Manned-Aircraft-Leader, Unmanned-Aircraft-Follower Teaming Architecture

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Abstract **- Unmanned Aerial Vehicles (UAVs), due to their remarkable development, relatively low cost, and low risk to human are a prime candidate for the teaming with manned aircraft in performing complex 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 architecture. The technical requirements for a manned-aircraft-leader, unmanned-aircraft-follower teaming are discussed. In addition, the teaming formulation, teaming laws, and sense-and-avoid system are developed. A particular teaming law and a guidance algorithm for a manned-aircraft-leader, unmanned-aircraft-follower teaming architecture are developed. At the end, the success of the teaming architecture and performance of the sense-and-avoid and guidance systems are examined through various flight simulations.**

Keywords - Manned-Unmanned Teaming; Unmanned Aerial Vehicle; and Sense-And-Avoid.

I. 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. Unmanned aircraft systems are subject to regulation by the Federal Aviation Administration (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 [16] dramatically. One of the main goals for the manned-unmanned teaming is to provide flexible and safe flight operations. Teaming a UAV system with manned systems will offer advantages 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. An efficient teaming will create an environment such that both parties operate within their limits, while generating an unachievable goal by one party. The functions of a UAV in a team with manned aircraft depend in nature on the different UAV configurations and their characteristics.

A literature survey has reflected that various technical documents have investigated many aspects of manned-unmanned teaming. Unmanned vehicle systems are being introduced into Army systems to extend manned capabilities and act as "force multipliers" [1]. Jameson et al. [2] have presented the collaborative autonomy for manned/unmanned teams. The researchers in [3] have 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 [4]. Clough et al. [5] have presented a perspective on the autonomous control challenges for UAVs from a researcher's point of view. Autonomous vehicle technologies for small fixed-wing UAVs have been discussed in [6]. There is a number of consequences for UAV design requirements especially on UAV modeling and simulation, some of which have been investigated in [7]. The augmentations, motivations, and directions for aeronautics applications of man–machine integration design and analysis system have been explored in [8].

The researchers in [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 are presented in the next section. A team of a manned aircraft and an UAV in a flight mission is a complex system [10] and requires the approach of multidisciplinary systems engineering. Fundamentals of manned-unmanned aircraft teaming are presented in [17].

In the literature survey, we did not find any publication that fully develops the manned-aircraft-leader, unmanned-aircraft-follower teaming architecture. There is a number on-going research projects by National Aeronautics and Space Administration (NASA) in this area employing various manned aircraft and UAVs. The major contributions of this paper are to provide a model for decision making within the realms of guidance, sense-and-avoid and teaming, as well as to provide a teaming formulation and a teaming law.

The rest of the paper is structured as follows. In Section II, teaming problem formulation including three categories of teaming is presented. The line of sight guidance law to guide the UAV is developed in Section III. The UAV in turning flight has a couple of constraints and limits, these constraints and limits are introduced in Section IV. Collision avoidance is a primary concern in full integration of UAVs with manned aircraft; Section V presents the sense-and-avoid problem. Section VI introduces the manned-aircraft-leader, unmanned-aircraft-follower teaming law. Finally, the success of the teaming architecture and performance of the sense-and-avoid and guidance systems are examined via flight simulations in Section VII. We conclude the paper in in Section VIII.

II. 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. Fig. 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.

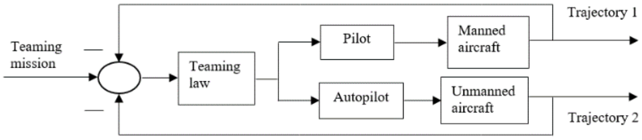

Figure 1. Functional block diagram of a teaming flight operation

Fig. 1 contains information concerning dynamic behavior, but it does not include any information on the physical construction of the team. Each team member has a unique trajectory which is controlled by its controller (one by a pilot, and one by an autopilot). Both UAV and manned aircraft provide a feedback to another team member. The teaming law governs the relationship between team members in conducting a flight team mission. The Guidance, Navigation and Control (GNC) of the UAV is within the autopilot, while the pilot will guide and control the manned aircraft.

The mathematical model of aircraft/UAV (dynamics model), and autopilot have been provided by [12]. 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. This paper is primarily focusing on category 2.

Each teaming case has a number of advantages and disadvantages, and is 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 1 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 2 is illustrated in Fig. 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. 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 various techniques and guidance laws.

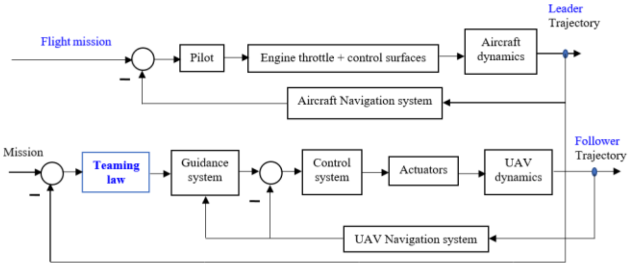

Figure 2. Manned-aircraft-leader, UAV-follower teaming block diagram

In the second category, 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 mathematical formulations of control systems, guidance systems, and navigation systems are presented by many books and papers including [12].

III. GUIDANCE LAW

The UAV must employ a guidance law to follow the manned aircraft. 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. Navigation system is mainly responsible for measuring the flight variables including the aircraft's angles, the rate of change of the angles, and the body axis accelerations. The guidance system compares the location of the aircraft 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 may be based on categories; for this teaming formation, the Line-Of-Sight (LOS) seems a good fit which satisfies the teaming requirements. The basic principle in LOS guidance law is to guide the UAV on a LOS course in an attempt to keep it on a line joining the target and the ground station (tracking line). For a teaming of two, the line of sight is defined as the line joining the follower UAV and the leader UAV. In addition, the leader UAV is following a moving ground target. For this law, the target-tracking radar acquires the target shortly after take-off and then guides the UAV into the beam of the target-tracking radar. For the guidance command, the actual distance from the tracking line to the UAV is required.

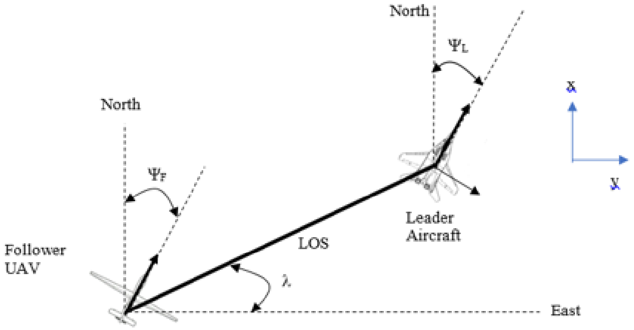

Figure 3. Line-Of-Sight (Top view)

An imaginary line between the follower-UAV to the leader UAV is referred to as line-of-sight. The line of sight angle (λ) is determined by forming a right triangle, when putting follower UAV and target, each at a corner. Then, the hypotenuse is along the line of sight. The line of sight angle is calculated by trigonometry from Fig. 3 as:

$$\lambda = tan^{-1}\left(\frac{y_T - y_U}{x_T - x_U}\right) \tag{1}$$

where x_T and x_U represent the distance between target and UAV to a reference line along x-axis, and y_T and y_U represent the distance between target and UAV to a reference line along y-axis. If the reference is selected to be at the UAV location, both y_U and x_U will be zero. The instantaneous distance between UAV and the target will be:

$$D_{TU} = \sqrt{(y_T - y_U)^2 + (x_T - x_U)^2} \tag{2}$$

The closing velocity (V_c) - the negative rate of change of separation between UAV and target - is obtained [11] by:

$$V_c = \frac{-\left(V_{TUx}(x_T - x_U) + V_{TUy}(y_T - y_U)\right)}{D_{TU}} \tag{3}$$

where V_{TUx} and V_{TUy} are components of the relative velocity and are given by

$$V_{TUx} = \dot{x}_T - \dot{x}_U \tag{4}$$

$$V_{TUy} = \dot{y}_T - \dot{y}_U \tag{5}$$

The instantaneous line-of-sight rate is computed by taking the derivative of the equation 1, which leads to:

$$\dot{\lambda} = \frac{V_{TUy}(x_T - x_U) - V_{TUx}(y_T - y_U)}{D_{TU}^2} \tag{6}$$

In the line-of-sight guidance law, the velocity of the follower UAV (V_n) perpendicular to the LOS should be equal to the LOS rate at that point. It is assumed that the LOS value is available from the use of onboard sensors (e.g., radar).

$$V_n = D_{TU}\dot{\lambda} \tag{7}$$

where $\dot{\lambda}$ is the rate of change of the line of sight angle, and D_{TU} denotes the distance between the follower UAV and the target or leader UAV. Moreover, V_n is velocity of the follower UAV perpendicular to the LOS. Hence, the guidance command is perpendicular to the line of sight. The guidance system output in xy plane (V_C) may be readily converted to a sideslip angle (β) command to control system. There is a relationship between this speed (i.e., in y-direction) and sideslip angle as:

$$\beta = \frac{V_n}{V_{oU}} \tag{8}$$

where V_{oU} is the initial UAV airspeed. So, the follower UAV is guided so as to remain on the commanded LOS. 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 aircraft such that to keep a constant line-of-sight angle. The LOS variables are available in both manned and unmanned aircraft from the use of onboard vision sensors. The guidance equations derived for the xy plane. However, similar governing equations are derived and used in xz plane.

IV. MANEUVERABILITY CONSTRAINTS

One of the basic maneuvers to make a flight smooth, and to correct the line of sight, is to turn around to follow the leader UAV. A turning flight has a couple of constraints, including: 1. Maximum turn rate (ω_{max}), 2. Minimum turn radius (R_{min}), 3. Maximum load factor (n_{max}), 4. Minimum and maximum airspeed (V_{min}, V_{max}), 5. Maximum bank angle (ϕ_{max}). The following set of equations governs the relation between parameters of a turning flight. The load factor is a function of bank angle. The maximum allowable bank angle is limited by the load factor:

$$\phi_{max} = \cos^{-1}\left(\frac{1}{n_{max}}\right) \tag{9}$$

The turn radius (R) and turn rate (ω) are functions of airspeed (V), and load factor (n):

$$R = \frac{V^2}{g\sqrt{n^2 - 1}} \tag{10}$$

$$\omega = \frac{g\sqrt{n^2 - 1}}{V} \tag{11}$$

The stall speed during a turn is a function of bank angle:

$$V_{S_t} = \sqrt{\frac{2mg}{\rho S C_{L_{max}} \cos(\phi)}} \tag{12}$$

where S denotes the wing area, m the UAV mass, ρ the air density, and C_{Lmax} the UAV maximum lift coefficient.
When the theoretical airspeed corresponding to the minimum turn is less than the stall speed, the UAV has to turn with the corner speed (V^*):

$$V^* = \left[\frac{2n_{max}W}{\rho S C_{L_{max}}}\right]^{\frac{1}{2}} \tag{13}$$

Moreover, a turn must be coordinated in order to keep the radius of turn constant. For the requirements of a coordinated turn, you may refer to references, such as [3]. The trajectory smoother must take into account all of these performance constraints to convert an initial path into a smooth trajectory.

V. SENSE AND AVOID

Collision avoidance is a primary concern and a critical challenge in full integration of unmanned aircraft systems. One of the major limitations to the widespread use of unmanned vehicles in teaming with manned aircraft has been the detect-and-avoid problem. When a group of UAVs (e.g., three Reapers) are following a manned aircraft (e.g., F/A-18), a sense-and-avoid system will be needed to prevent collision between UAVs.

In general, there are five functions required in a sense-and-avoid system: 1. Detect the intruder/obstacle, 2. Track, 3. Evaluate, 4. Calculation, 5. Command, 6. Execute. There is currently a large amount of research projects [16] being conducted in the area of sense-and-avoid. In selecting a surveillance system, a number of factors should be evaluated. They are range, timeliness (update rate), field of view, simplicity, cost, design challenge, reliability, accuracy, size, weight, technology level, flexibility, and integration.

When a conflict resolution algorithm is feasible, various guidance laws may be employed for a collision avoidance. For instance, the proportional navigation guidance with a proportional navigation constant less than one (i.e., $N < 1$). In such case, the UAV will be turning slower than the LOS, thus continuously falling behind the target (i.e., another aircraft). Another appropriate guidance law for a collision avoidance (as in a formation flight) is the line of sight guidance law. This law may be implemented by assuming the goal (i.e., target) of the follower UAV to be constantly at a desirable distance behind or at the side of the leader UAV. This paper is mainly focusing on the sense-and-avoid system of one UAV to follow a manned aircraft.

VI. TEAMING LAW

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.

A fully autonomous UAV should be capable of trajectory tracking, defined as tracking a time-parameterized reference. However, for trajectory tracking there exist fundamental performance limitations that cannot be overcome by any control system. Moreover, to meet temporal specifications, the airspeed profile often needs to be controlled independently. To overcome this challenge, temporal constraints are not frequently imposed in path-following problems, and the vehicle is allowed to converge to and follow a path without imposing any temporal specifications. This will result in a smoother convergence to the path, and the control signals are less likely to be saturated. This approach must also avoid collision in multi-vehicle cooperative missions.

In a path following problem, the designer is required to design an algorithm for a given path satisfying the given bounds such that the generalized error converges to a neighborhood of the zero. 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 sense or 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.

The teaming law is established based on three fundamental principles: 1. Keep the UAV at a line of sight, 2. Keep UAVs at a safe distance from the leader aircraft and each other, 3. Each team member should fly within its safe flight envelope. Sections IV, V, and VI provide the concept and governing equations for each principle. The guidance system will generate a command for the control system to maintain the LOS. Ref. [20] has presented a modeling and decentralized control for the multiple UAVs formation based on Lyapunov design.

The sense-and-avoid system subsystem should make the necessary correction to keep the follower UAV at a safe distance (D_{TU}) from leader aircraft (i.e., target) by sending the proper signal to the control system.

$$C_1 \leq D_{TU} \leq C_2 \tag{14}$$

In addition, the sense-and-avoid subsystem should make the necessary correction to keep the follower UAVs at a safe distance (D_{UU}) from each other.

$$C_3 \leq D_{UU} \leq C_4 \tag{15}$$

The C_1, C_2, C_3, and C_4, are constant values and are given by the designer. These constants are functions of many factors including UAV vision sensor features, the UAV maneuverability, weather conditions, and flight altitude. When the UAV is at a safe distance (D_{TU}) from the leader aircraft, it must follow every flight maneuver of the leader aircraft. The only difference is that every maneuver is performed by the follower UAV after a time delay (T_d), which is the ratio of the safe distance (D_{TU}) to the target speed (U_T):

$$T_d = \frac{D_{TU}}{U_T} \tag{16}$$

For two reasons of 1. UAV airworthiness, and 2. Successful payload application (e.g., aerial photography); the trajectory must be smooth. A well-designed smooth trajectory has ideally no abrupt and significant changes on the movement of the UAV. The trajectory smoother should apply changes to make the assigned trajectory kinematically feasible in terms of constraints.

A limitation of this algorithm is that the trajectory is composed of a number of time-stamped curves, which specify the desired location of the UAV at a specified time.

Tracking the movement state estimation of an UAV basically concerns inferring the latent state of interest based on discrete time series noisy observations. The time of interest may be the past (namely, smoothing), the present (tracking) or the future (forecasting).

VII. SIMULATION

Two sets of simulations are presented to demonstrate the efficacy of the proposed algorithm and teaming law: 1. A UAV is following a manned aircraft in longitudinal plane (i.e., xz), 2. A UAV is following a maneuvering manned aircraft in the xy plane (i.e., turning flight). In the first simulation, the UAV (as the follower) with a conventional configuration, has a wing span of 20 m, length of 15 m, a stall speed of 70 knot, and a maximum speed of 250 knot. Moreover, the manned aircraft (as the leader), with a conventional configuration has a wing span of 15 m, length of 12 m, a stall speed of 100 knot, and a maximum speed of 400 knot. For this formation flight, the UAV is required to stay behind and follow the manned aircraft and keep a safe distance. The distance between the UAV and the manned aircraft should be between 100 to 120 meters. Hence,

$$100\ m < D_{TU} < 120\ m$$

Next, the UAV is required to follow a random trajectory (as if a manned aircraft is flying/leading) to simulate a manned-unmanned aircraft teaming flight. For this mission, the UAV is required to stay behind the manned aircraft at a safe distance. For the initial conditions, the leader aircraft is flying at a constant altitude with a velocity of 130 knot. The follower UAV is right behind the manned aircraft with a distance of 200 m, and an initial velocity of 120 knot. The UAV performance limits and constraints are tabulated in Table 1.

TABLE 1. UAV PERFORMANCE LIMITS AND CONSTRAINTS

No	Parameter	Value	Remarks
1	Maximum load factor	2	Structural limit
2	Maximum bank angle	60 deg	Structural limit
3	Maximum airspeed	250 knot	Engine limits
4	Minimum airspeed	1.2 V_s	Airworthiness, stall
5	Maximum bank angle	60 deg	Structural limit, camera view
6	Maximum possible turn rate	20 deg/sec	Fastest turn limit
7	Minimum turn radius	50 m	Tightest turn limit

A linear state-space dynamic model for both the manned aircraft and the UAV have been employed. For both vehicles, typical stability and control derivatives for a dynamically stable vehicle are utilized.

$$\dot{x} = Ax + Bu \qquad (17)$$

$$y = Cx + Du$$

The A, B, C, and D matrices are generated by a matlab code. The four state-variables are airspeed (V), climb angle (γ), heading angle (ψ), and sideslip angle (β). Furthermore, four control-variables are throttle (δ_T), elevator (δ_E), aileron (δ_A), and rudder (δ_R). Thus, the state variables are: $x = [V, \gamma, \psi, \beta]^T$ and input variables are $u = [\delta_T, \delta_E, \delta_A, \delta_R]^T$.

Four PID control laws (one for each controller) are employed for controlling the UAV in the three dimensional space. A Simulink model (Fig. 9) is developed to model all subsystems of both the follower UAV and the leader manned aircraft including LOS, navigation, guidance and control systems.

A. LONGITUDINAL FLIGHT TEAMING

The first simulation is to examine a team of one follower UAV and a manned leader aircraft in a 50 second longitudinal flight maneuver (cruise/climb/cruise). The leader aircraft will cruise for 20 seconds, and then, climb to 100 meters in another 20 seconds.

Fig. 4 shows velocities, distance, and heights of UAV and manned aircraft for this teaming flight operation. The top Figure shows the velocities of UAV and manned aircraft, and the middle Figure demonstrates the heights of UAV and manned aircraft. The bottom Figure illustrates the distance between UAV and manned aircraft. As the Fig. 5 demonstrates, the follower UAV is perfectly following the leader aircraft, and performs every flight operation by a delay of 1.5 seconds.

As the simulation results indicate, the UAV accelerates in the beginning to reduce the distance of 200 m to the desired value of 100 m. Then, it will keep the velocity equal to the velocity of the leader aircraft. Due to the desired distance of 100 m, and the velocity of the leader aircraft (130 knot), the time delay is about 1.5 seconds (i.e., 100/(130×0.5144)).

Fig. 5 illustrates the elevator deflections and throttle settings of the UAV for this teaming flight operation. The initial elevator angle is -2 deg, but during the flight, it varies to maintain the longitudinal trim. The initial throttle setting is 20 deg, but during the flight, it varies to maintain the forward velocity.

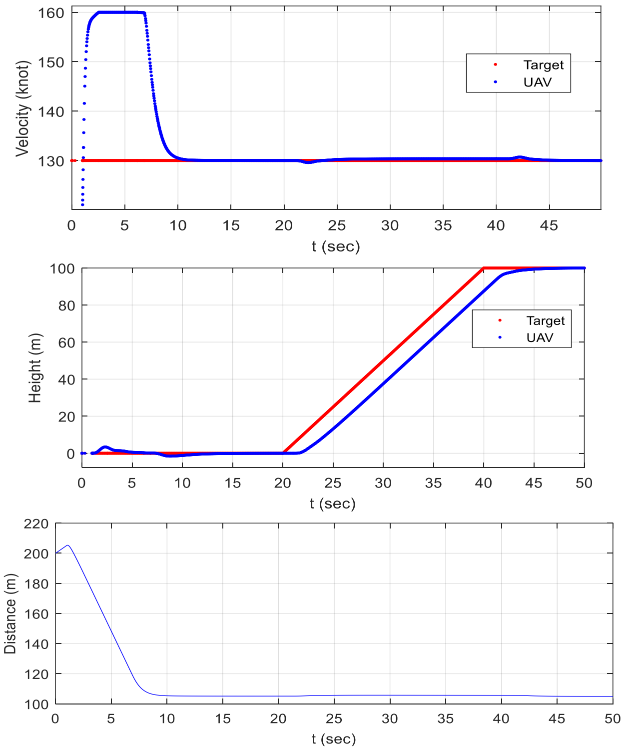

Figure 4. Velocities, distance, and heights of UAV and manned aircraft in a teaming flight for a longitudinal flight maneuver

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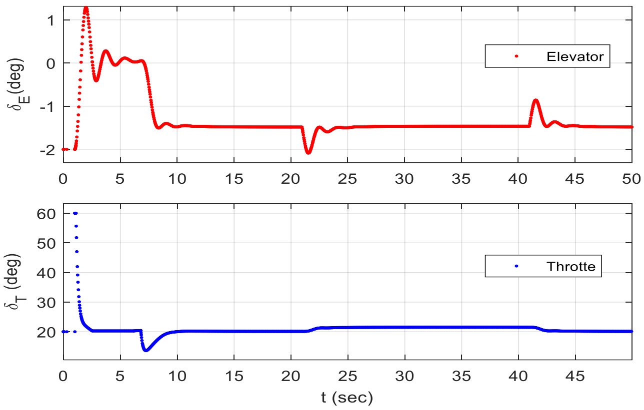
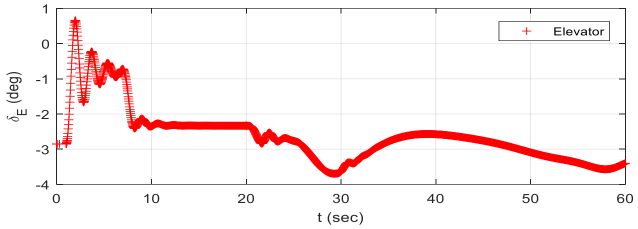
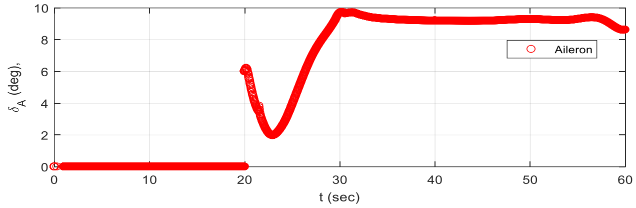


Figure 5. Elevator deflections and throttle settings of the UAV in a teaming flight for a longitudinal flight maneuver

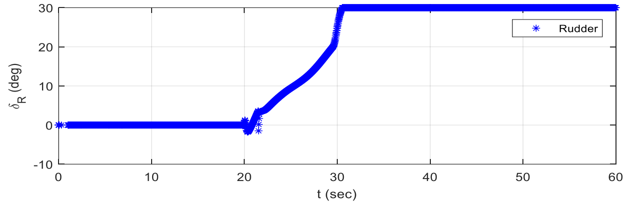
Both UAV elevator and engine throttle are varying to change the velocity and altitude to follow the manned leader aircraft.



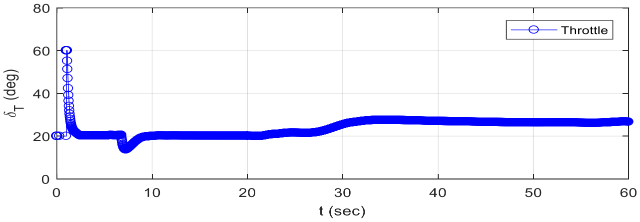
a. Elevator deflections



b. Aileron deflections



c. Rudder deflections

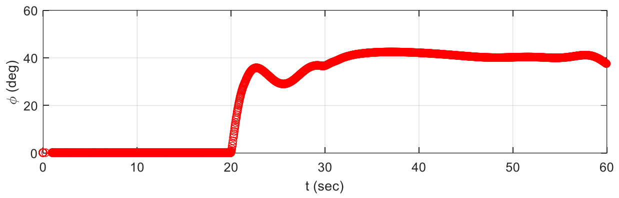


d. Throttle setting

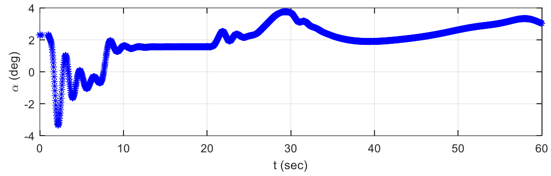
Figure 6. Control surfaces of UAV in a teaming flight for a turning flight maneuver

B. TURNING FLIGHT TEAMING

The second simulation is to examine a team of one follower UAV and a manned leader aircraft in a 60 second turning (lateral-directional) flight. The leader aircraft will cruise for 20 seconds, and then, have a 360 level turn to the left (one full turn in 40 seconds). Fig. 6 shows control surfaces (i.e., elevator, aileron, and rudder) deflections and throttle settings of the UAV in a teaming flight for a turning flight maneuver.



a. Bank angle



b. Angle of attack

Figure 7. Control surfaces and flight parameters of UAV in a teaming flight for a turning flight maneuver

The UAV accelerates in the beginning to reduce the distance of 200 m to the desired value of 100 m. Then, it will decelerate to keep the velocity equal to the velocity of the leader aircraft.

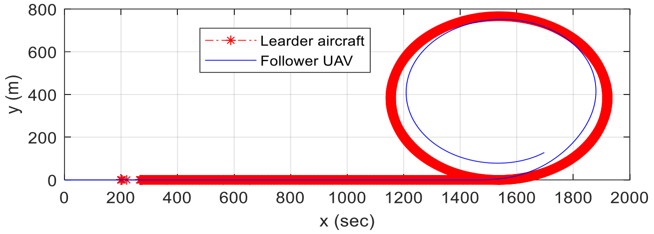


Figure 8. Flight parameters of UAV and manned aircraft in a teaming flight for a turning flight

During the turn, the UAV bank angle is about 40 degrees (Fig. 7), while the angle of attack is about 3 degrees. Fig. 8 illustrates the flight path of both UAV and leader aircraft. As the Figure demonstrates, the follower UAV is perfectly following the leader aircraft, and performs every flight operation by a delay of 1.5 seconds.

As the flight simulations indicate, both teaming operations are successful, and the UAV is tracking and following the manned aircraft for both longitudinal and direction flight maneuvers. In both flight missions, the UAV continuously keeps a distance of 100 m from leader aircraft to avoid a collision. In all flight motions, the UAV maneuverability constraints were observed, and the UAV did not fly beyond the flight envelope.

The simulation employs a UAV linear state-space dynamic model with four PID controllers. However, in reality, the dynamics of a UAV is nonlinear. Moreover, other control laws (e.g., robust nonlinear) may offer better outcomes. The objective of the paper is to present the fundamentals of the teaming technique with an application. This technique may employ UAV nonlinear model with more complex control laws. Each dynamic model and each control law has unique advantages and disadvantages. The current application is simple and efficient, but may not handle nonlinearities.

VIII. CONCLUSION AND FUTURE WORK

This paper explores the manned-aircraft-leader, unmanned-aircraft-follower teaming architecture. There are various challenges and techniques for manned-unmanned aircraft collaboration. This paper develops the concept of manned-unmanned aircraft teaming, as well as teaming architecture. The technical requirements for a manned-aircraft-leader, unmanned-aircraft-follower teaming are discussed. In addition, the teaming formulation, teaming laws, and sense-and-avoid system are presented. A particular teaming law and a guidance algorithm for manned-aircraft-leader, unmanned-aircraft-follower teaming architecture are developed.

At the end, the efficacy of the teaming architecture and performance of the sense-and-avoid/guidance systems are examined through formation flight simulations. The simulation results confirm that the suggested teaming law is applicable and efficient in following the flight team mission and in avoiding any obstacle. In future, the teaming law will be redesigned to improve the efficiency of the team. Moreover, the future work will include a team of three UAVs to follow a manned aircraft in 3d flight maneuvers.

REFERENCES

[1] A. Freedy, E. DeVisser, G. Weltman, and N. Coeyman, “Measurement of trust in human-robot collaboration”, International Symposium on Collaborative Technologies and Systems, 0-9785699-1-1, IEEE, 2007.

[2] S. Jameson, J. Franke, R. Szczerba, and S. Stockdale, “Collaborative Autonomy for Manned/Unmanned Teams”, American Helicopter Society, 61th Annual Forum, Grapevine, TX, June 1-3, 2005.

[3] S. J. Gaydos and I. P. Curry, “Manned-Unmanned Teaming: Expanding the Envelope of UAS Operational Employment”, Journal of Aviation, Space, and Environmental Medicine, Vol. 85, No. 12, December 2014.

[4] M. M. R. Mostafa, “Accuracy Assessment of Professional Grade Unmanned Systems for High Precision Airborne Mapping”, ISPRS Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Presented at the UAVg 2017, Bonn, Germany, September 4 – 7, 2017.

[5] M. Clough and T. Bruce, “Unmanned Aerial Vehicles: Autonomous Control Challenges, A Researcher's Perspective”, Journal of Aerospace Computing, Information, and Communication, 1542-9423, Vol. 2, No. 8, 2005.

[6] R. W. Beard et al., “Autonomous Vehicle Technologies for Small Fixed-Wing UAVs,” Journal of Aerospace Computing, Information, and Communication, 1542-9423, Vol. 2, No. 1, 2005.

[7] H. Friehmelt, “Some Consequences of UAV Design Requirements Especially on UAV Modeling and Simulation”, AIAA-2003-5688, AIAA Modeling and Simulation Technologies Conference and Exhibit, Austin, Texas, Aug. 11-14, 2003.

[8] B. F. Gore, “Man–machine integration design and analysis system, V5: Augmentations, motivations, and directions for aeronautics applications”, In P. C. Cacciabu, M. Hjalmdahl, A. Luedtke, & C. Riccioli, Human modelling in assisted transportation, Heidelberg, Germany, Springer, pp. 43–54, 2010.

[9] E. DeVisser, R. Parasuraman, A. Freedy, E. Freedy, and G. Weltman, “A Comprehensive Methodology for Assessing Human-Robot Team Performance for Use in Training and Simulation”, Proceedings of the Human Factors and Ergonomics Society Annual Meeting, October 2006, Vol. 50.

[10] B. S. Blanchard, and W. J. Fabrycky, “Systems Engineering and Analysis”, Fourth Edition, Prentice Hall, 2006.

[11] P. Zarchan, “Tactical and Strategic Missile Guidance”, 6th Ed., American Institute of Aeronautics and Astronautics, Reston, VA, 2013.

[12] B. L. Stevens, F. L. Lewis, and E. L. Johnson, “Aircraft Control and Simulation: Dynamics, Controls Design, and Autonomous Systems”, 3rd ed., John Wiley, 2015.

[13] C. Kaufman, R. Perlman, and M. Speciner; “Network Security: Private Communication in a Public World”, 2nd Edition, Prentice Hall, 2002.

[14] MIL-STD-1797A, “Flying Qualities of Piloted Aircraft”, Department of Defense Interface Standard, 2004

[15] US Department of Transportation, Federal Aviation Administration (www.faa.gov), “FAR 23, FAR 25”, retrieved: Feb. 2019.

[16] P. Angelov and P. Angelov, “Sense and Avoid in UAS: Research and Applications”, Wiley, 2012.

[17] M. Sadraey, “Manned-Unmanned Aircraft Teaming”, International IEEE Aerospace Conference, Big Sky, Montana, March 3-10 2018.

[18] M. A. Goodrich and R. W. Bear, “Semi-Autonomous Human-UAV Interfaces for Fixed-Wing Mini-UAVs”, Brigham Young University, 2004.

[19] V. Cichella, et al., “A 3D Path-Following Approach for a Multirotor UAV on SO(3)”, 2nd IFAC Workshop on Research, Education and Development of Unmanned Aerial Systems, Compiegne, France, November 20-22, 2013.

[20] H. Zhicheng, F. Isabelle, and Z. Arturo, “Modeling and Decentralized Control for the Multiple UAVs Formation based on Lyapunov design and redesign”, 2nd IFAC Workshop on Research, Education and Development of Unmanned Aerial Systems, Compiegne, France, November 20-22, 2013.

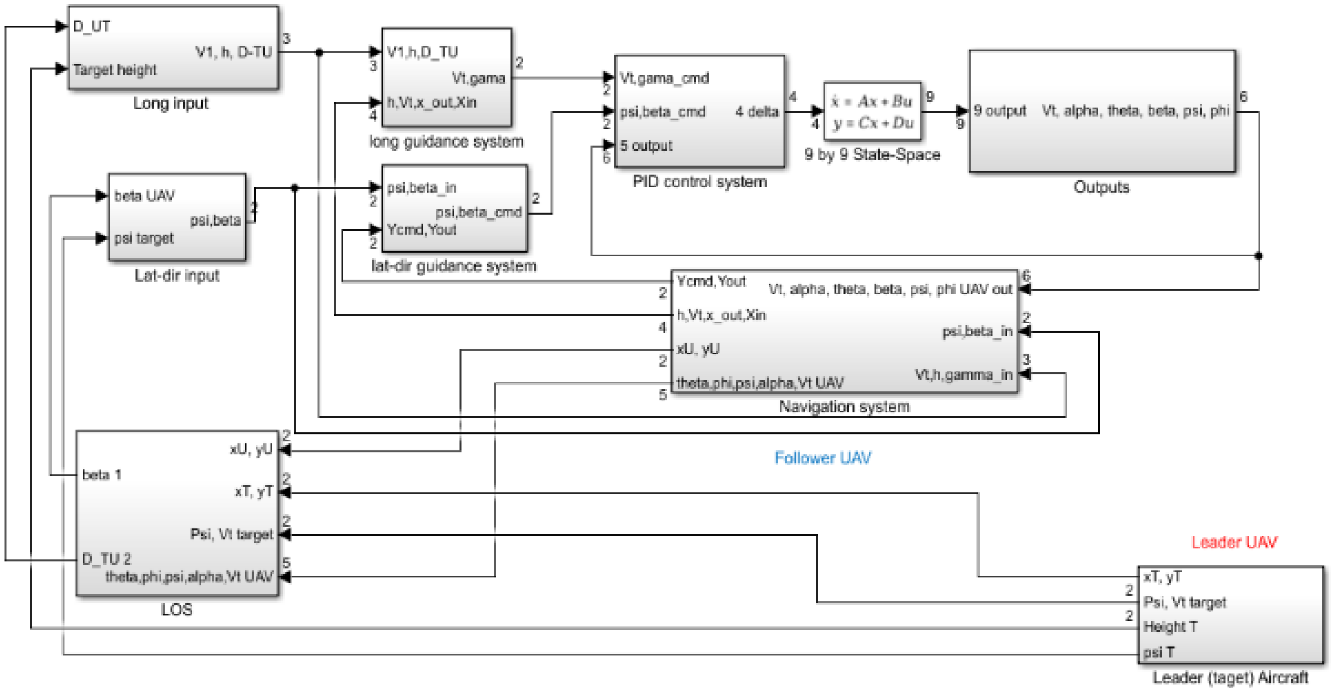


Figure 9. Simulink model for subsystems of the follower UAV and the leader manned aircraft