2024 European Control Conference (ECC)
June 25-28, 2024. Stockholm, Sweden

A negative imaginary solution to an aircraft platooning problem

Yu-Hsiang Su, Parijat Bhowmick, *Member, IEEE*, and Alexander Lanzon, *Senior Member, IEEE*

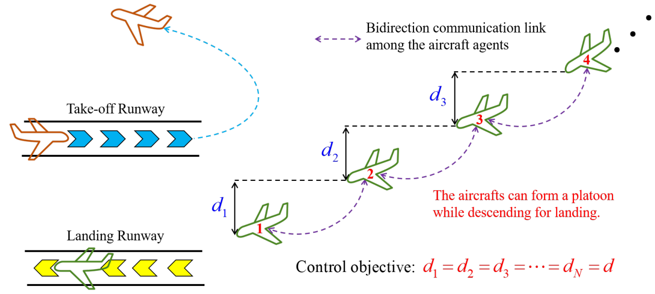
***Abstract*— Over the next decade, the growth of commercial aircraft is expected to increase by 30%, causing significant challenges in air traffic management and control. To address this problem, we propose the idea of *aircraft platooning* during the descending and pre-landing phases. The objective is to design a distributed flight guidance and control system that assists onboard pilots in finding a feasible and collision-free trajectory from descent to pre-landing. The proposed aircraft platoon control scheme comprises a feedback linearising controller in the inner loop that transforms the nonlinear aircraft dynamics into a MIMO double-integrator, inherently a Negative Imaginary system. The outer loop employs a distributed output feedback Strictly Negative Imaginary controller, enabling networked aeroplanes to maintain the desired inter-aircraft spacing along each coordinate by synchronising their velocities. In addition, a contingency strategy is proposed to handle potential runway failures (e.g. sudden blockage, damage, etc.) by switching a descending aircraft platoon into a time-varying hover formation for each aircraft, maintaining a safe vertical gap. Finally, a comprehensive MATLAB simulation case study is conducted to test the feasibility and performance of the NI theory-based aircraft platoon control scheme.**

I. Introduction

Due to the consistent growth in the civil aviation sector over the last three decades, the number of commercial aircraft has continuously increased [1], consequently leading to a sharp rise in the number of incoming flights (i.e. those approaching for landing) at each airport. This trend is particularly concerning and significant for busy airports such as Atlanta, Dubai, Tokyo, London Heathrow, Dallas, Los Angeles, Paris, Frankfurt, Istanbul, etc. Despite the dedicated efforts of Air Traffic Control (ATC) at every airport, there remains a risk of failure if the number of incoming air traffic exceeds the maximum capacity of an airport or in emergencies. One possible solution is expanding the capacity of an airport. However, this might not always be feasible due to geographical, socio-economic, and safety constraints [2]. Another approach involves optimising the aircraft scheduling problem [3] through improved communication systems, advanced routing algorithms, and fail-safe ATC software.

This work was supported by the Engineering and Physical Sciences Research Council (EPSRC) [grant number EP/R008876/1] and the Science and Engineering Research Board (SERB), DST, India [grant numbers SRG/2022/000892 and CRG/2022/006114]. All research data supporting this publication are directly available within this publication. For the purpose of open access, the authors have applied a Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript version arising.

Y.-H. Su and A. Lanzon are with the Control Systems and Robotics Group, Department of EEE, School of Engineering, University of Manchester, Manchester M13 9PL, UK, and P. Bhowmick is with the Department of EEE, IIT Guwahati, Assam - 781039, India. Emails: Yu-Hsiang.Su@manchester.ac.uk, parijat.bhowmick@iitg.ac.in, Alexander.Lanzon@manchester.ac.uk.



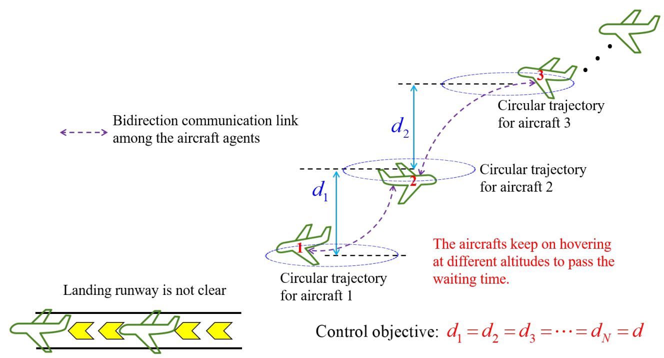


Fig. 1. (a) A descending aircraft platoon proceeding for a regular (or uninterrupted) landing; (b) The descending aircraft platoon switches to a hovering state to wait when the landing runway is not ready.

A potential alternative is introducing the idea of *aircraft platooning*, as illustrated in Fig. 1. This new concept demonstrates how a fleet of descending aircraft aiming to land at a particular airport can form a platoon and synchronise their motions to maintain the desired inter-aircraft spacing throughout the descending and pre-landing phases. Aircraft platooning significantly helps reduce air traffic congestion, improve operational efficiency, and enhance safety. In addition, it greatly reduces dependence on a centralised and human-operated air traffic control system while optimising runway usage.

The idea of aircraft platooning has been inspired by the concept of *vehicle platooning* (see [4] and the references therein), which ensures a desired inter-vehicular spacing by synchronising the velocities of all the vehicles in a fleet [5]. Major applications of vehicle platooning include the cruise control of automated vehicles (such as cars, buses, trucks) [6], control of connected train platoons [7], energy-saving aircraft formation flight [8]. With the advancements of graph theory-based cooperative control of multi-agent systems (MASs) [9], [10], the literature on vehicle platooning has been substantially enriched. Lately, the Negative Imaginary (NI) systems theory has also emerged as a vital technique for multi-agent vehicle platooning since its introduction in 2007-2008 [11]. This property is commonly observed in flexible structures and Euler-Lagrange systems with collocated position sensors and force actuators [11], [12]. Over the last few years, the NI systems theory has found promising applications in the cooperative control of various MASs, starting with [13], particularly in multi-UGV systems [14], multi-UAV systems [15]–[18], and train platoons [7].

Driven by a strong urge to find a feasible, reliable and fail-safe solution to the continuously increasing air traffic problem, especially at busy airports, we bring the idea of aircraft platooning during the descending and pre-landing phases. Below, we outline the primary contributions of this paper and the salient features of the proposed two-loop aircraft platoon control scheme in a concise manner:

- This paper introduces the idea of aircraft platooning to facilitate a smooth, hassle-free, minimum-delay and fail-safe landing, especially at busy airports. It ensures that the descending aircraft agents maintain the desired inter-aircraft spacing in all coordinates;
- An NI theory-based two-loop control scheme is proposed to achieve the desired aircraft platooning objectives. The inner loop applies a feedback-linearising control action to transform the nonlinear translational dynamics of an aircraft into a three-input-three-output double-integrator system. While the outer loop implements a distributed output feedback SNI controller;
- To tackle the runway unavailability issues due to blockage or disruptions, a contingency strategy is devised that helps a descending aircraft platoon switch to a hover formation at different altitudes, maintaining a constant vertical gap while waiting for a landing runway;
- The proposed control scheme is completely distributed and requires only the output feedback (i.e. the position information) of the neighbouring aircraft agents, as illustrated in Fig. 1 and Fig. 2b.

The notations and acronyms adhere to standard conventions. The set of real numbers is denoted by $\mathbb{R}$. The 2-norm of a vector is denoted by $\|.\|$. $A > 0$ denotes that a matrix A is positive definite. The complex conjugate transpose of a matrix A is denoted by A^*. The Kronecker product of two matrices, A and B, is represented by $A \otimes B$. $\mathscr{R}^{m\times n}$ denotes the space of all real, rational, proper transfer function matrices of dimension $(m \times n)$.

II. Technical Background

A. Definitions of NI and SNI systems

This subsection revisits the definitions of NI and SNI systems.

Definition 1: (**NI Systems**) [19] A system $T(s) \in \mathscr{R}^{m\times m}$ is said to be an NI system if: (i) it has no right-half plane poles; (ii) $j[T(j\omega) - T(j\omega)^*] \geq 0 \ \forall \omega \in (0, \infty)$ except the values of ω where $s = j\omega$ is a pole of $T(s)$; (iii) $s = j\omega_0$ with $\omega_0 \in (0, \infty)$ is a pole of $T(s)$, then it is at most a simple pole and $\lim_{s\to j\omega_0} (s - j\omega_0)jT(s) \geq 0$; and (iv) $s = 0$ is a pole of $T(s)$, then $\lim_{s\to 0} s^kT(s) \geq 0 \ \forall k \geq 3$ and $\lim_{s\to 0} s^2T(s) \geq 0$.

Definition 2: (**SNI Systems**) [11], [19] A system $T(s) \in \mathscr{RH}_\infty^{m\times m}$ is said to be an SNI system if $j[T(j\omega) - T(j\omega)^*] > 0 \ \forall \omega \in (0, \infty)$.

B. Interaction topology

We describe the interaction topology among networked aircraft agents using a weighted and undirected graph $\mathscr{G} = \{\mathscr{V}, \mathscr{E}, \mathscr{A}\}$. $\mathscr{V} = \{1, \ldots, N\}$ is the node-set, $\mathscr{E} \subset \mathscr{V} \times \mathscr{V}$ is the edge set, and $\mathscr{A} = [a_{ij}] \in \mathbb{R}^{N\times N}$ is the adjacency matrix. The edge $e_{ji} = (v_j, v_i) \in \mathscr{E}$ denotes the information flow from node j to node i. We denote the neighbour set of node i as $\mathscr{N}_i = \{v_j | (v_j, v_i) \in \mathscr{E}\}$. a_{ij} represents the weight of e_{ji}, with $a_{ij} > 0$ if $e_{ji} \in \mathscr{E}$. The in-degree matrix is denoted by $\mathscr{D} = \mathrm{diag}\{d_1, d_2, \cdots, d_N\}$ with $d_i = \sum_{j=1}^{N} a_{ij} \ \ \forall i \in \{1, \ldots, N\}$. The Laplacian matrix $\mathscr{L} \in \mathbb{R}^{N\times N}$ is given by $\mathscr{L} = \mathscr{D} - \mathscr{A}$. If the i^{th} aircraft is connected to the virtual leader agent (denoted as '0') via a directional link, an edge e_{0i} exists between them, characterised by a positive pinning gain $g_i > 0$. The pinning-gain matrix is denoted by $\mathbb{G} = \mathrm{diag}\{g_1, g_2, \cdots, g_N\} > 0$.

Assumption 1: The interaction topology of N networked aircraft agents is described by an undirected and connected graph $\mathscr{G}$. We assume there is a root node (known as the 'virtual leader') that provides a reference trajectory (i.e. $\mathbf{r_0} \in \mathbb{R}^3$) to the aircraft platoon (at least to one aircraft agent).

Due to Assumption 1, in the case of an undirected graph $\mathscr{G}$, we can derive that $(\mathscr{L} + \mathbb{G}) > 0$.

C. Properties of multi-agent NI and SNI systems

This paper employs multi-agent NI theory to model and control an aircraft platoon whose nonlinear dynamics can be feedback-linearised into a decoupled three-input-three-output double-integrator system that automatically exhibits the NI systems properties. This subsection will revisit some useful properties of multi-agent NI systems.

Lemma 1: [20], [21]. Let a homogeneous networked stable NI (or SNI) system be comprised of N agents $T(s)$ that satisfies Assumption 1. Then, $\bar{T}(s) = (\mathscr{L} + \mathbb{G}) \otimes T(s)$ is stable NI (or SNI) if and only if $T(s)$ is NI (or SNI).

Theorem 1: [15] Consider a double-integrator MAS, $I_N \otimes T(s)$, coupled with an undirected graph $\mathscr{G}$ satisfying Assumption 1. Let this MAS be interconnected with a distributed SNI controller, $I_N \otimes \beta T_c(s)$, via positive feedback, as shown in Fig. 2a. Then, the closed-loop system is asymptotically stable for any $\beta \in (0, \infty)$ if $T_c(0) < 0$.

III. Modelling and Problem Formulation

This section derives the feedback-linearised aircraft model and formulates the aircraft platooning problem.

A. Dynamic model of an aircraft

We consider a point-mass aircraft model [22], [23] to describe the motion of each aircraft in the networked aircraft

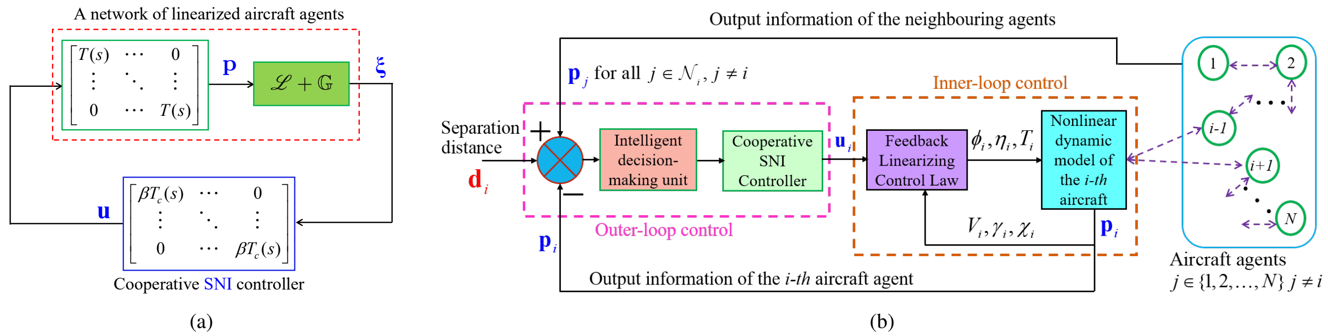


Fig. 2. (a) A positive feedback interconnection of a double-integrator MAS and a distributed SNI controller; and (b) A distributed NI theory-based two-loop aircraft platoon control scheme.

platoon. The kinematic equations of the i^{th} aircraft can be represented by

$$\begin{cases} \dot{x}_i = V_i \cos\gamma_i \cos\chi_i, \\ \dot{y}_i = V_i \cos\gamma_i \sin\chi_i, \\ \dot{h}_i = V_i \sin\gamma_i, \end{cases} \tag{1}$$

where x_i is the downrange, y_i is the cross-range, h_i is the altitude, V_i is the airspeed, γ_i is the flight-path angle and χ_i is the heading angle. The equations governing the dynamics of the i^{th} aircraft are given by

$$\begin{cases} \dot{V}_i = \dfrac{T_i - D_i}{m_i} - g\sin\gamma_i, \\ \dot{\gamma}_i = \dfrac{g}{V_i}\left(n_i \cos\phi_i - \cos\gamma_i\right), \\ \dot{\chi}_i = \dfrac{g n_i \sin\phi_i}{V_i \cos\gamma_i}, \end{cases} \tag{2}$$

where T_i represents the engine thrust, D_i denotes the aerodynamic drag, m_i is the mass of the aircraft, and g is the acceleration due to gravity. In this model, the control variables are the engine thrust T_i controlled by the throttle, the g-load n_i regulated by the elevator, and the banking angle ϕ_i manipulated through the rudder and ailerons.

The above nonlinear aircraft model in (1) and (2) can be effectively transformed into a decoupled three-input-three-output double-integrator system via feedback linearisation [22], [23]. By differentiating the kinematics in (1) w.r.t. time and substituting with the dynamics in (2), one obtains

$$\begin{cases} \ddot{x}_i = u_{x_i} = \dfrac{T_i - D_i}{m_i} c\gamma_i c\chi_i - g n_i (s\gamma_i c\chi_i c\phi_i + s\chi_i s\phi_i), \\ \ddot{y}_i = u_{y_i} = \dfrac{T_i - D_i}{m_i} c\gamma_i s\chi_i - g n_i (s\gamma_i s\chi_i c\phi_i - c\chi_i s\phi_i), \\ \ddot{h}_i = u_{h_i} = \dfrac{T_i - D_i}{m_i} s\gamma_i + g n_i c\gamma_i c\phi_i - g, \end{cases} \tag{3}$$

where u_{x_i}, u_{y_i}, and u_{h_i} are the new control variables (i.e. the acceleration components of the i^{th} aircraft in each coordinate) in the linearised double-integrator model. Note that $c\phi \triangleq \cos\phi$ and $s\phi \triangleq \sin\phi$. The relation between the new control variables and the actual control variables can be expressed as follows:

$$\begin{cases} \phi_i = \tan^{-1}\left[\dfrac{u_{y_i} c\chi_i - u_{x_i} s\chi_i}{c\gamma_i (u_{h_i} + g) - s\gamma_i (u_{x_i} c\gamma_i + u_{y_i} s\chi_i)}\right], \\ n_i = \dfrac{c\gamma_i (u_{h_i} + g) - s\gamma_i (u_{x_i} c\gamma_i + u_{y_i} s\chi_i)}{g + c\phi_i}, \\ T_i = \left[s\gamma_i (u_{h_i} + g) + c\gamma_i (u_{x_i} c\chi_i + u_{y_i} s\chi_i)\right] m_i + D_i. \end{cases} \tag{4}$$

B. Problem statement

Consider N aircraft agents whose nonlinear dynamics model can be feedback-linearised into a decoupled three-input-three-output double-integrator system: $\dot{\mathbf{p}}_i = \mathbf{v}_i$, $\dot{\mathbf{v}}_i = \mathbf{u}_i$, where $\mathbf{p}_i = [x_i, y_i, h_i]^\top$ is the position vector, $\mathbf{v}_i = [v_{x_i}, v_{y_i}, v_{h_i}]^\top$ is the velocity vector and $\mathbf{u}_i = [u_{x_i}, u_{y_i}, u_{h_i}]^\top$ is the control input vectors of the i^{th} aircraft. The aim is to develop a distributed flight guidance and control system to address the challenge of aircraft platooning, as illustrated in Fig. 1. The control objectives are as follows:

1) During regular aircraft landings, as described in Fig. 1a, each aircraft in the platoon should maintain the desired inter-aircraft spacing with successive aircraft along each coordinate. Furthermore, all aircraft should converge towards a constant velocity, synchronising with the speed of the virtual leader agent. That is

$$\begin{cases} \lim\limits_{t\to\infty} \mathbf{p}_i(t) - \mathbf{p}_j(t) = \mathbf{d}_i - \mathbf{d}_j, \\ \lim\limits_{t\to\infty} \mathbf{v}_i(t) - \mathbf{v}_0(t) = 0, \end{cases} \tag{5}$$

for all $i,\ j \in \{1, 2, \ldots, N\}$ and $i \neq j$, where $\mathbf{v}_0(t)$ is the velocity of the virtual leader agent. The desired inter-aircraft spacing is defined as $\mathbf{d}_i = [i \times d_x, i \times d_y, i \times d_h]^\top \quad \forall i \in \{1, 2, \ldots, N\}$, where d_x, d_y, and d_h represent the projected distances along the X, Y, and altitude coordinates, respectively.

2) When a runway fault occurs during aircraft landings, as described in Fig. 1b, each aircraft should transition to a time-varying hover formation at a different altitude while maintaining a constant vertical gap. That is

$$\lim_{t\to\infty} \mathbf{p}_i(t) - \mathbf{p}_j(t) = \mathbf{d}_i(t) - \mathbf{d}_j(t), \tag{6}$$

where the time-varying hover formation is defined as $\mathbf{d}_i(t) = [i \times d_x + f_x(t), i \times d_y + f_y(t), i \times d_h]^\top \quad \forall i \in$

$\{1, 2, \ldots, N\}$. Here, $f_x(t)$ and $f_y(t)$ are the pre-specified time-varying hover formation configurations.

IV. An NI theory-based aircraft platoon control scheme

This section establishes the theoretical foundation for the proposed two-loop aircraft platoon control scheme, as shown in Fig. 2b, relying on the NI systems theory. The idea stems from the observation that a nonlinear aircraft model can be feedback-linearised into a decoupled three-input-three-output double-integrator system that inherently exhibits the NI property. Drawing insights from recent advancements in NI-based cooperative control techniques, we propose a novel distributed SNI output feedback cooperative controller to achieve the stated aircraft platooning objectives.

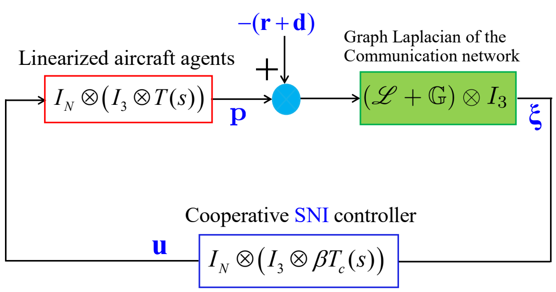


Fig. 3. An NI theory-based output feedback aircraft platoon control scheme for a networked linearised aircraft agents.

Theorem 2: Consider a platoon of N aircraft agents whose nonlinear translational dynamics can be feedback-linearised into a three-input-three-output double-integrator system $I_3 \otimes T(s)$, where $T(s) = \frac{1}{s^2}$. Suppose the interaction topology satisfies Assumption 1. Choose a distributed SNI controller $T_c(s)$ with $T_c(0) < 0$. Let $\mathbf{r} = \mathbf{1}_N \otimes \mathbf{r_0} \in \mathbb{R}^{3N}$ be the desired reference generated by the virtual leader agent, and $\mathbf{d} = [\mathbf{d}_1, \mathbf{d}_2, \cdots, \mathbf{d}_N]^\top \in \mathbb{R}^{3N}$ be the desired inter-aircraft spacing ($\mathbf{d}_i \in \mathbb{R}^3\ \forall i$) along the X, Y and altitude coordinates. Then, the desired aircraft platooning objectives are fulfilled by the control scheme in Fig. 3, deploying the following distributed output feedback SNI control law

$$\mathbf{U}_i(s) = \beta T_c(s) \sum_{j \in \mathscr{N}_i} a_{ij}\big((\mathbf{P}_i(s) - \mathbf{d}_i) - (\mathbf{P}_j(s) - \mathbf{d}_j)\big) + g_i\big(\mathbf{P}_i(s) - \mathbf{d}_i - \mathbf{r_0}\big) \qquad \forall i \in \{1, 2, \ldots, N\} \tag{7}$$

for any $\beta \in (0, \infty)$. The notations $\mathbf{U}_i(s)$ and $\mathbf{P}_i(s)$ denote the Laplace Transform of the real-valued time-domain signals $\mathbf{u}_i(t)$ and $\mathbf{p}_i(t)$, respectively, for all $t \geq 0$.

Proof. The closed-loop stability of the positive feedback interconnection of a distributed feedback-linearised aircraft agents $I_N \otimes \big(I_3 \otimes \frac{1}{s^2}\big)$ and a distributed SNI controller $(\mathscr{L} + \mathbb{G}) \otimes (I_3 \otimes \beta T_c(s))$ in Fig. 3 can be established by extending Theorem 1 for any $\beta \in (0, \infty)$ under the condition $T_c(0) < 0$. Let $\mathbf{p} = [\mathbf{p}_1, \mathbf{p}_2, \cdots, \mathbf{p}_N]^\top \in \mathbb{R}^{3N}$ denote the stacked position vector (i.e. the output vector) of all aircraft agents. We will now prove the asymptotic convergence of the tracking error, denoted as $\boldsymbol{\xi} = [\boldsymbol{\xi}_1, \boldsymbol{\xi}_2, \cdots, \boldsymbol{\xi}_N]^\top \in \mathbb{R}^{3N}$. The tracking error dynamics $\Xi(s) = \big[I - \big((\mathscr{L} + \mathbb{G}) \otimes \big(\frac{\beta}{s^2} T_c(s) I_3\big)\big)\big]^{-1}$ can be readily derived from Fig. 3. Then, the steady-state error $\boldsymbol{\xi}_{ss}$ can be obtained as follows:

$$\begin{aligned}
\boldsymbol{\xi}_{ss} &= \lim_{t\to\infty} \boldsymbol{\xi}(t) = \lim_{s\to 0} s\, \Xi(s) \\
&= \lim_{s\to 0} s \big[I - \big((\mathscr{L} + \mathbb{G}) \otimes \big(\tfrac{\beta}{s^2} T_c(s) I_3\big)\big)\big]^{-1} \tilde{\mathbf{R}}(s) \\
&\qquad [\text{denote } \tilde{\mathbf{r}} = -(\mathbf{r} + \mathbf{d}) \text{ and } \tilde{\mathbf{R}}(s) = \text{Laplace of } \tilde{\mathbf{r}}] \\
&= \lim_{s\to 0} s^2 \left[s^2 I - ((\mathscr{L} + \mathbb{G}) \otimes (\beta T_c(s) I_3))\right]^{-1} (s \tilde{\mathbf{R}}(s)) \\
&= -\big[(\mathscr{L} + \mathbb{G}) \otimes \big(\beta T_c(0) I_3\big)\big]^{-1} \big(\lim_{s\to 0} s^2 I\big) \times \\
&\qquad \big(\lim_{s\to 0} s \tilde{\mathbf{R}}(s)\big) = [0, 0, \cdots, 0]^\top
\end{aligned}$$

because $T_c(0) < 0$, $(\mathscr{L} + \mathbb{G}) > 0$ and $\mathbf{r}(t)$ and $\mathbf{d}(t)$ are all bounded signals $\forall t \geq 0$. Therefore, at the steady-state, $\mathbf{p} \to -\tilde{\mathbf{r}} \to (\mathbf{r}+\mathbf{d})$. Furthermore, this implies that the control objective in (5) holds when the desired inter-aircraft spacing is static, i.e., $\mathbf{d}$. However, for a time-varying but bounded formation configuration, i.e., $\mathbf{d}(t)$, the control objective in (6) remains valid. This completes the proof. ■

Remark 1: We assume the virtual leader agent is positioned at the front of the aircraft platoon, guiding all networked aircraft. By choosing a positive value for the projected distance in the altitude coordinate, i.e., $d_h > 0$, the distributed output feedback SNI control law in (7) enables the networked aircraft to achieve the desired platoon during the descending and pre-landing phases. On the other hand, a negative value for the projected distance in the altitude coordinate, i.e., $d_h < 0$, is selected for the taking-off phase.

Remark 2: When a runway fault occurs during the descending and pre-landing phases, the intelligent decision-making unit in Fig. 2b switches a descending aircraft platoon into a time-varying hover formation for each aircraft, ensuring a safe vertical gap is maintained.

Algorithm 1 A distributed flight guidance and control system for aircraft platooning.

for each aircraft $i \in \{1, 2, \ldots, N\}$ **do**
  select an SNI controller $T_c(s)$;
  if Descending and Pre-landing **then**
    choose $d_h > 0$;
    if A runway fault occurs **then**
      choose a time-varying $f_x(t)$ and $f_y(t)$;
      set a time-varying $\mathbf{d}_i(t)$;
      compute the control protocol in (7);
    else
      set a static $\mathbf{d}_i$;
      compute the control protocol in (7);
    end if
  else if Taking-off **then**
    choose $d_h < 0$;
    set a static $\mathbf{d}_i$;
    compute the control protocol in (7);
  end if
end for

Building upon Theorem 2 and Remarks 1 and 2, we summarise the proposed distributed flight guidance and control system for aircraft platooning in Algorithm 1.

V. Simulation Case Study

This section provides a MATLAB simulation case study to validate the effectiveness of the proposed NI theory-based two-loop aircraft platoon control scheme.

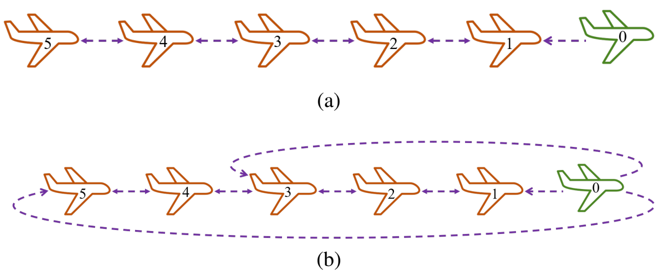


Fig. 4. (a) Topology 1 was used in Case study 1; (b) Topology 2 was used in Case study 2. [Label '0' denotes the virtual leader agent.]

A. Regular aircraft landings

We considered a platoon of five aircraft agents and a virtual leader for a regular (or uninterrupted) aircraft landing scenario. All aircraft agents are connected through the interaction topology described in Fig. 4a. The primary objective is to ensure that the five networked aircraft agents maintain the desired inter-aircraft spacing by synchronising their velocities with a virtual leader agent. In the simulation, the virtual leader was given a forward velocity of 2 miles per minute and a descending velocity of -1000 feet per minute. Each aircraft was required to maintain a projected distance of 3 miles in the X coordinate, 0 miles in the Y coordinate and 1000 feet in the altitude coordinate. An SNI controller $T_c(s) = -\frac{3s^3+30s^2+90s+30}{s^3+15s^2+75s+125}$ was selected to be implemented as the outer loop controller in Fig. 2b.

Fig. 5 presents the results of the regular aircraft landing scenario. The aircraft flight trajectories in the X and altitude coordinates are illustrated in Fig. 5a. Furthermore, Fig. 5b shows the projected distances between successive aircraft, where each aircraft maintains the desired projected distances along the X, Y and altitude coordinates. Fig. 5c indicates that the velocity of each aircraft achieves a constant speed synchronised with the virtual leader agent. These results validate that a group of five networked aircraft successfully achieved the objective of the regular aircraft landing. They effectively maintained the desired inter-aircraft spacing and synchronised their velocities with the virtual leader agent, employing the proposed aircraft platoon control scheme.

B. Aircraft landings in the event of a runway blockage

Next, we considered a scenario where a runway blockage occurs during aircraft landings. In such an event, the intelligent decision-making unit in Fig. 2b should switch a descending aircraft platoon into a time-varying hover formation for each aircraft at different altitudes while awaiting the resolution of the runway blockage. In this scenario, five aircraft, connected via the interaction topology described in Fig. 4b, were considered. Each aircraft was required to achieve a time-varying hover formation specified by

$$\begin{bmatrix} d_{i_x}(t) \\ d_{i_y}(t) \end{bmatrix} = \begin{bmatrix} -3 \times i + \cos\left(0.03t\right) \\ 0 \times i + \sin\left(0.03t\right) \end{bmatrix} \quad \forall i \in \{1, 2, ..., 5\}$$

while maintaining a projected distance of 1000 feet in the altitude coordinate. An SNI controller $T_c(s) = -\frac{3s^3+30s^2+90s+30}{s^3+15s^2+75s+125}$ was selected to be implemented as the outer loop controller in Fig. 2b.

Fig. 6 presents the results of the scenario where a runway blockage occurs during aircraft landings. The aircraft flight trajectories along X, Y and altitude coordinates are illustrated in Fig. 6a, where each aircraft achieves a time-varying hover formation at a different altitude and maintains a constant vertical gap. Moreover, as shown in Fig. 6b, the 2-norm of the tracking error for each aircraft converges to zero. Fig. 6c shows the velocity of each aircraft across each coordinate. These results validate that five networked aircraft successfully transitioned to a time-varying hover formation during a runway blockage, employing the proposed aircraft platoon control scheme.

VI. Conclusions

This paper proposes a solution to air traffic management and control to accommodate the continuously increasing air traffic, particularly at busy airports, by introducing the idea of aircraft platooning. An NI theory-based two-loop aircraft platoon control scheme is developed to achieve the aircraft platooning objectives. The inner loop applies a feedback-linearising control action to transform the nonlinear translational dynamics of an aircraft into a three-input-three-output double-integrator system. While the outer loop implements a distributed output feedback SNI controller. In addition, a contingency strategy is devised that helps a descending aircraft platoon switch to a hover formation at different altitudes, maintaining a constant vertical gap while waiting for a clear landing runway. The simulation case study demonstrates the usefulness of the proposed NI theory-based aircraft platoon control scheme.

References

[1] Boeing, "Commercial Market Outlook 2023–2042."

[2] G. Clare and A. G. Richards, "Optimization of Taxiway Routing and Runway Scheduling," *IEEE Transactions on Intelligent Transportation Systems*, vol. 12, no. 4, pp. 1000–1013, Dec. 2011.

[3] A. Lieder and R. Stolletz, "Scheduling aircraft take-offs and landings on interdependent and heterogeneous runways," *Transportation Research Part E: Logistics and Transportation Review*, vol. 88, pp. 167–188, Apr. 2016.

[4] S. Eben Li, Y. Zheng, K. Li, Y. Wu, J. K. Hedrick, F. Gao, and H. Zhang, "Dynamical modeling and distributed control of connected and automated vehicles: Challenges and opportunities," *IEEE Intelligent Transportation Systems Magazine*, vol. 9, no. 3, pp. 46–58, July 2017.

[5] Y. Li, C. Tang, K. Li, X. He, S. Peeta, and Y. Wang, "Consensus-Based Cooperative Control for Multi-Platoon Under the Connected Vehicles Environment," *IEEE Transactions on Intelligent Transportation Systems*, vol. 20, no. 6, pp. 2220–2229, June 2019.

[6] J. Hu, P. Bhowmick, F. Arvin, A. Lanzon, and B. Lennox, "Cooperative control of heterogeneous connected vehicle platoons: an adaptive leader-following approach," *IEEE Robotics and Automation Letters*, vol. 5, no. 2, pp. 977–984, Apr. 2020.

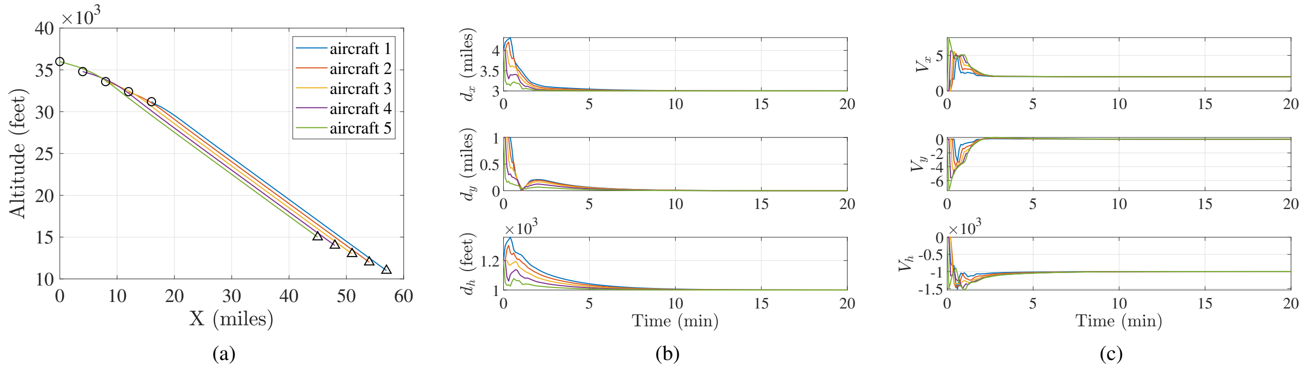


Fig. 5. [Results for Case study 1:] (a) The aircraft flight trajectories in the X and altitude coordinates. The circles and triangles mark, respectively, the initial and final positions of the aircraft; (b) The projected distances between successive aircraft in the X, Y, and altitude coordinates; (c) The aircraft velocities in each coordinate. The units for V_x, V_y, and V_h are miles/min, miles/min, and feet/min, respectively.

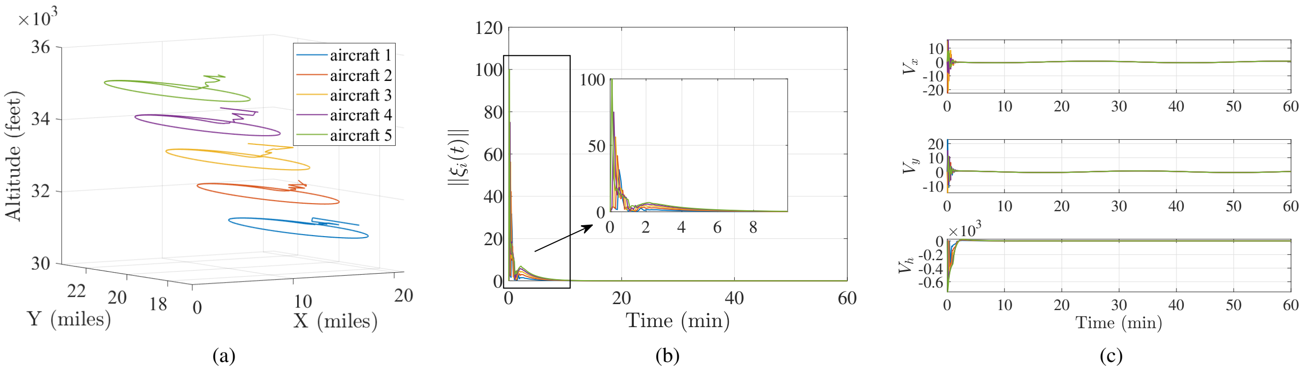


Fig. 6. [Results for Case study 2:] (a) The aircraft flight trajectories in the X, Y and altitude coordinates; (b) The 2-norm of the tracking error for each aircraft; (c) The aircraft velocities in each coordinate. The units for V_x, V_y, and V_h are miles/min, miles/min, and feet/min, respectively.

[7] C. Li, J. Wang, J. Shan, A. Lanzon, and I. R. Petersen, "Robust cooperative control of networked train platoons: A negative-imaginary systems' perspective," *IEEE Transactions on Control of Network Systems*, vol. 8, no. 4, pp. 1743–1753, Dec. 2021.

[8] J. R. Riehl, E. A. L. Hufstedler, P. Chatelain, and J. M. Hendrickx, "String Stability of Energy-Saving Aircraft Formations," *Journal of Guidance, Control, and Dynamics*, vol. 45, no. 5, pp. 935–943, May 2022.

[9] Y.-H. Su and A. Lanzon, "Formation-containment tracking and scaling for multiple quadcopters with an application to choke-point navigation," in *Proceedings of the 39th IEEE International Conference on Robotics and Automation*, May 2022, pp. 4908–4914.

[10] Y.-H. Su, P. Bhowmick, and A. Lanzon, "A robust adaptive formation control methodology for networked multi-UAV systems with applications to cooperative payload transportation," *Control Engineering Practice*, vol. 138, p. 105608, Sept. 2023.

[11] A. Lanzon and I. R. Petersen, "Stability robustness of a feedback interconnection of systems with negative imaginary frequency response," *IEEE Transactions on Automatic Control*, vol. 53, no. 4, pp. 1042–1046, May 2008.

[12] B. Bhikkaji, S. O. Reza Moheimani, and I. R. Petersen, "A negative imaginary approach to modeling and control of a collocated structure," *IEEE/ASME Transactions on Mechatronics*, vol. 17, no. 4, pp. 717–727, Aug. 2012.

[13] J. Wang, A. Lanzon, and I. R. Petersen, "Robust output feedback consensus for networked negative-imaginary systems," *IEEE Transactions on Automatic Control*, vol. 60, no. 9, pp. 2547–2552, Sept. 2015.

[14] O. Skeik, J. Hu, F. Arvin, and A. Lanzon, "Cooperative control of integrator negative imaginary systems with application to rendezvous multiple mobile robots," in *Proceedings of the 12th International Workshop on Robot Motion and Control*, July 2019, pp. 15–20.

[15] Y.-H. Su, P. Bhowmick, and A. Lanzon, "A Negative Imaginary Theory-Based Time-Varying Group Formation Tracking Scheme for Multi-Robot Systems: Applications to Quadcopters," in *Proceedings of the 40th IEEE International Conference on Robotics and Automation*, May 2023, pp. 1435–1441.

[16] ——, "Cooperative control of multi-agent negative imaginary systems with applications to UAVs, including hardware implementation results," in *Proceedings of the 21st European Control Conference*, June 2023.

[17] ——, "Properties of interconnected negative imaginary systems and extension to formation-containment control of networked multi-UAV systems with experimental validation results," *Asian Journal of Control*, Dec. 2023.

[18] D. Abara, P. Bhowmick, A. Lanzon, and S. Member, "Cooperative control of multi-tilt tricopter drones applying a 'mixed' negative imaginary and strict passivity technique," in *Proceedings of the 21st European Control Conference*, June 2023.

[19] A. Lanzon and H.-J. Chen, "Feedback stability of negative imaginary systems," *IEEE Transactions on Automatic Control*, vol. 62, no. 11, pp. 5620–5633, Nov. 2017.

[20] P. Bhowmick and S. Patra, "On decentralized integral controllability of stable negative-imaginary systems and some related extensions," *Automatica*, vol. 94, pp. 443–451, Aug. 2018.

[21] J. Hu, B. Lennox, and F. Arvin, "Robust formation control for networked robotic systems using Negative Imaginary dynamics," *Automatica*, vol. 140, p. 110235, June 2022.

[22] P. K. A. Menon, "Short-range nonlinear feedback strategies for aircraft pursuit-evasion," *Journal of Guidance, Control, and Dynamics*, vol. 12, no. 1, pp. 27–32, Jan. 1989.

[23] J. Wang and M. Xin, "Integrated Optimal Formation Control of Multiple Unmanned Aerial Vehicles," *IEEE Transactions on Control Systems Technology*, vol. 21, no. 5, pp. 1731–1744, Sept. 2013.