Development of Urban Air Mobility (UAM) Vehicles for Ease of Operation

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Abstract. To date the air transportation system has been developed with the incremental introduction of new technology and with highly experienced air transport pilots and air traffic controllers overseeing flight operations. Thus, we currently have one of the safest commercial aviation systems in the world. General Aviation (GA) in the United States, however, has not always followed the same cautious and monitored approach to implementation; consequently, the GA safety record does not meet the high standards of commercial aviation. Recently, a new system known as Urban Air Mobility (UAM), is attracting considerable interest and investment from industry and government agencies. UAM refers to a system of passenger and small-cargo air transportation vehicles within an urban area with the goal of reducing the number of times we need to use our cars, thus improving urban traffic by moving people and cargo from crowded single passenger vehicles on our roads to personal and on-demand air vehicles. These UAM vehicles will be small and based on electric, Vertical-Take-Off-and-Landing (eVTOL) systems. A significant component of UAM is offloading of flight-management responsibilities from human pilots to newly-developed autonomy. Currently, over 100 UAM vehicles are either in development or production. Most, if not all, have a goal of fully autonomous vehicle operations, but fully autonomous flying vehicles are not expected in the near future. Therefore, we are developing concepts for UAM vehicles that will be easy to fly and/or manage by operators with minimal pilot training. In this paper we will discuss our human-automation teaming approach to develop an easy-to-operate VTOL aircraft, and some of the fly-by-wire technology needed to stabilize the vehicle so that a simple ecological mental model of the flying task can be implemented. We will discuss the requirements for a stability augmentation system that must be developed to support our simple pilot input model, and also present design guidelines and requirements based on a pilot input and management model. Finally, our approach to vehicle development will involve considerable operator testing and evaluation: improving pilot model, inceptors, displays and also work on a plan for how a UAM vehicle can be integrated with terminal area air traffic control airspace with minimal impact on controller workload.

Keywords: Urban Air Mobility, eVTOL, Stability Augmentation.

1 Why UAM?

A pressing issue in global ground transportation is traffic congestion in major metropolitan areas. In modern cities and suburbs drivers today spend hours in traffic during short trips. A global traffic scorecard published by INRIX in 2018 [1] showed that five of the most congested cities in the world are located in the United States. Also, according to INRIX, Los Angeles is the most congested city and drivers in Los Angeles spent an average of 102 hours annually in traffic jams during peak congestion hours, costing drivers $2,828 each and the city $19.2 billion from direct and indirect costs. Direct costs relate to the value of fuel and time wasted, and indirect costs refer to freight and business fees from company vehicles idling in traffic. Those fees are then passed on to households through higher prices.

The congestion data provides a view into each city's unique set of transportation problems and how they might be solved, or made worse, with technology and new forms of transportation such as ride-hailing, car-sharing, and eventually autonomous vehicles, both ground and air. Urban Air Mobility (UAM) is a term used to describe a system that enables on-demand, highly automated, passenger or cargo-carrying air transportation services within and around a metropolitan environment. It is expected that UAM vehicles will utilize electric vertical takeoff/landing (e-VTOL) procedures, fly at relatively low altitudes and require very high degrees of automation, up to and including full automation (self-piloted).

1.1 Current and Proposed UAM Areas of operations

In the latest survey of UAM operations, UAM systems are now operational in no less than 64 towns and cities globally. UAM airspace has recorded the launch of operational and research programs around the world. Below are four examples, most notability is the program in Iceland [2].

AHA and Flytrex Reykjavik, Iceland.

AHA and Flytrex have become the world leaders in UAM. The companies fly 13 routes, making deliveries to public pickup areas and backyards across Reykjavik. In 2015, AHA, one of Iceland's largest eCommerce companies, contracted with Flytrex, an Israeli company, to develop a global positioning system tracker and logistics system to support its drone delivery service concept. Their drones were not fitted with any sensors for traffic avoidance, cameras, radar or any vision systems. The drone flies a GPS coordinate path along routes certified clear of obstacles from where the food is prepared to their delivery location. Using the drone delivery service reduces delivery time from 25 minutes by road, to 4 minutes by air. AHA received the go ahead for the delivery operation from the Icelandic authorities in 2018. AHA's drone delivery approach would not be approved in most parts of the world and seems to violate the FAA’s beyond visual line of sight rules for drone operation [3].

Airbus Singapore, Malaysia.

Airbus recently signed an agreement with Civil Aviation Authority of Singapore (CAAS) to continue testing its Skyway air traffic manage (ATM) concept that uses autonomous technology to deliver 3D parts to ships docked in Singapore, and to deliver packages to a parcel station network on the campus of Singapore University. Through this network users will be able to send and receive important or urgent items, such as documents or small parcels. According to the Airbus “Wayfinder” Project Lead, the shift from automation to autonomy is not an all or none thing, but a tailored combination of humans and machines evolving over time to maintain or improve required levels of safety. Similar to the Boeing philosophy (see 2.0 Automation and Aviation Safety), systems are being managed by automation which allow the pilot to focus on dynamic situation assessment and decision making [4].

Tokyo Japan.

In Japan, Bell is partnering with Japan Airlines and Sumitomo, a global conglomerate with businesses in aerospace, transportation, construction and more. The group plans to use their individual business portfolios to support the development of the necessary infrastructure and business use cases for air mobility in Japan. In addition to building the aircraft, Bell is building the digital infrastructure to support the operation, maintenance and booking of air taxi services through its AerOS UAS Traffic Management (UTM) services. Since Japan does not allow individually-owned ride-sharing services, they expect to partner with taxi companies. These partnerships offer a great opportunity to move UAM from concept to implementation [2].

Uber USA.

Bell is also one of Uber’s many partners in the Elevate UAM Ecosystem concept that plans to bring airborne ride-sharing to Los Angeles, Dallas and Melbourne by 2023, with plans to later expand into Uber’s global ridesharing network [2].

1.2 UAM vehicle design and assumptions about Autonomy

Even though the talk of the UAM industry has been on the development of autonomous ridesharing and package delivery vehicles, all systems currently being developed to support these operations are expected to have either a ground or an onboard pilot. However, unlike ridesharing drivers who own and are licensed to operate their own vehicles, future UAM rideshare or ground pilots will need significant training to become certified for urban mobility operations. Given the pilot shortage forecasted by Boeing and the considerable time needed to train commercial pilots, we need to develop different approaches to shorten the training time to certification. One approach that our group is working on that was postulated by Goodrich and Schutte [5] was to reduce the complexity of the flying task. In the next section we will describe our human-centered model for controlling the aircraft and its implementation in our Cave Virtual Reality simulator.

2 Automation and Aviation Safety

The safety record of the U.S. commercial aircraft fleet has seen a steady improvement in safety with the incremental introduction of flight deck automation. With increased automation we have seen improvements in both economics and flight efficiency. Automation has allowed airlines to reduce the number of flight-crew-members and to improve all weather operations. According to Stoll from Boeing Commercial, during his presentation at a 1988 NASA/FAA/Industry workshop on Flight Deck Automation, there is no question that the reduction in human error rates and thus improvements in flight safety, are due in part to the introduction of automation on the flight deck [6]. The consensus of the workshop participants was that automation along with crew resources management improved systems' overall efficiency and reduces errors in the aggregate. Stoll, who presented Boeing's philosophy for transport automation, reported that Boeing follows a very straightforward approach to automation; simplicity first, followed by redundancy then finally automation. Norman [6] chaired the workshop and presented a number of examples of how automation and simplicity were used to reduce human error. One example that stood out was the automating of system functions necessary to fire wall the engines (advance throttles to max power) during go-around. After simplifying and automating subsystems, the pilots only needed to advance the throttles to full power during this critical phase of flight. Another member of the workshop, John Miller from Douglas Aircraft, emphasized the role of the pilot in any decision to automate functions on transport aircraft. Miller reported that Douglas' philosophy was that any irrevocable action required a manual pilot input. Both manufacturers' (Boeing and Douglas) design philosophies emphasize that the pilot should primarily be responsible for flying the aircraft, and that a minimum number of crew procedures will facilitate this philosophy.

Over the years Boeing has followed the automation philosophy outlined above except on their recent introduction of the maneuvering characteristics augmentation system (MCAS) in the 737 Max which has been blamed for two crashes in 2018 and 2019 [7]. Despite a few exceptions like this one, the aviation system has seen steady improvement in safety and efficiency.

Automation such as FMS, EICAS, and ECAM, has contributed to the reduction in the number of manual tasks performed by flight crews: increasing passenger comfort, improving flight path controls and expanding operations under reducing weather minimums. Automation has also played a central role in reducing the number of repetitive tasks, which humans are ill-suited for, through its ability to perform these tasks precisely when needed. For example, one of the many jobs of the flight engineer was to maintain cabin temperature; for the communication officer one task was position reporting during a trip. These tasks and jobs were eliminated by automation. Good automation has aided in reducing pilots' workload, freeing attentional resources to focus on other higher-level tasks. On the flipside, poorly designed automation has been shown to reduce pilots' situational awareness, particularly as it relates to monitoring and data entry, which places additional load on the pilot and may increase workload. Automation can be a real problem when misunderstood or misused; in the case of MCAS, automation could get the aircraft into undesirable states from which it is impossible to recover, when the pilot is hand-flying the aircraft.

2.1 Automation Philosophies

Woods [6] who also participated in the workshop, identified two automation philosophies: Human-centered and automation-centered. In his discussion of automation-centered technology, the human is a sub-component or an interchangeable part of the system, and the human or system agent can be substituted for one another without adverse impact on the system. On the other hand, for human-centered automation, Woods identified three important factors that make the automation human-centered. First the human must have the locus of control: 1) effective authority and responsibility, 2) control of the machine resources – ability to change or direct lower order machine agents, and 3) the automation should always provide support to the human – avoid cases where the system forces fully automated or fully manual operation. Second, the general role of the human is to supervise or monitor the activities of lower order processes. This role requires greater situation awareness to support situation assessment which allows the human to track the machine's state and to predict future states. Third, the automation should support the human's role in error detection and mitigation.

2.2 Function allocation

Miller and Stroll [6] also presented a chart similar to the one below which illustrates their automation philosophy by pilot function allocation. They postulated that sub-system management should be most amenable to automation because of the highly procedural nature of these tasks. Their philosophy also suggests that guidance and control would be the least amenable and should remain with the pilot because of the dynamic nature of these tasks.

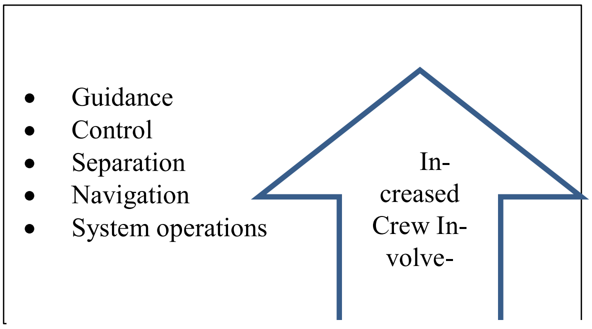

Fig. 1. Automation philosophy by function: guidance and control will be the most difficult to automate.

Although, most of the discussion about urban air mobility (UAM) has centered on autonomous-vehicle operations in urban environments, which will be discussed more later (see 4.0 UAM Vehicle Design and Assumptions about Autonomy), we should make clear the meaning of full autonomy. We should first define what we mean by autonomous flight operations, since we tend to use the terms “highly automated” and “autonomous” interchangeably. Lacher, Grabowski and Cook [8] in their paper on autonomy and trust in transportation, state, “autonomous systems decide for themselves what to do and when to do it.” Given this definition we can easily distinguish between a highly automated and an autonomous system. For example, many describe Global Hawk UAV flights as autonomous because after takeoff it can conduct a flight without interacting with a ground operator. More appropriately, the Global Hawk should be thought of as fully automated, given that it follows a pre-scripted mission plan, but cannot change its mission plan based on unanticipated changes in the aircraft or environment. We will use the term autonomous to mean a vehicle that requires no human interaction. Goodrich and Schutte [5] provided an assessment of the state of the art on autonomous vehicles from knowledgeable demonstration passengers who reported that while the technology was impressive, it had a long way to go before it achieved widespread public use.

Given the state of the art in autonomous vehicle technologies, most companies are resigned to the fact that UAM vehicles will need onboard or ground pilots for the foreseeable future. This factor presents an additional challenge to UAM implementation in the near term: the availability of appropriately trained UAM pilots.

3 Pilot shortage

According to Boeing, the aviation industry will need 804,000 new airline pilots worldwide between now and 2038 based on their aviation forecast [9]. This shortage will be due to fleet growth, retirement and attrition. This 20-year forecast shortage is based on the demand for commercial aviation aircraft with over 30 seats, business jets and commercial helicopter pilots. The shortage does not include the demand for UAM pilots over the same period. And since the projections for a fully autonomous UAM vehicle is not expected until ~2034 at the earliest, according to some estimates. Therefore, the success of UAM will depend on the success of recruitment and training efforts, combined with designing UAM vehicles that are easy to fly.

3.1 Time and Expense to training commercial pilot

The cost to earn a pilot license can range between $5K dollars and $16K, and require ~60 hours of flight time, depending on the school that you attend and the type of license you want to earn. Typically, a student starts with the private pilot license. To obtain a private pilot’s license requires knowledge, skills and risk management in pre/post flight planning, airport operations, slow flight and stalls, navigation, and air space operations. The cost including airplane rental fees, flight instructor time, ground school training, FAA test fees, other supplies and, to reduce airplane time, simulator cost. To carry passengers in visual meteorological conditions (VMC) a pilot needs a private license plus a commercial-license endorsement, another $6K and ~250 flight hours with an instructor. To carry passengers in all weather conditions, an instrument endorsement will be needed, another $7K and ~50 hours with an instructor. Based on today's requirements to safely operate a passenger-carrying helicopter in marginal weather conditions (special visual flight rules), one statue mile visibility, our pilot would have to spend $18K and ~350 hours of flight time. In addition to the commercial pilot certificate, the pilot must fly for a company that holds a Part 119 certificate for the operation or the pilot can obtain this certification for themselves [10]. Through our human-centered vehicle design and interfaces, we can reduce pilot training time and the cost to train UAM pilots.

3.2 Rotorcraft Pilot

Training for rotorcraft pilots is more critical: The Joint Helicopter Safety Analysis Team (JHSAT) reported that 68% of calendar year 2006 helicopter accidents were attributed to poor pilot judgement." It was also found that 18% of all accidents occurred during training, highlighting the need for more training. Also, Rao and Marais [11] analyzed 5051 accidents between 1982-2008. The top-five hazardous states were caused by inflight loss of control, control flight into terrain, weather and failure to maintain physical clearance/altitude from objects.

3.3 Type Ratings

At the present time it is difficult to estimate what training will be required to manage the first generation of urban air vehicles given that over 100 different vehicles are being proposed and/or already in production. Additionally, the procedures needed for interfacing with the air traffic management system in today's national airspace have yet to be established. A number of concepts have suggested that two separate systems need to be developed, given the increased volume of traffic. However, there will be points where the systems will come together and need to coordinate separation and control responsibility. If UAM vehicles will be transporting goods and passengers to and from major airports, there will be places where the systems will need to either transfer control responsibility or coordinate to maintain current levels of safety. To support aircraft conducting visual flight rules with the vehicles providing self-separation, new rules will need to be developed. In addition, new protocols for digital or verbal communication will be required to transition between the two systems. At a minimum, however, simplifying the UAM vehicle aviate and tactical navigation tasks, with simplified interfaces augmented with automation, will be an important step in freeing up pilot resources so that they can take on the additional communication and coordination tasks.

4 UAM vehicle design and assumptions about autonomy

4.1 Aerial Vehicle Model

We modelled the virtual aircraft as an enlarged quadcopter that can take off and land vertically [12]. The vehicle was modified from a hexacopter 3D drone model available through the Professional Drone Pack (Professional Assets, Unity Asset Store [13]). The interior and the exterior of the original drone model were modified using open-source 3D computer graphics software, Blender, to create a quadcopter that is scaled to fit 2-4 passengers with cockpit displays of heading and speed for the pilot. It is important to note that the dynamics of the vehicle are based on a simple rigid body model. Several modifications were made to the exterior of the vehicle, including moving the propellers above the pilot's line of sight and using a darker color to increase its visibility when flying around and over buildings.

4.2 Initial flight control inceptor implementation

Goodrich et. al.,[5] in their discussion of haptic-multimodal flight controls suggested that loss of control and avoiding hazardous weather, terrain, obstructions and traffic would eliminate approximately 80% of current fatal accidents. Moreover, the key to achieving the desired increase in safety is preventing loss of control. They also suggested that the most important component of training is the amount of effort spent becoming proficient at basic flying skills. These skills are learning to manipulate flight control (stick and rudder) and throttle to make the vehicle go where directed. Our simplified ecological, human-centered model for controlling the quadcopter focuses on mapping action/inputs to the pilot world view.

The model supports two modes. The first mode "Hover" allows the operator to maneuver the vehicle during operations at speeds below 5kts. In Hover mode, no winds, the aircraft can climb or descend or rotate around the vertical using buttons 2-5, see Figure 2. To climb press and hold button 3, to descend press button 2, to turn right press the right button 5 and to turn left press the left button 4 on the joystick [12]. These controls support hovering in the vehicle's current location while rotating around the vertical axes. For example, if the vehicle was heading/pointing north and the right joystick button was pressed the heading would change in an easterly direction; if the left button was pressed the heading would change in a westerly direction. In the hover-only mode, when the pilot pulls back on the stick the vehicle moves rearward; when the stick is pushed forward the vehicle moves forward. These controls map onto the pilots' world view of the movement of the vehicle and were easy to learn, with the sky being back or up and the ground being forward or down (see Figure 2, for a depiction of the controls).

Fig. 2. Hover Mode vehicle controls.

Fig. 3. Flight Mode Stick inputs.

Fig. 4. Trigger to set current forward speed.

The second mode is the “Flight” mode which integrates the throttles for forward speed into the forward deflection of the joystick. This allows the operator to point the vehicle in the direction they want to go while increasing forward speed. When the vehicle reaches the desired speed the operator/pilot uses the trigger on the joystick, (see Figure 4), to set the speed and direction of the vehicle with one simple input. To increase speed the operator just pushes forward on the stick or to reduce speed pulls back on the stick; and again, when the desired speed is reached the operator toggles the trigger to again set the forward speed. With the vehicle moving in the desired direction at the desired speed the operator can remove all forces from the stick, again making the vehicle easy to manage.

Until we reach full autonomy, pilot-in-the-loop flight will be the norm and we must design flight deck interfaces to reduce the effort of managing the flight tasks so we can reduce training time. Our initial design configuration that supports the aviate and tactical navigation tasks primarily is very much in line with our initial Concept-of-Operations (ConOps) where the operator/pilot manages the vehicle along a predefined route in visual meteorological conditions (VMC) using visual references in the terrain (pilotage); i.e., Bay Bridge, highways, San Francisco Bay at Candlestick point, Oracle Towers and the SFO Control Tower.

Current day VFR pilots have three primary tasks: Aviate, Navigate and Communicate. This paper will primarily focus on the Aviate and Navigate tasks and offer considerations for making the vehicle easy to fly and manage. According to the Boeing philosophy, we can either build a vehicle and then define the training required to manage it or start with a concept of a very stable vehicle and then design a human-centered interface that matches the new operator’s mental model? As the discussion above shows, we started with a good mental model of the operator and the task to be performed and now we are beginning the process of mapping the operational concept and pilot model onto the UAM vehicle.

5 Vehicle stability augmentations

5.1 Stability Augmentation

An important task for any pilot is aviate. Therefore, making the UAM vehicle easy to fly and safe, will require vehicle stability augmentation. In our discussion so far, we have not dealt with low speed operations in windy conditions. When flying in major cities our UAM vehicle and pilot may experience rapid changes in wind direction and velocity due to urban canyons. Wikipedia describes an Urban Canyon as a place where the street is flanked by buildings on both sides creating a canyon-like environment. Such human-built canyons are created when streets separate dense blocks of structures, especially skyscrapers. This topic is important for UAM because UAM vertiports will be located in and around the city centers, where UAM vehicles will be picking up and delivering passengers and cargo. Some of the unusual flight characteristics of Urban Canyons are rapid changes in winds, temperature and views of the sky which will affect the stability of the vehicle and its access to GPS positioning data. For this paper we will only address the effects of rapidly changing wind speed and direction. The unique thing about urban canyons is that these changes can happen at any street intersection, and due to changes in temperature may occur mid-block. To anticipate these rapid or sudden changes, a stability augmentation system will be needed. Goodrich, et.al, [5] discussed the need for a stability augmentation system to make the vehicle easy to fly. They cited multiple simulation studies that have shown the benefits of pathway-in-the-sky displays to intuitively show where the vehicle should be flown combined with flight-by-wire (FBW) or -by-light (FBL) controls that significantly reduce the complexity of the manual control task of flying the vehicle. A FBW system is the complete replacement of the mechanical linkages between the pilot's stick and the control surface actuators using electrical signal wires. As aircraft have become more complex and unstable, manufacturers have added increased stability augmentation to reduce the complexity of the flight control task and cognitive demands on the pilot. For a history of stability augmentation and how the systems have evolved see Garg, Linda, and Chowdhury, [14].

5.2 No Augmentation.

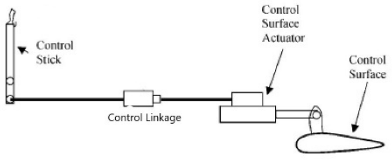

Fig. 5. Simple illustration of single path control system.

Stability augmentation systems (SAS) have been used in the past to allow us to fly even the most unstable vehicles. However, before discussing the first systems we will describe a system without stability augmentation where there is a single path to the controlling surface linked to a stick controlled by the pilot (Figure 5) [15].

5.3 Initial Stability Augmentation System

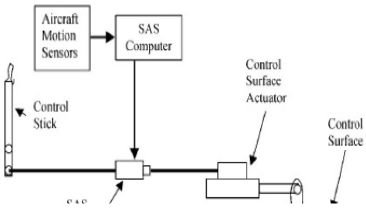

Fig. 6. Simple illustration of Stability Augmentation System.

SAS was the first feedback control system design intended to improve dynamic stability characteristics of an aircraft. In a SAS system there are two paths to the SAS Actuator and thus, to the control surface – input from aircraft motion sensors, and input from pilot/flight stick. SAS was implemented in several century series fighters (F4, F104, T38, etc.) and was found to be very effective but SAS had its drawbacks: pilot input and SAS computer input sometimes were in conflict and limited control authority (no more than 10%) was given to the SAS computer.

5.4 Control Augmentation System

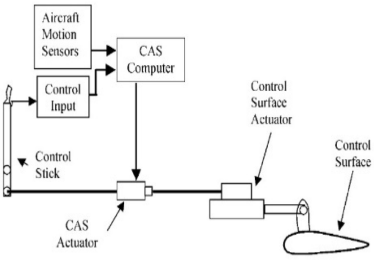

Fig. 7. Simple illustration of Control Augmentation System.

An improvement to SAS was the implementation of a Control Augmentation System (CAS). This system also had two paths to the flight control actuator but had two significant improvements to the SAS; flight stick input also went directly into the CAS computer and CAS control authority was increased to 50%. With CAS, the aircraft's dynamic motion response was well-damped, and control response is scheduled with the control system gains to maintain desirable characteristics throughout the flight envelope. CAS provided dramatic improvements in aircraft handling qualities. Both dynamic stability and control response characteristics could be tailored and optimized to the mission of the aircraft. CAS was implemented in aircraft such as the A-7, F-111, F-14, and F-15.

5.5 Fly-By-Wire Augmentation

The last augmentation system, one in use on most new fighter and commercial jet and propeller aircraft, is the Fly-By-Wire or By-Light system. In this system all pilot input, as well as information on dynamic motion, goes through the FBW computer which controls the FBW actuator/flight controls, thus reducing the need to schedule inputs since the FBW computer has full control authority based on pilot input and dynamic motions of the aircraft, See Figure 8. With full authority to dampen all undesirable motion in Roll, Pitch, Yaw, Load and Angle of attack due to environmental factors, the vehicle can be made stable in most flight regimes. The two major commercial aircraft manufacturers have two very different philosophies to implement their augmentation systems. For Airbus the final control authority is given to the FBW computer that tries to make sure that the vehicle does not get into any unusual altitudes (stall, fly into the terrain, or other malfunctions). Conversely, Boeing gives final control authority to the pilot allow them to push through FBW Computer inputs that are designed to prevent stalls and system malfunctions.

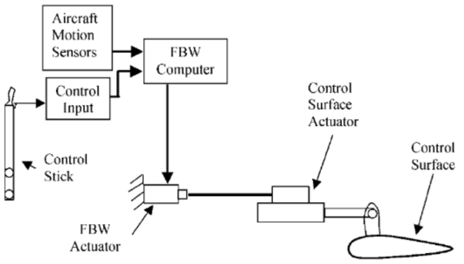

Fig. 8. Simple illustration of Fly By Wire Augmentation: no direct stick input.

With a stable platform, our next task is to design a user interface that is ecologically aligned with the pilot/operator mental model for moving the vehicle through all flight regimes from departure to landing.

6 Conclusions: UAM Vehicle and Mission

If our industry is to meet the demand for UAM pilots to support the current vision of on-demand ride sharing and UAM package delivery we must reduce the time required for pilots to achieve full proficiency in the many envisioned UAM vehicles proposed. In this paper we highlighted an approach to UAM vehicle design that will make the vehicle easy to operate, reducing training time and time to certification. It is important, we believe, to make the vehicle easy to fly. We proposed a human-centered approach by teaming the automation with the human pilot through an intuitive mental model of tasks and direct mapping of inceptor input to task goals so as to directly command the velocity vector of the aircraft coupled with stability augmentation to create a stable platform that is easy to fly and will be acceptable to UAM ride-sharing passengers.

Our initial design of the input controls that make the vehicle easy to fly has only been evaluated by its developers and will be tested in our near-term studies. We expect these initial concepts will evolve to support a true operator-centered system for controlling and managing the vehicle and the strategic navigation and communication tasks of the UAM pilot. And we hope that by highlighting the need for FBW control systems, others will also see the need to build these systems into the design. Although we did not explicitly discuss Human Autonomy Teaming, it will be this coupling of humans with well-designed human-centered automation that will eventually aid us in achieving truly autonomous UAM flight.

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