On ‘Living in a Box’

Distributed Control and Automation Surprises

Sam Hind

Abstract
This article interrogates an aircraft control system referred to as ‘fly-by-wire’. First developed in the 1960s, fly-by-wire replaced mechanical and hydraulic aircraft control systems with an electronic, computer-mediated system capable of relaying, responding to, and sometimes restricting, human inputs from pilots. In so doing, fly-by-wire enabled an entirely new world of flight in which human decisions were subject to machinic, and electronic, approval. The article examines the effects of fly-by-wire on the socio-technical control of aircraft, with repercussions for how one considers contemporary questions regarding the interweaving of automation, control, knowledge and safety. It proceeds in two parts. Firstly, it argues that fly-by-wire is a form of ‘distributed control’. Dependent upon situated automation, the ability to control, steer and manoeuvre the aircraft is variously distributed beyond the cockpit and human pilots, to integrated components, sensors, physical surfaces, and systems throughout the aircraft itself. In so doing, new and novel operational capacities are reached depending on the situation; shifting and re-calibrating the relationship between pilots and aircraft. Secondly, and more specifically, I suggest that distributed forms of control in the shape of aircraft fly-by-wire systems yield so-called ‘automation surprises’. The effect of distributing decision-making to a wider assemblage of components, sensors, surfaces, and systems is that operational asymmetries occur in the otherwise smooth collaboration between pilot and machine. I discuss recent Boeing 737 accidents in order to evidence this argument, contending that recent additions to fly-by-wire have led to novel re-distributive control effects. As the development of prototype autonomous vehicles abounds, historical lessons drawn from aircraft control, decision-making and safety should be of critical importance.

Überblick
Dieser Artikel diskutiert ein Flugzeugsteuerungssystem, das als ‘Fly-by-Wire’ bezeichnet wird. ‘Fly-by-Wire’, das ursprünglich in den 1960er Jahren entwickelt wurde, ersetzte mechanische und hydraulische Flugzeugsteuerungssysteme durch ein elektronisches, computervermitteltes System. Dieses ist in der Lage, Eingaben von Piloten zu übermitteln, auf diese zu reagieren und sie teilweise auch einzuschränken. Damit ermöglichte ‘Fly-by-Wire’ eine völlig neue Art des Fliegens, in der menschliche Entscheidungen maschinelle und

elektronische Genehmigungen erforderten. Der Artikel untersucht die Auswirkungen von ‘Fly-by-Wire’-Systemen auf die sozio-technische Kontrolle von Flugzeugen, insbesondere im Hinblick auf deren Relevanz für gegenwärtige Fragen zur Verflechtung von Automatisierung, Steuerung, Wissen und Sicherheit. Der Artikel besteht aus zwei Teilen. Im ersten Teil wird argumentiert, dass ‘Fly-by-Wire’ eine Form von „verteilter Steuerung“ (distributed control) ist. Als Folge situierter Automatisierung ist die Fähigkeit, das Flugzeug zu kontrollieren, zu steuern und zu manövrieren, über das Cockpit und die menschlichen Piloten hinaus in unterschiedlicher Weise auf integrierte Komponenten, Sensoren, physikalische Oberflächen und Systeme innerhalb des Flugzeugs selbst verteilt. Neue und neuartige operative Kapazitäten, die auf diese Weise situationsabhängig erschlossen werden, verschieben und rekalibrieren die Beziehung zwischen Piloten und Flugzeugen. Im zweiten Teil arbeitet der Artikel sogenannte Automatisierungsüberraschungen (automation surprises) heraus, die sich aus einer solchen verteilten Steuerung im Rahmen von ‘Fly-by-Wire’-Systemen für Flugzeuge ergeben. Die Verteilung der Entscheidungsfindung auf ein breite Ansammlung von Komponenten, Sensoren, Oberflächen und Systeme hat zur Folge, dass sich in der ansonsten reibungslosen Kollaboration zwischen Pilot und Maschine operative Asymmetrien herausbilden. Die jüngsten Boeing-737-Unfälle werden als Beispiel dafür diskutiert, wie die jüngsten Ausbaustufen von ‘Fly-by-Wire’ zu neuartigen Effekten von „Re-Distributive Control“ geführt haben. Im Hinblick auf den aktuellen Boom bei der Entwicklung prototypischer autonomer Fahrzeuge sollten historische Erkenntnisse aus der Luftfahrt in Bezug auf Steuerung, Entscheidungsfindung und Sicherheit von entscheidender Bedeutung für die gegenwärtige Debatte sein.

Introduction

> Flight is and has always been a mediated activity; even before the airplane cockpit was identified as a distinct spatial enclosure, the central problem of flight was one of establishing the mediations that would allow for the production of control. In this mediation the perception and agency of the pilot are translated through the interface of flight controls and instrumentation to establish a relation with the physical interface of laminar airflow over an airfoil in order to achieve controlled flight.[1]

> The A320 lives in a box—it can’t go slow; it can’t go too fast.[2]

This article examines a common aircraft control system called ‘fly-by-wire’, and its effect on human control, skill, attention and expertise. It does so at a time when automation has returned to the fore. As questions are being asked of control and decision-making capacities afforded to prototypical autonomous

---

[1] Branden Hookway, Interface (Cambridge 2014), 36–37.

[2] Airbus A320 test pilot quoted in Graham Warwick, “A320. Fly-by-Wire Airliner”, Flight (1986), https://www.flightglobal.com/pdfarchive/view/1986/1986%20-%202148.html, accessed May 31, 2019.

vehicles,[3] this article returns to debates around fly-by-wire at the time of its introduction over 30 years ago; for possible insights into, if not answers to, questions of automation and decision-making. It does so for two reasons.

Firstly, historical connections between automation efforts in automotive and aviation worlds are evident, if rare. They include attempts to replicate fly-by-wire systems in vehicles, such as General Motor’s 2002 concept car, the ‘Hy-wire’;[4] and more superficial branding exercises such as Tesla’s Autopilot feature, purporting to offer ‘full self-driving capability’.[5] Aviation control systems are clearly an inspiration for automotive manufacturers today, but the significance of these original systems themselves has been under-explored.

Secondly, the aviation industry arguably operates to a higher safety standard than the automotive world. Whilst accident recording (‘black boxes’), safety notifications (airworthiness directives), accident bureaus (US Federal Aviation Administration [FAA] etc.), and testing procedures (mechanical load and ‘stress’ evaluations) are likewise replicated by vehicle manufacturers and transportation administrations, those used in aviation generally demand greater rigor; operating under more stringent safety expectations. This has resulted in a largely comparable risk of exposure between air travel and automobile travel.[6] Recent recommendations that Uber implement a Safety Management System (SMS) like that commonly found in aviation, when testing their autonomous vehicle systems, reiterates this connection.[7] As such, these examples serve as a useful comparison for thinking about how the automotive industry might implement novel safety protocols in an increasingly automated world.

The article returns to the design of fly-by-wire systems in order to translate debates being had within engineering into wider social disciplines. In geography and media studies, for instance, there is a considerable body of work

---

[3] David Bissell, “Automation Interrupted. How Autonomous Vehicle Accidents Transform the Material Politics of Automation”, Political Geography 65 (2018), 57–66; Jack Stilgoe, “Machine Learning, Social Learning and the Governance of Self-Driving Cars”, Social Studies of Science 48, No. 1 (2018), 25–56.

[4] Adrian Chernoff, “The General Motors Hy-Wire. Reinventing the Automobile”, 2018, https://www.adrianchernoff.com/project/hywire, accessed August 20, 2019.

[5] “Future of Driving”, Tesla (2019), https://www.tesla.com/en_GB/autopilot, accessed August 20, 2019; Jack Stilgoe, “Seeing Like Tesla. How Can We Anticipate Self-Driving Worlds?”, Glocalism: Journal of Culture, Politics and Innovation 3 (2017), 1–20.

[6] Charles Perrow, Normal Accidents. Living with High-Risk Technologies (New York 1984), 129.

[7] Mark A. Dombroff and David K. Tochen, “Independent Review of the Safety Culture of Uber Technologies, Inc.’s Advanced Technologies Group: Final Report”, LeClairRyan PLLC (2018), https://dms.ntsb.gov/public/62500-62999/62978/629732.pdf, accessed November 27, 2019; National Transportation Safety Board, “Operations Factors Group Chairman’s Factual Report”, NTSB (2019), https://dms.ntsb.gov/public/62500-62999/62978/629727.pdf, accessed November 27, 2019.

on ‘aeromobilities’,[8] military[9] and recreational drones,[10] and vertical forms of visioning, sensing and capturing more generally.[11] Much of this work has centered on the generative effects of aerial bodies and machines, as well as the lines of sight, action and execution enabled by them. In STS and organizational sociology, there is a significant body of work dedicated to examining interconnected systems and their effect on flight itself, including work by Perrow on accidents,[12] Law on design[13], and Budd on air traffic control. [14] Work by Dodge and Kitchin on cockpit code/spaces,[15] Kitchin and Dodge on aircraft code/spaces,[16] and Hookway on cockpit instrumentation,[17] have also focused attention on the technological management of space. It is between these contributions that this article is intended to sit.

The article is divided into two parts. Firstly, I argue that fly-by-wire aircraft demonstrate a form of ‘distributed control’, dependent upon situated automation, in which control of the aircraft is variously ‘distributed’ to control systems and components throughout an aircraft, beyond the cockpit and pilot.[18] Distinct from distributed cognition, and more than mere supervisory

---

[8] Peter Adey, “Getting Into the Flow. Airports, Aeromobilities and Air-Mindedness”, in Aeromobilities, ed. S. Cwerner, S. Kesselring and J. Urry, (London 2008), 194–209; Peter Adey, Aerial Life. Spaces, Mobilities, Affects (Oxford 2010).

[9] Derek Gregory, “From a View to a Kill. Drones and Late Modern Warfare”, Theory, Culture & Society 28 (2011), 188–215; Derek Gregory, “Drone Geographies”, Radical Philosophy 183 (2014), 1–19; Lisa Parks and Caren Kaplan (eds.), Life in the Age of Drone Warfare (Durham 2017); Jeremy Crampton, “Assemblage of the Vertical. Commercial Drones and Algorithmic Life”, Geographica Helvetica 71 (2016), 137–146; Ian Shaw, Predator Empire. Drone Warfare and Full Spectrum Dominance (Minneapolis 2016); Grégoire Chamayou, Drone Theory (London 2015).

[10] Julia Hildebrand, “Situating Hobby Drone Practices”, Digital Culture & Society 3, No. 2 (2018), 207–218; Hendrik Bender, “The New Aerial Age. Die wechselseitige Verfertigung gemeinsamer Raum- und Medienpraktiken am Beispiel von Drohnen-Communities”, in Kollaboration. Beiträge zu Medientheorie und Kulturgeschichte der Zusammenarbeit, ed. N. Ghanbari, I. Otto, S. Schramm and T. Thielmann (Paderborn 2018), 121–145.

[11] Denis Cosgrove, “Contested Global Visions. One-World, Whole-Earth, and the Apollo Space Photographers”, Annals of the Association of American Geographers 84, No. 2 (1994), 270–294; Chris Perkins and Martin Dodge, “Satellite Imagery and the Spectacle of Secret Spaces”, Geoforum 40, No. 4 (2009), 546–560; Derek McCormack, Atmospheric Things. On the Allure of Elemental Envelopment (Durham 2018).

[12] Perrow, Normal Accidents, 123–169.

[13] John Law, Aircraft Stories. Decentering the Object in Technoscience (Durham 2002).

[14] Lucy Budd, “Air Craft. Producing UK Airspace”, in Aeromobilities, ed. S. Cwerner, S. Kesselring and J. Urry (London 2008), 115–134.

[15] Martin Dodge and Rob Kitchin, ”Flying Through Code/Space. The Real Virtuality of Air Travel”, Environment and Planning A: Economy and Space 36, No. 2 (2004), 195–211.

[16] Rob Kitchin and Martin Dodge, “Airport Code/Spaces”, in Aeromobilities, ed. S. Cwerner, S. Kesselring and J. Urry (London 2008), 96–114.

[17] Hookway, Interface.

[18] I limit this discussion on distributed control to the aircraft itself. Whilst air traffic control operators play a significant role in regulating air traffic, including airport arrivals and departures, they do not have the capacity to regulate aircraft control itself. That is, the control of

control, I argue that emphasizing how control is distributed focuses attention of the situated nature of ‘taking’ and ‘assuming’ control. It is, through various modes, default or otherwise, that control of an aircraft is afforded. Such a technical history explicates, not only how aircraft control has been variously re-distributed over time, through the establishment of new modes and technologies of control, but also how contemporary aircraft control is executed through a temporal looping of capacities. Control, in other words, always hangs in the balance. I will detail the foundational technical features of fly-by-wire, before discussing the operational benefits of fly-by-wire to control, steering and maneuverability.

Secondly, I argue that fly-by-wire systems—as examples of distributed control—necessarily yield ‘automation surprises’,[19] in which pilots fail to comprehend the aircraft’s actions and decisions. I suggest that the distribution of control within the aircraft, and thus the generation of surprises, is dependent upon external sensors. Here, the act of controlling an aircraft is a situated practice, dependent upon the sensing, and interpretation, of atmospheric states. Yet, a necessary reliance upon external sensors, namely ‘pitot tubes’, creates the possibility of discordance between the sensed and ‘actual’ state of the aircraft. To evidence this, I discuss two recent, connected, air disasters involving Boeing 737 aircraft. In the final section I suggest that the integration of fly-by-wire systems into commercial aircraft has led to new forms of machine supervision enabled by sensors; posing questions as to who, or what, is in control. These shifts are now being replicated in the operation of automobiles, constituting new forms of supervision and distributed control.[20]

Distributed Control: Fly-by-wire

Fly-by-wire is an electronic system that enables the automation of flight actions, translating human control gestures into component movements via a computer network. These differ from mechanical systems, in which a steering device is directly connected via metal cables or rods, to movable, physical surfaces on the wings or tail of an aircraft. Many smaller aircraft, including

---

an aircraft’s immediate steering, stabilization and manoeuvrability as opposed to control of multiple aircraft in relation to each other and the sky. Perrow refers to these as the ‘airways system’ and the ‘aircraft system’, respectively.

[19] Nadine Sarter and David Woods, “Team Play with a Powerful and Independent Agent. Operational Experiences and Automation Surprises on the Airbus A-320”, Human Factors 39, No. 4 (1997), 553–569; Nadine Sarter, David Woods and Charles Billings, “Automation Surprises”, in Handbook of Human Factors (2nd ed.), ed. G. Salvendy (Hoboken 1997), 1926–1943; David Woods and Nadine Sarter, “Learning from Automation Surprises and ‘Going Sour’ Accidents”, in Cognitive Engineering in the Aviation Domain, ed. N. Sarter and R. Amalberti (Boca Raton 2000), 327–353.

[20] Sam Hind, “Digital Navigation and the Driving-Machine. Route-Calculation, Terrain-Optimization, and Object-Recognition”, Mobilities 14, No. 4 (2019), 3.

microlights, still utilize traditional mechanical control systems, as opposed to fly-by-wire.

The Airbus A320 was the first commercial aircraft to launch with a fly-by-wire system, in 1988. Prototype systems were first pitched to the US Air Force in 1968 at a special conference held at the Flight Dynamics Laboratory at Wright-Patterson Air Force Base in Ohio, USA, by Sperry Flight Systems and the Douglas Aircraft Company.[21] Nowadays, all commercial aircraft are controlled using fly-by-wire; integrated with an array of other 'autopilot'-style systems for navigation and communication. Since April 1988, when Air France and British Airways began operating A320s on various routes,[22] the total number of passengers travelling on all commercial carriers has risen nearly 400%, from 953,896,012 million to 3.979 billion in 2017.[23] Fly-by-wire is an integral factor in this rise, increasing global aircraft capacity exponentially. This is principally for two reasons.

Firstly, such systems incorporate 'high-integrity automatic stabilisation of…aircraft to compensate for the loss of natural stability and thus enables a lighter aircraft with a better overall performance to be produced compared with a conventional design.'[24] Capable of making hundreds of 'micro-decisions'[25] each minute to constantly correct and adjust a plane's movements, fly-by-wire systems naturally extend and exceed the abilities of any human pilot. Essentially, fly-by-wire systems enabled the invention of naturally unstable planes, controllable only through such systems. For the commercial aviation industry, this has enabled the production and operation of larger, more profitable planes, as pilots delegate responsibility for stabilizing the aircraft.

Secondly, fly-by-wire systems have eased the flying of aircraft within specific 'performance envelopes', limiting the range of permissible actions, so they can be flown at a safe speed and altitude without the threat of stalling. Such systems principally aid the manoeuvrability of modern aircraft, improving their 'natural flying qualities'.[26] Or as Collinson explains, '[o]ne of the unique benefits of a [fly-by-wire] system is the ability to exploit aircraft configurations

---

[21] James E. Tomayko, "Blind Faith. The United States Air Force and the Development of Fly-by-Wire Technology", in Technology and the Air Force. A Retrospective Assessment, ed. J. Neufeld, G. Watson Jr. and D. Chenoweth (Washington DC, 1997), 162–185.

[22] David Learmount, "A320 In Service. An Ordinary Aeroplane", Flight International (1988), https://www.flightglobal.com/pdfarchive/view/1988/1988%20-%202445.html, accessed June 28, 2019.

[23] International Civil Aviation Organization (ICAO), "Air Transport, Passengers Carried" (2019), www://data.worldbank.org/indicator/is.air.psgr?end=2017&start=2017&view=map, accessed May 31, 2019.

[24] R. P. G. Collinson, "Fly-by-Wire Flight Control", Computing and Control Engineering Journal 10, No. 4 (1999), 141.

[25] Florian Sprenger, Politics of Micro-decisions. Edward Snowden, Net Neutrality, and the Architecture of the Internet (Lüneburg 2015).

[26] Charles Favre, "Fly-by-Wire for Commercial Aircraft. The Airbus Experience", International Journal of Control 59, No. 1 (1994), 140.

which provide increased aerodynamic efficiency, like more lift and lower drag’.[27] Fly-by-wire systems have enabled aircraft to be flown in different modes, responsive to changing flying conditions (fog, wind, rain), and thus enabling their flying in a much wider range of situations (high temperatures, poor visibility, turbulence, crosswinds, engine failures).

I characterize fly-by-wire as a distributed control system; similar to industrial control systems now commonplace in factories, power plants and transportation networks. This term is commonly used in engineering,[28] and software development,[29] and is indebted to cybernetic models of organization, management and decision-making.[30] The term is often applied to control rooms in which human operators oversee an integrated system such as a surveillance camera network,[31] or shipping port,[32] but also to other less synoptic systems, such as anti-aircraft gun ‘directors’.[33] When a system is described as having a distributed form of control, this means that, whilst human operators may still have a role in the initiation and management of particular work processes, the tasks themselves are performed by different technological components or modules.

Following this approach, the focus is not on the distribution of cognition—or how cognitive processes are embedded in, or constitutive of the material world[34]—but on the execution of control itself. Whilst cognition, or forms of calculation, are indeed ‘distributed’ in the aviation cases in this article, I conceive the distribution of control as a bundling of situated practices. In other words, the aim is to elucidate the technical history of automation in

---

[27] Collinson, “Fly-by-Wire Flight Control”, 141.

[28] Thomas Stout and Theodore Williams, “Pioneering Work in the Field of Computer Process Control”, IEEE Annals of the History of Computing 17, No. 1 (1995), 6–18; Zdenek Binder and René Perret (eds.), Components and Instruments for Distributed Control Systems (Oxford 1983); Juan de la Puente and Mike Rodd, Distributed Computer Control Systems (Oxford 1995).

[29] Veli-Pekka Eloranta, Marko Leppänen, Johannes Koskinen and Ville Reijonen, Designing Distributed Control Systems. A Pattern Language Approach (Chichester 2014).

[30] Stafford Beer, Decision and Control. The Meaning of Operational Research and Management Cybernetics (Chichester 1994 [1966]); Norbert Wiener, Cybernetics or Control and Communication in the Animal and the Machine (Cambridge 1985 [1948]).

[31] Andrés Luque-Ayala and Simon Marvin, “The Maintenance of Urban Circulation. An Operational Logic of Infrastructural Control”, Environment and Planning D: Society and Space 34, No. 2 (2015), 191–208; Robert Goodspeed, “Smart Cities. Moving Beyond Urban Cybernetics to Tackle Wicked Problems”, Cambridge Journal of Regions, Economy and Society 8, No. 1 (2014), 79–92.

[32] Asher Boersma, “Mediatisation of Work. A History of Control Room Practice”, in Homo Faber, ed. J. Schick, M. Schmidt, U. van Loyen and M. Zillinger (Bielefeld 2018), 113–132.

[33] David Mindell, Between Human and Machine. Feedback, Control, and Computing before Cybernetics (Baltimore 2002); David Mindell, “Anti-Aircraft Fire Control and the Development of Integrated Systems at Sperry”, IEEE Control Systems Magazine 15, No. 2 (1995), 108–113.

[34] Edwin Hutchins, Cognition in the Wild (Cambridge 1995).

aviation *through* the changing practice of manoeuvring an aircraft. Moreover, to articulate the significance of control 'situations' in which particular actions are performed, albeit in a distributed manner.

One parallel example is how industrial robots, and conveyor belts, are used on vehicle assembly lines. Here, industrial robots typically perform welding tasks assigned, and overseen, by human operators. Meanwhile conveyor belts move vehicle components and assembled bodies through a factory; either according to a set schedule, or at the command of human operators. In both these cases, human operators are still involved, but rather than perform the tasks themselves (using welding tools, or manually moving objects), they are variously 'distributed' to machine systems. Accordingly, we can say that the distribution of these capacities shifts, and re-calibrates, control over these tasks. Human operators, therefore, no longer have direct, nor singular, control of these activities; significantly affecting their own skill and expertise.[35]

Yet neither is the intention in this article to restate, or reformulate, 'supervisory control'.[36] Instead, it is to provide an account of how the distribution of control within an aircraft variously enables or disables certain control capacities and roles.[37] As Sheridan explains, the term supervisory control, 'is used commonly to refer to human supervision of any semi-autonomous system'.[38] The contention here is that an emphasis on the 'distribution' of that control—whether through a transfer of human responsibility or otherwise—allows for an analysis of the ongoing 'accomplishment' of control.[39] Control is not assumed or confirmed through the delegation of supervisory responsibility, but precariously enacted in the act of 'taking' or 'assuming' control. Moreover, forms of supervisory control must be placed alongside other kinds of control, and so a focus on control as a practice allows for the tracing of control procedures throughout an aircraft.

I argue that fly-by-wire has enabled the (re)distribution of control within, and of, aircraft. This has enabled new (situated) capacities to be reached; establishing new responsibilities and limits on control and manoeuvrability, akin to these other noted systems. Whilst I acknowledge the significance of other electronic and digital systems within aircraft that enable the monitoring of an aircraft's state, I argue that in the same way that industrial robots and conveyor belts have expanded the welding and moving of vehicle parts, so

---

[35] Lisanne Bainbridge, "Ironies of Automation", Automatica 19, No. 6 (1983), 775–779.

[36] Thomas Sheridan, "Telerobotics", Automatica 25, No. 4 (1989), 487–507; Thomas Sheridan, "Supervisory Control", in Handbook of Human Factors and Ergonomics, ed. G. Salvendy (Hoboken 2006), 1025–1052.

[37] Johannes Weyer, "Can Pilots Still Fly? Role Distribution and Hybrid Interaction in Advanced Automated Aircraft", Soziologisches Arbeitspapier 45 (2015), 1–44.

[38] Sheridan, "Telerobotics", 488.

[39] Allison Hui, "Things in Motion, Things in Practices. How Mobile Practice Networks Facilitate the Travel and Use of Leisure Objects", Journal of Consumer Culture 12, No. 2 (2012), 195–215.

fly-by-wire systems have directly, and significantly, expanded the control and movement of aircraft.

I will now discuss the technical features, and operational benefits, of fly-by-wire systems in turn. In so doing, I contrast this with early aircraft—otherwise equipped with simple instruments—which lack the ability to automatically adapt to changing atmospheric conditions. I offer this comparison not as a strict technological lineage, but to suggest that the sensing of flying conditions, however rudimentary, is as old as flying itself. Moreover, that sensors—whether in the form of an anemometer or a pitot tube—are integral to the distributed control of aircraft.

Technical features

Collinson details the basic elements of a fly-by-wire system. Firstly, a fly-by-wire system eliminates the need for mechanical connections between a steering device or ‘yoke’ and control flaps called ‘ailerons’ positioned on the trailing edge of an aircraft’s wings. These allow the plane to roll or bank, affording the aircraft manoeuvrability. Instead, ‘all commands and signals are transmitted electrically along wires’;[40] hence the name (figure 1). Early aircraft, such as the Wright Flyer (1903) and Blériot XI and XII (1909), were controlled by mechanical systems, as many smaller aircraft, such as the Cess-

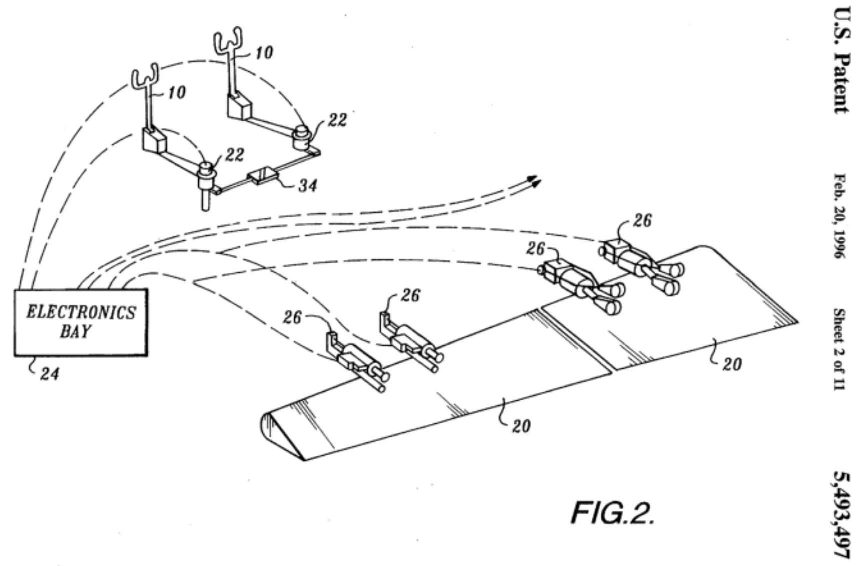

FIG.2.

Fig. 1: A simplified schematic diagram of a fly-by-wire control system. Note the use of dashed lines for the electric signals. Credit: US5493497A patent (The United States Patent and Trademark Office, 1996)

---

[40] Collinson, Fly-by-Wire Flight Control, 142.

na 172 Skyhawk (1955–present) and Piper PA-28 Cherokee (1961–present), continue to be today.

Secondly, a fly-by-wire system mediates this relationship between yoke and ailerons with an on-board computer (represented as an 'electronics bay' in figure 1). The computer transmits the commands issued by the pilots—such as roll left—to the physical 'control surface actuators'[41] embedded in the aircraft's wings. Historically, the manoeuvring of an aircraft was the sole responsibility of a single pilot, charged with physically moving a yoke. Early aircraft such as the Blériot XI and XII, designed by French engineer Louis Blériot in 1909, pioneered the use of mechanical wire control systems in aircraft. Pilots would typically sit underneath a singular fixed wing (hence a 'monoplane'), with a yoke positioned between their legs. The control stick would be attached to mechanical wires which in turn would be attached to simple moveable surfaces positioned at the back of the aircraft (Blériot XI) and attached to the frame immediately underneath the pilot (Blériot XII). Thus, as Hookway has suggested, '[f]light is and has always been a mediated activity',[42] involving a form of 'hybrid collaboration'[43] long before the introduction of automated systems. However, fly-by-wire systems replace the mechanical wire, and later rods, connecting the yoke(s) to the ailerons with an electronic relay. Consequently, the form of mediation changed significantly; introducing novel qualitative effects of controlling an aircraft with fly-by-wire as opposed to with a mechanical system. Fly-by-wire systems thus introduce another actor into the control of contemporary aircraft, complicating the relationship between pilot(s) and machine.

Thirdly, fly-by-wire aircraft are fitted with 'motion sensors which feed back the components of the aircraft's angular and linear motion to the computer'.[44] The Blériot XI was equipped with just two instruments: an oil pressure gauge and a tachometer (measuring engine RPM).[45] The Wright Brothers' earlier Wright Flyer (1903) was equipped with three on-board instruments: a Richard anemometer (measuring wind speed), a Veedor tachometer, and a stop watch.[46] None of these aircraft were equipped with instruments that could directly measure the aircraft's angular and linear motion, integral to modern fly-by-

---

[41] Ibid.

[42] Hookway, Interface, 36.

[43] Johannes Weyer, "Confidence in Hybrid Collaboration. An Empirical Investigation of Pilots' Attitudes Towards Advanced Automated Aircraft", Safety Science 89 (2016), 167–179.

[44] Collinson, "Fly-by-Wire Flight Control", 142.

[45] David Levin and Lexi Krock, "A Daring Flight. Tour a Blériot XI", PBS Nova (2005), https://www.pbs.org/wgbh/nova/bleriot/tour-nf.html, accessed April 19, 2019.

[46] "The Wright Brothers. The Invention of the Aerial Age", Smithsonian National Air and Space Museum (2019), https://airandspace.si.edu/exhibitions/wright-brothers/online/fly/1903/flightcontrol.cfm, accessed April 19, 2019; "Wright Flyer Flight Controls and Instruments", Smithsonian National Air and Space Museum (2019), www.airandspace.si.edu/multimedia-gallery/5819hjpg?id=5819, accessed August 22, 2019.

wire systems (although the Wright Flyer’s on-board anemometer would have measured the effect of wind on the physical state, and thus manoeuvrability, of the aircraft). As explained by Taylor, flying a Blériot XI would have involved simply ‘feeling’ how the aircraft was ‘that particular day’,[47] asking questions such as ‘[d]oes it feel light?’ in order to gauge the correct control response.

A final fail-safe feature is integrated into the fly-by-wire capability, in order to account for possible failures. Collinson notes the system ‘must have the same level of safety and integrity as the simple mechanical linkage system it replaces’,[48] a sentiment echoed by early fly-by-wire engineers at the Flight Dynamics Laboratory.[49] Systems equipped to deal with catastrophic failures are referred to as having ‘redundancies’: ‘[t]hese integrity requirements’ says Collinson again, ‘can only be met by designing the system so that it has sufficient redundancy to survive any two successive failures and carry on working satisfactorily.’[50] This includes the need for ‘independent electrical and hydraulic supplies’[51] in which different ‘lanes’ of sensors and computers are each able to control a ‘quadruplex actuator system’.[52] To put it otherwise, two such lanes could fail (a somewhat remote possibility), and actuator control—and therefore aircraft manoeuvrability—can still be maintained.

This technical comparison between earlier aircraft and fly-by-wire enabled aircraft is drawn in order to emphasize three things. Firstly, that fly-by-wire systems *transformed* the practical control of aircraft. Secondly, that fly-by-wire aircraft *intensified* the dependence on sensing instruments for such control. And thirdly, that fly-by-wire systems *strengthened* fail-safe systems to prevent a total, and catastrophic, loss of control. This demonstrates therefore, that the mediated activity mentioned by Hookway, or the hybrid collaboration noted by Weyer, have long been integral to flying. Whilst the technologies involved might have changed, the differences between early flying configurations and fly-by-wire are differences of degree. In the next section I further articulate the operational transformations of fly-by-wire.

Operational benefits

There are numerous advantages to a fly-by-wire system over a mechanical alternative. Collinson places them into four groups: general performance and economy, aircraft control, aircraft manoeuvrability, and system integration. As well as improved performance, fly-by-wire systems enable a reduction in overall weight due to the eradication of heavy metal rods and connectors,

---

[47] Dan Taylor, “A Daring Flight. Tour a Blériot XI”, PBS Nova (2005), www.pbs.org/wgbh/nova/bleriot/tour-nf.html, accessed April 19, 2019.

[48] Collinson, “Flight-by-Wire Flight Control”, 150.

[49] Tomayko, Blind Faith, 163.

[50] Collinson, “Flight-by-Wire Flight Control”, 150.

[51] Ibid.

[52] Ibid.

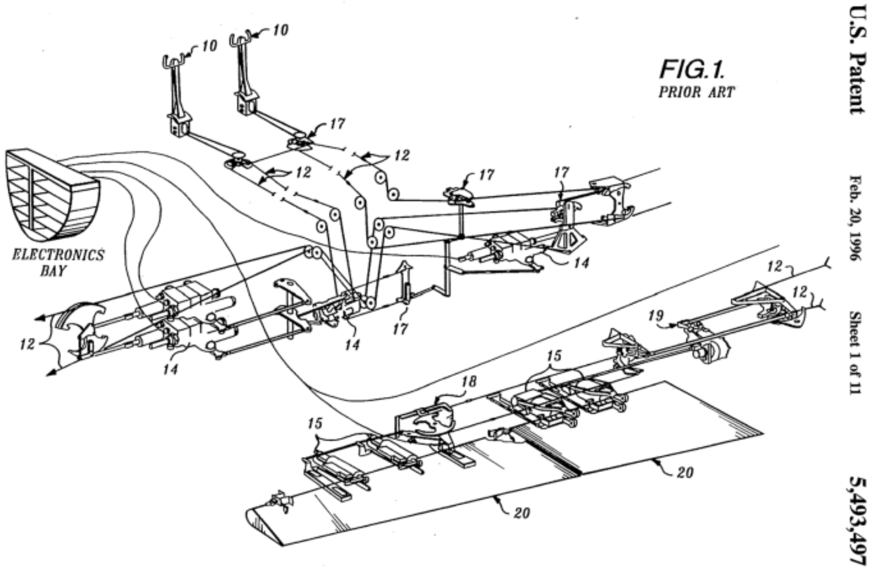

Fig. 2: A schematic diagram of a cable-based aircraft flight control system. Note the use of solid lines for the mechanical cables. Credit: US5493497A patent (The United States Patent and Trademark Office, 1996)

which would otherwise connect significant distances between the cockpit and wings. Early Blériot aircraft were already lightweight designs, with wooden frames supported by thin wire cross-braces, attached to the corner of each frame section. Yet until fly-by-wire systems were developed, aircraft were still reliant on mechanical rods directly connecting control yokes in the cockpit, to actuators on the wings (figure 2). In early aircraft such connectors are ordinarily visible, with later models incorporating such systems into the aircraft body (such as in a Cessna 172 Skyhawk, or Piper PA-28 Cherokee).

In addition, the transition to fly-by-wire eradicated the use of other mechanical components including all manner of push/pull rods, link rods, and bellcranks used to connect parts together, facilitate rotation and enable general operation (again, see figure 2 for detail). Before the commercial launch of fly-by-wire, larger aircraft were equipped with hydro-mechanical systems; in which hydraulic pumps and pipes assisted with the movement of mechanical components, such as in the original Boeing 707 (1958). An entirely new, parallel hydraulic system only added to the weight of such aircraft, meaning fly-by-wire was now twice as attractive to manufacturers.

Collinson also notes the advantage of using ‘mini control sticks’[53] that free up valuable ‘real estate’[54] within the cockpit itself. Through these, aircraft

---

[53] Ibid., 147.

[54] Ibid.

control was reduced in size and resembled a ‘joystick for a computer game’,[55] with none of the weight required to leverage control like with a mechanical yoke. Side-stick varieties (Airbus A320), made possible with the development of electronic control systems, removed the need for a central pillar either between the legs of the pilot, or protruding from a central dashboard. This freed up the ‘real estate’ mentioned by Collinson. In part, this granted pilots an uninterrupted view of cockpit instrumentation, as well as a possibly more comfortable seating position and angle. As Airbus test pilot, Gordon Corps said on the launch of the Airbus A320:

> If sidesticks were the normal way for flying aircraft, no one would even consider changing to a control column [yoke] that makes it difficult for the pilot to get into his seat and which blocks his view of the instrument panel when he’s there—besides, thanks to the A320’s side-stick and pull-out table, the pilot can at least eat his lunch in comfort.[56]

Furthermore, Collinson notes that the benefit of ‘[h]ands-off stability’[57] removes the need for pilots to actively engage in the stabilisation of the aircraft. Early aircraft were especially sensitive to slight control movements, with any abrupt or heavy turn, twist or flick of the yoke liable to send the aircraft spiralling. In the Blériot XI, this was largely because of an underpowered engine. Blériot himself crossed the English Channel with only a 25hp Anzani motorbike engine.[58] As Flight magazine reported:

> As to the technical phases of the latest and most dramatic feat so far recorded in connection with heavier-than-air machines, it is interesting to find that it stands to the credit of a machine in which the principle of automatic stability has been carried very far indeed; also that, while being exceedingly speedy, the machine in question employs a very modest amount of horse-power, and besides is itself of very small dimensions as these things go.[59]

These early ‘heavier-than-air machines’ were normally, naturally, ‘automatically stable’ ones in which pilot interference would only disrupt this careful balancing act. Hydro-mechanical systems developed in the mid-20th century, between these early machines and later fly-by-wire systems, arguably strengthened this default stability; enabling larger aircraft to demonstrate the same stable qualities as those designed throughout the early 20th century.

---

[55] Barnaby Feder, “The A320’s Fly-by-Wire System”, New York Times (1988), https://www.nytimes.com/1988/06/29/business/business-technology-the-a320-s-fly-by-wire-system.html, accessed June 28, 2019.

[56] Warwick, “A320. Fly-by-Wire Airliner”, 86.

[57] Collinson, “Fly-by-Wire Flight Control”, 148.

[58] Taylor, A Daring Flight.

[59] “The Channel as a Popular Educator”, Flight (1909), https://www.flightglobal.com/pdfarchive/view/1909/1909%20-%200450.html, accessed April 19, 2019.

By contrast, fly-by-wire systems inverted this default stability, creating the rise of normally, naturally automatically *un*stable machines unable to stay airborne without continuous, active, machine interference. As Favre notes, the 'stability augmentation' offered by fly-by-wire, ensures the aircraft 'remains stable in the case of perturbations such as gusts or engine failures',[60] yet does so by removing the passive or 'static' stabilization offered by non-computer-mediated aerodynamic design.[61] Furthermore, in doing so, this 'significantly reduces the crew workload' to such that two control loops now exist: an inner or 'closed loop' consisting of the fly-by-wire system in charge of immediate stabilisation; and an outer or 'open loop'[62] consisting of the pilots engaged in 'objective management'.[63] Fly-by-wire systems are significant because they represented not only a clean break with prior systems, but inverted the founding principles of flight; that aircraft are, or need to be, naturally stable. Instead,

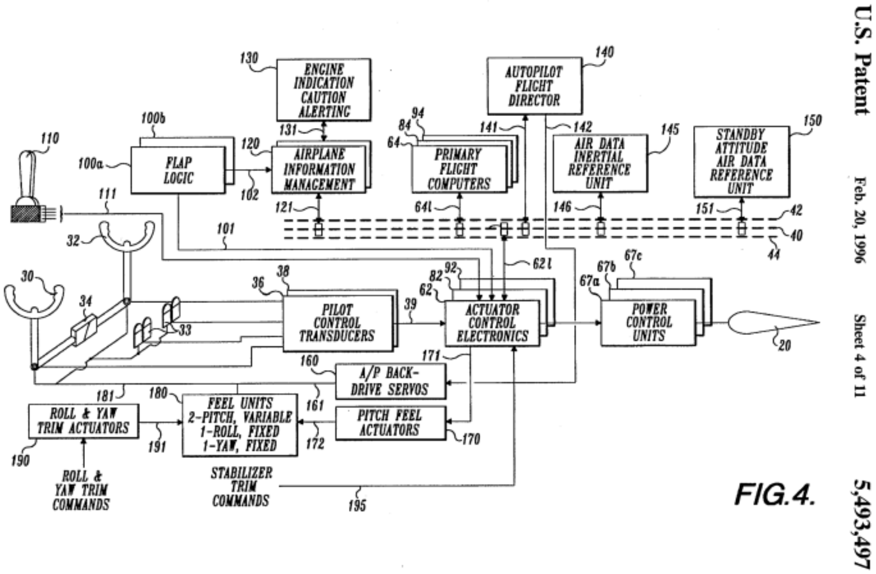

Fig. 3: A 'block diagram' of a fly-by-wire control system. Note the control sticks (left, 30 and 32), flight control surface (right, 20), and various other integrated systems (airplane information management, 120; primary flight computers, 64; and autopilot flight director, 140). Credit: US5493497A patent (The United States Patent and Trademark Office, 1996)

---

[60] Favre, "Fly-by-Wire for Commercial Aircraft", 141.

[61] Robert Nelson, Flight Stability and Automatic Control (New York 1998), 40.

[62] Sheridan, "Supervisory Control", 1025.

[63] Favre, "Fly-by-Wire for Commercial Aircraft", 141.

fly-by-wire systems demand the continuous attention of a control system in order to account for an aircraft's default instability.[64]

This has profound implications for how such control is enabled, performed, and managed. Indeed, for *why* control needs to be re-distributed during specific moments of atmospheric turbulence. In this regard, sensors assume greater significance. Their instrumental power, previously as mere 'indicators', become critical sources of operational data through which the aircraft is reliant to make decisions.

Interestingly, Favre also suggests that fly-by-wire systems enable 'carefree manoeuvring'[65] in which pilots are now released from the mental and physical pressure of manoeuvring a large aircraft in sometimes challenging circumstances. This means pilots are free to perform manoeuvres in the knowledge that the fly-by-wire system establishes an outer limit for their actions, protecting the structural integrity of the aircraft and the safety of those onboard. The second half of this article, however, will challenge how 'carefree' this manoeuvring can be in a fly-by-wire aircraft.

Another benefit suggested by Collinson is that fly-by-wire establishes 'manoeuvre command control'[66] in which the system can manage the 'rate of roll'; preventing the aircraft from overshooting a roll manoeuvre. The roll rate of an aircraft is usually expressed in degrees per second, with the Airbus A320 ordinarily capable of performing a modest roll rate of 25°/s;[67] largely due to its size and wing span. Other benefits Collinson identifies are centred on its 'integrative' nature; both the '[a]bility to integrate additional controls' and the '[e]ase of integration of the autopilot' (see figure 3 for details).[68] Thus, fly-by-wire systems constitute a holistic transformation of control, both in respect to the actual cockpit actions and activities, and the underlying technical architecture supporting it.

With all these factors combined, there is a clear argument for stating that fly-by-wire—an electronic system that enables the automation of flight actions—can be understood as a form of 'distributed control'. Rather than an example of distributed cognition, or seen as only enabling supervisory forms of control, fly-by-wire instead enables the distribution of various flight prac-

---

[64] Hydro-mechanical systems developed during the mid-20th century are worthy of note, because of their role in making larger commercial aircraft viable. However, the control of such systems merely represented a continuation, or a marginal update, of control practices found in the use of mechanical systems.

[65] Ibid., 148.

[66] Collinson, "Fly-by-Wire Flight Control", 148.

[67] Warwick, "A320. Fly-by-Wire Airliner", 86. By comparison, a Eurofighter Typhoon can perform a roll rate 10x that of the Airbus A320, see David Cenciotti, "Watch a 360 Roll in One of the World's Most Advanced Jet Trainers", Business Insider (2015), https://www.businessinsider.com/watch-a-360-roll-in-one-of-the-worlds-most-advanced-jet-trainers-2015-5, accessed May 31, 2019.

[68] Collinson, "Fly-by-Wire Flight Control", 150.

tices integral to the control and manoeuvre of aircraft. In doing so, fly-by-wire ushered in an era of default instability, in which computer-mediated operations provided ongoing stabilization. This default instability, I will argue, is dependent upon the increasing use of—and, indeed, reliance on—external sensors in order to gauge the situational state of any aircraft. Sensors assume a new power as operational data sources rather than mere indicators of atmospheric conditions. In the next section I examine how various automation 'surprises' arise out of this entanglement.

Surprises, Sensors, and Supervision

As Perrow noted even before the integration of fly-by-wire systems into commercial production, 'the aircraft is a model of automation, as well as of complexity', and '[d]espite the automation, the complexity of the system keeps the crew extremely busy at peak times'[69]; far from the "carefree" experience suggested by Favre. Echoing Perrow, 20 years later Budd admits that '[g]iven the computer-mediated environment in which they work, the perceptual demands placed on pilots are considerable'.[70] Automation, in the shape of fly-by-wire, has not led to a reduction in pilot responsibilities. Rather, as Perrow and Budd both contend, such an automated, distributed control system has actually led to increased perceptual pressures, even when pilots are seemingly reduced to being 'system managers'.[71]

In the second half of this article I will discuss how fly-by-wire systems have led to the generation of 'automation surprises'.[72] These, I suggest, are principally an effect of the intermittent failure of the distribution of control between pilot and machine; dependent upon external sensors measuring flying conditions such as air speed, air temperature, or 'angle of attack' (AOA). Here, supervisory control, as envisioned by Sheridan, is afforded only in specific situations triggered by the switching of operational 'modes'. I discuss two recent incidents involving Boeing 737 aircraft that exemplify these issues. In order to explore the issues concerning distributed control, I primarily use flight investigation reports issued in the aftermath of said incidents. The use of crash documentation to analyse socio-technical failures is commonplace in STS and related disciplines,[73] including in work by Perrow on marine accidents,[74]

---

[69] Perrow, Normal Accidents, 130.

[70] Budd, "Air Craft. Producing UK Airspace", 129.

[71] Weyer, "Confidence in Hybrid Collaboration", 171.

[72] Sarter and Woods, "Team Play"; Sarter, Woods and Billings,"Automation Surprises"; Woods and Sarter. "Learning from Automation".

[73] Christian Kehrt, "New Perspectives in Aviation History. Flight Experiences of German Military Pilots", Mobility in History 6, No. 1 (2015), 41–53. Whilst Kehrt does not list crash reports as sources for the historical analysis of flying practices, he does mention 'exposés, handbooks, military and technical experience reports, training material [and] technical descriptions'. Crash documentation can be considered as similar to those above.

[74] Perrow, Normal Accidents, 170–231.

Law and Law and Mol on train crashes,[75] and Stilgoe on ‘autonomous’ vehicle accidents.[76] In these accounts, such documentation carry significant weight. Ordinarily compiled by official crash investigators and/or technicians with expertise in the systems under scrutiny, they function as important documents, used as evidence for political intervention and regulatory decision-making; shaping such systems’ effect on wider society. I conclude by emphasizing the importance of machine supervision to technical safety.

Surprises

One effect of fly-by-wire systems enabling aircraft to be operated in multiple configurations, is that pilots can encounter ‘mode errors’,[77] resulting in ‘mode confusion’.[78] These arise when pilots fail to understand an aircraft’s actions, thus limiting how they might successfully react to a situation. Sarter and Woods suggest that, with a rise in automated systems, there is also a ‘proliferation of modes’ any one system can operate under.[79] This is certainly true for those ‘involving a large number of highly dynamic interacting subcomponents’[80] such as fly-by-wire aircraft, which typically run with numerous interconnected navigational, control and fuel systems (again, see figure 3). As Perrow contends, pilot workloads have become ‘bunched’ with ‘long periods of inactivity and short bursts of intense activity’, and with both states ‘error-inducing modes of operation’.[81]

As Sarter and Woods further suggest, quoting Norman, ‘if one wishes to create or increase the possibilities for erroneous action, one way is to “change the rules. Let something be done one way in one mode and another way in another mode”’.[82] Multiplying the number of different ways a system can be run optimizes it for different situations and conditions; the configurative opportunities noted earlier by Collinson. For a fly-by-wire aircraft, specific modes might stabilize the aircraft better in turbulent conditions; either by allowing the system to carry out ‘micro-decisions’[83] to correct a plane’s movements, or by handing control over to the pilots to avoid stalling. Different modes, however, have different rules—shifting the balance of hybrid collaboration. When a pilot mistakes one mode for another, they might ‘commit an erroneous

---

[75] John Law, After Method. Mess in Social Science Research (London 2004), 93–100; John Law and Annemarie Mol, “Local Entanglements or Utopian Moves. An Inquiry Into Train Accidents”, The Sociological Review 50, No. 1 (2002), 82–105.

[76] Stilgoe, “Machine Learning”, 36–47.

[77] Nadine Sarter and David Woods, “How in the World Did We Ever Get Into That Mode? Mode Error and Awareness in Supervisory Control”, Human Factors 37, No. 1 (1995), 5–19.

[78] Jan Bredereke and Axel Lankenau, “A Rigorous View of Mode Confusion”, International Conference on Computer Safety, Reliability and Security 2434 (2002), 19–31.

[79] Sarter and Woods, “How in the World Did We Ever Get Into That Mode?”, 5.

[80] Ibid.

[81] Perrow, Normal Accidents, 131.

[82] Donald Norman, The Psychology of Everyday Things (New York 1988), 179.

[83] Sprenger, Politics of Micro-Decisions.

action by executing an intention in a way that is appropriate to one mode when the device [aircraft] is actually in another mode'.[84]

Mode confusions are just one example from a suite of possible automation surprises to be found in modern aircraft. Such surprises occur when systems with significant degrees of autonomy, such as in fly-by-wire aircraft, display 'behavior [that] violates operators' expectations'.[85] Surprises in such complex systems, it can be said, are normal occurrences. 80% of Airbus A320 pilots asked by Sarter and Woods whether they'd been 'surprised' by its automated systems responded affirmatively.[86] As they expand:

> Automation surprises begin with misassessments and miscommunications between the automation and the operator(s), which lead to a gap between the operator's understanding of what the automated systems are set up to do and how the automated systems are or will be handling the underlying process(es). The gap results in the crew's being surprised later, when the system's behavior does not match the crew's expectations.[87]

As Budd similarly suggests:

> [Pilots] must continually synthesize accurate spatial awareness from a considerable amount of coded raw data, a task that requires training, skill, discipline and judgement in an uncertain and changing environment, together with quick, prudent decision-making based on a knowledge of the aircraft's systems and natural environment, crew capabilities and personal limitations.[88]

Dealing with automation surprises is part-and-parcel of operating a fly-by-wire aircraft. Sarter and Woods identified eight surprising situations in interviews with A320 pilots, ranging from '[i]ndirect mode transitions' to '[u]nexpected airspeeds' during an aborted landing.[89] These surprises are the norm, rather than an exception; if not built into the automated systems themselves, then built into the *relation* between system and pilot. In other words, they emerge in the attempted accomplishment of control, as 'normal, natural troubles'.[90] 'The critical question' ask Sarter and Woods again, is 'whether or not operators detect unexpected and undesirable process behavior in time to prevent or recover from negative consequences'.[91]

Airbus aircraft, for example, usually operate under four modes or 'laws': normal, alternate, direct and mechanical. Each permit the pilots to perform a variety of manoeuvres and make a variety of decisions. Some (such as direct

---

[84] Sarter and Woods, "How in the World Did We Ever Get Into That Mode?", 6.
[85] Sarter and Woods, "Automation Surprises", 554.
[86] Ibid., sample size of 167.
[87] Ibid.
[88] Budd, "Air Craft. Producing UK Airspace", 129.
[89] Sarter and Woods, "Automation Surprises", 559–561.
[90] Harold Garfinkel, Studies in Ethnomethodology (Englewood Cliffs 1967), 191.
[91] Sarter and Woods, "Automation Surprises", 554.

and mechanical law) are essentially overrides, allowing operators to intervene if there are critical component (engines, ailerons, flight computers etc.) failures. Others, such as alternate law, offer the pilots an increased range of possible actions but still within set parameters. Normal law is the default mode in which a fly-by-wire system and integrated control systems are operative. The default is ‘living within a box’ as the A320 test pilot contends.[92] In any case, slipping from one law to another re-distributes control. Hybrid collaboration, in other words, is not a static form. Control is only afforded through the sensing of a new, evolving situation through which it is necessarily re-distributed.

Mode confusion can arise when system operators lack the requisite capacities to evaluate an emergent situation, with confusion most likely when pilots believe the aircraft is flying under a different law. Thus, decisions made by the pilots might have different outcomes, depending on the situation. The fatal Air France flight 447 crash in 2009 was partially attributed to the aircraft switching modes from normal to alternate law.[93] In doing so, this eliminated protection against stalling and roll control; operational benefits ordinarily offered by a fly-by-wire system. Neither pilot was aware of this mode switch, supposing that the aircraft was still operating under normal law conditions, therefore providing adequate protections against both stalling and rolling. Under alternate law, however, the pilots were afforded greater control and responsibility; loosening these restrictions.

Sensors

A critical feature of a distributed control system is a reliance on sensors. These are external devices attached to the body of an aircraft to provide pilots with atmospheric readings. They furnish the system with situational information necessary for controlling an aircraft. As the Wright Flyer showed, instrumentation has been an integral part of flying since the early 20th century. I argue here, however, that in a fly-by-wire era, sensors assume a new power as an operational data source rather than a mere indicator of atmospheric conditions. What this means is that sensed data is used to determine under which law an aircraft is operating, and as such, how control is distributed.

Yet these sensor systems are not entirely fail-safe, despite the presence of redundancies. The Air France aircraft mentioned previously had switched operational modes because of a fault in the aircraft’s ‘pitot tubes’; devices typically attached to the nose of the aircraft to monitor air speed. On this occasion, there had been a ‘temporary inconsistency between…measure air speeds’, after which the aircraft’s pitot tubes had ‘likely’ become ‘obstructed’

---

[92] Warwick, “A320. Fly-by-Wire Airliner”.

[93] Bureau d’enquêtes et d’analyses la sécurité de l’aviation civile (BEA), “Final Report. On the Accident on 1st June 2009 to the Airbus A330-203 Registered F-GZCP Operated by Air France Flight AF 447 Rio de Janeiro – Paris” (2012), www.bea.aero/docspa/2009/f-cp090601.en/pdf/f-cp090601.en.pdf, accessed June 4, 2019.

with ice crystals, rendering the devices inoperable and leading to 'autopilot disconnection and a reconfiguration to alternate law'.[94] The aircraft had opted to switch modes knowing that the air speed readings were improbable.

Two more recent, connected, cases have exemplified the importance of sensors to the distributed control of aircraft. The first involved Lion Air flight JT610 which crashed into the sea close to Jakarta in October 2018; the second was the tragic crash of Ethiopian Airlines flight ET302 in March 2019. Both involved Boeing 737 aircraft, with scrutiny of the sensors themselves, operational procedures concerning reaction to sensor readings, and automated control, stability and manoeuvring decisions made as a result of sensor readings.

In the first incident, erroneous inputs from the aircraft's AOA sensors had led to incorrect speed readings being displayed; panicking the pilots into making the wrong manoeuvre.[95] AOA sensors—ordinarily located next to an aircraft's pitot tubes—measure the 'difference between the pitch angle (nose direction) of the airplane and the angle of the oncoming wind', providing 'angle of attack information to onboard computers'.[96] A preliminary report into the crash noted that the aircraft had had its AOA sensors replaced prior to the flight, with the 'left Pitot Air Data Module (ADM)'—a device transmitting air data from pitot tubes to the cockpit—subsequently 'flushed' by an engineer on arrival in Jakarta.[97] However, the issue persisted, with the aircraft's Digital Flight Data Recorder (DFDR, or black box) registering a 'difference between left and right Angle of Attack…of about 20°'[98] until the end of the recording. This difference led the pilots to believe the aircraft was in a grave situation, requiring immediate manual correction to prevent a stall. A former National Transportation Safety Board (NTSB) investigator speaking to the media suggested the cause of the accident was 'what investigators call a "startle factor"'.[99] In other words, an automation surprise.

In response to the crash, Boeing issued an Operations Manual Bulletin (OMB) 'directing operators [pilots] to existing flight crew procedures [in order] to address circumstances where there is erroneous input from an AOA

---

[94] BEA, Final Report, 17.

[95] Rob Davies, "Lion Air Crash. Boeing Tells Pilots How to Deal with Faulty Sensors, Guardian (2018), https://www.theguardian.com/business/2018/nov/07/lion-air-crash-boeing-and-faa-to-issue-advice-to-airlines-on-737-max-jets-report, accessed November 18, 2018.

[96] "Max Updates", Boeing (2019), https://www.boeing.com/commercial/737max/737-max-software-updates.page, accessed June 6, 2019.

[97] Komite Nasional Keselamatan Transportasi (KNKT), "Preliminary Aircraft Accident Investigation Report" (2018), https://reports.aviation-safety.net/2018/20181029-0_B38M_PK-LQP_PRELIMINARY.pdf, accessed June 6, 2019.

[98] Ibid., 22.

[99] Alan Levin, Julie Johnson and Harry Suhartono, "Boeing Issues Bulletin for 737 Max After Indonesia Jet Crash", Bloomberg Online (2018), https://www.bloomberg.com/news/articles/2018-11-07/boeing-issues-bulletin-for-737-max-after-indonesia-jet-crash, accessed June 6, 2019.

sensor’.[100] A subsequent Airworthiness Directive (AD) issued by the FAA instructed 737 owners to revise operational procedures concerning any ‘uncommanded [automated] nose down stabilizer trim’ movements,[101] in which pilots are instructed to essentially disengage (switch off) the ‘nose down’ feature. Instead, pilots were expected to perform these manoeuvres manually.

In the second incident, an anti-stall feature was automatically activated, forcing the plane’s nose down, again based on erroneous sensor readings.[102] Like Lion Air flight JT610, Ethiopian Airlines flight ET302 had experienced a discrepancy between AOA sensors. Despite taking-off at 5.37am with ‘normal values of left and right’ AOA,[103] as the preliminary report contends, just a minute later these figures deviated. Firstly, the left AOA value decreased to 11.1° before increasing to 35.7°. The right AOA sensor maintained a reading of 14.94°. In less than another minute, with the right AOA sensor showing 15.3°, the left AOA value increased to 74.5°. This was enough for the ‘left stick shaker’ to initiate a stall warning; designed to call the pilot into immediate action. A variety of other values including ‘airspeed, altitude and flight director pitch bar values’[104] derived from the left side had deviated from corresponding sensors on the right.

Here, as with the Lion Air flight, there were evidently problems with the AOA sensors.[105] But what is further detailed in the preliminary report into the Ethiopian Airlines crash, is that the pilots repeatedly attempted manual trim movements, as ordinarily instructed to do by usual operating protocol and reiterated by the subsequent OMB issued after the first crash in October 2018. Between 5.38am and 5.44am when the aircraft crashed, the pilots had to contend with the recurrent re-engagement of the aircraft’s automated anti-stall system known as the Manoeuvring Characteristics Augmentation System (MCAS). Each time the pilots took control to correct the situation, MCAS automatically readjusted the nose position; the ‘uncommanded [automated] nose down stabilizer trim’ movements mentioned earlier. The preliminary report mentions that the ‘DFDR recorded an automatic aircraft nose down

---

[100] “Boeing Statement on Operations Manual Bulletin”, Boeing (2018), https://boeing.mediaroom.com/news-releases-statements?item=130327, accessed June 6, 2019.

[101] Federal Aviation Administration, “Emergency Airworthiness Directive 2018-23-51”, FAA (2018), https://rgl.faa.gov/Regulatory_and_Guidance_Library/rgad.nsf/0/83ec7f95f3e5bfbd8625833e0070a070/$FILE/2018-23-51_Emergency.pdf, accessed July 1, 2019.

[102] Gwyn Topham, “Anti-Stall System Was ‘in Play’ on Ethiopian’s Boeing 737 Max”, Guardian (2019), https://www.theguardian.com/world/2019/mar/25/anti-stall-system-was-in-play-on-ethiopians-boeing-737-max, accessed April 19, 2019.

[103] Aircraft Accident Investigation Bureau (AIB), “Aircraft Accident Investigation Preliminary Report, Report No. AI-01/19” (2019), https://assets.documentcloud.org/documents/5793877/Preliminary-Report-B737-800MAX-Ethiopia.pdf, accessed June 6, 2019.

[104] Ibid., 9.

[105] That both crash reports noted problems with left pitot tubes, specifically, might not be coincidental.

(AND) trim command four times without pilot's input'.[106] In short, the pilots were fighting a losing battle against their own aircraft, with direct and immediate control out of reach. Here we find confusion and surprise in equal measure: confusion at the aircraft repeatedly entering a different mode, and surprise it failed to yield to manual corrections. The re-distribution of control was perceived but not actual, with the pilots believing their corrective actions were permissible. Even 'interim stabilization' or a 'shared understanding of the situation' remained elusive to the pilots, unable to ascertain the intentions of MCAS.[107] Nowhere is the 'endless, ongoing, contingent accomplishment'[108] of situated, *distributable* control more evident than here.

Regulators in both cases recommended changes to flight protocol; one to AOA procedures, and one to the implementation of additional fail-safes. In each case sensors played a critical role in the mounting, operational confusion. Yet each yielded different automation surprises; the result of various manifestations of distributed control of a fly-by-wire aircraft. MCAS—a recent addition to the control of Boeing aircraft—re-distributed control in unexpected ways, mistaking the erroneous AOA readings as true. For Lion Air flight JT610, there was operational confusion over the correct and necessary manoeuvres to be made (by the pilots). For Ethiopian Airlines flight ET302, specific mode confusion over an operational decision (taken by the aircraft). These exemplify the myriad of ways in which the distribution of control in fly-by-wire aircraft can yield manifold, incalculable, *situated*, surprises.

Supervision

At particular moments, automation is followed by a rise in new forms of supervision, in which previously active operators become system supervisors or managers.[109] This is what Gent, in reference to algorithmic management in distribution centres, has referred to as 'sub-vision';[110] a situation in which operators of a system cede authority to the machine process, and in a sense are 'relegated' beneath it rather than principally responsible for the execution of decisions. However, machine supervision of automated processes and

---

[106] Ibid., 25.

[107] Jörg Bergmann, Kirsten Nazarkiewicz, Detlef Dolscius and Holger Finke, "Decision Making in the Cockpit", Bielefeld University (2005), https://www.uni-bielefeld.de/soz/personen/bergmann/cockpit/pdf/summary_research_project_decision_making_communication.pdf, accessed February 28, 2020.

[108] Garfinkel, Studies in Ethnomethodology, 1.

[109] Hind, "Digital Navigation and the Driving-Machine"; Sheridan, "Supervisory Control"; Weyer "Can Pilots Still Fly?".

[110] Craig Gent, The Politics of Algorithmic Management. Class Composition and Everyday Struggle in Distribution Work. PhD thesis. University of Warwick (2019); Craig Gent, "The All-Seeing Algorithm?", Novara Media (2019), https://novaramedia.com/2019/04/13/the-all-seeing-algorithm/, accessed June 27, 2019.

systems is nothing new in aviation. As Sarter and Woods describe in relation to an automated cockpit control system:

> Pilots can choose from at least five different methods at different levels of automation to change altitude. This flexibility is usually portrayed as a benefit that allows the pilot to select the mode best suited to a particular flight situation. However, this flexibility has a price: The pilot must know about the functions of the different modes, which mode to use when, how to “bumplessly” switch from one mode to another, and how each mode is set up to fly the aircraft as well as keep track of which mode is active.[111]

Thus, mode control becomes a significant perceptive duty for the pilot, in which they are tasked with providing a ‘meta-level’ oversight of altitude settings, as the example above contends. In other words, pilots must assume new supervisory duties in respect to specific modes and their suitability for particular flying situations. Pilots tasked with these new ‘attentional demands’[112]—attentive towards to the selection of flying modes—are thus expected to learn new perceptive skills integral to the flying of contemporary aircraft. Whilst Weyer contends that confidence in so-called ‘hybrid collaboration’ is high amongst many pilots,[113] this is based upon the acceptance of a ‘symmetrical relation of humans and automation on the flight deck’.[114] When this relationship becomes asymmetrical, i.e. when control is re-distributed, mode confusion is more likely to occur.

This is evident in the preliminary report from the crash of Ethiopian Airlines flight ET302. The pilots repeatedly struggled to switch off the default setting, in which MCAS would ordinarily move the position of the aircraft’s nose to prevent it stalling. As Sarter and Woods have remarked, automated systems ‘can change modes on their own, based on environmental inputs or for protection purposes, independent of direct and immediate instructions from the human supervisor’.[115] The pilots of flight ET302 were sufficiently trained in the operational protocol of dealing with erroneous sensor readings, as well as how to initiate manual nose corrections. What they arguably couldn’t do, however, was ‘track and…anticipate the behaviour of [the] automated system…’;[116] that is, to respond to repeated re-engagements by the system to perform nose down stabilizer trim movements.

Under normal law, pilots must ordinarily supervise. Under alternate law, with certain control systems disengaged, pilots are required to assume direct control. What is therefore interesting in the cases discussed, is how control shifts

---

[111] Sarter and Woods, “How in the World Did We Ever Get Into That Mode?”, 6.

[112] Ibid., 5.

[113] Weyer, “Confidence in Hybrid Collaboration”, 177.

[114] Ibid., 178.

[115] Sarter and Woods, “How in the World Did We Ever Get Into That Mode?”, 7.

[116] Ibid.

from one register to another. Or, how, under distributed control, the contingent or volatile nature of a situation results in the ongoing transformation of one form of control into another; not just of modes being 'bumplessly' switched by a pilot, but also such switching processes initiated by software, such as MCAS. Shared understanding of any given situation, is ordinarily shared between pilot, co-pilot, MCAS and assembled sensors in a form of hybrid collaboration; but, one which reveals the latent asymmetries of operational control.[117]

Conclusion

Automation is once again an issue. At an economic level, automation is being discussed because of the rise of big technology firms such as Amazon and Google, capable of commanding logistical control over whole supply-chains and industries.[118] Coupled with the longer-term stagnation of wages in many Western countries such as the US and the UK, and discussion of shorter working weeks and Universal Basic Income (UBI), automation is seen as a benefit to all parties; citizens, consumers, states and companies—with the possible exception of traditional trade unions.

At a socio-technical level, discussion of automation has taken a different path, principally focused on ethics. The automation of border control processes, involving the scanning of travel tickets, and the execution of security decisions have occupied a prominent position in these discussions.[119] Debate has also occurred regarding the ease of applying for short-term credit, and the automation of decision-making in such cases.[120] In these cases, the concern is that the automation of decision-making leads to ethical short-cuts that, by default, relegate human operators to being supervisors (or sub-visors), rather than executors of tricky decisions.

In this discussion of control of specific driving or flying machines, these debates have tended to oscillate between the two. On the one hand, economic, because of the possible gains from automating control, stability, and manoeuvring for manufacturers of such machines and their integrated systems; on the other, ethical, because of the decision-making protocols baked into the default

---

[117] Weyer, "Confidence in Hybrid Collaboration", 169.

[118] Shoshana Zuboff, "Big Other. Surveillance Capitalism and the Prospects of an Information Civilization", Journal of Information Technology 30, No. 1 (2015), 75–89; Nick Srnicek, Platform Capitalism (Cambridge 2016).

[119] Louise Amoore, "Biometric Borders. Governing Mobilities in the War on Terror", Political Geography 25, No. 3 (2006), 336–351; Louise Amoore and Alexandra Hall, "Border Theatre. On the Arts of Security and Resistance", Cultural Geographies 17, No. 3 (2010), 299–319; Mica Rosenberg and Reade Levinson, "Trump's Catch-and-Detain Policy Snares Many Who Have Long Called US Home", Reuters (2018), https://www.reuters.com/investigates/special-report/usa-immigration-court/, accessed June 27, 2019.

[120] James Ash, Ben Anderson, Rachel Gordon and Paul Langley, "Digital Interface Design and Power. Friction, Threshold, Transition", Environment and Planning D: Society and Space 36, No. 6 (2018), 1136–1153.

modes of soft- and hardware. These two frameworks are evidently connected and cannot ordinarily be considered alone. Profit margins (economic) and operational limits (ethical) form a dialectic relationship governing the actual existence and application of automation to situations.

This article has principally sought to contribute at the level of technical operation and machine control, reappraising the introduction of fly-by-wire systems into commercial aircraft and subsequent debate over their various effects on decision-making, expertise and safety. In particular, it has argued that fly-by-wire systems enabled ‘distributed control’ in which the capacity to execute operational decisions concerning stability and manoeuvrability of an aircraft is variously (re-)distributed throughout the aircraft. What is critical to this, I have suggested, is an understanding of the situated nature of aircraft control, dependent on the ongoing sensing of atmospheric conditions. It is through the erroneous sensing of the latter, that confusion and surprise radically limit the former.

To conclude this article, there are five ways in which fly-by-wire, the distribution of control within commercial aircraft, and resulting automation surprises can be brought to bear on contemporary issues; most notably, those concerning autonomous vehicles:

Firstly, the importance of automation to the economic viability of air travel, and by extension, personal car ownership models. Automation is invariably attractive to traditional vehicle manufacturers because of the potential to lower operational costs, through weight reductions, the streamlining of part procurement, increasing capacity or speed, and re-assigning human labour. In turn, this has the benefit of boosting long-term profitability for manufacturers and operators.

Secondly, the importance of developing novel safety regimes to deal with the automation of control. The introduction of fly-by-wire systems into commercial aircraft necessitated the integration of redundancies to provide fail-safe operation, something autonomous vehicle manufacturers are only just beginning to think about.[121] Recent accidents[122] have similarly compelled manufacturers to design ‘safety case frameworks’[123] and accept aviation-style safety policies,[124] to guide and govern autonomous vehicle development.

---

[121] Sean O’Kane, “Uber Debuts New Self-Driving Car with More Fail-Safes”, The Verge (2019), https://www.theverge.com/2019/6/12/18662626/uber-volvo-self-driving-car-safety-autonomous-factory-level, accessed June 27, 2019.

[122] Sam Levin and Julia Wong, “Self-Driving Uber Kills Arizona Woman in First Fatal Crash Involving Pedestrian”, Guardian (2018), https://www.theguardian.com/technology/2018/mar/19/uber-self-driving-car-kills-woman-arizona-tempe, accessed August 21, 2019.

[123] Eric Meyhofer, “Laying the Groundwork for Self-Driving Vehicle Safety”, Uber ATG (2019), https://medium.com/@UberATG/trailblazing-a-safe-path-forward-e02f5f9ef0cc, accessed August 21, 2019; “Our Safety Case. Uber’s Commitment to Self-Driving Safety”, Uber ATG (2019), https://uberatg.com/safetycase, accessed August 21, 2019.

[124] Dombroff and Tochen, “Independent Review of the Safety Culture of Uber Technologies”.

Thirdly, the importance of sensors, and operational protocols, to automated control. Sensors are the 'eyes and ears' of various moving machines, necessarily mediating and extending vision and measurement. Yet as the cases in this article have shown, they do not always provide faithful records of the environments and atmospheres they wish to sense. As such, operational protocols must ensure that troubleshooting and scrutinising sensors is an integral part of automation.

Fourthly, the normality of operational surprises, and the impossibility of 'designing out' their existence. Despite the wishes and attempts—by both software developers and physical engineers, but also by executives and PR departments—confusion and surprise can never be entirely eradicated. Automation will always bring surprises, with complex systems necessarily producing normal accidents.[125]

Lastly, the necessity of cultivating new expertise to cope with transitions between different modes of control. Under such expertise, the skills required to assess, interpret and respond to new data streams, interfaces, images and situations becomes integral to the successful flying of an aircraft, or driving of a vehicle. Such skills are to be found in other contemporary digital situations, as well as in the history of aircraft control.

The fatal Air France crash in 2009 highlighted a foundational problem rediscovered in the more recent incidents discussed in this article: A situation escalated not because conditions outside threatened the stability of the plane (the turbulence wasn't critical), but because the sensors had stopped sensing altogether. This meant the plane was generating impossible airspeed readings—but nonetheless the aircraft had switched modes; from normal to alternate law. However, the situation escalated precisely because the pilots believed they were operating in the same 'normal' mode all along. As William Langewiesche wrote, the 'episode should have been a non-event…if they had done nothing, they would have done all they needed to do'.[126]

The takeaway from this discussion is not that fly-by-wire aircraft introduce surprises which complicate the otherwise smooth, easy operation of flying an aircraft. Instead, it is to suggest that the automation of aircraft control systems has generated qualitatively different surprises, necessarily the result of automating aircraft manoeuvring, control, and stability, as well as introducing different operating modes. Qualitatively different surprises are a result of a concatenation of capacities; an effect of the ongoing, contingent, re-distribution of control.

Address of the Author: Sam Hind, Locating Media, University of Siegen, Herrengarten 3, 57072 Siegen, Email: hind@locatingmedia.uni-siegen.de

---

[125] Perrow, Normal Accidents, 5.

[126] William Langewiesche, "The Human Factor", Vanity Fair (2014), https://www.vanityfair.com/news/business/2014/10/air-france-flight-447-crash, accessed November 18, 2018.