident probability value found to be acceptable in the design of many aircraft components) and empirical analysis suggests that bird strikes remain more likely than drone strikes.[269].

If a drone collides with a large transport aircraft and causes a crash, it could result in many fatalities, but is it is hard to imagine how that may happen. A strike on the fuselage or on the leading edge of a wing or stabilizer might cause some damage but it would not interfere with aircraft control. A strike on the windscreen or ingestion into an engine might be more serious. While the flow around the windscreen on the nose of an aircraft deflects approaching objects from the windscreen, the same is not true of engine intakes. Indeed as the occasional instance of a ramp agent getting sucked into the intake of an engine shows, [270]objects within a certain distance of the intake of a running engine are likely to be ingested by the flow pattern around the intake.

Then, the question is whether the drone would break up, absorbing sufficient kinetic energy to avoid or minimize damage to the aircraft, or whether certain parts of it, such as such as a large lithium ion battery, would be sufficiently dense and hard to shift more of the kinetic energy of the collision to the aircraft. If that happens, aircraft components might deform or fracture to a greater extent.

One must have a vivid imagination to construct a scenario in which a crash of a DJI Phantom, Mavic, Inspire, or an M600 capturing news imagery or taking promotional video of real estate would cause serious injuries. But, the possibility of accidents causing fatalities or serious injuries

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[268] The author is a commercial helicopter pilot. Loss of a tail rotor makes any helicopter uncontrollable.
[269] Eli Dourado & Samuel Hammond, *Do Consumer Drones Endanger the National Airspace? Evidence from Wildlife Strike Data*, MERCATUS CENTER GEO. MASON U. (Mar. 14, 2016), https://www.mercatus.org/publication/do-consumer-drones-endanger-national-airspace-evidence-wildlife-strike-data.
[270] Engineer sucked into engine aftermath, Liveleak, May 13, 2010, https://www.liveleak.com/view?i=1ae_1273782186.

is greater as one considers the risk exposure of drone systems flying beyond the line of sight to deliver packages in residential neighborhoods and cities. As drones become more complex, the risk that some component will fail increases. That is a statistical reality depending directly on the number of components. In addition, greater proximity of larger numbers of vehicles to larger numbers of people increases the risk of injury when a component failure does occur.

Despite this, the risk of serious injury remains low, and this justifies a regulatory policy that facilitates getting new technologies to market quickly. The low risk also justifies shifting from a pre-sale regulatory approval strategy to post-sale products liability litigation, a subject considered more fully in section VII.A. The low level of damage and injury also means that it will not be worth suing over most accidents. The response to the question posed by this article's title will be, "the victim pays." Someone whose arm gets a small cut is not likely to sue.

In any event, drone accidents will happen and some will result in lawsuits. Interesting questions will arise when a drone injures someone uninvolved in the drone operation or damages her property. Contracts between drone vendors and users and between participants and drone operators will attempt to limit the liability of the manufacturer of the drone and to indemnify the vendor even though it is the entity best able to cover the cost of an accident. [271]

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[271] The following is an excerpt of the language contained in the standard sales agreement for a 3DR Solo, a $1000 low-end professional drone:

> By downloading, copying, installing, or using all or any portion of the software, or any updates to the software (collectively, the "Software"), you accept all the terms of this agreement.
>
> . . . .
>
> **6. Limited Warranty**
>
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> **7. Disclaimer**
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> THE LIMITED WARRANTY ABOVE IS THE ONLY WARRANTY OFFERED BY 3DR, ITS AFFILIATES, SUPPLIERS, AND DISTRIBUTORS AND IT STATES THE SOLE AND EXCLUSIVE REMEDIES FOR 3DR'S, ITS AFFILIATES', SUPPLIERS', OR DISTRIBUTORS' BREACH OF THAT WARRANTY. THE LIMITED WARRANTY ABOVE AND ANY STATUTORY WARRANTY AND REMEDY THAT CANNOT BE EXCLUDED OR LIMITED UNDER LAW ARE THE ONLY WARRANTIES APPLICABLE TO THE SOFTWARE. OTHER THAN THOSE OFFERED AND STATUTORY WARRANTIES AND REMEDIES, 3DR, ITS AFFILIATES, SUPPLIERS, AND DISTRIBUTORS DISCLAIM ALL WARRANTIES, CONDITIONS, REPRESENTATIONS, AND TERMS, EXPRESS OR IMPLIED,

The courts are showing little willingness to question the enforceability of such provisions in "clickwrap" agreements, which impose standard terms favoring the drafter of the contract on e-commerce customers who have never read them.[272] Even if consumers did read the agreement language, they have no bargaining power and no practical ability to contact anyone representing the other party to the contract who has the power to agree to any changes. The legal relationship, like the product, is automated beyond human control.

B. More Challenging Proof of Facts

Drone accidents are more likely to result from anomalies in navigation system software and radio signal processing than from mechanical failure or pilot error. Litigating a drone accident case successfully will require drilling down into the intricacies of automatic control circuit design, computer programming and radio engineering.

C. More Evidence

More data is likely to be available for drone accidents than for manned aircraft accidents because

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Solo App End User License Agreement, 3DR, http://3dr.com/support/articles/208764226/solo_app_end_user_license_agreement/, (last visited Oct. 23, 2016 5:58 PM).

[272] *But see* Berkson v. Gogo LLC, 97 F. Supp. 3d 359, 403 (E.D. N.Y. 2015) (holding clickwrap agreement unenforceable; reviewing and analyzing standards for enforcing shrinkwrap, clickwrap, and other contracts of adhesion); Meyer v. Kalanick, 199 F. Supp. 3d 725, 765 (S.D. N.Y. 2016) (holding arbitration agreement unenforceable because cellphone user ordering Uber did not have "reasonably conspicuous" notice).

even the least expensive drone generates large quantities of telemetry about its flight profiles and system behaviors. Additionally, drone flight crews will usually be available to testify, unlike many aircrews of manned aircraft involved in serious accidents.

VI. Practical Litigation Issues

A. Lining Up the Defendants

The vast majority of product liability litigation involves substantial information asymmetry as between plaintiff and defendant. Typically, a plaintiff must plead generally and hope discovery produces specific facts that enable her to prove a case. At the same time, plaintiffs must be mindful of Fed. R. Civ. P. 11 and its counterparts in state procedural rules. Rule 11 requires a plaintiff to have a reasonable basis for asserting facts. It would violate Rule 11 to assert that an autopilot on a drone had a manufacturing defect if the plaintiff has absolutely no reason for believing that is the case. The mere possibility that manufacturing defects exist and that, statistically, a certain percentage of drones sold have autopilots with manufacturing defects is not enough.

The plaintiff does not have to prove her case to avoid Rule 11 sanctions and losing at trial does not automatically result in Rule 11 sanctions. But, referring to the language of Rule 11—"to the best of the person's knowledge, information, and belief, formed after an inquiry reasonable under the circumstances . . . the factual contentions have evidentiary support or, if specifically so identified, will likely have evidentiary support after a reasonable opportunity for further investigation or discovery"—plaintiff's counsel needs to be able to explain her reasonable basis for pleading facts.

This need interacts with legal doctrine. As § 519 explains, delivering an abnormally dangerous product into the stream of commerce can result in liability when it causes injury, even without proving fault. So, a plaintiff who pleads an abnormally dangerous product claim under section 519 need only have a reasonable basis for believing causation and the characteristics that make the product abnormally dangerous and need not have a basis for believing that the product vendor was negligent in its design or manufacture. Similarly, when the tort doctrine of *res ipsa loquitor* applies, the plaintiff need not assert conduct relating to the design or manufacture because fault is inferred from the fact of the accident.

Rule 11, however, also imposes obligations with respect to legal assertions as well as factual allegations. Rule 11 requires that "the claims, defenses, and other legal contentions are warranted by existing law or by a nonfrivolous argument for extending, modifying, or reversing existing law or for establishing new law."[273]

At the pleading stage, the plaintiff should make sure to name every potential defendant against whom a claim can be asserted, consistent with Rule 11. Further investigation and discovery will cause some of these defendants to be dismissed and the case against others to be relatively stronger or weaker depending on the evidence and the power of the trial counsel's story to move the fact finder.

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[273] Fed. R. Civ. P. 11(b)(2). *See* Zuk v. Eastern Pa. Psychiatric Institute of the Medical College of Pennsylvania 103 F.3d 294, 299 (3d Cir. 1996).

Accordingly, a central part of assessing the case is to lay out from a theoretical standpoint everything that anyone might have done wrong that could have contributed to the mishap.

A starting point is to a define characteristics of the drone that could make it abnormally dangerous:

- It has sharp edges on its rotors that are capable of inflicting lacerations and serious injuries to eyes
- It has one or more dense batteries which will not shatter on impact and can inflict bruises and fractures
- It is capable flying almost 40 miles an hour at 3 feet above the ground, a height at which it easily can contact human beings
- The range with which it is controllable by an operator is limited; beyond that range it is not controlled by anyone

The next step is to identify areas of possible fault in many cases.

Perhaps the vendor was negligent.[274] For example:

- The basic configuration (quadcopter versus hexacopter or octocopter) was inappropriate for missions advertised by the vendor; it could have reduced risk by delivering a hexacopter or octocopter configuration which would have been more likely to recover safely from a single engine failure and which would have had the useful weight necessary to carry additional safety devices, such as parachutes or airbags
- Specific features of the propulsion system were designed so as to allow open circuits, short-circuits, and other electrical malfunction to be induced by vibrations and shocks that could be expected in operation
- The rotors, motors, and booms were designed and manufactured so as to allow them to separate in flight
- The navigation and attitude control systems were designed and manufactured to be insufficiently robust
- Only one GPS receiver allows for a higher probability of lost-GPS lock
- Placement and design of the GPS antennas allows too great a probability of lost GPS lock
- Interference between other components of the drone and the GPS system were not properly considered in the design process
- The attitude control system was not designed and manufactured to permit stable flight by a reasonably competent remote pilot in the event of loss of GPS lock
- The sensors for determining height above the ground, magnetic heading, speed, and orientation were inadequate under foreseeable flight conditions
- The drone lacked autonomous safety features
- Its return to home feature was unreliable
- Its land immediately feature was unreliable or too difficult to trigger

[274] The vendor will not have done all the design and manufacture of all the subsystems itself; indeed, is extremely likely that it would have bought some components off-the-shelf from other manufacturers. When multiple designers and manufacturers are involved, the same types of faults should be pleaded against each of them as is consistent with their roles. Investigation and discovery should be tailored accordingly.

- The autonomous features made it too difficult for the operator to regain manual control
- The autonomous systems made it likely that the operator could accidentally trigger a flyaway
- The default settings for the autonomous systems were not the safest ones
- It was too difficult for an average operator to navigate the menu structure to set appropriate values for autonomous systems and flight envelopes

Perhaps the operator was negligent. For example:

- The operator was unfamiliar with how to operate the drone and how to trigger safety features
- The operator did not conduct an adequate preflight inspection, which would have revealed faults and how the drone would perform
- The operator allowed the drone to fly beyond the operator's line of sight
- The operator allowed the drone to fly above 400 feet
- The operator flew the drone from a moving vehicle in a congested area
- The operators input the wrong values for the autonomous systems
- The operator failed to use a visual observer
- The operator positioned the visual observer in an inappropriate place
- The operator and the visual observer failed to communicate effectively with each other
- The operator failed to secure the operating area and to make sure that people not connected to the operation were not in danger
- The operator failed to ensure that meteorological conditions were suitable for the mission

B. Joinder Strategies for Plaintiffs

A plaintiff may, of course, name as a defendant anyone who conceivably might bear some responsibility for the accident.[275] Some defendants may be dropped as the case proceeds by amending the complaint if the plaintiff discovers she cannot prove a case against them. Alternatively, the court also may dismiss the case against a defendant on the pleadings or by summary judgment if he or she persuades the court that the plaintiff has not demonstrated the potential to succeed on the merits against that party.

There are also other non-merits-based reasons a plaintiff might exclude potential defendants. The court in which she filed her suit might lack personal jurisdiction over them, or she may be unable to serve them. The plaintiff may also choose not to include these parties if their joinder may destroy diversity jurisdiction in the situation where she wants to file her suit in federal court.[276]

After the plaintiff has chosen whom to name as a defendant, her available resources will inevitably drive her strategy. Proving negligence or defect in high technology products is extremely challenging. Expert witnesses, simulations, laboratory and flight tests, and extensive data analysis almost certainly will be necessary to establish her claim that the hardware or

[275] Rule 11 and its state counterparts limit this to the parties against which there are reasonable grounds to believe that evidence can be developed that prove their liability.
[276] Conversely, she may want to name a non-diverse defendant, even though she has only a weak case against that party, to defeat federal diversity jurisdiction and make sure she stays in state court.

software in the drone was either defective or malfunctioned. Except in large class actions,[277] the plaintiff is not likely to have the resources to undertake the investigation necessary to uncover evidence to mount a successful suit. But, if she can prove her case against a single defendant, she will effectively shift the burden to that defendant to prove other defendants were partially at fault.

This will only work, however, in certain circumstances. In a proportionate-several liability jurisdiction, any defendant can reduce its liability by showing that another party was partially responsible. However, if such a defendant reduces its own liability substantially by persuading the fact finder that the percentage of responsibility allocable to an absent defendant is substantial, the plaintiff will get no judgment against the absent potential defendant.

Alternatively, in common-law joint and several liability, the original defendant must implead other defendants to seek contribution. Otherwise, the original defendant gains nothing by proving that another party was also *partially* responsible.

In either situation, however, the plaintiff pursues the strategy of naming only one defendant at her peril, as it allows the defendant to cast blame on unnamed parties. For example, suppose the plaintiff sues only the entity whose brand is on the drone, against whom she has a strong *res ipsa loquitur* argument. This would allow the defendant to argue that another entity, such as the supplier of the off-the-shelf control software of the machine, was ultimately the negligent party or otherwise delivered a defective product. A conclusion by the fact finder that this supplier was primarily responsible for causing the accident may then be enough to defeat the plaintiff's *res ipsa loquitur* argument. Or, if the defendant successfully argues that fault for the accident lies solely with an unrelated subsystem supplier, the original defendant may be absolved of all liability.

In this situation, the plaintiff's fate may be tied to whether she can amend her pleading to join this third party. If she cannot, *res judicata* will bar a second lawsuit against this third party. In colloquial terms, the plaintiff gets only one bite at the apple.

C. Availability of Evidence

Much aviation litigation involves guesswork as to what happened because the aircrew is killed in the crash. Not all aircraft giving rise to crash litigation have cockpit voice recorders and flight data recorders. The pilot community complains that this makes it too easy to blame the pilot, who is not available to defend himself. It is also true, however, that when the pilot is available, his testimony may make it easier to pin the blame on him, as in the *Penn Maritime* case. The court's extensive explanation about why operator error was at least as likely as any other cause made it clear that the master's testimony undermined his position.

TWA Flight 800 crashed into the Atlantic Ocean on 17 July 1996. The most extensive and expensive NTSB investigation in history, supported by FBI and CIA resources, concluded that the crash was caused by an explosion of fuel-air vapors in the center fuselage fuel tank, ignited

[277] The possibility of larger recoveries in class actions provides an economic incentive to finance the cost of litigation.

by an unknown source, maybe a short circuit in the fuel quantity measuring system.[278] Other causes for an explosion, including missile impacts, were ruled out. Debate continues 30 years later about the cause of the crash, with conspiracy theories abounding.[279]

The allegations in one of the original complaints, filed in Missouri state court,[280] illustrate the legal theories asserted by the passengers' survivors:

> COUNT I
>
> NEGLIGENCE OF DEFENDANT BOEING
>
> 12. Plaintiffs herein reavert and reallege each prior allegation as if specifically restated herein, paragraph for paragraph and word for word.
>
> 13. Defendant Boeing owed duties to Plaintiffs and Plaintiffs' decedent to use due care and circumspection in its design, manufacture, testing, inspection, sale, marketing, distribution, and injection into the stream of commerce the subject Boeing 747-100 aircraft.
>
> 14. Notwithstanding it duties, Defendant Boeing breached its duties in the following particulars:
>
> a. when it negligently designed, manufactured, tested, inspected and misrepresented as airworthy the subject Boeing 747-100 aircraft with a dangerous and defective fuel storage and delivery system, and negligently sold, distributed, marketed, and injected into the stream of commerce a dangerous and defective aircraft;
>
> b. when it negligently designed, manufactured, tested, inspected and misrepresented as airworthy the subject Boeing 747-100 aircraft with disregard to the propensity and probability of fire and explosion in the fuselage fuel tanks, i.e., the existence of an explosive atmosphere above the fuel, the pressures and temperatures possible in the atmosphere above the fuel, the possible sources of ignition of the atmosphere above the fuel, etc.;
>
> c. when it negligently failed to set a reasonable cycle life and time for the fuselage strict use on the subject Boeing 747-100 aircraft;
>
> d. when it negligently failed to perform a complete 'failure mode and effect analysis' on the fuel storage and delivery system for the subject Boeing 747-100 aircraft;

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[278] *Accident Report: In-flight Breakup Over the Atlantic Ocean, Transworld Airlines Flight 800, NTSB/AAR-000/03*, NAT'L TRANSP. SAFETY BD. xvi (July 17, 1996), http://www.ntsb.gov/investigations/AccidentReports/Reports/AAR0003.pdf.

[279] *See* Lahr v. Nat'l Transp. Safety Bd., 569 F.3d 964, 971 (9th Cir. 2009) (affirming in part and reversing in part FOIA decision on more than 150 requests by conspiracy theorist).

[280] First Amended Complaint Clara Ersoz at 5-16, *In re* Air Crash on July 17, 1996, No. 96-CV-7986, 1998 WL 292333 (S.D.N.Y. June 2, 1998), ECF No. 112, 1998 WL 34778577 (appending Complaint, Ersoz v. Trans World Airlines, Inc., No. 22972-97, (Mo. Cir. Ct. 22d Cir. Feb. 10, 1997)).

e. when it negligently failed to provide adequate, safe methods for discharging static electricity which could foreseeably build up near the fuselage fuel storage and delivery systems on the subject Boeing 747-100 aircraft;

f. when it negligently failed to adequately isolate the heat sources from the fuselage fuel storage system on the subject Boeing 747-100 aircraft;

g. when it negligently failed to fully comply with the design and manufacturing requirements of 14 C.F.R. sec. 21.3, 25.981 and 25.1309 with regard to the fuel storage and delivery system on the subject Boeing 747-100 aircraft;

h. when it negligently failed to instruct and/or warn users and consumers of the dangers inherent in the subject Boeing 747-100 aircraft, including its dangerous and defective fuel delivery and storage system; and

i. when it was generally negligent in its design, manufacture, engineering, testing, inspection, representation, instruction, and warning as to use, operation, and maintenance of the fuel system on the subject Boeing 747-100 aircraft.

15. The July 17, 1996, failure of the subject Boeing 747-100 aircraft being operated by TWA as TWA flight 800, the resulting explosion, crash, injuries, and death, and Boeing's conduct in that regard as referenced above was grossly negligent, outrageous, and/or showed a reckless indifference to the rights of Plaintiffs' decedent and others, or showed complete indifference or conscious disregard for the safety of Plaintiffs' decedent and others, and Plaintiffs and the survivors of the estate of Clara Jean Ersoz are entitled to punitive and exemplary damages.

16. As a proximate result of Defendant Boeing's negligence, gross negligence, and outrageous and reckless conduct, Plaintiffs and the survivors of the estate of Clara Jean Ersoz suffered substantial injuries, and Plaintiffs' decedent suffered substantial injuries and death as more fully explained below.

COUNT II

PRODUCTS LIABILITY OF DEFENDANT BOEING

17. Plaintiffs herein reavert and reallege each prior allegation as if specifically restated herein, paragraph for paragraph and word for word.

18. Defendant Boeing, in the business of designing, manufacturing, inspecting, testing, selling, marketing, and distributing Boeing 747-100 aircraft, is liable to Plaintiffs for products liability in that it designed, manufactured, inspected, tested, sold, marketed, distributed, and injected into the stream of commerce the subject Boeing 747-100 aircraft when it was in an unsafe, dangerous, and defective condition.

19. Defendant Boeing designed, manufactured, sold, marketed, distributed, and injected into the stream of commerce the subject Boeing 747-100 aircraft containing substandard and defective fuel system design, guarding and warning. Defendant Boeing disregarded: (i) the possibilities and probabilities of fire and explosion in the fuselage fuel tanks (i.e., the existence of an explosive atmosphere above the fuel, the pressures and temperatures possible in the atmosphere above the

fuel, the possible sources of ignition of the atmosphere above the fuel, etc.); (ii) a reasonable cycle life for the fuselage strict use; (iii) discharge of static electricity which could build up near the fuselage fuel storage system; and (iv) heat source isolation from the fuselage fuel storage system.

20. Defendant Boeing also failed to perform a complete 'failure mode and effect analysis' on the fuel storage and delivery system for the subject Boeing 747-100 aircraft, and failed to fully comply with the design and manufacture requirements of 14 C.F.R. sec. 21.3, 25.981 and 25.1309 with regard to said system.

21. Defendant Boeing had both actual and constructive knowledge of the defects at the time of the sale of the subject Boeing 747-100 aircraft and, thus, its conduct was outrageous and/or showed reckless indifference to the rights of Plaintiffs' decedent and showed complete indifference to and conscious disregard for the safety of Plaintiffs' decedent and others, and Plaintiffs and the survivors of the estate of Clara Jean Ersoz are entitled to punitive and exemplary damages.

22. As a proximate result of the defects in the subject Boeing 747-100 aircraft and Defendant Boeing's outrageous and reckless conduct in that regard, Plaintiffs and the survivors of the estate of Clara Jean Ersoz suffered substantial injuries, and Plaintiffs' decedent suffered substantial injuries and death as more fully explained below." The complaint also alleged claims against the operator, TWA.[281]

The complaint explicitly pleads facts to support:

- Common-law negligence duty,[282]
- Breach of the duty with respect to nine specific aspects of the design and testing of the aircraft and its subsystems,[283]
- Causation.[284]

It also pleads products liability by pleading:

- Defective aircraft,[285]
- Defective systems, specifically identifying four such systems,[286]
- Failure to perform adequate testing,[287]
- Causation.[288]

In *In re Air Crash Off Long Island, New York, on July 17, 1996*, the United States Court of Appeals for the Second Circuit affirmed the district court's refusal to dismiss civil damages actions growing out of the crash of TWA Flight 800.[289] The appeal covered 145 cases

281 *Id.*
282 *Id.* at 8 ¶ 13.
283 *Id.* at 7-9 ¶ 14.
284 *Id.* at 9-10 ¶ 16.
285 *Id.* at 10 ¶ 18.
286 *Id.* ¶ 19.
287 *Id.* ¶ 20
288 *Id.* at 11 ¶ 22.
289 *In re* Air Crash on July 17, 1996, 209 F.3d 200, 215 (2d Cir. 2000).

consolidated for pretrial proceedings by the Judicial Panel on Multidistrict Litigation.[290] The appeal involved only the question of whether the Death on the High Seas Act barred recovery for non-pecuniary damages. The Second Circuit held that it did not,[291] opening the way for settlement of the claims. Therefore, there are no reported judicial opinions on the merits of the negligence and products liability claims.

Parallel FOIA litigation over the investigation, however, illustrates the types of information likely to be generated and fought over in products liability litigation involving complex systems. To reach its conclusions, the NTSB did extensive simulations and animations projecting the effect of various system failures and external forces.[292]

Among many other things the FOIA plaintiff requested the software and data used in the CIA and NTSB simulations.[293] The court of appeals approved withholding three memoranda and draft reports under FOIA's deliberative process exemption, which resembles the work-product privilege in civil litigation.[294] It also approved withholding simulation software and data, because it was privileged national security information in one case, and because the requested data was not used in the investigation in the other case.[295]

Two facts make the evidence available in drone liability litigation different from usual aviation litigation. First, the remote pilot is likely to be alive and available to testify.[296] Second, most drones keep elaborate data on flight telemetry, enabling a more robust forensic investigation as to what went wrong.[297]

In drone accidents that result in injuries, the police likely would do a fairly thorough accident investigation. An early and urgent priority of this investigation would be to ensure that the drone, and particularly whatever software and data it might contain, gets preserved. Then, at an appropriate point after suit is filed, the plaintiff and any other parties can serve a request for production on the drone vendor to get a copy of the software and any data it saved. Whether or not the operator has the data, and whether or not it is preserved on storage in the drone, it likely was uploaded to the vendor. As long as the requesting party shares the cost, E-discovery caselaw makes it clear that a party responding to a request for production has an obligation to render the requested information into an understandable form.[298]

[290] *Id.* at 200 (describing procedural history).
[291] *Id.* at 215.
[292] *See* Lahr v. Nat'l Trans. Safety Bd. 569 F.3d 964, 969-71 (reviewing investigation).
[293] *Id.* at 972.
[294] *Id.* at 983-84.
[295] *Id.* at 985-86.
[296] Most serious manned aircraft accidents are fatal to the pilot.
[297] Many general aviation aircraft do not have cockpit voice recorders or flight data recorders.
[298] *In re* Toyota Motor Corp. Unintended Accel. Mktg., Sales Practices, and Prods. Liab. Litig., 978 F. Supp. 2d 1053 (C.D. Cal. 2013) (suggesting that a vendor's failure to provide for recording of data relevant to a malfunction may relax the proof standards to which a plaintiff is held.); *id.* at 1080 (noting that Toyota's engine control module software lacks an event-logging facility and therefore expert need not identify specific software fault).

D. Economics of Litigating

Section V.A, *infra*, argues that drone crashes are unlikely to result in injury or damage. That means that the amount at stake for almost any drone accident is likely going to be too small to persuade a lawyer to get involved on a contingency basis and almost certainly not large enough to cover the fact-finding and marshaling of proof necessary to mount a strong case. But, this is not uncommon in consumer products liability litigation.[299]

Most consumer products liability plaintiffs get past this by filing a class-action lawsuit; however, this type of lawsuit may not be feasible in most drone accident cases. The requirements for class action status under Rule 23 of the Federal Rules of Civil Procedure, and under virtually every state procedural system, are (1) numerosity, (2) commonality, (3) typicality, and (4) adequacy of representation. Each one of these is problematic in the drone accident context.

First, the numerosity requirement will likely be undermined because an incident involving a single drone is not likely to injure more than one or two people, even a popular model is unlikely to be involved in many accidents involving injuries. Second, each accident is likely to have unusual circumstances in which defects in the drone's physical systems will combine with human behavior in unique ways. The circumstances leading up to each accident, the physical environment, the wind, the distance between drone and operator, and what the operator does will be different in each case. That will weaken both the commonality and typicality arguments for forming a class.

Finally, the quality of the representation may be significantly lower for drone crashes than is typical for a 787 crash. The proof difficulty may be greater in a drone case and the incentives for the best mass tort lawyers to participate energetically and with all their resources is reduced.

As in any class action, identifying a consistent course of conduct that breaches the duty of care is helpful, not only to establish liability, but also to get a class certified. Design defects in software are attractive possibilities in this regard, as are inadequate provision of product support. All the possibilities identified in section VI.A may produce a pattern of malfunctions that help with the commonality and typicality elements

VII. Law's Role

The approach proposed in *Making civilian drones safe: performance standards, self-certification, and post-sale data collection*[300] represents the best technology policy for drones. That article proposes that traditional regulatory obstacles for drone vendors be abandoned in order to allow them to bring their products and new technologies to market more quickly. Part of the bargain proposed, however, is that these vendors must be accountable for shortcomings

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[299] Small drones are consumer products, based on their mass production and relatively low value, even though they are used as capital products. Understanding the litigation possibilities, benefits from thinking of them as consumer products.

[300] Henry H. Perritt, Jr. & Albert J. Plawinski, *Making civilian drones safe: performance standards, self-certification, and post-sale data collection*, 14 NW. J. TECH. & INTELL. PROP. 1 (2016) [hereinafter *Making Civilian Drones Safe*].

discovered in the marketplace. Part of that accountability is paying the cost of injuries their products cause, especially when the injuries results from poor product support.

A. Data Collection and Analysis

In *Making Civilian Drones Safe*, Albert Plawinski and this article's author argue the low risk of a drone crash causing serious damage or injury justifies a lighter pre-sale regulatory touch, but greater attention to post-sale data collection and remedial action, the remedial action being design changes. The article's proposal also would change accident litigation compared with, for example, the typical light airplane or helicopter crash, because it would make far more post-accident data available.[301]

A drone may be defective because its designer fails to conduct sufficient testing, [302] such as verifying flight characteristics verification and the functionality of its automated emergency protocol. But, adequate testing requires data. One regulatory proposition which would ensure that designers conduct sufficient testing requires designers to collect data and evaluate it according to certain criteria and algorithms.[303] This approach, however, steers the drone certification process in the direction of traditional certification, which is overly burdensome.

A presale flight-test program, resembling that for conventional airworthiness certification, is not necessary. Thousands of drones are already flying with safety subsystems that collect this sort of data.

Most of the microdrones on the market collect data on flight profiles and parameter values so that they can be fed down to the DROP through a telemetry link (usually a channel on the control link). Many also provide the option of uploading the data to a website so that one can review flight profiles graphically or otherwise. As more of these vehicles are sold and flown, an enormous stockpile of data will be generated.

The advantage of this approach is that it does not impose delays and regulatory costs before vendors bring new technology to market. It accomplishes this by aligning regulatory requirements with market forces. Drone vendors already advertise product safety features and this would enable them to bolster their marketing efforts using data-based indicia of safety.

The suggested approach presents two challenges: first, ensuring that the data is captured and second, that it is transmitted to the ground. The first challenge is easier to meet than the second,

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[301] *See* NTSB letter to Michael P. Huerta, Administrator, Federal Aviation Administration, A-15-1 through -8 (Jan 22, 2015), https://www.ntsb.gov/safety/safety-recs/recletters/A-15-001-008.pdf (recommending flight data recorders and cockpit voice recorders).

[302] *See* First Amended Complaint Clara Ersoz at 7-9 ¶14, 10 ¶ 20, *In re* Air Crash on July 17, 1996, No. 96-CV-7986, 1998 WL 292333 (S.D.N.Y. June 2, 1998), ECF No. 112, 1998 WL 34778577 (alleging failure to "perform a complete 'failure mode and effect analysis").

[303] *See*, Jeffrey C. Elias et al., *Large School Bus Safety Restraint Evaluation, No. 313*, NAT'L HIGHWAY TRAFFIC SAFETY ADMIN., http://www.nhtsa.gov/DOT/NHTSA/NRD/Multimedia/PDFs/ESV/18/Files/18ESV-000313.pdf (illustrating test data evaluation methodology); *Chapter 7, Use of Nondestructive Testing in the Evaluation of Airport Pavements, FAA AC No. 150/5370-11B*, FED. AVIATION ADMIN. 37-69 (Sep. 30, 2011), http://www.faa.gov/documentLibrary/media/Advisory_Circular/150_5370_11b.pdf (illustrating evaluation of test data).

as most drones in production today already have the capability to collect the relevant data.[304] But uploading data from the drone requires human intervention. One possibility is to upload data every time drone firmware is updated. Because both DJI and 3DR require firmware updates before the drone will fly, users must establish an Internet connection to the drone before using it. Uploading log data easily can be made an invisible prerequisite for downloading the software update.

Vendors would capture and record data regarding the drone's position and the state of its GPS system, as well as the flight path data from its IMU and magnetometer and barometric altimeter values. The frequency of data capture might be once per second—the same as that transmitted by ADS-B out.[305] Frequency of capture need to be high to make sure that system state is recorded before a mishap occurs.

Tort law can reinforce the incentives to collect post-sale data, simply by shifting the burden of proof to a defendant who does not collect data, as in the Toyota case discussed in section IV.B.5.b).[306]

B. Recalls

When post-sale data shows a defect in drone performance, the vendor can cut off liability by recalling the drones.[307] This is exactly what GoPro did in late 2016, after experience in the market showed that its first drone had a defect in its power management system. [308] The expense and adverse reputational effect of recall provides an incentive for vendors to deliver defect-free products.

The Restatement (Third) of Torts: Products Liability does not impose a general duty to recall defective products.[309] It does, however, impose such a duty when a recall has been mandated by a regulatory agency,[310] or when the vendor voluntarily undertakes a recall.[311]

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[304] Most microdrones on the market capable of carrying cameras and performing commercial work capture data on position and state of the GPS system. Typically, they allow the DROP to specify that some or all of these data be downlinked to the DROPCON as telemetry. Many also record the data by writing it to an onboard memory chip such as an SD card in the form of log files.

[305] *See The Ins and Outs of ADS-B*, FED. AVIATION ADMIN. (last visited March 10, 2017 4:14 PM), https://www.faa.gov/nextgen/equipadsb/ins_and_outs/ (explaining ADS-B).

[306] *In re* Toyota Motor Corp. Unintended Acceleration Marketing, Sales Practices, and Products Liability Litigation, 978 F. Supp. 2d 1053, 1102 (C.D. Cal. 2013) ("[T]he Camry software does nothing to track its own failures.").

[307] *Making Civilian Drones Safe*, *supra* note 300, at 5 (evaluating alternative recall processes).

[308] *See* Christina Cardoza, *GoPro recalls the Karma drone*, INTERDRONE (Nov. 9, 2016, 10:43 AM), http://www.interdrone.com/news/gopro-recalls-the-karma-drone?utm_campaign=InterDrone+News&utm_source=hs_email&utm_medium=email&utm_content=37406994&_hsenc=p2ANqtz-8_No2oX9ePeKTzsLusqCd_ot1G5-7vcvHLzbAq5jTGbPZejIgY4AQY99IbG-62hZQUFXDUBR_NqKeNgYEYUb_RC4Z2_A&_hsmi=37406994 (reporting that GoPro recalled all its Karma drones because of a defect that causes the drones to lose power in flight).

[309] RESTATEMENT (THIRD) OF TORTS: PRODUCTS LIABILITY § 11, § 11 cmt. a (1998).

[310] *Id.* § 11(a)(1), § 11 cmt. b.

[311] *Id.* § 11(a)(2), § 11 cmt. c.

C. Waiting for Reality

Regulation in a modern state takes two basic forms: *ex ante* and *ex post*. *Ex ante* regulation is crafted by legislatures and administrative agencies exercising delegated legislative power. It prohibits the sale or use of a product unless it meets certain standards or restricts how they are used. Design criteria for aircraft, speed limits for automobiles, and rules of the road for water vessels are examples. *Ex post* regulation, on the other hand, takes the form of lawsuits filed in response to accidents that have already occurred, shifting the cost of harms suffered back to the manufacturer.

Ex ante regulation has the benefit of producing greater certainty, but it inhibits choice in the marketplace. *Ex post* regulation permits actors to do almost anything they want but imposes consequences on actors that make the wrong choices. *Ex post* regulation results in considerable uncertainty about what might produce liability and what might not.

Law is often criticized for being behind technology. That is not a weakness; it is a strength. I have often written that the law *should* lag technology. For, if law were to lead technology, innovation would be stifled. What is legal ultimately depends on guesses by lawmakers about the most promising directions of technological development. Those guesses are rarely correct. When law follows technology, it is able to fill in gaps and correct the directions of other societal forces that shape behavior: economic stress, embedded societal pressure, and private lawsuits.

Here is how law should work: a new technology is developed. A few entrepreneurs build it into their business plans. In some cases it will be successful and spread; in most cases it will not. New technologies that spread successfully will impact other economic players. They will threaten to erode market shares; they will confront non-adopters with the necessity of utilizing new technology to remain economically viable.

New technology will probably cause accidents, injuring and killing some of its users and injuring the property and persons of bystanders. Widespread use of the technology will also have adverse effects on other intangible interests, such as privacy and intellectual property. Those suffering injury will seek compensation from those using the technology and try to get them to stop using it.

Most of these disputes will be resolved privately without recourse to governmental institutions of any kind, but some of them will find their way to court. Lawyers will have little difficulty framing the disputes in terms of well-established rights, duties, privileges, powers, and liabilities. The courts will hear the cases, with lawyers on opposing sides presenting creative arguments as to how the law should be understood in light of new technology. Judicial decisions will result, carefully explaining where the new technology fits most appropriately within long-accepted legal principles.

Law professors, journalists, and interest groups will write about the judicial opinions and gradually, conflicting views will crystallize as to whether the judge-interpreted law is correct for channeling the technology's benefits and costs. Eventually, if the matter has sufficient political traction, someone will propose a bill in a city council, state legislature, or the United States Congress to change the standards being applied by the courts. Alternately, an administrative agency will issue a notice of proposed rulemaking and a debate over codification of legal principles will begin.

This is a protracted, complex, and unpredictable process, and that may make it seem undesirable. But, it is beneficial because the adversarial, deliberative interplay that results from a process like this produces good law. It is the only way to test legal ideas thoroughly and assess their fit with the actual costs and benefits of technology as it is actually deployed in a market economy.

Accordingly, understanding tort liability for drone mishaps is an essential aspect of understanding and crafting drone regulation.[312]

[312] *Making Civilian Drones Safe*, *supra* note 300, at 35 (suggesting tort claims for mis-self-certification).