Manned-Unmanned Aircraft Teaming

Mohammad H. Sadraey
Associate Professor
College of Engineering, Technology, and Aeronautics,
Southern New Hampshire University
Manchester, NH, 03106
m.sadraey@snhu.edu

Abstract - **Unmanned aerial vehicles, due to their incredible development, relatively low cost, and low risk to human can become a prime candidate for the teaming with manned aircraft in performing complex/dangerous missions. There are various challenges and techniques for manned-unmanned aircraft collaboration. This paper introduces the concept of manned-unmanned aircraft teaming, as well as teaming categories. The technical differences between two team members; namely human pilot and autopilot are discussed. In addition, the teaming formulation, teaming laws, decision making process and communication between human pilot and autopilot is developed. An optimal control law for the state-space representation of the teaming is finally presented.**

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1. INTRODUCTION

Today's aircraft inventory includes a diverse mix of manned and unmanned systems. Unmanned aerial vehicles, are a prime candidate for the teaming with manned aircraft in performing complex/dangerous missions. The statistics is growing exponentially. Unmanned aircraft systems are subject to regulation by the FAA to ensure safety of flight, and safety of people and property on the ground. Incidents involving unauthorized and unsafe use of small, remote-controlled aircraft have risen dramatically. Pilot reports of interactions with suspected unmanned aircraft have increased from 238 sightings in all of 2014 to 780 through August of 2015. One of the main goals for the manned-unmanned teaming is to provide flexible flight operations. Teaming a UAV system with manned systems will offer advantage to both.

To achieve the full potential of unmanned systems at an affordable cost, efforts must be conducted to implement technologies and evolve tactics, techniques and procedures that improve the teaming of unmanned systems with the manned aircraft. In flight teaming cases, overall system designers should engineer a platform to support the human in the loop and maximize their chances of performing their critical functions successfully. A framework needs to be developed to analyze the root cause of failures that have been attributed to "human error", or system error. An efficient teaming will create an environment such that both parties operate within their limits, while generating an unachievable goal by one party.

In a conventional autopilot, three laws are governing simultaneously in three subsystems: 1. Control system through a control law, 2. Guidance system via a guidance law, and 3. Navigation system through a navigation law. The relation between the control system, the guidance system, and the navigation system is shown in Figures 2 and 3.

A literature survey has indicated various papers and technical documents has investigated many aspects of manned-unmanned teaming. Unmanned vehicles systems are being introduced into Army systems to extend manned capabilities and act as "force multipliers" [1]. Ref [2] has presented the collaborative autonomy for manned/unmanned teams. Ref. [3] has explored the expansion of the envelope of unmanned aircraft systems operational employment for manned-unmanned teaming. Accuracy assessment of professional grade unmanned systems for high precision airborne mapping is investigated in ref [4]. Ref. [5] has presented a perspective on the autonomous control challenges for UAVs as a researcher point of view.

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Autonomous vehicle technologies for small fixed-wing UAVs has been discussed in Ref. [6]. There are a number of consequences for UAV design requirements especially on UAV modeling and simulation, some of which have been investigated in Ref. [7]. The augmentations, motivations, and directions for aeronautics applications of man–machine integration design and analysis system has been explored in Ref. [8].

Ref. [9] developed new methodologies and quantitative measurements for evaluating human-robot team performance to achieve effective coordination between teams of humans and unmanned vehicles. Significant challenges facing a successful teaming is presented in the next section. A team of a manned aircraft and an UAV in a flight mission is a complex system (Ref. [10]), and requires the approach of systems engineering.

This paper is organized as follows. Section 2 will present pre-requisites of manned-unmanned teaming and introduces new technologies and techniques that must be develop to realize this concept. The technical differences between two team members; namely human pilot and autopilot is discussed in section 3. Categories of teaming techniques, as well as the teaming formulation, teaming laws, and decision making process is developed in section 4. Since the human pilot needs to make decision in working with an autopilot, the decision making process in briefly described in section 5. For the category of manned-aircraft-leader, UAV-follower; Section 6 provides the line-of-sight law for the guidance system of the UAV. In section 7, the communication process between UAV autopilot and the pilot of manned aircraft is described. Finally in section 8, the teaming law is derived.

2. Pre-requisites of Manned-Unmanned Teaming

The functions of a UAV in a team with manned aircraft depend in nature on the different UAV configurations and their characteristics. To this end, the critical challenges must be identified for further growth to fulfill expanding UAV roles in supporting the aviation safety goals in a team with a manned aircraft. Moreover, new technologies need to be developed, and new regulations must be prepared.in this section, pre-requisites of manned-unmanned teaming are briefly described.

Collision avoidance is a primary concern to the FAA regarding aircraft safety. UAVs are seen as potential key airspace users in the future of air transportation, which necessitates additional research and study of safety measures. One of the major limitations to the widespread use of unmanned vehicles in civilian airspace has been the detect-and-avoid problem. In manned civilian aviation, "see-and-avoid" is the primary mechanism by which piloted aircraft avoid collisions with each other. Obviously, this is impractical for widespread use of unmanned vehicles, so they must achieve an equivalent level of safety/reliability/assurance to that of manned aircraft operations. Currently, the traffic alert and collision avoidance system (TCAS) is the primary cooperative collision avoidance system and is in use by a variety of airspace users.

There is currently a large amount of research projects being conducted in the area of detect-and-avoid. Active solutions include the use of machine vision, and GPS/radar to detect collision threats, and precision control to avoid collision. However, the current adapting technologies are not at such reliable level. In addition, high computational requirement is another obstacle. A major design issue of UAVs is that any black box is additional weight, and weight restrictions for some smaller UAVs may restrict UAV functionality or the inclusion of cooperative systems.

Another challenge in the execution of automated control is the automated recovery. Here the recovery could be either regular automated landing or to recover by some means such as a net. Since physical pilot control is not present, there is a high potential for unsuccessful recovery. The UAV must have a number of fail-safes in place in case of any elemental failure. Another source of failure is communication failure or link loss. In the event that, command and control links have been completely severed between an UAV and the manned aircraft, the UAV should be switched to pre-programmed mode to attempt for some fixed period of time to re-establish communications, or to independently complete the mission. This is another big area of research for several research institutes and UAV industries.

Unscheduled UAV maintenance creates a lot issues and cost for large UAV operator units, because spare parts are not always available at any place and sometimes have to be shipped across the world. Moreover, if a flight mission has to be canceled or even delayed, the UAV causes significant costs. Hence, reducing the number of unscheduled maintenance is a great cost factor for UAV operators. For this objective, and to ensure the integrity of the UAV systems, fault monitoring must be continually conducted on flight. Fault monitoring ensures that undetected system faults will not lead to a catastrophic failure of the aircraft's systems which may eventually lead to human casualties on the ground.

Failure prediction is the combination of condition (i.e., health) monitoring and condition prediction to forecast when a failure will happen. The objectives of Fault Monitoring are: 1. Reduction of unscheduled maintenance, 2. Advanced failure prediction, 3. Condition monitoring, 4. Ability to better plan maintenance, and finally 5. Prevent failures. In the event of system faults, the UAV must have the capability to reconfigure itself and re-plan its flight path in a fail-safe manner. The predictive UAV health monitoring is able to predict failures so that maintenance can be planned ahead.

An intelligent UAV system must have the ability to plan and re-plan its own flight path, to cope with undesired situations. This results in the requirement for advance sensors, and a high-level computing environment where flight planning algorithms can be executed. The intelligent flight planning requires a significant improvement in software and hardware performance. The flight planning process requires knowledge of the UAV's surroundings; including airspace, terrain, other traffic, weather, restricted areas obstacles and closest airfield. The UAV must plan the optimal route for its mission, considering the local environment, to minimize the flight time and fuel usage. The intelligent planning will detect any incoming aircraft for collision avoidance.

The core components of autonomy are command, control, navigation and guidance. Higher levels of autonomy, which reduces operator workload, include (in increasing order) sense-and-avoid, fault monitoring, intelligent flight planning and reconfiguration. An autonomous behavior includes observe, orient, decide, and act. The aviation industry objective is that eventually autonomous UAV will be able to operate without human intervention across all flight sectors. Such objective requires advances in various technologies including guidance system, navigation system, control system, sensors, avionics, communication systems, infrastructures, and software, microprocessors. This paper will present elements and requirements for manned-unmanned aircraft teaming. In addition, it investigate the communication and management techniques which enables objectives such as safety, effectiveness, and integration.

This paper will investigates and present elements and requirements for manned-unmanned aircraft teaming. In addition, it will provide the communication and management techniques which enables objectives such as safety, effectiveness, and integration. Moreover, a few experiments (Team of an UAV and a manned aircraft) will be conducted to make sure the new system is working and efficient.

3. TEAMING PROBLEM FORMULATION

Formulation of manned-unmanned teaming problem basically requires mathematical modeling of UAV flight dynamics, human decision making process, and communication between human and autopilot. Figure 1 demonstrates the functional block diagram of a teaming flight operation. In principle, there are two independent decision makers: 1. Autopilot for UAV, and 2. Human pilot for the manned aircraft. Moreover, there are two separate trajectories, and two feedbacks. The teaming law creates command for both manned and unmanned aircraft. There is one group of input (mission parameters) and two outputs (i.e., trajectories). Both trajectories are fed back to the same point for comparison with the mission input. Any difference will create an error signal for the teaming law block. The teaming law will generate two signals; one for the pilot of maned aircraft, and one for the autopilot of the UAV.

Figure 1 contains information concerning dynamic behavior, but it does not include any information on the physical construction of the team. The mathematical model of aircraft/UAV (dynamics model), and autopilot have been provided by ref. [12]. In this paper, a mathematical model for the decision making process of the pilot will be discussed. In addition, a teaming law will be presented in Section 4. In general, there are three categories of teaming, each governed by a distinct law: 1. UAV-leader, manned-aircraft-follower; 2. manned-aircraft-leader, UAV-follower; and 3. mixed leader-follower.

Each teaming case has a number of advantages and disadvantages, and suited for specific applications and flight missions. For instance, the teaming category 1 (i.e., UAV-leader, manned-aircraft-follower), is appropriate for a flight mission where the operation involves some hazards to human. Two examples for teaming category one are: 1. Observing a volcano, 2. Monitoring a target in the enemy zone for a military mission. In such a mission, the UAV takes the lead and the manned aircraft will follow suit. If any hazard arises, the UAV will be the first to face and handle it. This category will guarantee the safety of human plot in the manned aircraft. A pictorial representation of the functions performed by each team member in the category 1 is illustrated in figure 2.

The UAV flight parameters are measured by both UAV avionics and manned aircraft measurement devices. Thus, the manned aircraft has two feedbacks; one from the UAV, and one from its own flight. The UAV will fly to accomplish the trajectory as the leader, while the manned aircraft will be guided and controlled based on the teaming law. The pilot decision making process has overlap with the teaming law, as he/she uses the eyes as a navigation instrument.

However, the teaming category 2 is appropriate for a flight mission where the UAV acts as a reserve and no hazard is involved to human pilot. The teaming law for this category may be based on many already developed techniques and guidance laws. One simple and effective guidance law is the line of sight and is presented in Section 5.

In the second category (figure 3), the manned aircraft flight parameters are measured by both UAV avionics and manned aircraft measurement devices, as well as the pilot's eyes. Thus, the UAV has two feedbacks; one from the manned-aircraft-leader and one from its own flight. The manned aircraft (human pilot) will fly to accomplish the mission trajectory as the leader, while the UAV will be guided and controlled based on the teaming law. The pilot decision making process could be independent from the teaming law, as he/she plays the role of the leader.

The third teaming category is the most challenging one and requires the development of a new communication system between human pilot and autopilot. Theory, concepts, challenges of human communication is presented by Ref. [11]. The mathematical formulations of control systems, guidance systems, and navigation systems are presented by many books and papers including Ref. [12]. This paper mainly concentrates on the formulation of communication system between manned and unmanned aircraft as well as the teaming law.

4. Technical Features of Team Members

A manned-unmanned aircraft team have at least two distinct piloting members, namely a human pilot, and an autopilot. There are various technical differences between capabilities of human pilot and autopilot where a teaming protocol must consider. Human has various limitations (power, size, tolerance). For instance, human pilot needs rest, is not very accurate, and may get sick. Moreover, human is [13] incapable of securely storing high-quality cryptographic keys, and they have unacceptable speed and accuracy when performing cryptographic operations. They are also large, expensive to maintain, difficult to manage, and they pollute the environment. It is true that these human elements continue to be created and deployed. But they are sufficiently pervasive that we must design our protocols around their limitations.

Table 1 provides a technical comparison between features of a human pilot and an autopilot and avionics. There are some weaknesses for a human pilot (e.g., short endurance) and a number of strengths (e.g., survivability) that an autopilot lacks. However, there are some weaknesses for an autopilot (e.g., no verbal communication) and a number of strengths (e.g., IR/radar sensors) that a human pilot lacks. A teaming framework must be designed such that these two players can overlap their roles. An efficient teaming will create an environment such that both parties operate within their limits, while generating an unachievable goal by one party.

The weaknesses/strengths of each team member must be included in the determination of teaming category, and also in evaluation of the mission efficiency.

5. Decision Making Process

In the manned-unmanned teaming, the UAV autopilot will perform based on the control law and guidance law which have been programmed for. However, the pilot of the manned aircraft should make decision at every instance before any Implementation. Decision making is a vital skill in the pilot side of the teaming, particularly when the manned aircraft is the follower. Following a logical procedure along with being aware of common challenges, can help ensure both best decision making and a safe flight. The following are the basic steps (Figure 4) of the decision making process.

1. **Define the problem.** The first step in making the right decision is recognizing the teaming problem and deciding to address it. Determine why this decision will make the flight safe and successful.
2. **Collect data.** Second step is to gather flight data information so that pilot can make an aircraft control decision based on real flight data. This requires making a value judgment, determining what information is relevant to the decision, along with where to find it.
3. **Identify alternatives.** Once pilot have a clear understanding of the issue, it's time to identify the various solutions at your disposal. It's likely that you have many different options when it comes to making your decision, so it is important to come up with a range of options. This helps you determine which course of action is the best way to achieve your objective.
4. **Weigh the evidence.** Now, pilot will need to evaluate the feasibility and acceptability of various alternatives. Pilot should weigh pros and cons, then select the option that has the highest chances of success.
5. **Choose among alternatives.** When it's time to make the decision, make sure that you understand the risks involved with your chosen course of action.
6. **Implement the decision.** You should create a plan for implementation. This involves identifying what components and equipment are utilized.

7. **Evaluate the consequences.** You need to observe the consequences; and to evaluate the decision for effectiveness.

The decision making process which is illustrated in figure 4 will be formulated in the section 8. Common challenges of decision making are: 1. having not enough information, 2. misidentifying the problem, 3. Overconfidence in the outcome.

6. LINE-OF-SIGHT GUIDANCE LAW

In the category of manned-aircraft-leader, and UAV-follower; the UAV employs a guidance law to follow the manned aircraft. One of the efficient guidance laws for this category is the light-of-sight. Guidance is defined as the process of producing a trajectory based on what is received from the command subsystem and the feedback from the navigation system. The guidance subsystem produces the desired states which go to the control subsystem. The output of the guidance subsystem is sent to the control subsystem; based on the guidance law. The control system implements this command through actuators driving control surfaces such as the elevator, aileron, and rudder. Guidance is mainly responsible for measuring and controlling the flight variables including the aircraft's angles, the rate of change of the angles, and the body axis accelerations. The navigation system calculates the location of the aircraft, compares it with the pre-determined reference trajectory, and modifies the autopilot commands to drive the error to zero. The guidance subsystem often produces an acceleration command. Thus, the guidance subsystem makes the necessary correction to keep the vehicle on course by sending the proper signal to the control system of an autopilot.

The guidance system categories includes: 1. Line Of Sight, 2. Navigation Guidance (e.g., Inertial Navigation, GPS), and 3. Homing (e.g. radar, infra-red, and television). The typical guidance law includes: 1. Collision, 2. Proportional navigation guidance, 3. Constant Beam Course, 4. Pursuit Guidance, 5. Three Point Guidance, 6. Optimal control guidance, 7. Lead Guidance, 8. Lead Angle, 9. Preset.

In general, the primary criteria for the design of guidance system are as follows: 1. manufacturing technology, 2. required accuracy, 3. range, 4. structural stiffness, 5. load factor, 6. weather, 7. maneuverability, 8. reliability, 9. life-cycle cost, 10. UAV configuration, 11. stealth requirements, 12. Maintainability, 13. endurance, 14. Communication system, 15. aerodynamic considerations, 16. Processor, 17. complexity of trajectory, 18. compatibility with control system, 19. compatibility with navigation system, and 20. weight.

The type of guidance system used depends upon the type and mission of the UAV being controlled, and they can vary in complexity such as an inertial guidance system. In any case, the guidance command serves as the input to the UAV control system. The command may be in the form of a heading or attitude command, a pitching or turning rate command, or a pitch or yaw acceleration command, depending upon the type of guidance scheme used. There are several guidance laws and several guidance system types. In the second category of teaming, a line-of-sight guidance law is advised. Basically, an imaginary line between the follower-UAV to the leader aircraft referred to as line-of-sight (LOS). In this category, a spatial distance between two team members and a desired LOS are determined.

Based on the line-of-sight guidance law, the follower-UAV is guided so as to remain on the commanded LOS and required distance. Based on the desired flight mission, the following relationships may be derived by observation:

$$\Psi_F - \Psi_L = a \tag{1}$$

where parameter "a" could be any angle between -90 to +90 degrees and is a function the distance between two aircraft. In addition, the LOS azimuth angle (Ψ_{LOS}); the angle between the LOS and the North (Figure 5); may be any angle between -45 to +45 degrees.

$$-45\deg < \Psi_{LOS} < +45\deg \tag{2}$$

When the follower-UAV is turning/climbing/descending, the spatial distance with the leader aircraft is achieved using the engine throttle and control surfaces. When is different than the desired value, the throttle is deflected in order to increase/decrease the engine thrust and accelerate/decelerate the UAV. Moreover, the control surfaces are deflected to change the attitude angles. As an example, for the case of a team of two aircraft to circle around a target (Figure 6), the LOS angle is best to be 45 degrees.

In case that the angle between LOS and the follower UAV heading angle is less than 45 degrees, the throttle is deflected such that to decrease the engine thrust and decelerate the UAV. As soon as the follower UAV is reached to the commanded circle around the target and stabilized, the guidance system will be activated to guide the UAV such that to keep a constant 45 degree of line-of-sight angle. When the follower UAV's line-of-sight is different than the commanded LOS, the guidance system generates a yaw rate (R) and a change in the UAV linear speed (i.e., $\dot{U}$) for control system:

$$R = k_1\left(\Psi_{LOS} - \Psi_{LOS_C}\right) \tag{3}$$

$$\dot{U} = k_2 \cdot D_{LF} \tag{4}$$

where k_1 and k_2 are constants, and D_{LF} denotes the distance between the follower UAV and the leader UVA. The constants k_1 and k_2 are derived such that engine throttle and rudder deflection are employed to restore the LOS. The LOS variables are available in both manned and unmanned aircraft from the use of onboard vision sensors.

7. Communication Process

In section 3, three possible configurations were considered in the maned-unmanned aircraft teaming. In all three cases, there must be a communication system available and working in entire flight mission. An important aspect of a manned-unmanned aircraft teaming is the communication between UAV autopilot and the pilot of manned aircraft. In this section, the communication process for the third teaming configuration (i.e., mixed leader-follower) is explored. As a basic case, a team of only two members; one UAV, and one manned aircraft is considered.

Figure 7 demonstrates the block diagram including the communication process for a team of two members (one manned, and one unmanned aircraft) in the mixed leader-follower configuration. Bothe team members have the same mission (e.g., engaging with one target), but each member has a separate but coordinated trajectory. The coordination is created through an effective communication system based on the teaming law. The process involves four feedbacks; two for manned aircraft, and two for UAV. Moreover, there are four error signal; two signals in the UAV control/guidance system, and two signals in the manned aircraft control/guidance system.

As expected, the human pilot talks (creates a voice signal) to communicate with the UAV, but the UAV creates a written text to communicate with the manned aircraft. A Voice-to-Text (V/T) converter in the manned aircraft will converts the voice of human pilot to a text. Then, a transmitter send this text out to UAV as a radio wave. The UAV receiver will then receive this signal, and the autopilot will process and employ this signal in controlling the UAV. The processor of such signal will be in the microcontroller.

In the meantime, when the UAV creates a signal for delivering to the manned aircraft, the signal will be transmitted through the UAV transmitter to the manned aircraft. When the manned aircraft receiver receives such signal, it will process the signal and creates a text. The last step is for the manned aircraft Text-to-Voice (T/V) converter to convert the UAV signal to a voice. When the pilot hears the voice, he/she will process/make-decision/react to the signal according to the teaming law and the required mission. The necessary technology for voice-to-text and text-to-voice has long been developed and practiced. The challenges and opportunities of speech-to-text conversion in real-time have been discussed in [16].

The UAV must have a number of fail-safes in place in case of any elemental failure. A source of failure is communication failure or link loss. In the event that, links have been completely severed between an UAV and the manned aircraft, the UAV should be switched to pre-programmed mode to attempt for some fixed period of time to re-establish communications, or to independently complete the mission.

8. Teaming Laws

In order to begin the synthesis of the teaming law, the design requirements relative to both parties must be technically established. Based on handling qualities [14], and also airworthiness standards [15], the following items are typical design requirements to be used in the design process: cost, stability of the overall teaming system; output (or state tracking) performance; accuracy from command to response; overshoot; steady state error; rise time; and settling time. In addition, the law must be robust with respect to aircraft type, communication elements, and mission.

Even with the current advanced and sophisticated computers and software packages, some tasks rely on human knowledge that is currently difficult for a computer to reason about or process. For example, humans are much better than computers at recognizing faces in crowds or noticing a target in an environment with similar objects. Therefore, the team law must consider the human factors as well as the weaknesses and strengths of all team members.

There are fundamental principles which govern an efficient teaming law; some of which are presented in this section. As the most important principle, the safety of the manned aircraft (in fact, the human pilot) is of much higher priority compared with the UAV airworthiness. Thus, the collision avoidance and see-and-detect are two primary concerns to teaming success. Moreover, when the leader aircraft is out of sight of the follower, the follower aircraft must circle around to detect the leader. In the UAV-Leader, manned-aircraft-follower teaming, the teaming law may dictate the human pilot no to follow the UAV.

The state-space approach may be utilized to model the team of n UAVs and m manned aircraft. If a linear model is considered, the state space representation of the team will be:

$$\begin{aligned} x &= Ax + Bu \\ y &= Cx + Du \end{aligned} \tag{5}$$

where x, y, and u denote the state, output, and input variables. In addition, A, B, C, and D are state, input, output, and transmission matrices. When the team is comprised of one UAV and one manned aircraft, there are two inputs and two outputs. Hence, all four matrices are two-by-two.

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} d_{11} & d_{12} \\ d_{21} & d_{22} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \tag{6}$$

The output y_1 represents the flight trajectory of the UAV, and the output y_2 represents the flight trajectory of the manned aircraft. Using state and output feedbacks, a nominal linear control signal will be:

$$u = -K(x, y) => \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix} \begin{bmatrix} x_1 & y_1 \\ x_2 & y_2 \end{bmatrix} \tag{7}$$

In order to optimize the performance of the team, an optimal control law may be used to minimize the performance index, J:

$$J = \int_0^{\infty} (x^* Q x + u^* R u + y^* S y) dt \tag{8}$$

where Q, R, and S are the symmetric weighting functions of state, input, and output variables respectively. In determining the elements of the weighting functions, the priority will go to the performance and safety of the manned aircraft. Substituting equation 7 into equation 8 will deliver an optimization problem. Employing an optimization technique such as solving the Reccati equation will yield the control signals. Since two aerial vehicles are flying simultaneously, the teaming laws are solved within each vehicle separately; and two set of results will be created; one for the UAV and one for the manned aircraft. The autopilot of the UAV will follow one solution, and human pilot will follow the second solution. The teaming law will guarantee the success of the formation flight.

9. CONCLUSIONS

This paper introduces the concept of manned-unmanned aircraft teaming, as well as teaming categories. Unmanned aerial vehicles are the main candidate for the teaming with manned aircraft in performing complex/dangerous missions. There are various challenges and prerequisites for manned-unmanned aircraft collaboration. The technical differences between two team members; namely human pilot and autopilot have been discussed. In addition, the teaming formulation, teaming laws, decision making process and communication between human pilot and autopilot will be developed. An optimal control law for the state-space representation of the teaming is finally presented.

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BIOGRAPHY

Mohammad Sadraey has over twenty years of teaching experience at a number of institutions including Southern New Hampshire University, Daniel Webster College and the University of Kansas. He has both an M.Sc. and Ph.D. in Aerospace Engineering in 2006. He is a senior member of the American Institute of Aeronautics and Astronautics (AIAA), member of Sigma Gamma Tau, and the American Society for Engineering Education (ASEE). He is also listed in Who's Who in America. He is the author of five books, including Aircraft Design: A Systems Engineering Approach published by Wiley in 2012, Aircraft Performance by CRC in 2016, and UAV design by Morgan & Claypool in 2017.

APPENDIX A

FIGURES AND TABLE

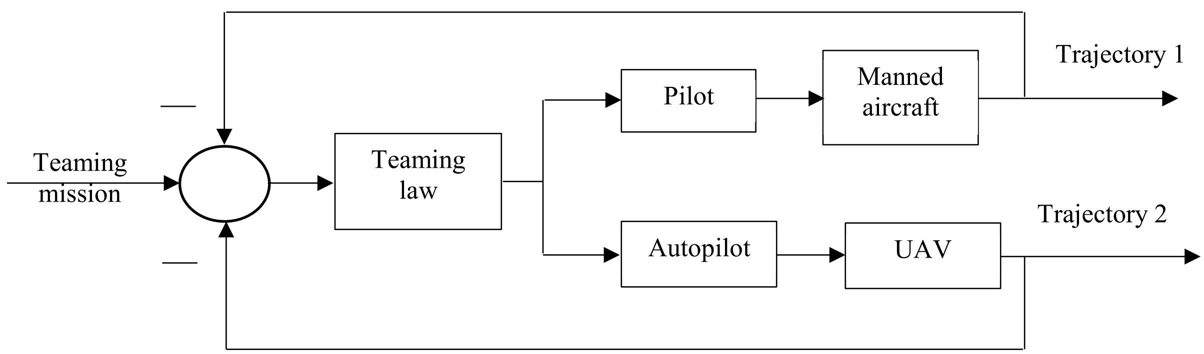

Figure 1. Functional block diagram of a teaming flight operation

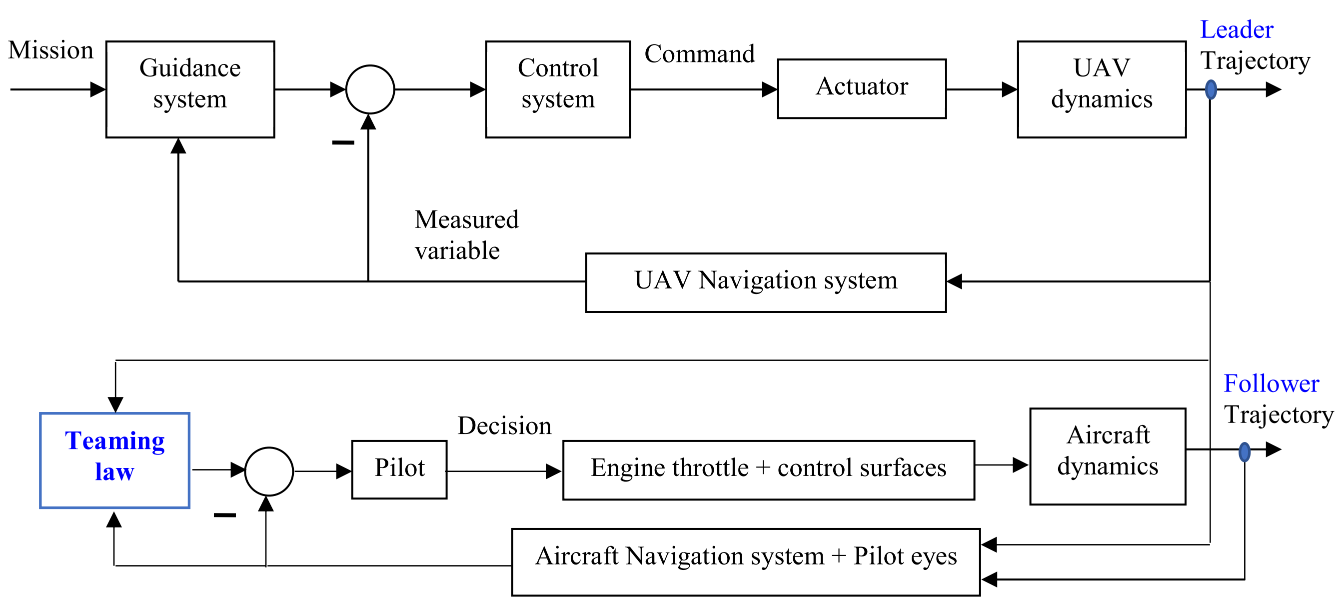

Figure 2. UAV-Leader, manned-aircraft-follower teaming block diagram

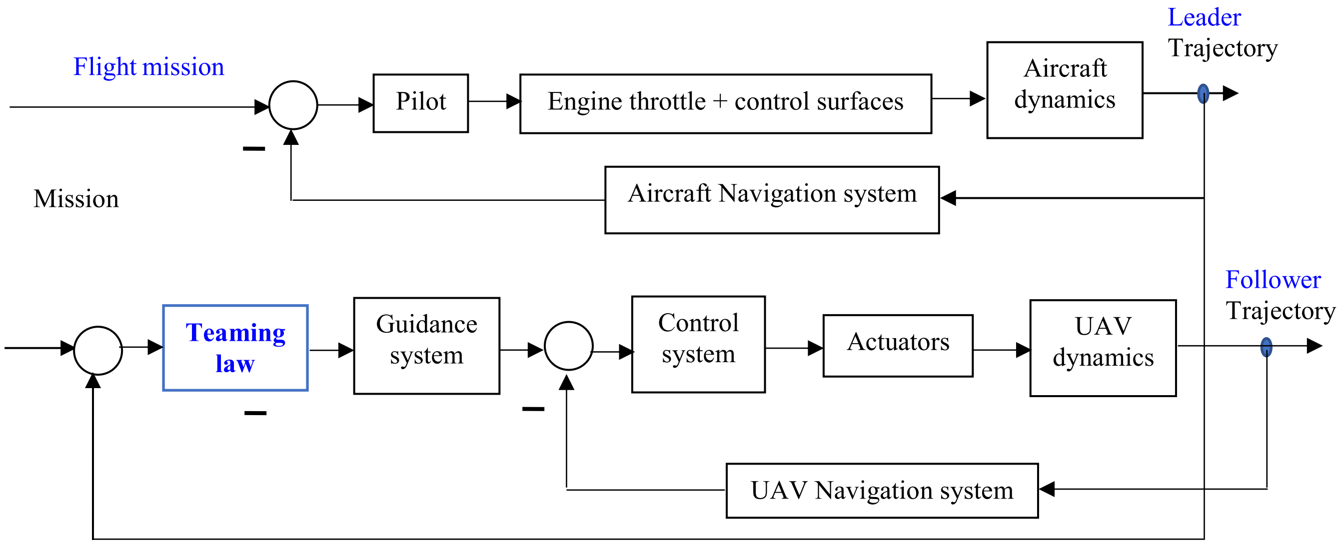

Figure 3. Manned-aircraft-leader, UAV-follower teaming block diagram

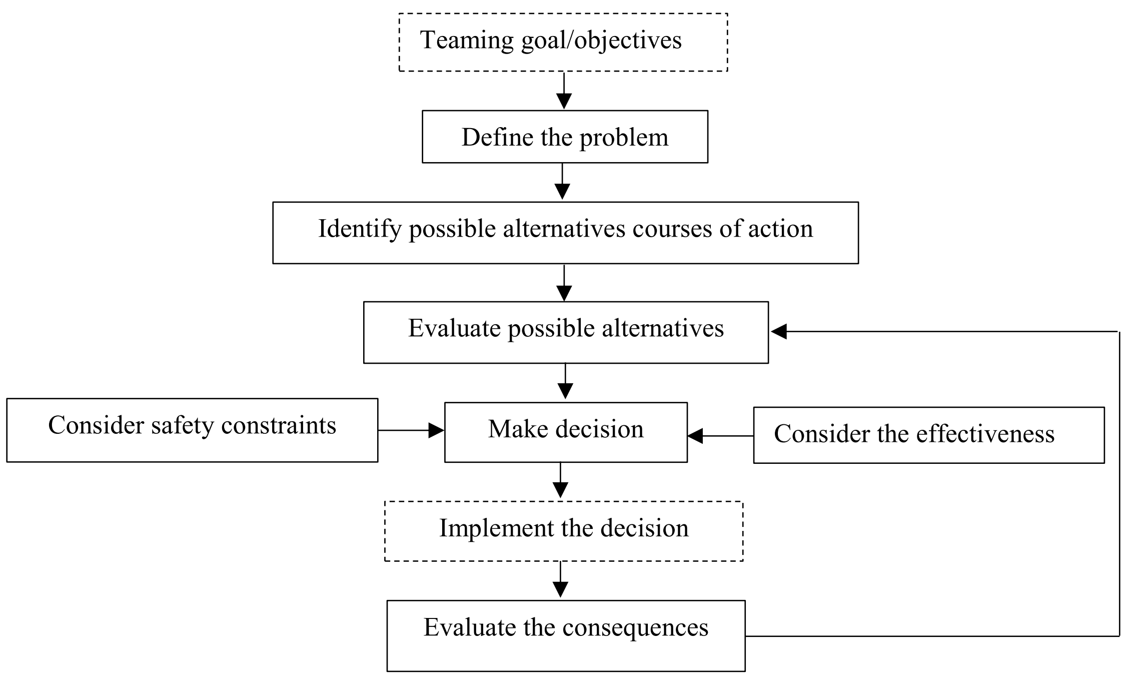

Figure 4. Decision Making Process for pilot as the follower of an UAV

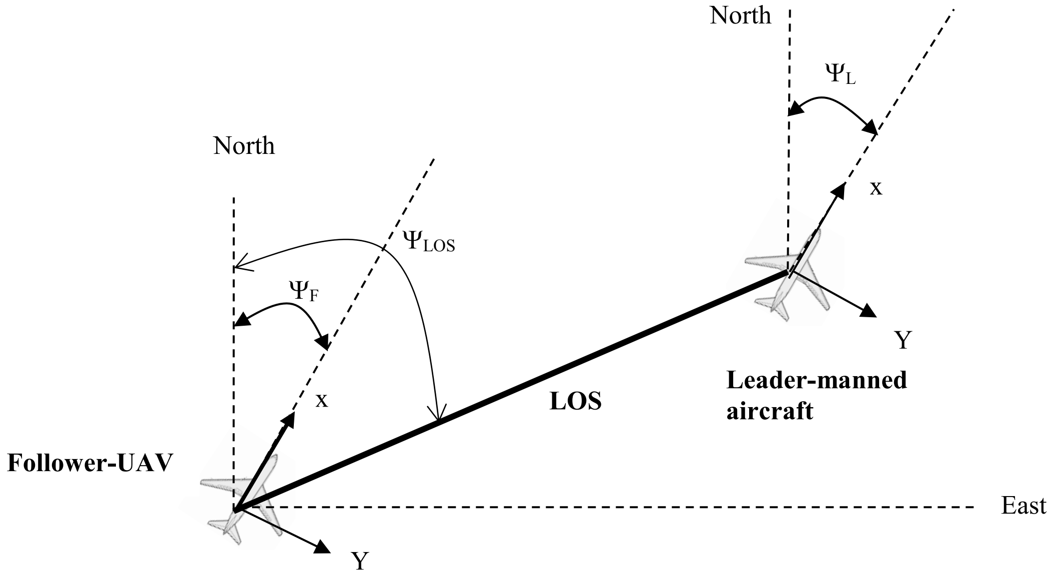

Figure 5. Line-Of-Sight (top-view)

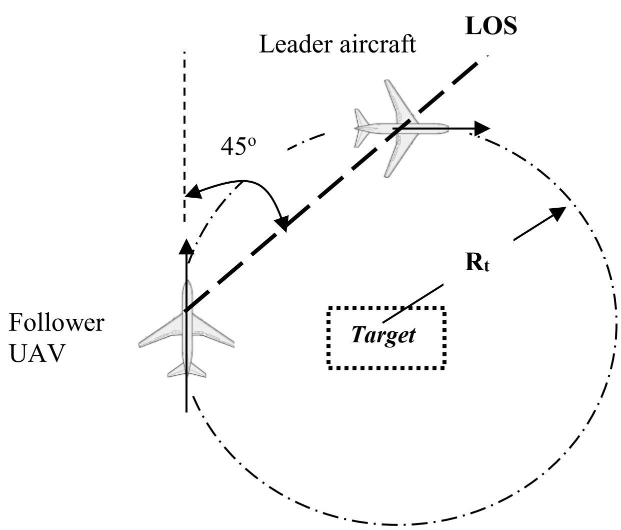

Figure 6. Leader-follower UAV geometry

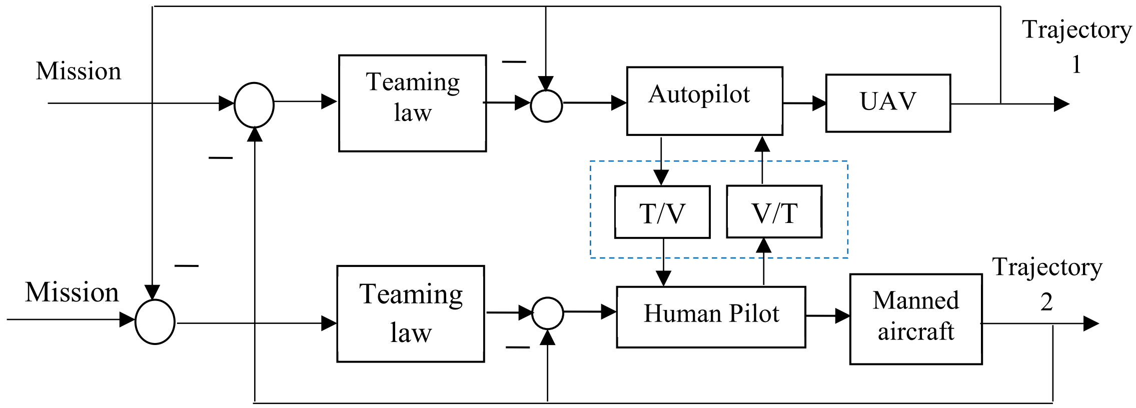

Figure 7. Communication between manned and unmanned aircraft

Table 1. Comparison technical between features of a human pilot and an autopilot and avionics

No.	**Attribute**	**Human pilot**	**Autopilot and avionics**
1	Mathematical operation	Pilot has a limited ability to perform calculations in flight	Autopilot's computer can perform millions of calculations per second.
2	Pressure limit	0.75 – 1 atm	Mechanical-electric-avionic equipment can perform under any pressure; even in vacuum.
3	Temperature limit	50 – 120 ^{o}C	-20 – 180 ^{o}C
4	Acceleration	1 – 9 g	0 – 50 g
5	Orientation	Upright (on the seat)	No limit (upright, up down, or sideward).
6	Upgradability	Pilots cannot be upgraded.	Major upgrades in autopilot and avionics occur every few years.
7	Survivability	Pilots are able to react to any unexpected situations, and survive.	Autopilot can only perform as programmed, and will crash in undefined flight conditions.
8	Visual performance	The eye can see only in visual bands (400 – 700 nm)	Can operate in day/night using optical/IR sensors and radars.
9	Recognition/detection	Able to recognize objects only in short distance.	Barely able to recognize objects. Can detect some objects in long distance.
10	Endurance	8 – 12 hours, rest is required.	Can work for months/years.
11	Communication	Talk, hear, see, and type commands. Incapable of detecting radio frequencies and radar signals.	No verbal communication (sound sensors). Radio frequencies are employed.
12	Facing risk	Avoids dangerous arenas.	Does not care about dangerous situations.