Autopilot Systems

An Investigation of the C4I Methodologies Used in Autopilot Systems

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List of Figures

Figure 1: 1947 autopilot system [2] .................................................................................. 6
Figure 2: Representation of autopilot control [2] ............................................................... 7
Figure 3: Predator UAV [6] .............................................................................................. 11
Figure 4: Space shuttle systems breakdown [11] ........................................................... 12
Figure 5: 2008 Opel Vectra, with autopilot [10] ............................................................ 14

List of Tables

Table 1: Instrument landing categories [5] ........................................................................ 8
Introduction
Since the Wright brothers first flew in an airplane on 17 December 1903, airplanes have become ubiquitous to society. Aircraft are involved in every aspect of our daily lives, from personal and business transportation to the movement of the goods we buy at the grocery store to our National defense.

A key component of modern aircraft is the autopilot system, officially referred to as the automatic flight control system, which has made the use of aircraft easier than ever imagined by the Wrights. This paper will examine autopilot systems with respect to their utilization of Command, Control, Communication, Computer and Intelligence (C4I) methodologies. The paper will investigate the history of autopilot systems, their modern uses and their future applications.

History
From the first days of air flight, autopilot systems were thought of as a future addition to aircraft. The Wright brothers, bicycle mechanics by trade, understood the tendency of a bicycle to remain upright while moving [2]. This phenomenon intrigued them and they began investigating gyroscopic systems. Though never implemented, their early worked showed that autopilot systems were not merely an afterthought of aircraft, but something that was thought of from the very first days of air flight.

Why Autopilot Systems Arose
In 1908, Elmer Sperry, a famous American inventor, developed the gyrocompass: a large, gyroscopic based system which provided navigational
assistance to ships [3]. After its inception, this device quickly became a critical component of American warships due to magnetic compasses having problems operating on large, steel ships. While large and cumbersome, this invention showed that gyroscopic navigation systems were practical. Though Elmer Sperry was able to develop a gyroscopic system, his invention was in no way suited for use in aircraft. It was his son, Lawrence Sperry, who in 1912 developed the first autopilot system for aircraft, based on his father’s design [4].

After seeing his father’s invention at work, and sharing the same fascination the Wright brother’s had for the stability of bicycles in motion, Sperry set out to develop a system that could manage the three flight axes of aircraft: yaw, pitch and roll.

Sperry’s work did not arise from any need of an autopilot system, but instead originated in the same way as many early American inventions – through creativity and determination of gifted inventors.

**How Early Systems Functioned**

Sperry’s first autopilot system utilized four separate gyroscopes, each spinning at 7,000rpm. The gyroscopes were designed to maintain a “zero setting”, for all control services of the plane, and were mechanically connected to each of the aircraft control mechanisms. First debuted at the Airplane Safety Competition in 1914, the Sperry autopilot not only won first place in the competition, but also succeeded in stunning the crowd and earning him a number of contracts [1].
The most spectacular aspect of Sperry's demonstration was his final aerial pass, where his mechanic sat on one wing and he sat on the other, as the aircraft flew on its own.

Even more significant than the ability to fly a plane unassisted, when the first military demonstration of the system was given, spectators not only witnessed unassisted flight navigation, but a system that could also take off and land without human intervention. This shows that from their infancy, autopilot systems incorporated many of the same aspects as modern day systems.

![Figure 1: 1947 autopilot system [2]](image)

Despite his success, Sperry faced a number of systems engineering challenges during the invention of his device, however the greatest was caused by the fragmentation of the aircraft industry. Each manufacturer had their own way of
controlling aircraft and Sperry had to design a system that would interoperate with each of them.

**Modern Systems**

Modern autopilot systems are far more encompassing than the original system created by Sperry nearly 100 years ago. Most autopilot systems can now handle all aspect of flight, with the exception of taxiing, including: take-off, ascent, level, descent, approach and landing. These systems have gone from a simple tool to ease the burden of long flights to complicated systems capable of operating the entire aircraft.

As with autopilots in Sperry’s day, modern autopilots still have systems to control each of the flight axes, with these systems being intertwined to operate the aircraft. Below is a representation of one flight surface, with the communication and processing required for an autopilot system to function. The system operates as a loop, continuously providing feedback to the controller so aide in future decisions.

![Figure 2: Representation of autopilot control](image)

Page 7 of 20
In addition to being able to operate all aircraft systems, autopilots have become vital to the airline industry for cost and safety reasons. Autopilot systems typically fly an aircraft with less fuel consumption than a human pilot, reducing airline costs and increasing flight safety for passengers [2]. As example of how autopilots have increased safety, modern systems include intricate components capable of detecting and avoiding collisions with other objects and can allow aircraft to land in situations where a human cannot even see the runway. Of the FAA-defined landing categories shown below, autopilot systems are capable of all of them, though they are not authorized for Category IIIc.

1. ILS Category I - An ILS approach procedure that provides for approach to a height above touchdown of not less than 200 ft and with runway visual range of not less than 1,800 ft.
2. ILS Category II - An ILS approach procedure that provides for approach to a height above touchdown of not less than 100 ft and with runway visual range of not less than 1,200 ft.
3. ILS Category III—
   a. IIIA - An ILS approach procedure that provides for approach without a decision height minimum and with runway visual range of not less than 700 ft.
   b. IIIB - An ILS approach procedure that provides for approach without a decision height minimum and with runway visual range of not less than 150 ft.
   c. IIIC - An ILS approach procedure that provides for approach without a decision height minimum and without runway visual range minimum.

Table 1: Instrument landing categories [5]
While autopilots do not seem incredibly complex at first glance, in actuality they are multi-faceted systems interconnected to nearly every component on the aircraft, as well as many systems on the ground. Figure 2, above, outlined the basic mechanisms of just one subcomponent of a single autopilot subsystem. The rudder component must be combined with the other two flight axes, just to make up the basic flight subsystem of an autopilot system. On top of that, you have the interaction of the five other autopilot functionalities, as well as communication with ground based components. Ground communications include automated communication with flight control, receipt of outer marker indicators detailing proximity to airports and the intricate sensors required to remotely land an entire aircraft without human intervention.

Due to all the complexity of autopilot systems, it is possible that portions of the system, or the entire system, can fail. There have even been reports of airplane crashes due to autopilot failures. Fortunately, because of the way the systems are integrated into aircraft, no system can prevent a manual override, as long as the pilot first disengages the autopilot, which can be done two ways; either by flipping the power switch or else removing the circuit breaker. Flight recorder records indicate that crashes that were “caused” by the autopilot systems typically happened because a pilot did not disengage the system before attempting to manual resume control of the aircraft [2].
Non-Traditional Systems
In addition to the well known autopilot systems for aircraft, there are similar automatic control systems for a variety of other vehicles. While the details of these systems will not be examined in depth, a brief overview of these systems will highlight the similarities and differences to convention autopilot systems.

Unmanned Aerial Vehicle (UAV)
Though “unmanned aerial vehicle” is a term used to describe any type of remotely controlled aerial platform, it is most commonly associated with remotely controlled airplanes, so this section will deal primarily with that category of UAV. As could be expected, autopilot systems for remotely controlled airplanes include nearly all of the same features as their counterparts on conventional aircraft. UAV platforms share the same flight dynamics, the same systems and have similar takeoff and landing procedures.

The largest difference between the two platforms is the presence of a human to interact with the system. The first challenge that becomes obvious is how to communicate with the aircraft. This is done through one of two mechanisms – either a direct line of site communications link, or a Ku-band satellite link [6]. In the latter case, due to the nature of satellite communications, there is roughly a 600msec delay between a human control decision and the aircraft’s ability to respond, making timing critical. While reliable, these communications paths do fail, and in the event the UAV is left to navigate and fly on its own, typically executing a “return to home” routine or, worst case, crashing.
Another challenge of UAV autopilot systems is the event of a failure. Whereas in traditional aircraft a human is able to resume manual control of the vehicle, if the autopilot on a UAV fails, the pilot must remotely control the aircraft through a small view screen from a remote location, potentially navigating with over a half a second of latency in the control system. These challenges are not faced by pilots of conventional aircraft, making training for UAV “pilots” very unique.

**Space Shuttle**
While the space shuttle physically resembles a conventional airplane, in actuality its flight system is completely different, making the autopilot system worth mentioning. Unlike airplanes, which have control of engines, as well as mechanical devices that can physically alter each of the three flight axes, the
space shuttle “flies” primarily by controlling its engines. It could also be argued the space shuttle actually cannot fly at all, but instead can merely control its decent in the atmosphere through the use of its thrusters.

The launch and ascent of the space shuttle is an intricately controlled process, more like the launching of a missile, and as such we will not look at that process. What will be more interesting to examine is the return to Earth, and how the autopilot system aides in that process. In order for the space shuttle to return to Earth, it must execute a complex series of steps including a complete inversion (it orbits upside down), reducing velocity to de-orbit, passing through the atmosphere at a precise angle and gliding to a landing at a decent angle far greater than any commercial aircraft [7]. The autopilot system is responsible for executing each of these steps.

In addition to the complicated procedure above, the space shuttle autopilot system also requires precise timing. Since the aircraft is merely a glider, it is
unable to circle a runway for a second approach, so the timing must be exact. The return sequence is planned out in detail long before a launch ever takes place, based on the exact orbiting altitude of the space shuttle and a number of other variables, and typically has a small window each day when it can be executed. As routinely seen, if that return window is unable to be used, typically due to bad weather at the landing site, the shuttle must wait another day in orbit for its next decent opportunity.

**Automobile**
The last interesting autopilot concept to examine is for automobiles. While cruise control has been around for decades, a system to truly automate the driving experience still is not common. Though Lexus recently introduced a car that can parallel park itself, it still requires a human to position the car and control the pedals in order to operate. Autopilot systems for automobiles have been looked at in by a number of organizations, but most notably by the Defense Advanced Research Projects Agency (DARPA). DARPA is hoping to use this technology to automate battlefield vehicles, which could end up saving soldier's lives [8].

The biggest challenge of automobile-based autopilot systems is the proximity of other vehicles. Airplanes are dispersed throughout the sky and the space shuttle is unique, but the closest automobile may just be a few feet away. This creates an environment where an autopilot system has to be incredibly precise, in order to prevent serious accidents. Another serious challenge is varying
speed limits, and how to ensure the vehicle knows how fast it is able to drive. Once concept to solve this problem is intelligent highways, where portions of the highway will be “tagged” with relevant information, similar to how ILS sensors can help direct an aircraft to land on a runway. Similarly, these tags can be updated to indicate traffic, accidents or other situations that a vehicle will need to be aware of [9].

In terms of a practical application, General Motors plans to deploy a self-driving car in 2008, capable of traveling at up to 60 miles an hour. This vehicle will use lasers and cameras to detect obstacles and remain on the road [10].

![Figure 5: 2008 Opel Vectra, with autopilot [10]](image)

**Alignment with C4I Principles**
Though all autopilot systems discussed so far operate differently, on various vehicle platforms, it is obvious that they share many principles in terms of their structure, function and purpose. In addition, these systems also share similar alignment to each of the key principles used to describe C4I systems.

**Uncertainty**
Autopilot systems have two ties to uncertainty, the first of which is uncertainty in the systems themselves. Unfortunately, autopilot systems are full of uncertainty.
Uncertainty comes from the data that sensors are providing the system, the system’s interpretation of that data and possible erroneous control signals that are being outputted as a result. These unknown factors cause a number of problems for autopilot systems.

One key problem, briefly discussed earlier, was safety. While autopilots have been shown to make airplane flight safer as a whole, there have been times where the system itself, due to inaccurate data, has been the cause of accidents. Similarly, inaccurate data in UAV flights frequently results in the loss of these aircraft. Due to the serious consequences that uncertainty can have in an autopilot system, the ability for human override is critical to ensuring maximum safety.

The other aspect of uncertainty that autopilot systems deal in is human uncertainty. As discussed in table 1, there are numerous situations where a human is unable to make a decision on how to control a vehicle, for various reasons, including poor visibility, too high of a velocity, etc. It is in these situations, where a human is uncertain how to proceed correctly, that autopilots are relied upon to safely navigate.

**Timeliness**
Timeliness is probably the most critical principal that affects autopilot systems. After seeing the steps required for the space shuttle to return to earth properly, it should be obvious that timing is critical to any autopilot system. Due to the small
margin of error the space shuttle has for re-entering the atmosphere, the final engine burns must be precisely executed. Similarly, when dealing with conventional aircraft, the precise timing and feedback from the ILS sensors to the navigation computer to the wing flaps must be executed in an exact fashion to ensure an airplane safely lands.

Timing is also key to the success of UAV-based systems. In particular, due to the latency with which the sensors can relay data to the human who is in control of the aircraft, not only must maneuvers be executed on time, they must be done nearly a second in advance, or failure may occur.

An automobile-based system requires equal amounts of timing precision, despite traveling at much slower speeds. Due to the proximity of traffic and the fraction of time a system has to safely react, the sensors (video, laser, etc) must provide feedback in a timely manner, for the computer to make a decision on how to proceed. Though the severity of the situation is more difficult to see on a smaller scale, even a self-parking car must ensure the wheels are turned at the exact right moment, or a low-speed fender bender can occur.

**Hierarchy, Interaction and Interoperability**
As discussed with reference to each of the autopilots examined above, these systems are not simple. Autopilots rely on an immensely complicated set of subsystems that much interact together, in a precise manner, in order to accomplish their purpose.
Figure 2, above, showed the components of a rudder control subsystem. Within that figure were numerous components each of which has to interoperate with the others in order to simply control the rudder. When that is added to the systems to control the other two flight axes, the system to control the airspeed and landing gear and the system that talks to the instrument landing sensors, it is clear that without proper interaction, interoperability and a structured hierarchy, there would be chaos. Autopilot systems interact with every component of the vehicles they reside in, and as such must be incredibly precise in their actions.

**Human Aspect**
The human aspect of autopilot system comes in two forms. First, and foremost, autopilots are largely present in order to simplify the lives of humans. At the same time, they are charged with the safety of those lives. Secondly, autopilot systems typically have some sort of human override, so that manual intervention is possible in the event of a system failure. This ensures that while the autonomous system is in charge most of the time, the human intelligence is the final decision maker.

**Information Warfare**
As with virtually any system, if an enemy relies on its use, it can be exploited in the event of a war. The most obvious way to exploit autopilot systems is the same technique used to exploit GPS, and many other technologies: spoofing the sensors. If an enemy were to spoof autopilot ILS sensors, they could force an aircraft to land where this is no runway, or else give false indications of where
ground level truly was. If a plane were to attempt a landing, but did not know where ground level was, there would be no possible safe way for the aircraft to land.

**Survivability**
Just like all other systems charged with the responsibility for human safety, autopilot systems must be survivable. If an autopilot system was not robust, reliable and capable of functioning in virtually any situation, they could no be trusted to put into use.

**Conclusion**
Autopilot systems can be adapted to work in virtually any vehicle and environment. Though only a few were examined, it is clear that they share many of the same components, purposes and limitations, including their alignment with C4I principles.

Interestingly enough, the technology is not the limiting factor when it comes to autopilot systems. Current systems are far more capable than humans when it comes to the navigation and control of vehicles, including aircraft systems that can land a plane when humans are unable to even see out of the cockpit window. The major obstacle in the way of modern autopilot systems is the legislation on how they can be used. For example, airplanes are unable to perform stage IIIc landings with an autopilot engaged, as discussed in table 1. Ironically, it is precisely in these situations, when a human is unable to complete a task, where autopilots would be most beneficial.
Though Sperry's first autopilot systems were incredibly advanced, including even the capability to land without human intervention, his invention has gone through marked advancement in the last century and now works on virtually every vehicle that has been made.
References