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REVIEW ARTICLE

A review of control strategies used for morphing aircraft applications

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Abstract This paper reviews the various control algorithms and strategies used for fixed-wing morphing aircraft applications. It is evident from the literature that the development of control algorithms for morphing aircraft technologies focused on three main areas. The first area is related to precise control of the shape of morphing concepts for various flight conditions. The second area is mainly related to the flight dynamics, stability, and control aspects of morphing aircraft. The third area deals mainly with aeroelastic control using morphing concepts either for load alleviation purposes and/or to control the instability boundaries. The design of controllers for morphing aircraft/wings is very challenging due to the large changes that can occur in the structural, aerodynamic, and inertial characteristics. In addition, the type of actuation system and actuation rate/speed can have a significant effect on the design of such controllers. The aerospace community is in strong need of such a critical review especially as morphing aircraft technologies move from fundamental research at a low Technology Readiness Level (TRL) to real-life applications. This critical review aims to identify research gaps and propose future directions. In this paper, research activities/papers are categorized according to the control strategy used. This ranges from simple Proportional Integral Derivative (PID) controllers at one end to complex robust adaptive controllers and

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Nomenclature

Abbreviation	Full name
3D	Three dimensional
ADP	Adaptive dynamic programming
ADRC	Active disturbance rejection control
ADT	Average dwell time
ARDC	Actively rejecting disturbance control
ASAPP	Active span morphing and passive pitch
ATED	Adaptive trailing edge
BLDC	Brushless direct current
BLF	Barrier Lyapunov function
BRL	Bounded real lemma
CAN	Controller area network
CAS	Command augmentation system
DNN-MRFT	Deep neural network and the modified relay feedback test
DO	Disturbance observer
DOF	Degrees of freedom
DSC	Dynamic surface control
ESO	Extended state observer
FFT	Fast fourier transforms
FishBAC	Fish bone active camber
FOSD	First-Order Sliding mode Differentiator
GA	Genetic algorithm
GUI	Graphic user interface
HARV	High-alpha research vehicle
HBMA	High-bandwidth morphing actuator
HFVTE	Higher frequency vibrating trailing edge
ICE	Innovative control effector
IMC	Internal model control
IR	Infra-red
LFR	Linear fractional representation
LFT	Linear fractional transformation
LMI	Linear matrix inequalities
LPV	Linear parameter varying
LQ	Linear -quadratic
LQG	Linear quadratic gaussian
LQR	Linear quadratic regulator
LTI	Linear time-invariant
LTR	Loop-transfer recovery
LVDT	Linear variable differential transformer
MDADT	Mode-dependent average dwell time
MFC	Macro fiber composite
MIMO	Multi input multi output
MLA	Maneuver loads alleviation
MLP	Minimal learning parameter
MSLS	Modified sequential least-squares
NDI	Nonlinear dynamic inversion
N-MAS	Nextgen's morphing aircraft structure
NN	Neural networks
PD	Proportional derivative
PDC	Parallel-distributed compensation
PI	Proportional integral
PID	Proportional integral derivative
PSO	Particle swarm optimization
PWM	Pulse width modulation
QLF	Quadratic Lyapunov function
RA	Reference aircraft
RBF	Radial-based function
RBFNN	Radial basis function neural networks
RHO	Receding-horizon optimal
SISO	Single input single output
SJA	Synthetic jet actuators
SMA	Shape memory alloys
SMC	Sliding mode control
SRAD	Stochastic robustness analysis and design
STDs	Standard deviations
TP	Tensor product
TRL	Technology readiness level
T-S	Takagi-Sugeno
UAM	Urban air mobility
UAV	Unmanned aerial vehicle
VMCS	Virtual morphing control surface
ZN	Ziegler–Nichols

deep learning algorithms at the other end. This includes analytical, computational, and experimental studies. In addition, the various dynamic models used and their fidelities are highlighted and discussed.

1. Introduction

1.1. Definition

A morphing aircraft is a flight vehicle capable of altering its configuration to achieve maneuverability and fuel efficiency for multi-role missions, such as dash, high-speed maneuvers, and long endurance loiter.[1–4] This is not a new concept, as the very first airplane, the Wright Flyer, used the same concept to control the roll motion. According to the NATO RTO technical team, morphing is the real-time adaptability of a flight vehicle to enable multi-point optimized performance.[5] A morphing aircraft enhances the control authority, flight performance, and multi-mission capability by continuously adjusting its geometry.[6–9] The geometry mainly denotes lift-generating surfaces, especially the aircraft's wing. Morphing aircraft technologies can be categorized in several ways. The most popular ways are either according to the degree of free-

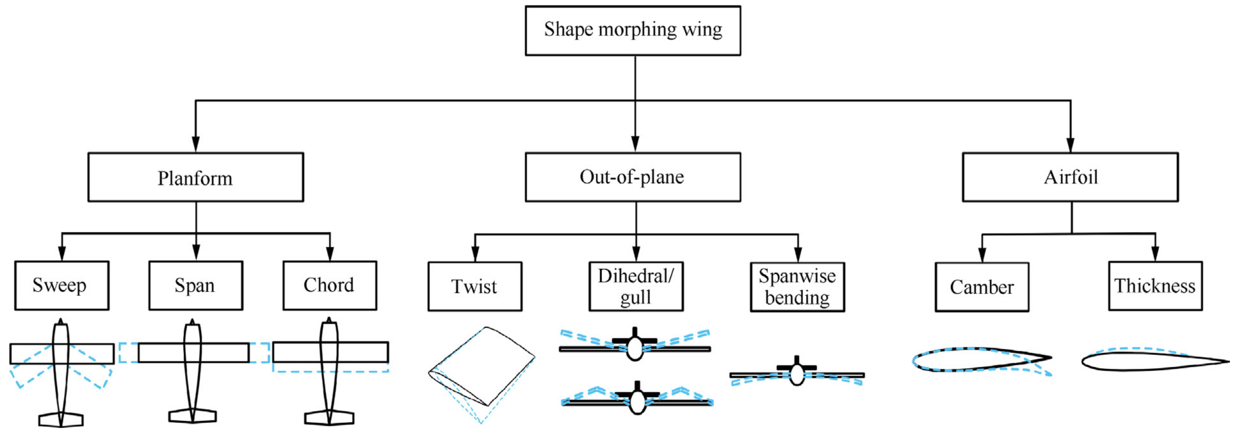

Fig. 1 Morphing wing degrees of freedom.

Table 1 Definitions of discrete and continuous morphing.[9]

Category	Definition
Discrete morphing	Singular functionality Adopted locally on the airframe Operated at a few points within the flight envelope Suppress couplings
Continuous morphing	Multiple functionalities Distributed over the airframe Operated continuously throughout the flight envelope Exploit couplings

dom or according to functionality. Sofla[10] and Barbarino[8]et al. introduced the categorization according to the degree of freedom. They arranged the degrees of freedom as planform morphing (span, sweep, and chord), out-of-plane morphing (twist, dihedral/gull, and spanwise bending), and airfoil morphing (thickness and camber) as shown in Fig. 1.

On the other hand, Ajaj et al. [9] used functionality as the basis for categorizing morphing technologies. They introduced the concepts of continuous morphing and discrete morphing. The definition of each category is listed in Table 1.[9] It should be noted that flaps, slats, and retractable landing gears can all be regarded as discrete morphing.

1.2. Motivation

A conventional aircraft is usually designed to have optimal flight characteristics at specific flight conditions and certain mission segments.[11] In contrast, a morphing aircraft is capable of tailoring its configuration to adapt to very dissimilar flight conditions and mission profiles, which can reduce the design compromises required. The ability to adapt its geometry implies that a morphing aircraft is usually associated with significant changes in the aerodynamic loads, structural/elastic properties, inertial properties, aeroelastic behavior, flight dynamics, and stability characteristics. This necessitates effective and robust control strategies to ensure certain stability and performance criteria are met during the morphing process. In addition, wing-shape changes require effective controllers to provide suitable actuation under various flight conditions and mission profiles. In summary, morphing can lead to a complex time-varying nonlinear dynamical model with internal and external uncertainties, which should function under the gust and disturbance of the atmosphere.[12,13] These uncertainties and time-varying characteristics demand sophisticated control systems to ensure the stability and performance of the morphing wings while achieving the desired geometry based on the mission. From a control technology perspective, the challenges faced in controlling morphing aircraft include:

(1) Development of a control algorithm that can handle the changing dynamics (time-varying) and uncertainties associated with morphing aircraft. The algorithm should provide stability, performance, and robustness across a wide range of morphing configurations.
(2) Estimating the aerodynamic characteristics and dynamic behavior of the morphing aircraft during different configurations is crucial for control system design. The control algorithm should adapt according to the dynamic model of the morphing configuration.
(3) Control hardware, actuator design, choice, and placement of actuators are important considerations. The control system should be compatible with the morphing mechanisms and actuator dynamics, ensuring effective control of the changing aircraft configurations.
(4) Integration of the control system with the aircraft's avionics and flight management systems, and validation of its performance pose additional challenges. Ensuring the control system's compatibility and reliability with the overall aircraft operation is a critical technological challenge.
(5) Accurate and reliable sensor data is crucial for the control of morphing aircraft. Integrating different sensors, such as strain gauges, accelerometers, or shape sensors, and fusing their data to provide a comprehensive understanding of the aircraft's shape, position, and aerodynamic forces during morphing configurations is a complex technological challenge.

Feedback control logic based on classical linear control and modern nonlinear control theories has been investigated in the literature [14] for dynamic morphing of the actuated flexible wing to obtain desired aerodynamic properties. From the literature, it is evident that various control strategies have been used for morphing aircraft applications, such as PID controller,[15] Linear Quadratic Regulator (LQR),[16] Linear Quadratic Gaussian (LQG) algorithm,[17,18] pole placement method,[19] Nonlinear Dynamic Inversion (NDI),[20] optimal feedback control [21,22], time-delayed feedback control,[23,24] Active Disturbance Rejection Control (ADRC),[25] fuzzy control,[22,26–28], robust control [23,29–31], H_∞ control theory [32–35], mixed H_∞/H_2 algorithm [36], back-stepping,[37] Linear Parameter Varying (LPV) control,[38,39] Sliding Mode Control (SMC),[11,23] adaptive control,[40–42] and robust adaptive.[43]

As per the author's knowledge, no attempt has been made to present a comprehensive review that is dedicated to control strategies for flight-dynamic control, wing-shape control, and aeroelastic control of fixed-wing morphing aircraft. Although attempts were made by others to present reviews on the control of morphing aircraft, every work that has been published before was not completely dedicated to the control of fixed-wing morphing aircraft. For instance, the review by Chu et al.[44] was focused on the design, modeling, and control of morphing aircraft, addressing the control methods for solving flight control problems, along with methods to design the configuration of morphing aircraft, aerodynamic interference, and nonlinear dynamic characteristics caused by morphing aircraft. This paper reviews the development of the control strategies used for fixed-wing morphing aircraft applications that have occurred over the last fifteen years (2005–2022). This includes flight dynamics control, wing-shape control, and aeroelastic control. Analytical, computational, and experimental studies are considered. In Sections 2, 3, and 4 research activities are categorized according to the control strategy used. Section 5 presents the key findings and discussions on the controller type used. Finally, in Section 6, the major conclusions and future trends are highlighted.

1.3. Control strategies

In general, there are a large number of control algorithms, which can be categorized depending on different points of view. Classical control algorithms and many modern control approaches are model-based algorithms despite more recent approaches, which introduce model-free control methods. In model-free control techniques the dynamical behavior of the unknown system should be determined without the requirement of mathematical models of the system but only using the data measured from the input and output of the system. It is worth noting that the dynamic behavior of the system to be controlled should be estimated online to update the actual dynamics. Some intelligent control approaches like fuzzy control methods were originally introduced and developed as a model-free control design approach. Despite the strong research and work in this area, there are still aspects to be improved in the area of model-free control methods, especially in real-world practical implementations. In contrast to model-free control methods, a large group of control methods are model-based approaches. Most presented works in aircraft morphing control are model-based control approaches. Based on the system model different categorizations can be introduced. Models can be divided into lumped parameter and distributed parameter systems, based on considering the system elements as lumped or distributed in the mathematical modeling. A lumped system is one in which the system parameters are not functions of spatial variables and therefore the mathematical equations governing lumped elements are ordinary differential equations. Considering the physical quantities as components distributed in space lead to partial differential equations in terms of time and spatial variables.

Representation of the system model in terms of continuous-time and discrete-time models can determine a category of control algorithms corresponding to the models, defined as continuous-time (analog) control and discrete-time (digital) control systems. Accordingly, controlling a system including both continuous and discrete states specifies another class of control system known as hybrid control systems. It is noted that in this study, hybrid control denotes systems where two types of controllers have been used. Based on the system model, control systems can also be classified into time-variant and time-invariant control systems. Time-variant control systems include systems with time-dependent parameters while time-invariant systems include constant parameters. In addition, control systems can be divided into linear and nonlinear control systems corresponding to the assumed model of the system. Control algorithms corresponding to linear systems are linear control algorithms and the control strategies related to nonlinear models of the system are known as nonlinear control algorithms. There are a large number of control methods developed for linear and nonlinear systems including PID controllers, LQR, SMC, robust control, adaptive control, and so on. The number of control inputs and outputs can be considered as another view in the categorization of control systems. Accordingly, the control systems can be divided into two groups: the Single Input Single Output (SISO) and Multi Input Multi Output (MIMO) control systems. In MIMO control systems, either more than one control input is determined by the controller, or more than one output of the systems is controlled. With similar logic, control methods can also be considered into two divisions of classical and modern control methods. The scope of classical control theory is limited to SISO system design, which is carried out in the s-domain (Laplace transform) or frequency domain. Modern control theory, which is more recent with respect to the classical control algorithms, deals with MIMO systems and is mostly developed in the time domain based on the linear and nonlinear state-space models of the system. A more recent group of control algorithms are known as intelligent control systems. Intelligent control is a class of control techniques that use various artificial intelligence computing approaches like Neural Networks (NN), fuzzy logic, machine learning, evolutionary computation, and genetic algorithms. A more general classification of control systems is to divide them into open-loop and closed-loop control systems. In closed-loop control, the control action from the controller is dependent on feedback from the system, which is provided by the sensors' measurements. Open-loop control algorithms are independent of the system outputs, which usually correspond to time-dependent switching on/off actions or predefined optimal strategies. Consequently, closed-loop systems are often called feedback control systems while open-loop systems are also known as non-feedback controls.

Based on the control strategies applied in morphing aircraft according to the reviewed literature and the above discussion, the following classification is considered for morphing control strategies in this paper. The control strategies are mainly divided into three groups: closed-loop (feedback), open-loop, and hybrid control strategies. Inside the closed-loop control, three sub-categories of linear, nonlinear, and intelligent control algorithms have been considered. The Open-loop control strategy mainly includes the feedforward control strategy for morphing aircraft. Finally, the last category, hybrid control, presents the studies in which combinations of control strategies have been considered.

2. Closed-loop/feedback control strategies

Controllers that generate the new control inputs to make the system behave as desired, by observing the output signals are known as feedback controllers. A typical feedback control system consists of four subsystems: a process to be controlled, a set of sensors and actuators, and a controller. The process is the actual physical system that cannot be modified. Sensors and actuators are selected based on physical and economic constraints and application. The controller is to be designed for a given plant (the overall system including process, sensors, and actuators). The main reason to use the feedback control is to reduce the uncertainty effect, which could be either in the form of a disturbance/noise or as a modeling error in the plant description.[45] In what follows, various types of feedback controllers used for morphing aircraft are summarized into four categories. In the first category, dynamic control, the main objective of the controller is to either keep the aircraft dynamically stable or to keep the attitude of the aircraft stable during the morphing process. In the second category, shape control, the main reason for designing the controller is to track the shape morphing so that it can reach the predefined optimum shape in each flight condition. The third category, aeroelastic control, summarizes the studies dealing with the design of controllers for enhancing the aeroelastic stability of the response of the morphing aircraft. Finally, the fourth category, multipurpose control, presents the studies that aimed to design the controller for a combination of the previous three categories.

2.1. Linear control approaches

There are many linear control system design techniques, such as the well-known PID control, pole placement method, LQG, Gain scheduling control, LPV, LQR, H_2, and H_∞ control techniques, together with some newly developed design techniques, such as the robust and adaptive control methods. In the following, linear control techniques applied for aircraft morphing control are reviewed.

2.1.1. Dynamic control

Bai and Dong [16] designed the longitudinal short period motion closed-loop switched control system suitable for a sweep morphing aircraft using switched system theory as shown in Fig. 2.[16]

Firstly, the multi-body nonlinear dynamic model of a morphing Firebee aircraft was developed with the assumption of rigid body systems. Then considering certain design points in a range of sweep angles, the model was linearized. Using the optimal control LQR method, the subsystem controller was developed for each linear model. Finally, using switched system theory, all the subsystems were integrated to build the longitudinal short-period switched control system by considering the sweep angle as the decision variable. To confirm the stability of the switched control system, the Lyapunov function was constructed, and linear matrix inequality was used. The results of this study showed that the sweeping change altered the pitch angular velocity and angle of attack smoothly with strong anti-perturbation ability. In addition, the linear results were very close to nonlinear modeling results.

Zhang and Wu[29] developed a robust controller for an aircraft (Teledyne Ryan BQM-34 "Firebee") capable of span and sweep morphing based on the Stochastic Robustness Analysis and Design (SRAD) method as shown in Fig. 3.[29]

The controller consisted of a LINEAR QUADRATIC (LQ) output feedback regulator and tracking error Proportional Integral (PI) compensator. The LQ approach ensures stability under a fixed-shape state and the PI compensator keeps the steady-state error to be zero while tracking the command. The SRAD method was used for the optimization of controller parameters, where the Genetic Algorithm (GA) was used as the optimization algorithm. The longitudinal dynamic model of the morphing aircraft was considered for the controller design based on two aerodynamic configurations. The aerodynamic coefficients were calculated using the software Missile Datcom.[46] The results showed that the controller can stabilize the system before and after the morphing process, can suppress the outside interferences during the transition process, and has strong robustness.

Dong et al.[47] proposed a nominal robust smooth controller for the " Firebee " sweep morphing unmanned aircraft. Firstly, a dynamic model of the morphing aircraft was established according to the concept of the chained switching law with consideration of large-scale continuous perturbations in the aerodynamic parameters during sweep morphing. Secondly, based on the model, a dynamic smooth switching controller was designed that consisted of two steps. Step one was the design of the nominal controller without consideration of input saturation. The second step was the design of an anti-windup compensator with the consideration of actuator saturation that can compensate the control inputs effectively and reduce the affected time by saturation constraints significantly. Finally, numerical simulations were carried out to show the effectiveness of the control strategy. The results showed that the control strategy could effectively compensate the control when saturation occurs and thereby shortening the system's time affected by the saturation constraints. In addition, it could keep the height/altitude of the aircraft stable during the transformation process and the states of the aircraft could remain finite time-bounded. He et al. [48] studied a Tensor Product (TP) model-based control for a sweep morphing aircraft. Firstly, the longitudinal dynamics of the morphing aircraft subjected to a large transition process were established using the LPV modeling method. The presented LPV method neither needs a trim map nor numerical calculation. The pitch angle, pitch angular velocity, angle of attack with small variations, and flight velocity with large variations were the variables considered to establish the dynamic equations. The perturbations in variables with small changes were handled using the Jacobian linearization approach. Then the longitudinal LPV model was transformed into a TP-augmented model using the Parallel-Distributed Compensation (PDC) control framework in Takagi-Sugeno (T-S) fuzzy system theory. The control sys-

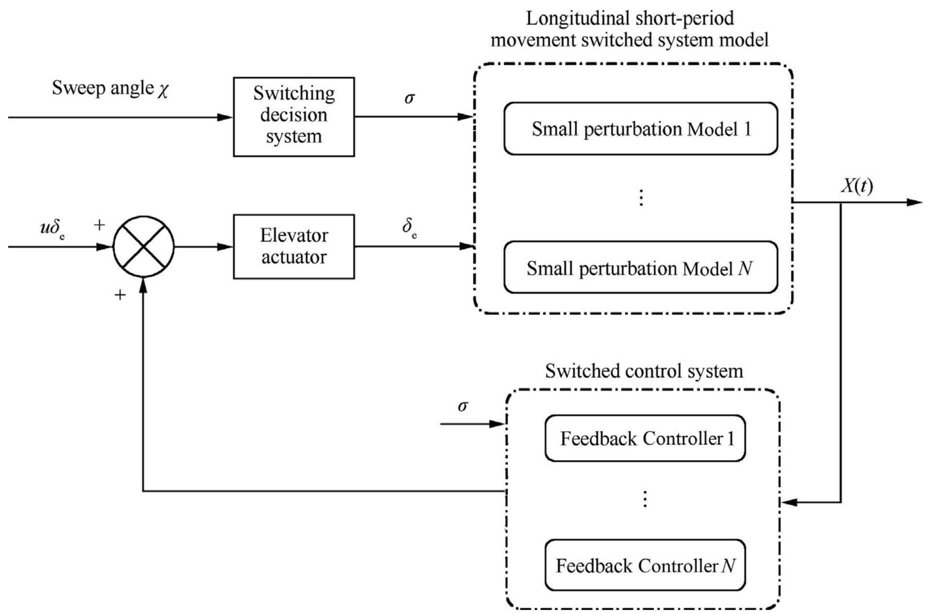

Fig. 2 Structure of switched control system (reproduced from Ref. 16).

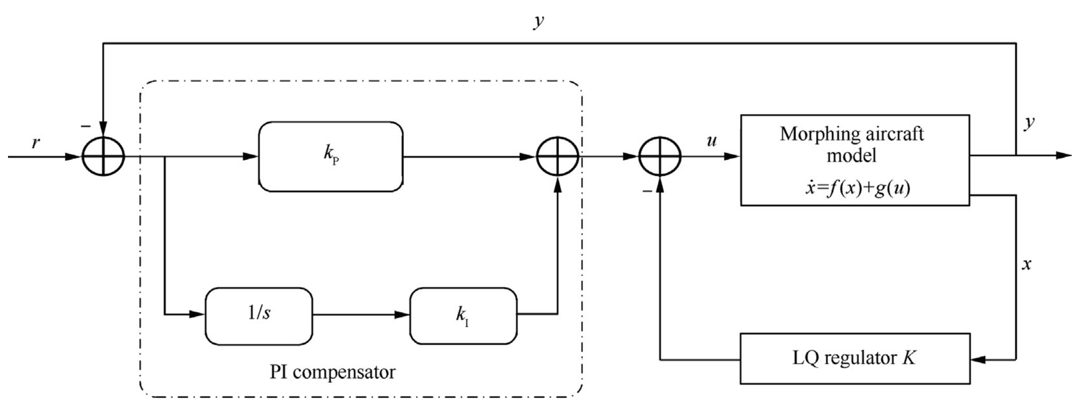

Fig. 3 Robust controller's structure (reproduced from Ref. 29).

tem design was performed fully based on Linear Matrix Inequalities (LMI) that can be easily solved by the MATLAB® toolbox. The simulations showed that the proposed control design is effective in the whole allowable flight range. Moreover, the system was capable of operating far from trimmed states during the rapid transition process.

Lee et al. [49] proposed a pitch autopilot for a polymorphing aircraft capable of sweep and span morphing using LPV control. A nonlinear parameter-dependent longitudinal dynamic model of the aircraft was established. The model was linearized and transformed into the LPV model. Linear Time-Invariant (LTI) models for nine morphing configurations were obtained at a fixed altitude of 300 m and airspeed of 20 m/s. The LPV controller was scheduled as a function of the morphing parameter and the rate of change of the parameters was assumed to be controlled and measured. The control design of the LPV was solved using the MATLAB® toolbox LPV Tools [50]. The numerical simulations at different morphing configurations showed that all configurations could properly follow the angle of attack command while following the corresponding reference model with zero steady-state error. The developed morphing aircraft model and the control design were useful for full envelope flight control system design for morphing aircraft. Liu et al. [51] proposed a new robust control for an uncertain Innovative Control Effector (ICE) morphing aircraft by updating the number of operating actuators. First, the time-continuous aircraft model was converted to a time-discrete model. Secondly, a flight control law was designed for the model to assure system stability. Then the control law was used to design the control allocation design. The control allocation design aims to distribute the total control effort on the effector arrays. The simulation results showed that the proposed design method is appropriate for the robust control of the ICE aircraft with uncertainty. In addition, the robustness of the closed-control loop was improved by integrating the flight control law with the adaptive allocation algorithm.

Cheng et al. [52] designed smooth switching LPV fault detection filters for morphing aircraft with asynchronous switching. Firstly, by considering the rate of wing sweep angle as the scheduling parameter LPV model was established for the morphing aircraft. Then the fault detection filters were established with the aid of Mode-Dependent Average Dwell Time

(MDADT) and the Lyapunov functional method, by considering the asynchronous switching caused by time delay and data missing. For the same, the whole set of scheduling parameters was divided into subsets with overlaps using an algorithm. Finally, the design model was applied to the ''Firebee'' aircraft with a sweep morphing wing, and simulations were carried out to confirm the validity. The residual signal and angle of attack response showed that the system can detect the fault and track the command signal efficiently even when there exist parameter uncertainties in aerodynamic forces and moments up to 15%. Thus, the smoothness, stability, and robustness of the system were confirmed. Jiang et al. [38] presented a systematic method of smooth switching LPV controller for a sweep morphing aircraft. Firstly, the LPV model was deduced with the consideration of the rate of change of the wing sweep angle as the scheduling parameter, which was measurable in real time. A switching law, which regulates the dynamic behavior of the plant and controller was implemented for the design of the closed-loop switched LPV system. The scheduling parameter was then partitioned into several subsets with overlaps by solving a series of LMI optimization problems. Then the output feedback smooth switching controllers were designed. An algorithm was developed for the partitioning and construction of switching controllers. Finally, simulations were carried out with a sweep morphing Teledyne Ryan BQM-34 ''Firebee'' aircraft by varying the sweep angle continuously from 15° to 60° and compared the effectiveness of the proposed controlled with a non-smooth switching controller. The nonlinear model of the aircraft was converted to the LPV model using the Jacobian linearization approach. The results showed that the proposed controller has better performance and tracking response for the angle of attack, pitch rate, and elevator deflection than the non-smooth switching controller. In addition, Monte Carlo simulation on the nonlinear model confirmed that the angle of attack has good tracking performance even though there are ± 15% parameter uncertainties in aerodynamic forces and moments.

Wang et al. [53] introduced a finite-time boundedness robust feedback controller to study the flight stability and control problems of a morphing aircraft (Firebee) during the fast reshaping process. An uncertain switched linear system model for the aircraft was established using the Jacobian method. Sufficient conditions were proposed in the form of LMI to ensure finite-time boundedness and robust performance. Two assumptions were considered to achieve the linear model for the control design: (A) the unsteady aerodynamics due to planform variations were minor enough and ignored and (B) the motion of each morphing structure was assumed to be rigid body motion during the transition process, which will cause inertia forces and moments. The simulations showed that the linear system was a suitable approximation of the nonlinear dynamics of morphing aircraft. Moreover, the proposed controller is effective and practicable for the altitude and attitude control of the wing sweeping flight. Baldelli et al. [54] presented a multi-loop controller for the aeroelastic morphing UAV concept capable of folding its wing. The controller in the inner loop was designed using the LQ output feedback approach, which provides stability and some level of performance to the morphing Unmanned Aerial Vehicle (UAV) dynamics while the outer loop LPV controller guarantees stability for fast flight condition transitions and better performance in cases where the inner-loop does not provide reasonable results. The Coprime Factor Approach, a robust control reduction technique was used to execute the reduction on the outer-loop LPV controller. Simulations were performed through simultaneous morphing configurations and acceleration changes. The results showed that the control approach can properly account for inflight transformation between vehicle states within less than 1 minute while maintaining overall stability and control.

Discussion 1. Discussion on dynamic control using linear control approach

The above reviewed papers investigating dynamic morphing control can be summarized as follows. Most papers examined their proposed model-based control algorithms in simulations on the longitudinal dynamics of Firebee UAV while considering the wing sweep morphing of aircraft. To use linear control approaches, either the LPV modeling method or switching between linear models is selected. Additionally, the combination of the above two methods has been used as the switching LPV method. Using the LPV or switched linear system, large morphing transitions can be considered. Model switching and the LPV-based model approaches mostly use robust control concepts to design the controller. The application of robust control can also remove the necessity of using switching between models if the morphing transition is not too large. The application of LPV methods seems to be more straightforward than the switching method, while stability proof in the presence of switching between models is a challenging problem. Based on the results presented by different research, the smooth switching LPV model with robust control can be introduced as a successful approach in the dynamics control of morphing aircraft. Robust control approaches can compensate for the system uncertainties and the nonlinearity effect simplifications in the linearization process on the system dynamics.

Except for the morphing of swept wings, dynamics control in the presence of other morphing parts of the aircraft and the dynamic control of morphing aircraft with experimental results require much more investigation in future research in this area.

2.1.2. Shape control

Coutu et al. [55] designed a real-time closed-loop control strategy to find the optimum actuator strokes to morph a variable thickness morphing wing at actuator lines according to the feedback parameter (lift-to-drag ratio) measured experimentally using a wind tunnel. Extensive wind-tunnel tests were carried out to design the algorithm and set up the parameters. A validated ANSYS-XFOIL coupled fluid–structure interaction was used to calculate the initial strokes of the actuators and thus accelerate the optimization procedure. The optimization algorithm aimed to search for the optimal morphing configuration. The actuator control loop (adjust wing shape based on information from the optimizer) uses a calibrated PID controller to ensure the stability and accuracy of the actuator response using linear potentiometer feedback. Before the wind-tunnel tests, the closed-loop control was validated via numerical simulation of the wing. The developed closed-loop controller (morphing profile realized from real-time optimization) was compared with an open-loop controller (morphing profile resulted from numerical modeling). The results showed that both the open and closed-loop control strategies allowed for an improvement in the lift-to-drag ratio compared with the non-morphed profile. The results of the open-loop control method confirmed the adequate performance of the numerical model and the closed-loop method appeared to be robust enough to control the wing morphing. Jodin et al. [56,57] presented a nested control loop architecture for a hybrid morphing wing that embeds both camber control and Higher Frequency Vibrating Trailing Edge (HFVTE) actuators. The control actuator was based on the surface embedded Shape Memory Alloys (SMA). Three SMA wires were embedded on both the upper and lower skin of the wing segment. Temperature and deformations sensors were used to precisely reach the desired deformation while controlling the SMA wires. Thermocouples and strain gauges were used to measure the temperature and reconstruct the trailing edge displacement. The nested closed-loop architecture uses these sensors to control the camber. The controller compares the camber change with the camber reference. A PI controller was implemented in the control system that sends an SMA temperature to the temperature controllers. Then the temperature controllers use this temperature sensor information to provide the heating and cooling commands via PI controllers. The performance assessment showed that the proposed control strategy could reduce the heating power by more than 20% of that required to maintain the camber displacement. In addition, the conducted wind-tunnel tests showed that the camber actuation could increase the lift-to-drag ratio by 16% and the actuated small vibrations could increase the performance by 2%.

Hubbard[58] presented a proof-of-concept control system design and simulation for a morphing airfoil. The HF20 pylon racing airfoil was considered for the study with the consideration of shape morphing only for the upper surface of the airfoil (modeled as a Bernoulli-Euler beam). Simulations were carried out assuming NASA Macrofiber-Composite (MFC) actuators were distributed spatially to control the shape morphing. The closed-loop shape controller was designed using the Loop-Transfer Recovery (LTR) method of modern robust control. Modern synthesis tools can be found in the Matlab® robust control toolbox. An LQG and an LTR design, which incorporates integral control and singular value matching at high and low frequencies was used to implement the multivariable design. A proof-of-concept simulation was carried out to investigate the efficacy of the commanded airfoil profile and the study showed that the commanded airfoil shape was achieved with less than 1% error compared to the reference. Dimino et al. [59] presented a tailored un-shafted distributed servo-electromechanical actuation system for a morphing Adaptive Trailing Edge (ATED) of large commercial aircraft capable of ± 5° camber variation. The actuation consisted of multiple lightweight compact lever mechanisms, each was rigidly connected to the compliant ribs and actuated by load-bearing motors. A Pulse Width Modulation (PWM)-based closed-loop motor servo controller was used to provide the actuator movement based on feedback and feedforward signals. The architecture was developed using Simulink. An FBG-based sensor system was used to monitor localized failures and to measure the chord-wise and span-wise strain distribution for the prediction of actual ATED shapes. The simulation results showed that the developed actuation system was capable of achieving a camber change with a precision of half a degree. In addition, the system responded faster than the assessed requirements.

Grigorie et al. [60] proposed an integrated architecture consisting of on–off and PI controllers for a morphing mechanism, which uses SMA actuators to modify the upper skin. The controller controls the actuators using an electrical supply, so the error in the vertical displacement can be eliminated. The integrated controller design consisted of four steps. Step one was the numerical simulation of the SMA model actuators for certain values of the forces in the system. The second step was the approximation of the system in the cooling and heating phases using the numerical simulation values from step one and the System Identification Toolbox in Matlab®. The third step involved the selection of the controller type and its tuning for the cooling and heating phases of the SMA actuators. In the final step, both on–off and PI controllers were integrated and validation was carried out. The Ziegler–Nichols (ZN) method was used to tune the PI controller for the heating phase. The study showed that in the absence of aerodynamic forces, a current intensity corresponding to a temperature of approximately 162° C was required to obtain a maximum vertical displacement of 8 mm. For the experimental validation, a rectangular wing model was manufactured. Two programmable switching power supplies AMREL SPS100-33 through a Quanser Q8 data acquisition card, and the controller by Simulink were implemented on the wing model to control the vertical displacement at actuation points. The bench test showed that the error in the vertical displacement was less than 0.05 mm and wind-tunnel tests proved that, even with the noise caused by instrumentation electrical fields and wind-tunnel vibrations, the amplitude of the actuation error was less than 0.07 mm. Kammegne et al. [61] designed and experimentally validated a position controller for a wing capable of morphing the upper skin. To control the vertical position/displacement in the skin, the torque in two eccentric shafts (located inside the wing and driven by DC motors) needed to be controlled. The torque control was achieved by a current controller. The complete architecture consisted of inner and outer loops. The outer loop was realized by a position controller, whilst the inner loop was realized by a current controller. The errors in the controllers were determined using unit feedback from the actuators. A PI controller was used to control the current, whilst a Proportional Derivative (PD) controller was implemented to control the position. The designed controller was validated by wind-tunnel tests, where the designed controller with Matlab® Simulink was reprogrammed using LabView. The test results showed that due to the improvement in the laminar flow with the proposed approach, the drag coefficient was reduced by 3% to 10.5% for different flight conditions.

Botez et al. [62] presented the design and modeling of an electrical miniature actuator integrated into the actuation mechanism of a wing with upper morphing skin. The miniature actuators to morph the wing consisted of a BrushLess Direct Current (BLDC) motor with a gearbox and a screw for pulling and pushing the upper surface morphing skin. The motor and screw are coupled through a gearing system. The actuator scheme was designed as an open-loop model using Matlab® Simulink, which consisted of schemes for a current controller and position controller. The scheme was called an open-loop as its output (vertical position in mm) was observed without any control. The current control loop was used to protect the motor against overcurrent. It consisted of a reference current generator block, which generates three reference currents based on the position information from a hall sensor, which was connected to the actuator motor. A PWM signal, which was produced by the error signal between the reference and the measured current used as a firing signal to the inverter power devices, which were connected to the motor. The position control was achieved by a closed-loop architecture which uses the information from the position sensor (measure position of the actuator motor) as the feedback signal. To track the position, a PD controller was used. The ZN method was used for tuning, as it is simple and easy to implement. The simulations result showed that all the parameters could be achieved with the designed model. Finally, the morphing wing was built, and bench tests (without the wind blowing) and wind-tunnel tests were carried out. The experimental tests confirmed a very good behavior of the actuation mechanism. In addition, the control absolute error for all tested conditions was less than 0.1 mm.

Wu and Lu[63] developed a distributed coordinated control scheme for a variable camber and thickness wing model suitable for ICE aircraft. The control scheme was a multi-agent system. Each agent was comprised of an Electromechanical Actuator (EMA) with sensors and a local controller. The agents were located on a lightweight plate that was placed in the middle of the wing. The agents transmit the sensed information to adjacent agents via the Controller Area Network (CAN) bus. Using this information, the local controller develops the control forces and moment to drive the EMAs that deform the airfoil to the desired shape by their movements. A simple diagrammatic stability analysis method was developed to ensure system stability with the consideration of the dynamic equations of the morphing wing system. Two simulations using the TureTime toolbox of MATLAB® were carried out to simulate cases where the aircraft changes from a subsonic cruise with an airfoil of NACA0012 to transonic attacks with an airfoil of RAE 2822. The simulation results showed that the morphing wing system was stable and the airfoil converged to the expected shape by maintaining smooth deformation during the motion. The experimental tests on a developed morphing wing segment confirmed the effectiveness of the control scheme in commanding the airfoil changes to the desired shape. Zhang et al. [64] provided a system-level insight through mathematical modeling, parameter analysis, and feedback control into dynamics applications of morphing camber. A promising active camber morphing concept was considered, known as the Fish Bone Active Camber (FishBAC), which uses a biologically inspired internal bending beam and elastomeric matrix composite as the skin surface. They ensured the stability of the deformable part, which is essential in such morphing camber applications. The active compliant segment can be used to stabilize the morphing aircraft while ensuring the compliant segment is also stable. The improvement in dynamic performance achieved by assessing feedback control schemes was discussed by numerical studies. The compliant segment was used to stabilize the morphing aircraft by feedback control.

Grigorie et al. [65] and Khan et al. [66] presented a control system architecture for an actuation mechanism containing miniature BLDC motors to morph the upper skin of a wing segment. The control system for each actuator consisted of three control loops for obtaining outputs (A) current, (B) speed of BLDC motors, and (C) actuation linear position. The control scheme takes DC bus voltage and load torque as inputs. A MATLAB/Simulink software model was developed to analyze the behavior of the morphing actuator. Control loops for current and motor speed use PI controllers while the loop for actuator linear position uses a proportional controller. Using the right values for proportional and integral gains in the electrical current can generate a duty cycle of high-frequency PWM signal which allows for proper control of motor speed and actuator position. The PI speed controller provides a reference value for the electrical current, which is actually input for the current controller. In addition, this reference value dictates the rotation sense of the motor rotor. The proportional controller in the outermost loop was reserved to control the linear position of the actuator. The control gains were tuned using the Internal Mode Control methodology (IMC)[65] and the Particle Swarm Optimization (PSO) method.[66] The wind-tunnel tests showed that the mean position of the laminar to turbulent flow transition improved over the whole wing with more than 2.5% of the wing chord. In addition, Popov et al. [15] studied a closed-loop scheme to control the upper morphing skin of a wing using SMA actuators. The loop consisted of 5 blocks. Block 1 consisted of inputs: skin deflection, actuator location Reynolds number, angles of attack, and Mach number while Block 2 receives these inputs and calculates the pressure coefficients with respect to chord and transition point positions for airflow conditions with an existing algorithm.[66] The PID controller in Block 3 sends commands to the SMA actuators (Block 4) located on the flexible airfoil upper skin to change the wing shape and therefore to move the transition point closer to the trailing edge. Block 5 then updates the actual pressure and transition point position and gives feedback to the PID controller (Block 3). Two methods were used to design the PID controller: ZN Method and IMC. The simulation study showed that the time response and time delay for IMC are better than the ZN Method, though it is more precise than IMC.

Furthermore, Grigorie and Botez[67] implemented a program to control the upper morphing skin of a wing using SMA actuators using Simulink. The control program provides a signal to the SMA actuators to control the current values through an analog signal. The controller receives feedback from actuators using the information from two position sensors (Linear Variable Differential Transformer, LVDT). Moreover, the system monitors the temperature in the SMAs as a safety feature for the experimental model. Three control strategies: (A) open-loop control, (B) closed-loop control, and (C) optimized closed-loop control were designed to obtain and maintain the optimized airfoils during tests performed using the wind-tunnel. The open-loop method uses reference airfoils for different airflow cases stored in the computer (user interface implemented in MATLAB/Simulink) and uses this information to obtain the optimized airfoil shape. The closed-loop method uses pressure signals from Kulite sensors (placed on the flexible skin) as feedback signals to control the actuator using the power supply. The optimized closed-loop was based on the pressure information received from sensors and on the transition point position estimation. The experimental tests showed that the open-loop method results are better from the point of view of the desired airfoil shape reproduction. The closed-loop method has the advantage that it can follow the pressure coefficient distribution that can change over time. On the other hand, the optimized closed-loop method needs approximately

10 minutes of convergence time due to the slow response of the SMA actuators.

Arena et al. [68] demonstrated an electro-actuation system for morphing flaps to assure high lift performance. The camber changes in the wing were achieved using morphing ribs and an un-shafted distributed electromechanical system arrangement that uses brushless actuators. An encoder-based distributed sensor system was implemented to generate the signals for appropriate feedback actions and simultaneously monitor the possible faults inside the actuation mechanism. Eight controllers (ServoOne Jr. by LTI® motion) [69,70] were mounted in the leading edge portion of the wing segment (3.6 m span) to drive the actuators. The encoders, placed at the chordwise hinges of the segment measure the relative camber rotation. These measured rotations were used to rationally drive the actuators and to preserve the commanded flap shape in case of variation induced by external perturbations (including aero-loads). The functionality tests showed the morphing capability of the conceived structural layout and the actuation system to withstand the static loads representative of expected aerodynamic pressure.

De Gaspari and Ricci [71] presented an optimized procedure for the shape design of morphing aircraft. The process utilized a knowledge-based framework that combined parametric geometry representation, multidisciplinary modeling, and GA. The parameterization method exploits the properties of the Bernstein polynomial least-squares fitting to enable precise control over both local and global shape changes. The framework effectively incorporated morphing shape modifications while considering structural components like the wing-box, the behavior of the morphing skins, and their impact on aerodynamic performance. It inherits CAD capabilities to generate 3D deformed morphing shapes and automatically produce aerodynamic and structural models linked to the same parametric geometry. Dedicated crossover and mutation strategies were implemented to efficiently integrate the parametric framework into the GA. This procedure was applied to the shape design of the Reference Aircraft (RA) to evaluate the potential performance benefits of morphing devices. A variable camber morphing wing was designed to examine the effects of conformal leading and trailing edge control surfaces. The study reported results for four distinct morphing configurations. Wang et al. [72] investigated the dynamic shape control of a flexible wing using piezocomposite materials to improve aerodynamic properties. They developed a feedback-tracking control approach for dynamic morphing, enabling the wing to follow predefined morphing trajectories. Through static shape control, they demonstrated the effective adjustment of the wing shape using piezocomposite actuators, resulting in enhanced aerodynamic lift properties. A time-varying LQG tracking control system was designed to enhance aerodynamic lift with pre-defined trajectories. Vibrations of the wing and fluctuations in aerodynamic forces have been caused by using static voltages directly. Simulations of static and dynamic shape control were presented for a scaled high-aspect-ratio wing model. With the feedback tracking control system, the actual lift response follows the reference trajectory well with preferable dynamic morphing performance. Moreover, Magar et al. [73] explored the use of origami to achieve camber morphing for vibration suppression and gust load alleviation in a typical wing section. The camber morphing was achieved as a parabolic camber change. An LQR controller was used to achieve the desired vibration suppression in a lightly damped aeroelastic system. The Arc-Miura origami pattern with optimal geometric parameters, that ensure a small chord deviation and an appropriate camber sensitivity with respect to fold angle, was used to achieve the desired camber shape change. The simulation results showed that the desired vibration suppression due to the initial condition was achieved within a camber change of 5% chord. Moreover, the proposed system was found to be effective to control both pitch and plunge degrees of freedom when excited with a gust. The gust load alleviation was achieved with a change in the camber within 1% of the chord length.

Fichera et al. [74] used a PID controller to mitigate the hysteric behavior of a light High-Bandwidth Morphing Actuator (HBMA) when following the prescribed camber deflection of a camber morphing trailing edge. The study aimed to investigate the aeroelastic behavior and flight mechanics of the model. HBMA used a tailored piezoelectric patch in a sandwiched configuration with a linear trailing edge slider to obtain the camber morphing. Laser displacement sensors positioned at three points along the chord of the morphing actuator detected camber variations at the trailing edge section. The PID controller utilized the sensor readings as position feedback, comparing them with the desired deflection through a real-time system. The preliminary tuning of the PID controller was achieved by applying the empirical ZN method.[75] The study showed that the actuator, aided by the controller, effectively tracked the desired output. Additionally, the displacement signal measurements from the first two sensors exhibited an anti-plateau effect induced by the controller. The study proved that the actuator bandwidth was up to 25 Hz and the equivalent maximum deflection was 15 degrees, and this was suitable for the first modes of most low-speed aeroelastic models. Sun et al. [76] developed a twist morphing control strategy for optimizing the design of an adaptive torsion wing. The wing incorporates movable spars to enable twist morphing. The controller receives the twist angle command, which was obtained from the desired shape wing using the inverse design technique based on the Mach number and altitude. The error between the desired wing twist angle and the current can be eliminated by changing the torsional stiffness. The stiffness and shear center of the adaptive torsion wing were changed by displacement of the spars. To make design easier, it was assumed that the shear center remains fixed. The controller uses the error in the twist angle using a twist angle sensor as a feedback signal to reduce the error. Using the control scheme, the required spar displacement for the desired twist was estimated for Mach 0.78 and Mach 0.6. The analysis results showed that the torsional stiffness varied linearly with deflections of the movable spars. Molinari et al. [77] used a robust feedback approach to ensure that the piezoelectric actuator introduces desired levels of camber deflections to a compliant adaptable wing. Two strain gauges in a half-bridge configuration were used as a sensor to measure the bending strain of the structure close to the trailing edge. The measurement signal was used in a feedback control loop to track the demanded displacement. The strain gauges were driven with a constant current. The measurement signal was amplified using a Maxim Mas1452 integrated chip and sampled at 10 Hz by the Atmel ATmega1280 microcontroller. A discrete PI feedback controller with anti-windup was implemented digitally, which receives the set value and feedback signal, and the output was fed as a PWM signal to the amplifiers. To tune the gains of the controller, the relay controller approach suggested by Aström and Hägglund [75] with the ZN method [76,78] was used initially. However, due to the limited peak-power capability of the amplifier, the gain had eventually to be tuned manually. The study confirmed the effectiveness of the simple feedback controller for compensating the nonlinear and hysteretic behavior of the actuators. This low-level controller allows safe manual flight, enabling the pilot to directly command deflections through remote control.

Discussion 2. Discussion on shape control using linear control approach.

In contrast to dynamics control, extensive experimental research including the control testbed and wind tunnel tests is carried out for the purpose of airfoil or wing shape control. In addition to the objective of shape control, some studies have concentrated on shape optimization for the purpose of aerodynamic advantages. Classical control methods including a different variant of PID controllers have been used for shape control. PID algorithms are effective and mature algorithms for practical control applications and are widely used in industrial control systems. The ZN method is a convenient way to determine the gains of the PID controller, as it has been applied in shape design control research. Besides the benefit of PID algorithms for practical applications, the reason for the wide application of PID algorithms in shape control is that the models are simpler and the model uncertainty is much less than for dynamic control. The lack of applications of other linear control strategies necessitates the examination of the other linear control algorithms, apart from PID controllers, for the task of shape control. According to the literature, thickness, and camber control have gained more attention in shape control research while the investigation of twist control has received little attention.

2.1.3. Aeroelastic control

Prime et al. [36] investigated limit cycle oscillation suppression of a two-degree-of-freedom aeroelastic system with a torsional stiffness nonlinearity. The control scheme utilized a Linear Fractional Transformation (LFT)/ LPV gain scheduling controller, incorporating mixed H_2/H_∞ performance criteria. By transforming the dynamics into a Linear Fractional Representation (LFR), the nonlinear effects of airspeed on the dynamics act as gain feedback to the nominal system. A controller in LFR, capable of scheduling with airspeed, was then synthesized using LMI. The performance objectives of the controller were the minimization of the H_2 norm from a gust input to the pitch and plunge outputs, as well as the H_∞ norm corresponding to systematic loop shaping. This method has a rigorous mathematical background that allows upper limits on these criteria to be established. Simulations of the nonlinear system and controller demonstrated robustness and effective rejection of gust disturbances across varying airspeed and gust conditions. The rational dependence of aeroelastic system dynamics on airspeed was effectively transformed into a linear system with airspeed dependence using an LFT. Although the controller performs well, it is conservative in that it does not take into account the finite rate of airspeed variation. Thus, alternative schemes that directly use LPV techniques may improve the closed-loop system performance.

2.1.4. Multipurpose

Gandhi et al. [79] proposed a closed-loop architecture for achieving wing-shape control and flight control in a morphing wing with the variable span, sweep, wing area, and chord. The morphing changes were achieved by manipulating two degrees of freedom: the sweep angle and the internal angle of the inboard trailing edge section. The study focused on the N-MAS wing, which was designed by NextGen Aeronautics. The adaptive control methodology consisted of two components: Modified Sequential Least-Squares parameter identification (MSLS) and Receding-Horizon Optimal control law (RHO). Robustness and versatility were the two reasons to choose this methodology. Firstly, using a quadratic constant function, the current system states, the current plant dynamics, and a model of the desired plant responses, a finite-time optimal control solution was computed. Then the first command (corresponding to the current time) was applied to the system. At the next update, the finite horizon optimization was redone using a new estimate of the desired control, current system, and plant dynamics. In this way the open-loop finite-horizon optimal control problem became closed-loop. In the control architecture, the adaptive control law tracks the response of the flying-qualities model that encapsulates the desired system dynamics. The MSLS coupled with the RHO control law provides real-time updates of dynamic characteristics. Finally, simulations were carried out to confirm the robustness of the strategy. The results of the simulations showed that the control architecture could hold the desired wing shape configuration (sweep angle of $-25°$ and internal angle of $-45°$) for more than forty seconds. The flight control simulation showed that the adaptive control law was able to yield consistent tracking without additional tuning. Gandhi et al.[80] extended their study by simplifying the wing-shape control problem using only one actuator for each wing degree-of-freedom. In addition, an integrated command generation module was added to the integrated morphing wing control architecture to intelligently schedule in-flight morphing to meet mission objectives. This module consisted of two steps: offline wing-shape analysis and online optimization routine. The offline wing-shape analysis analyses the available wing configurations to determine the potential avenues for optimization. After completion of the optimization process, an online optimization was created to find the best wing shape in flight. Batch simulations under two case studies, morphing while maneuvering and morphing to maneuver were conducted to confirm the robustness of the architecture. The simulations for morphing while maneuvering showed that the adaptive control law was able to yield a consistent response regardless of the morphing rate.

Yue et al. [81] studied gain self-scheduled H_∞ control for a tailless folding wing morphing aircraft. Nonlinear equations of dynamic responses of the aircraft were converted to the LPV model using the Jacobian linearization approach. The LPV model can capture the dynamic behavior of the morphing aircraft, matching the nonlinear model, and facilitate smooth transitions between morphing configurations. A multi-loop controller, comprising an inner-loop and an outer-loop, was formulated for the wing shape transition process. The inner-loop, an LQ controller with output feedback, ensures stability through classical techniques. The outer-loop, an LPV-based H_∞ controller solvable via a convex hull algorithm, maintains the altitude and speed of the morphing aircraft during wing folding. The study demonstrated the LPV model's ability to capture the complex behavior of morphing aircraft. The multi-loop approach effectively controlled wing folding with minimal impact on aircraft altitude and speed, while ensuring flight stability upon wing completion. Ma et al. [82] studied an LPV-based gain-scheduled H_∞ robust feedback control system for a morphing UAV with a folding wing. Parameterized LMI was used to extend the H_∞ feedback control to the LPV system. The Jacobian linearization method was used for the application of the LPV model of the UAV and the airspeed and folding angles were chosen as the varying parameters based on the flight envelope. Monte-Carlo simulation was performed to confirm the robustness of the LPV system. The result showed that the LPV controller has excellent control performance and stability in the parameter regions studied and confirmed the robustness. In addition, the LPV robust gain-scheduled model was simpler than the traditional method.

Guo et al. [32] developed a Bounded Real Lemma (BRL) theory-based H_∞ controller yielded from Lyapunov functions for attitude control of morphing gull wings. Firstly, the nonlinear dynamic equations were linearized with a perturbation approach by choosing gull folding angles as morphing parameters and presented as linear longitudinal and lateral models. Then, an H_∞ controller was introduced and applied to the gull wing. Finally, the pitch and roll tracking responses were investigated to confirm the efficiency of the proposed controller. The results from pitch tracking showed that there was no obvious difference between the nonlinear conventional system (control by elevator) and the nominal linear system and therefore nonlinear dynamics were insignificant in longitudinal movement. On the other hand, for the roll tracking response analysis, it is observed that the difference between the responses with nonlinear (control by aileron) and the nominal system was obvious. This indicated the quick growth of nonlinear dynamics for lateral movements. The attitude controller design and linearization modeling proposed were effective. Jie [33] developed an H_∞ robust adaptive controller consisting of SRAD and LPV control methods for a morphing cruise missile capable of sweep and span morphing. Firstly, the nonlinear model (longitudinal) of the morphing missile was transferred into a linear model using the LPV method. Secondly, the gain-scheduling H_∞ controller was developed based on LPV using the MATLAB® LMI tool. The SRAD method was used to optimize the controller to maintain robust performance under the random perturbation of LPV model parameters. Finally, the morphing process between four aerodynamic configurations was simulated to verify the adaptability of the developed controller. The simulation results showed that the controller has good global adaptability in maintaining the stability of aircraft between each morphing process. The controller could suppress the model uncertainties and influence of outside interferences during the transition between different morphing modes and hence confirm the robustness.

Cheng et al. [34] presented a non-fragile LPV H_∞ control for morphing aircraft with asynchronous switching as shown in Fig. 4[34].

Using the Jacobian linearization approach, the LPV model of the aircraft was established to describe the process of wing transformation. The solutions to the controller were formulated in the form of LMI by combining the MDADT method and the Lyapunov functional method. The MDADT method was used to analyze the asynchronous switching phenomenon while the H_∞ method was introduced to suppress the uncertainties of the controller. The developed control method was applied to the Teledyne Ryan BQM-34 "Firebee" aircraft capable of sweep morphing. The results of the study showed that the developed controller was capable of overcoming the influence caused by external perturbations, external switching, and controller uncertainties. To study the finite-time behavior of the morphing aircraft, they further extended their study using a non-fragile finite-time H_∞ controller, which was developed via asynchronously switched control. The study confirmed that the asynchronous controller was better than synchronous switching. Moreover, the MDADT method could reduce the undesirable response and overshoot and error of the angle of attack. In addition, the MDADT method could obtain better performance with less conservative stability results. Guo et al. [83] investigated the trajectory-attitude separation control using an active gull-morphing approach. For the control, first, an accurate nonlinear model of the morphing aircraft with the centroid dynamic equations was established. The translational and rotational dynamic equations were established, for which all morphing properties of the gull-wing could be explained. Then, to design the controller (state feedback with a feedforward H_∞ control), the dynamic equations were linearized using the LPV approach based on the Jacobian matrix. Secondly, a trajectory-attitude separation controller was devel-

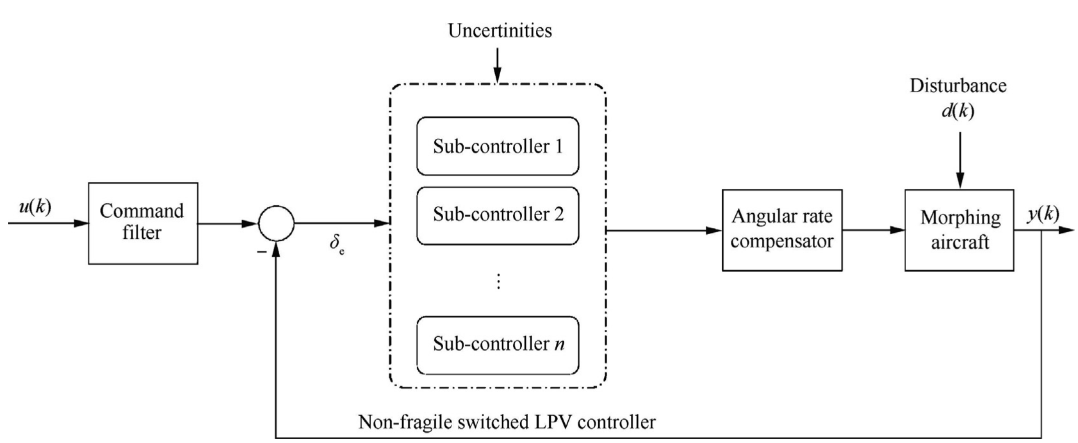

Fig. 4 Structure diagram of flight control system (reproduced from Ref. 34).

oped based on the LPV model of the aircraft. This aimed to control the attitude by conventional flaps and control the trajectory by morphing. The results of the height tracking responses with a 10 m descending command showed that the aircraft could reach the desired height after it descended for about 22 s and then moved to the new height.

Abdulrahim and Lind [34,84] presented a control approach for a MAV with a morphing gull wing. The lateral and longitudinal dynamic models of the morphing vehicle were established for four different flight missions: cruise, maneuvering, steep-decent, and sensor-pointing. Then a set of controllers was designed to obtain control responses for each of the target models. To synthesize the controller, the H_∞ technique was used. The input of the controller included the reference commands, actuator positions, and noise, whilst the output included actuation errors, performance errors, and states. During simulation, good closed-loop responses were achieved for each flight mission phase and the tracking performance was appropriate for each mission with respect to actuator rates and transient response. Given the requirement of increasing the flight endurance time of the morphing UAV, Yao and Wu [85] adopted the intermittent gliding flight method, where the flight progress was divided into two stages and a segmentation control law was proposed. During the intermittent gliding stage switching, the wing sweep angle and wingspan length were varied to accommodate the requirements of different stages. H_∞ robust control design method for gain scheduling based on the LPV model was used to ensure the stability of the morphing UAV during the wing change. The mathematical simulation verified the effectiveness of the morphing control algorithm and it has been verified that the morphing UAV can remain stable throughout the entire cycle of intermittent gliding.

Discussion 3. Discussion on multipurpose linear control approach

Among the studies with multipurpose control of morphing aircraft, the LPV method has gained much attention in presenting the plant dynamics. In fact, an LPV system is a nonlinear system whose properties vary with some set of parameters, and the plant itself can be considered linear at each point of the set of parameters. Robust control approaches are well established for linear systems and the LPV models. They can guarantee system stability in the presence of model uncertainty and external disturbances. Therefore, robust control approaches including H_∞ control and LMI-based methods are mostly used on LPV systems, especially, for the multipurpose morphing control application. The investigation of other control approaches appropriate for linear systems or LPV systems needs more attention in multipurpose control.

2.2. Nonlinear control algorithms

2.2.1. Dynamics control

Li et al. [86] designed a sliding mode control-based integrated flight control method for a morphing aircraft. The study was focused on the flight control of the aircraft by span morphing and the use of Synthetic Jet Actuators (SJA). The roll control model of the morphing aircraft at a high angle of attack was established using the computational fluid dynamic method and vortex lattice method. Then the controller was designed to ensure the desired closed-loop asymptotic stability. The controller was equipped with a Radial-Based Function (RBF) to provide the compensation induced by the input saturation constraint. Numerical simulations were carried out to confirm the effectiveness of the controller by considering different combinations of inputs to maintain the roll motion. The simulations showed that roll control with low frequency can be achieved by the span morphing motion that can track the ideal response within a few seconds. Liu and Zhang [30] developed a novel robust control framework for a class of morphing aircraft, which is called ICE aircraft. The framework was developed by considering an adaptive flight control law and an adaptive allocation algorithm. To stabilize and maneuver, the distributed arrays of hundreds of shape-changing devices were employed on the ICE morphing aircraft. First, the uncertain dynamic model of the ICE aircraft with the assumptions was presented and a state feedback control law was designed. The feedback control law guaranteed the state tracking and closed-loop stability of uncertain dynamics caused by the shape morphing of the wing due to different flight missions. The control allocation algorithm improved the robustness of the system by optimizing the distributed arrays. The results of the simulations showed that satisfying tracking performance could be achieved for the uncertain morphing aircraft model.

To track the reference trajectory, Yan et al. [11] used the adaptive super twisting sliding-mode control approach to model a wing-sweep morphing aircraft accounting for the variation in aerodynamics, mass, and inertial properties. Sliding mode control is a nonlinear control approach that provides robustness for the system. The simulation results showed that the designed controller works with good tracking performance and small chattering as compared with the normal mode sliding controller, and the robustness of the designed controller was verified by simulations in the presence of aerodynamic perturbations. It has the benefits of quick response, high robustness to parametric variations and disturbances, and is independent of system online identification. Tong and Ji [87] used the backstepping method for trajectory control and roll control of a sweep morphing UAV. A multi-body dynamic model of an asymmetric variable sweep wing morphing UAV was built based on Kane's method. This model describes the UAV's transient behavior during the morphing process and the dynamic characteristic of the variable sweep wings. Command filters were used in the backstepping design procedure to accommodate magnitude, rate, and bandwidth constraints on virtual states and actuator signals. The stability of the closed-loop system was proved using the Lyapunov method. Simulation of tracking the desired trajectory which contains two maneuvers demonstrated the feasibility of the proposed protocol and the morphing wing roll controller.

Discussion 4. Discussion on dynamic control using nonlinear control approach

As shown in the above research, Lyapunov-based control approaches are appropriate for controller design for complex dynamics such as the dynamic control of morphing aircraft. Dynamic control necessitates considering the nonlinear dynamics of flying vehicles. Integrating the nonlinear dynamics of the vehicle with the nonlinear equations accounting for the morphing parts leads to a complex nonlinear model of the system. The application of nonlinear control algorithms for the dynamic control of morphing aircraft, which is a complex nonlinear system, is a challenging task that has not been well examined in the literature and needs much more investigation in future research.

2.2.2. Shape control

Shi and Song[20] used the pseudo-coordinate Lagrange approach to simulate an inplane morphing aircraft and then used dynamic inversion and PID synthesis to create an improved controller. The efficiency of the dynamic model and controller was confirmed by simulation results. Li et al. [88] created a nonlinear dynamic inverse controller to regulate the attitude of a rotating wing morphing aircraft with significant coupling and nonlinear features. NDI, also known as exact linearization, is a structured way to cancel the dynamics and then control the system as a linear system. The NDI technique is a straightforward method and is generally utilized when system dynamics are known. When the system dynamics are subject to uncertainties, NDI-based algorithms can have difficulty in compensating for these uncertainties due to the increase in inversion error and therefore can fail to guarantee the system stability.

Wu et al. [89] created a compound anti-interference controller to help the morphing UAV fly better. A nonlinear Disturbance Observer (DO) was built in the inner-loop to estimate the inertial force and moment, and Command Filter Backstepping was used in the outer loop to ensure the closed-loop system's stability. The simulation findings showed that the system output can track the reference signal quickly during the simulation. Furthermore, the simulation results showed that throughout the transformation process of the UAV, the system output may quickly track the reference signal. Gong et al. [90] investigated the disturbance suppression control problem in morphing aircraft longitudinal dynamics. The Extended State Observer (ESO) assessed the disturbance, and the backstepping method was used to control the altitude subsystem's resilience. To prevent the complexity explosion problem, the changed dynamic surface was added in each step of the backstepping method. Shi and Peng [25,60] proposed a novel control strategy, ADRC with a Virtual Morphing Control Surface (VMCS) for morphing aircraft capable of actively rejecting the disturbances caused by the extreme complexity of aerodynamics and flight dynamics. By the strategy, the attitude controller generates the desired values for morphing parameters during the maneuvers in real-time, and therefore, the smart and autonomous morphing could be achieved according to the instantaneous flight state variables. As the morphing Degrees of Freedom (DOFs) in this strategy are used as virtual control surfaces, the desired morphing commands were generated by a control allocation law, which allocates a single control input variable. The control input variable was generated by a PID controller according to the tracking error of morphing actuators, deflections in the elevator, and pitch angle. In contrast to the conventional attitude ARDC system, the ARDC with VMCS used the shape control loop as an inner-loop, instead of a coordinated loop, of the attitude control loop. The simulation by applying the strategy on NextGen's Morphing Aircraft Structure (N-MAS) with two morphing DOFs (sweep and trailing edge deflection) showed that both the conventional and proposed strategies have excellent tracking performance in the presence of the uncertainty and disturbance without additional tuning. In addition, the use of VMCS dramatically reduced the requirements in both morphing shape changes and elevator deflection. This could lead to a significantly reduced energy consumption of both morphing actuators and elevators.

Discussion 5. Discussion on shape control using nonlinear control approach

Besides the NDI control approach, most above studies present a nonlinear observer-based control approach for the purpose of shape control. Observer-based methods, like the ADRC approach, have a DO part, which can estimate the unknown dynamics and unknown disturbance. The estimated disturbance based on the observer is considered in the controller design to reject the effect of unknown disturbance or unknown dynamics. Despite the NDI control approaches which assume knowing the system dynamics, observer-based methods are inherently based on unmodeled or unknown dynamics or disturbances in the system model. There is no experimental result in the above approaches to validate the applicability of the proposed controllers and their performance for the purpose of shape control but the observer-based controller seems to be more realistic compared to the NDI approach. Integrating a robust controller with the NDI algorithm while considering the unknown dynamics as uncertainty can compensate for the NDI approach drawback.

2.3. Intelligent control algorithms

Intelligent control methods are examined in two groups. The first group discusses fuzzy control strategies and the second group includes the NN and learning algorithms application in control strategies of morphing aircraft.

2.3.1. Fuzzy control

In general, fuzzy control is a control method that uses fuzzy logic. It is an effective approach for the control of nonlinear or large-scale systems, especially when mathematical models are difficult to obtain. It is considered a rule-based control system in which a set of rules, called fuzzy rules, define a control mechanism to adjust the system. The fuzzy control system generally consists of four principal components: a fuzzification interface, a knowledge base, an inference engine, and a defuzzification interface. The fuzzification interface identifies and measures the input variables and performs a scale transformation of the physical domain into a normalized or standard universe of disclosure, i.e., it converts the input data into suitable linguistic values. The knowledge base provides information required to devise linguistic control rules and the fuzzification/defuzzification procedures. The interference engine combines the input rules to produce a control output. Finally, the defuzzification interface converts the fuzzy control actions into nonfuzzy ones. [26] The following are the fuzzy controllers used for shape control of morphing aircraft.

Kammegne et al. [91] developed a control system for the actuation mechanism of a polymorphing wing segment capable of camber and thickness morphing as shown in Fig. 5.[91] The wing segment consisted of a flexible skin as an upper surface, an EMA for camber morphing, and four independent miniature actuators placed in two parallel actuation lines for thickness morphing. The control system was developed using a proportional fuzzy feed-forward architecture and feasibility was demonstrated through bench and wind-tunnel tests. The control system consisted of open and closed-loop architectures. In the open-loop, the aileron deflection was controlled

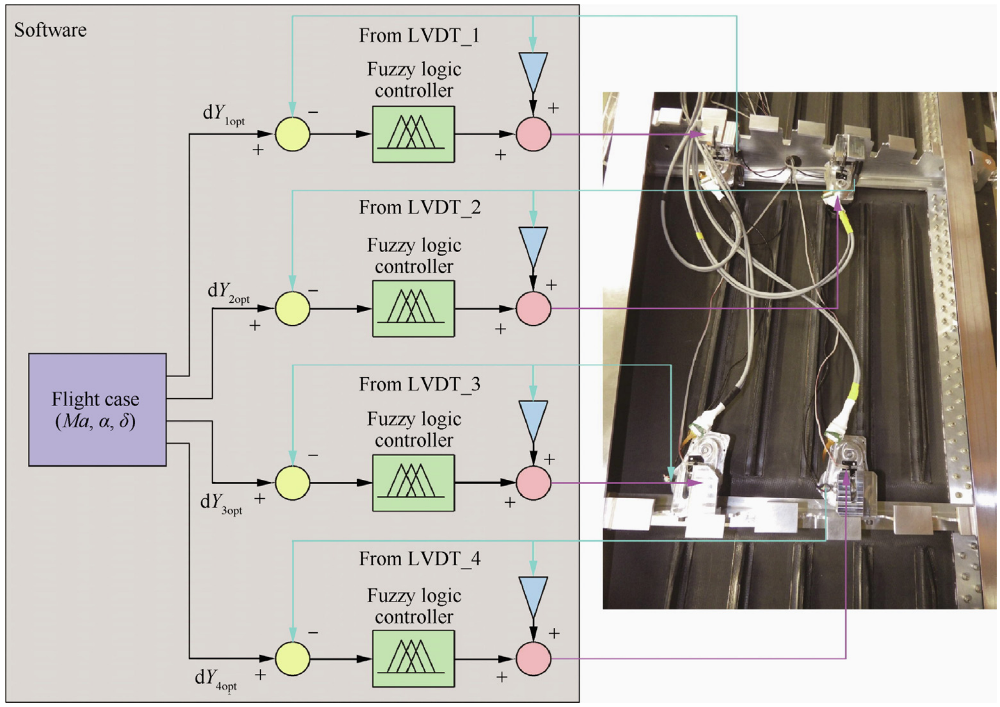

Fig. 5 Open-loop control architecture of morphing wing model.[91]

whereas, in the closed-loop, the open-loop was enclosed as an internal loop, and the thickness was controlled to change the transition point position using the information from pressure sensors on the upper surface of the wing. The results of the bench test showed that the actuators responded well with a slight time delay due to system inertia from both mechanical points of view and software processing. Similar to the bench test results, the wind-tunnel test results also showed that the actuators responded well with an error of less than 0.1 mm in the thickness of the segment.

Khan et al. [27] presented the design, numerical simulation, and wind-tunnel experimental testing of a fuzzy logic-based control system for a new morphing wing actuation system equipped with BLDC motors by using a full-scaled portion of a real aircraft wing equipped with an aileron. The target was to conceive, manufacture, and test an experimental (real models placed in the wind-tunnel) wing model able to be morphed in a controlled manner and to provide in this way an extension of the laminar airflow region over its upper surface, producing a drag reduction with direct impact on the fuel consumption economy. The control system structure for the morphing actuation system included three loops, the designed fuzzy logic-based control variant leading to the next configuration: a PD architecture for the position control loop, a PID architecture for the speed control loop, and a PI architecture for the electrical current control loop. All tests demonstrated a very good operation of the control system in all three control loops. In addition, Grigorie et al. [92] studied the approaches for the design and the validation of a smart concept for the actuation system control in a morphing wing. The developed morphing mechanism used smart materials such as SMA in the actuation mechanism. To design the control system, numerical simulations of the open-loop morphing wing system were performed first. The results obtained from the wind-tunnel tests of open-loop architecture showed that the controller performed very well in enhancing the wind aerodynamic performance.

Discussion 6. Discussion on fuzzy control for dynamic, shape, and aeroelastic controls

The fuzzy control method is an intelligent and advanced control technique to address the nonlinearity, MIMO, complexity, and coupling effect features of the systems. Despite the aforementioned advantage, there are some serious drawbacks to the fuzzy method. A major drawback of fuzzy logic control systems is that they are completely dependent on human knowledge and expertise. Therefore, approval and verification of a fuzzy information-based framework need broad testing with equipment. In addition, if the model is not known then it is impossible to achieve the stability of the controller system and guarantee the system's stability. As done in some of the above studies, verifying the performance of fuzzy control approaches in experimental tests can be a viable approach to relieve the drawbacks of the fuzzy control approach.

In addition to fuzzy logic, some researchers have applied NN and learning algorithms along with other control algorithms to control the morphing. In the following, these studies are investigated.

2.3.2. Neural network/deep learning/machine learning

In general, a NN (also known as an artificial NN) is defined as a biologically-inspired programming paradigm that enables a system to learn from observational data. The NN is considered as a subset of machine learning and is at the heart of deep learning. The NN is comprised of an input layer, one or more hidden layers, and an output layer. [93] Each layer has a different number of nodes/neurons. Each neuron is connected to another and has an associated weight and threshold. If the output of any of the neurons is above the specified threshold value, it sends data to the next layer of the network. Otherwise, no data passes along the next layer of the network. It is apparent from the literature that the research of NN/deep learning for morphing aircraft was focused mainly on the dynamics control of the vehicle.

Qiao et al. [94] designed a Radial Basis Function Neural Networks (RBFNN) based robust adaptive back-stepping controller for the nonlinear backward sweep morphing aircraft. As an initial step, the control-oriented longitudinal dynamic model of the morphing aircraft was defined. Then the controller was designed based on RBFNN. The designed controller was capable of estimating the uncertainties of the system and eliminating the approximation error between the real value and the evaluated value approximated by RBFNN. These capabilities of the controller were confirmed by Lyapunov synthesis based on stability analysis. Two types of simulations, based on the longitudinal model of the morphing aircraft were carried out to confirm the superiority of the developed controller. The fixed configuration simulation results showed that the proposed control method was better than the conventional back-sweeping method, which causes a larger tracking error in the angle of attack. The morphing configuration simulation confirmed that the proposed method was closer to the command signal during the morphing process. Lee et al. [92,95] presented a nonlinear control augmentation system for a span morphing aircraft using NN-based NDI. An F-18 High-Alpha Research Vehicle (HARV) was considered as the baseline aircraft and modified to emulate the span morphing effects. The aircraft has five control surfaces: a rudder, a pair of differential stabilizers, and a pair of ailerons. The morphing aircraft model was established by considering different parameters including control surface deflections and the ratio of extended span length to the maximum extra span length. A previously developed Command Augmentation System (CAS) [96] was implemented on the morphing control system. CAS generates the control surface deflection commands according to the received roll rate and normal acceleration data from the pilot. CAS consisted of a PI law-based command augmentation logic, a PD control law-based attitude control system, a dynamic model inversion, and a neural-based aerodynamic model inversion. The control augmentation logic generates the roll, pitch, and yaw rate commands according to the acceleration commands from the pilot. The attitude control system of CAS uses the roll, pitch, and yaw rate commands to generate the pseudo-control variables for roll, pitch, and yaw angles. Dynamic model inversion uses this data to generate the moments and the aerodynamic model inversion executes the control surface deflection. The simulation results showed that the deviation in roll/pitch angles and rates was less than 0.01° and 0.01°/s for the tested conditions and the error in altitude was less than 1 meter out of a few thousand meters total altitudes for the entire test duration.

Wu et al. [97] developed a Barrier Lyapunov Function (BLF) based adaptive neural Dynamic Surface Control (DSC) approach for a sweep-back morphing aircraft using the back-stepping technique. The control scheme was developed by combining Minimal Learning Parameter (MLP) and First-Order Sliding mode Differentiator (FOSD) techniques. First, the longitudinal dynamic model was established and divided into altitude and velocity subsystems based on functional decomposition. Then the controller was designed. The MLP was used to estimate the uncertainties, whilst the FOSD technique was used to compute the derivative of the virtual control algorithms and reduced the complexity of the back-stepping method. The NN was employed to approximate unknown nonlinear functions. The simulation results showed that the altitude and velocity tracking errors for the proposed control scheme were less than that of the Quadratic Lyapunov Function (QLF) controller [43] and the tracking error in the altitude decreased by about 0.2 m, whilst the output velocity was nearly constant during the sweep morphing process. Wu et al. [12] presented an adaptive neural control for the longitudinal dynamics of a morphing aircraft by decomposing the longitudinal dynamics into velocity and altitude subsystems as shown in Fig. 6. A robust adaptive neural controller based on high order integral chained differentiator was developed for the nonlinear longitudinal model of a morphing aircraft. For the velocity subsystem, the adaptive control was proposed via the dynamic inversion method using a NN, and to deal with input constraints, the additional compensation system was employed to help the engine recover from input saturation rapidly. For the altitude subsystem, a high-order integral chained differentiator was used to estimate the newly defined variables, and an adaptive neural controller was designed. Only one NN was employed to approximate the lumped uncertain nonlinearity. The altitude controller was viewed as the output feedback control problem with one NN to approximate the lumped uncertain nonlinearity while another adaptive NN controller was designed for the velocity subsystem. The numerical simulation study demonstrates the effectiveness of the proposed strategy, during the morphing process, in spite of some uncertain system nonlinearity.

Wang et al. [98] investigated the control problem of a morphing aircraft with variable-sweep wings based on switched nonlinear systems and Adaptive Dynamic Programming (ADP). The longitudinal altitude motion of the morphing aircraft was first modeled as switched nonlinear systems in lower triangular form. The designed controller was comprised of the basic part and supplementary part. For the basic part, the back-stepping technique was applied, and a modified dynamic surface was introduced to overcome the 'explosion of complexity' problem. DOs inspired by the idea of extended state observers were designed to obtain estimations of internal uncertainties and external disturbances. The common virtual control algorithms of the back-stepping method were developed by the DOs and radial basis function NN. On the other hand, for the supplementary part, an ADP approach with the name of action-dependent heuristic dynamic programming was used to further decrease the altitude tracking error, which generates an additional control input by observing the differences between the actual and desired values in the back-stepping design. The simulation results were compared with the controller which contains the basic part only. The proposed supplementary control input can further reduce altitude tracking errors and improve control performance. Morphing UAVs are now envisioned to autonomously maneuver in complex environments involving dynamics, narrow passages, and hazardous situations using reinforcement learning. In such scenarios, morphing UAVs must be equipped with hardware and software elements that enable them to autonomously adapt to the environment by changing their configuration to suit the task at hand. In Ref. 99, deep NN and a reinforcement learning agent have been developed to carry out the UAV deformation required for the task. More specifically, the goal

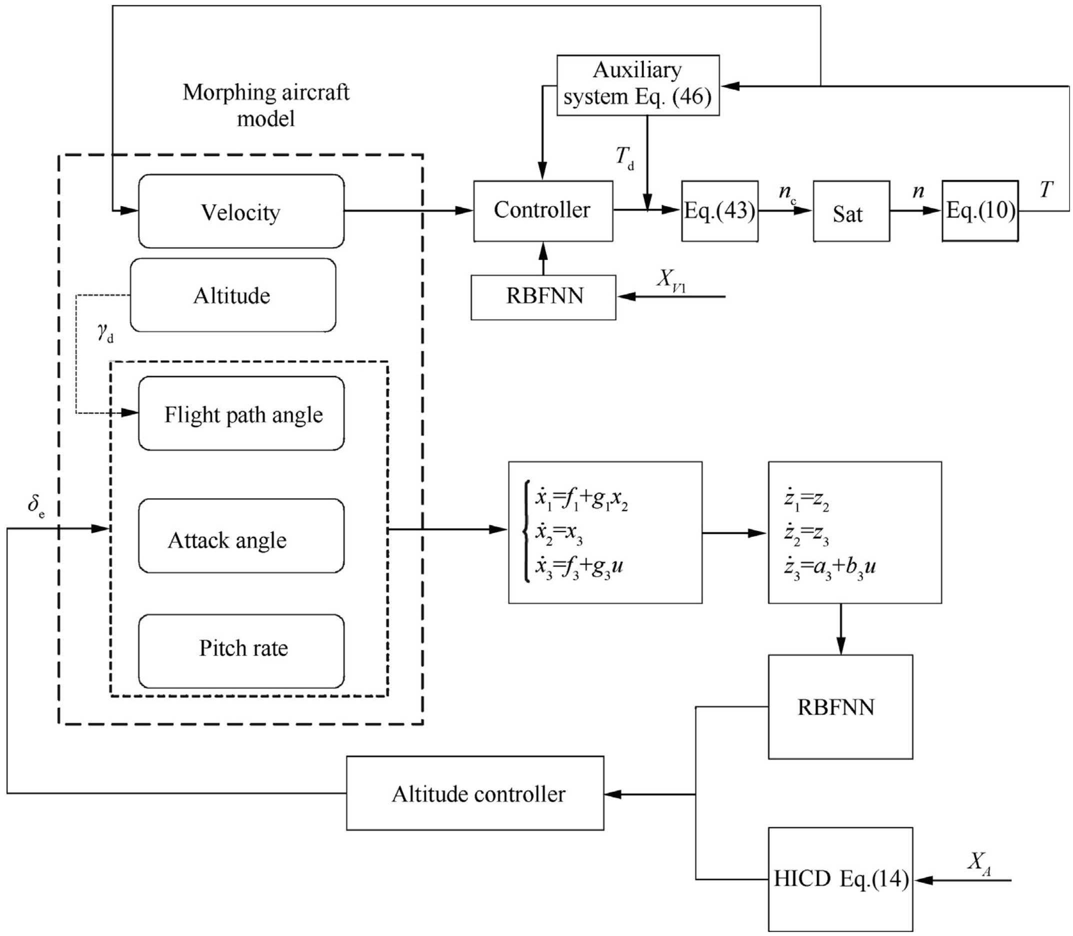

Fig. 6 Adaptive neural control scheme (reproduced from Ref. 12).

of reinforcement learning was to enable the steering gears on each side of the airfoils to provide suitable forces completing airfoil structure optimization throughout the flight envelope. In addition, autonomous morphing control was realized in Ref. 100 using deep reinforcement learning where shape optimization control was carried out using a deep deterministic policy gradient agent. An adaptive reinforcement learning agent was developed in Ref. 101 to learn how to optimally change the shape of a morphing aircraft in the presence of parametric uncertainties, unmodeled dynamics, and disturbances. Another shape-changing policy was proposed in Ref. 102 based on a reward function that considers the correspondence between the airfoil properties and the flight conditions. More specifically, the thickness and camber parameters are controlled by the RL agent to meet the requirements of the task. In Ref. 103, a reinforcement learning agent was developed to reduce the tracking altitude error of a morphing aircraft after a switched nonlinear system describes the aircraft's altitude change. Furthermore, the work presented in Ref. 104 verified the ability of reinforcement learning to control the morphing tail of an aircraft and achieve excellent attitude control ability.

Discussion 7. Discussion on NN-based controllers for dynamic, shape, and aeroelastic controls

NN-based controllers are rapidly developing in different engineering applications with control applications. The NN has the ability to learn and model non-linear and complex relationships. NN-based controllers basically involve two steps of system identification and control. The complex dynamical systems under significant uncertainty, such as the case of morphing aircraft, have led to a reevaluation of conventional control methods and new interest in NN-based or learning-based algorithms. In most of the above studies, NN have been employed along with a nonlinear control algorithm to compensate for the uncertainties in the morphing airplane. NNs and learning algorithms have been applied successfully in the identification of uncertainties due to morphing parts for the purpose of dynamic control. The approximation and learning capabilities of NNs make them an appropriate choice for implementing them in the nonlinear control of morphing aircraft. The application of artificial intelligence algorithms is mostly accompanied by adaptive control algorithms in morphing control. All the above studies are simulation-based due to some restrictions of the artificial intelligence algorithms. Artificial NNs are more computationally expensive than traditional algorithms and therefore, require processors with parallel processing power, in accordance with their structure. In addition, there is no specific rule for determining the structure of an artificial NN. Using artificial intelligence algorithms in experimental applications, especially for shape control and aeroelastic control, requires more attention in future research for morphing aircraft.

3. Open-loop control strategies

3.1. Feedforward controllers

The term feedforward refers to a pathway or element within a control system that passes a controlling signal from a source in its external environment to a load elsewhere in its external environment. Therefore, in contrast to feedback control, the feedforward control system responds to a predefined control signal without responding to how the output signal reacts. Some prerequisites are needed for a control system to be pure feedforward: the external controlling/command signal must be available and the effect of the output of the system on the load should be known. For the purpose of dynamic control, feedback is necessary in the control architecture to control the dynamic states of the aerial vehicle. Therefore, from the literature, it can be seen that the feedforward controller is just used in morphing aircraft for shape control and aeroelastic control purposes as follows.

3.1.1. Shape control

He et al. [39] investigated the open-loop control of LPV systems, which is suitable for a morphing wing using a novel switching strategy, MDADT based on parameter-dependent Lyapunov functions. Firstly, the general open-loop LPV model was established. Then, based on parameter-dependent Lyapunov functions, a set of switching signals with MDADT was designed. In addition, a set of switching signals was constructed with Average Dwell Time (ADT). Finally, the controller was applied to a morphing aircraft with a variable-sweep wing. Simulations were carried out by selecting equilibrium points as 15°, 30°, 45°, and 60° sweep angles and dividing this into 3 subregions (30° and 45°) corresponding to low sweep, transitional, and high sweep angle configurations. The results showed that both ADT and MDADT methods have the same switching signal and sweep signal initially, but 3 s later MDADT trajectory enhances its variation rate in Subregion 2. On the other hand, it decreases in Subregion 3.

3.1.2. Aeroelastic control

Fonte et al. [105] numerically assessed the potential of a feedforward Maneuver Loads Alleviation (MLA) controller for reducing the loads on the wing and morphing the winglet of a regional aircraft by means of static aeroelastic analyses. The adaptive winglet was equipped with two independent control surfaces. An MLA controller finds the best combination of the deflection of the control surfaces that minimize the internal loads and guarantee the equilibrium of the aircraft. The controller was developed using Matlab® Simulink by following mechanical and electrical specifications. A linear EMA with a peak force below 5kN was used for the actuation. A “control block” modeled in Simulink receives the commanded winglet deflection as input and drives the EMA model to reach the provided commanded position. Moreover, a brake management strategy was defined to optimize the motor current absorption when the movable surfaces reach the commanded position. Two models (EMA and winglet models) associated with winglets and motors were developed and validated in Ref.[106] The simulation results showed that the proposed system was able to reduce the wing loads at different flight conditions by ensuring enhanced aerodynamic efficiency with respect to the reference winglet architecture. The actuator dynamics reduced the performance of the system obtained with the MLA controller.

4. Hybrid controllers

A hybrid control system refers to studies in which a combination of various control strategies (closed-loop and/or open-loop) for morphing aircraft control is used. According to the literature, the hybrid controllers for morphing aircraft were mainly used for shape control as follows.

4.1. Shape control

Dimino et al. [107] studied a conceptual control platform for a morphing trailing edge. The concept consisted of a wing with active ribs, driven by a servo rotary actuator, and the airfoil shape is controlled by a dedicated algorithm according to a pre-defined geometry. The FBG sensors were used to monitor both the spanwise and chordwise trailing edge motions. The servo was driven by a PWM driver. The control algorithm consisted of both open (feed-forward) and closed (feedback) architecture to achieve the desired trailing edge shape. The open-loop control strategy executes the command from the information stored in the database whereas the closed-loop strategy uses information about the actual rotation of the actuator through the actuator encoder as well as from the sensor about the strain distribution over the structure for controlling the trailing edge motion. The closed-loop architecture was developed using a classical PID controller with constant proportional, derivative, and integral coefficients. The numerical simulations showed that by using both control logic adequately, a near-zero error can be obtained in the system. However, comparing the open-loop with the closed-loop the limiting factors are the resolution and accuracy. On the other hand, the robustness in the shape evaluation through strain measurements may affect the closed-loop structural feedback control. As a result, feedforward (open-loop) control may be needed to minimize the tracking error in addition to disturbance rejection through closed-loop architecture. Grigorie et al. [108] studied the design and validation of a controller for a new morphing mechanism using SMA-based smart materials for actuation. Also, an aeroelastic study for the morphing wing was performed. The final configuration of the integrated controller resulted in a combination of a bi-positional controller (on–off) and a PI controller, due to the two phases (heating and cooling) of the SMA wires interconnection. This controller behaved like a switch between the cooling and the heating phases, in situations where the output current was 0 A, or was controlled by a PI type law. The PI controller for the heating phase was optimally tuned using an integral criterion, the error minimum surface criterion (ZN). Also, a validation step of the controller was performed by using numerical simulations, bench testing, and wind-tunnel testing. Also, all validation cases of the designed controller showed that the controller performed very well in enhancing the wing aerodynamic performance and fully satisfy the project requirements. Grigorie et al. [109] further developed an actuation system concept for a variable thickness wing mechanism using SMA. An intelligent controller was developed that comprised open-loop and closed-loop control architectures where the closed-loop architecture included as an internal loop in the system. In the open-loop architecture, the system uses the information stored in the database while the closed-loop system considers the information received from the pressure sensors mounted on the upper surface of the wing and compares the information stored in the database. Thus, the closed-loop architecture acts as a feedback control system. To control the actuation line, a fuzzy PID controller with constant proportional, derivative, and integral coefficients was used. The numerical simulations for the controller confirmed that the controller worked well for different phases of the SMA actuators. To validate the numerical simulations, experimental bench tests without aerodynamic forces and wind-tunnel tests were carried out.

Popov et al. [110] presented an open-loop architecture for a wing with variable thickness capability. The study focused on the instrumentation of the morphing controller and the method to acquire the pressure data from the upper surface of the wing. The actuation system consisted of a cam at each actuating line that moves using SMA wires. The movement of the cam controls the up and down motion of the actuation rods. The control architecture consisted of a Simulink/xPC programmed Quanser Q8 control board that controls the movement of SMA wires. The Simulink code has an interface where a user can choose the desired shape of the airfoil. Each SMA actuator has a controller that maintains the actuator in the desired position. Two controllers were tested for controlling SMA actuators: a self-tuning fuzzy controller and a classical PID controller. The position of the actuator was recorded by an LVDT. The controller uses this feedback data to adjust the temperature in the SMA wire. The Kulite pressure sensors were placed on the upper surface for the real-time pressure data acquisition that will be used for the detection of the transition location and further development of a closed-loop architecture. Wind-tunnel tests were carried out to investigate the validity of the controllers. The Graphic User Interface (GUI) was used to investigate the response of the controller during wind-tunnel testing. The test results showed that the SMA actuators performed well and the wind-tunnel validated the self-tuning fuzzy controller and PID controller for open-loop operation. However, the study showed that the self-tuning fuzzy controller had a smoother control than the PID controller for the same displacement in the SMA actuators. Grigorie et al. [111] proposed a hybrid actuation control architecture consisting of a fuzzy logic PID plus a conventional on–off controller suitable for a morphing mechanism to modify the upper skin using SMAs as actuators as shown in Fig. 7.[111] The fuzzy logic model consisted of four parts: the fuzzifier, the knowledge base, the inference engine, and a defuzzifier. The fuzzifier reads, scales, measures the control variable, and transforms the measured numerical values to the corresponding linguistic variables with appropriate membership values. The knowledge base consisted of the required rules that specifies the control goals using linguistic variables and definitions of the fuzzy membership functions defined for each control variable. The inference engine receives the information from the fuzzifier and knowledge base to derive the linguistic values for the output linguistic variables. The defuzzifier converts the linguistic variables back to the numerical values. The simplified fuzzy logic controller is the proportional controller. To ensure stability and deal with the sustained steady-state error PID controller was integrated with the fuzzy controller. As stated earlier, the hybrid controller included an on–off controller, which was to ensure the switching between SMA's cooling and heating phases. The numerical and experimental validation of the controller was performed using the MATLAB® Simulink toolbox.[112] The numerical simulation showed that the hybrid controller worked very well in both the heating and cooling phases of the SMA actuators with a few seconds of easier latency in the time of the cooling phase compared to the heating phase. The bench test results showed small oscillations of the obtained displacements at the actuation points were around the desired input values. Wind-tunnel results showed that errors in the actuation (difference between the deflection obtained in experiments and the desired deflections) were less than 0.05 mm and this error did not affect the transition position.

Grigorie et al. [112,113] extended their study by investigating the use of an open-loop Mamdani-type fuzzy logic PD controller for the aforementioned morphing wing. The open-loop architecture used the desired displacement of the actuator from the database stored in the computer memory. The information on the position of an LVDT connected to the actuator was used as the feedback signal. This method is named ''open-loop control'' as it does not take direct information from the pressure sensors attached to the wing. A Mamdani-type PD fuzzy logic controller was selected, which receives the error and change in error as inputs and the voltage controlling the power supply current as the output. The Mamdani-type controller is widely accepted due to its simple structure of ''min-max'' operations. [114] In addition, a closed-loop architecture was used as an internal loop to generate the real-time optimized airfoil based on the information from the pressure signals measured by optical and Kulite sensors installed on the upper wing flexible surface. The simulations using MATLAB® Simulink showed that the system response was a critically damped one and an easier latency was observed in the cooling phase of the SMA than in the heating phase. The experimental tests including the bench test and wind-tunnel tests showed

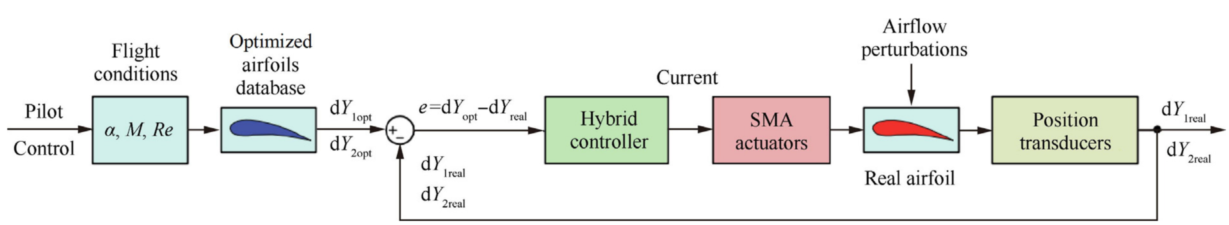

Fig. 7 Block diagram of controlled morphing wing system Ref. 111.

that the errors in the actuation were less than 0.05 mm.[115] Moreover, for the closed-loop, the transition was detected on the same pressure sensor as the open-loop case.[28]

Kammegne and Botez [116] presented the modeling of miniature EMAs used in a morphing wing application, the development of a control concept for these actuators, and the experimental validation of the designed control system integrated with the morphing wing-tip model for a real aircraft. The assembled actuator includes as its main component a BLDC motor coupled to a trapezoidal screw by using a gearing system. An LVDT was attached to each actuator giving back the actuator position in millimeters for the control system, while an encoder placed inside the motor provides the position of the motor shaft. The pole-zero cancellation method has been used to tune the torque controller and the position controller based on the encoder data, while the position control based on the LVDT data implementation used fuzzy logic technology. Two actuation lines, each with two actuators, were integrated inside the wing model to change its shape. A controllable voltage provided by a power amplifier was used to drive the actuator system. In this way, three control loops were designed and implemented, one to control the torque and the other two to control the position in a parallel architecture. The parallel position control loops use feedback signals from different sources. For the first position control loop, the feedback signal was provided by the integrated encoder, while for the second one, the feedback signal comes from the LVDT. The experimental validation of the developed control system was realized in two independent steps: bench testing with no airflow and wind-tunnel testing. Grigorie and Botez[117] developed and tested various control systems for a morphing mechanism (to modify the upper flexible skin and thereby reduce drag) using smart materials, such as SMA, as actuators. Two architectures were developed for the control system: an open-loop and a closed-loop. The strong nonlinearities of the SMA actuators' characteristics and the system requirements have led to various intelligent control structures for the inner-loop of the control system, called the open-loop architecture. The optimized closed-loop architecture was developed to generate real-time optimized airfoils starting from the information received from the pressure sensors and targeting the morphing wing's main goal: the improvement of the laminar flow over the wing's upper surface. All developed control structures were validated in wind-tunnel tests in parallel with the transition point real-time position detection and visualization and showed that all developed control structures were very good, the controllers fully matching the requirements.

5. Discussion and trends

It is apparent from the literature that the developments in control algorithms to study both dynamics and shape control are likely to continue. Table 2 summarizes the various control strategies used for the control of morphing aircraft. According to the literature, applications of open-loop control strategies are rare in aircraft morphing control and most approaches use feedback signals from sensors to create a closed-loop system for morphing control [17,18]. Most morphing control strategies have applied linear control algorithms for the purpose of dynamics,[16,29,47,48] shape [55–58], aeroelastic control, [36] or multi-purpose.[32,79,81] Nonlinear control algorithms have not been widely used in comparison to linear algorithms, especially for shape control and aeroelastic control. More recently, using intelligent algorithms, especially applications of learning algorithms, has attracted some interest among researchers. Controllers based on fuzzy logic have been widely used for shape control[27,91] while NN-based or learning algorithms have been mostly used for dynamics control [92,94,95]. The studies focused on control algorithms for both shape control and dynamics received the same attention and very few studies focused on aeroelastic control of the morphing aircraft. This may be due to the complexity of modeling such aeroelastic systems. Furthermore, in reality, when a morphing process starts, the system parameters go through changes which means that the system parameters are time-dependent. This will add more complexity when dealing with the aeroelastic stability of morphing aircraft. In the following, the control algorithms presented in the literature are summarized based on the application for different purposes and the type of algorithms, the key issues are concluded, the related gaps are specified, and then the potential future works are pointed out in each area.

The majority of cited works used closed-loop control algorithms as feedback controllers in morphing shape control, flight dynamics, and aeroelastic control. Among the algorithms, PID control algorithms and their different derivatives such as simple feedback gain controllers, PI,[56,57,60,61,118] and PD controllers have been employed a lot,[62] especially in the shape control area. In addition to different variants of the PID algorithm as a linear control approach, LQR [73] and LQG [72] control methods are the most applied algorithms in morphing control, especially for the purpose of aeroelastic control and shape control, respectively. Most linear control algorithms for dynamics control use the LPV models,[49,52] which is a simplified linear model of the nonlinear system. Due to complex nonlinear models for morphing aircraft, most researchers applied a kind of simplification or linearization methods for controller design. Employment of the H_∞ control algorithm,[32,81,82] which is a robust control approach is the next algorithm used for morphing control according to the literature. Considering the unmodeled dynamics or the nonlinear terms as the system uncertainty make the H_∞ control approach suitable for morphing control. The trend of converting the desired system to a linear model can be tracked even in nonlinear control approaches for morphing control. Nonlinear control algorithms based on feedback linearization and NDI,[20,88] which are nonlinear control algorithms change the system dynamics to linear models for controlling. Feedback linearization-based or NDI-based controller is used in several nonlinear control approaches.[20] Sliding mode control[11,86] is another method, which has been used as a nonlinear control algorithm for morphing control. In addition to the aforementioned algorithms, there are other control algorithms, which are mostly used for the dynamics control of the morphing wing rather than the shape or aeroelastic control. The application of different fuzzy logic approaches along with control algorithms is another trend according to the literature, which has been used in several studies as intelligent control approaches.[91,92] Recently, NN and learning-based control algorithms are being proposed but need more attention in future research.[94,95,97] Therefore, the application of nonlinear control approaches, especially advanced nonlinear control approaches such as robust adaptive controllers along with intelligent control meth-

Table 2 Studies on the control strategies used for morphing aircraft.

Reference	Morphing DOF	Controller strategy					Controller type	Controller objective
		Closed-loop			Hybrid	Open-loop		
		Linear	Nonlinear	Intelligent		Feedforward		
16	Sweep	√					LQR + switching system model	Longitudinal short-period
29	Span, sweep	√					Robust (LQ + PI)	Dynamic control
47	sweep	√					Robust + switching system model	Dynamic control
48	sweep	√					LPV + PDC and pole placement	Dynamic control
49	Span, sweep	√					LPV + Output feedback gain scheduling	Dynamic control
51	sweep	√					Robust	Dynamic control
52	sweep	√					Smooth switching LPV-fault detection filter	Dynamic control
38	sweep	√					LPV + Output feedback switching controller	Dynamic control
54	folding	√					LPV + robust control	Dynamic control and performance
55	thickness				√		PID	Shape control
56,57	Camber	√					PI	Shape control
58	thickness	√					Robust-LTR	Shape control
59	camber	√					PI	Shape control
60	thickness	√					PI	Shape control
61	thickness	√					PI	Shape control
62	thickness	√					PD	Shape control
63	Camber and thickness	√					P	Shape control
25,64,113	camber	√					LQR	Aeroelastic stability
15	thickness	√					PID	Shape control
65,67	thickness	√					PID	Shape control
72	twist	√					LQG	Shape control
73	camber	√					LQR	Vibration suppression
74	camber	√					PID	Shape control
76	twist	√					P	Shape control
77	camber	√					Robust, PI	Shape control
79	Span, sweep, chord, area	√					Adaptive (MSLS coupled with RHO)	Shape control, flight control
81	folding	√					LQ,H_∞	Shape control, flight dynamics
82	folding	√					Robust,H_∞	Shape control, attitude control
32	folding	√					H_∞	Flight dynamics, attitude control
33	Sweep, span	√					H_∞	Flight control, Dynamic control
34	sweep	√					H_∞	Shape control, flight dynamics
83	Folding	√				√	H_∞	Shape control, attitude control
84	folding	√					H_∞	Shape control, flight dynamics
36	camber	√					H_2/H_∞	Aeroelastic response
86	span		√				Sliding mode	Flight control
30	Wing shape		√				State feedback robust adaptive control	Dynamic control
11	sweep		√				Sliding mode	Dynamic control
87	sweep		√				Back-stepping	Dynamic control
20	Sweep, wing area		√				dynamic inversion and PID	Shape control
88	Wing skew angle		√				dynamic inversion	Shape control

Table 2 (*continued*)

Reference	Morphing DOF	Controller strategy					Controller type	Controller objective
		Closed-loop			Hybrid	Open-loop		
		Linear	Nonlinear	Intelligent		Feedforward		
89	sweep		√				back-stepping	Shape control
90	sweep		√				back-stepping	Shape control, Dynamic control
25	Multi DOF		√				Actively rejecting disturbance control	Shape control
91	Camber, thickness			√		√	Fuzzy	Shape control
27	wingtip			√			Fuzzy, PD, PID, PI	Shape control
92	thickness			√			Fuzzy	Shape control
94	sweep		√	√			RBFNN, back-stepping	Shape control
95	span		√	√			NN, dynamic inversion	Shape control, attitude control
97	sweep		√	√			neural DSC, back-stepping	Shape control, attitude control
12	sweep		√	√			NN, dynamic inversion	Shape control, attitude control
98	sweep		√	√			RBFNN, back-stepping	Shape control, attitude control
107	camber	√			√	√	PID, feedforward	Shape control
108	Thickness	√			√		PI, open-loop	Shape control, Aeroelastic stability
109	Thickness	√		√	√	√	Fuzzy PID, open-loop	Shape control
110	Thickness	√		√	√	√	Self-tunning fuzzy, PID, open-loop	Shape control
111	thickness	√		√	√	√	Fuzzy, PID, open-loop	Shape control
112	thickness	√		√	√	√	Fuzzy, PD, open-loop	Shape control
116	wingtip	√		√	√	√	Fuzzy, PD, PI, open-loop	Shape control
117	thickness	√		√	√	√	Fuzzy, PD, PID, open-loop	Shape control
105	winglet					√	open-loop	Aeroelastic response

ods needs to be investigated more seriously by researchers in the future. From the point of different control algorithm applications or diversity of control algorithms, dynamics control is much richer than shape control and aeroelastic control.

5.1. Shape control

Among the control algorithms, different types of PID controllers have been applied to control the shape during the morphing process so that it can reach the optimum shape in each flight condition.[54–57] Despite the simplicity of the above algorithms, good control performance has been achieved when applied to the shape control of morphing aircraft. PID algorithms are usually used in Laplace space for single input and single output systems and LQR algorithms are mostly used for the state space form of the model in the time domain. NDI[20,88] and ADRC are other methods used for shape control.[25] ADRC is a nonlinear observer-based robust control approach inherited from the PID control algorithm. The application of other control algorithms has not been well examined for shape control, especially in the area of nonlinear control. Due to the nonlinear and time-variable nature of morphing and the existence of uncertainty in the modeling, the application of nonlinear, robust, and adaptive control approaches can be more effective in comparison with linear algorithms. There exists a considerable gap in the literature respecting the diversity of control algorithms and the application of nonlinear control algorithms, especially the adaptive and robust nonlinear control algorithms. The performance of such algorithms should be investigated and compared with the existing results.

5.2. Dynamics control

A wide variety of control algorithms ranging from linear PID,[29] LQR,[16] H_∞[84] to nonlinear sliding mode,[86] back-stepping,[87] and robust adaptive [47] have been applied to control the dynamics of the morphing wing. Although most studies are based on linear control methods, the application of different control algorithms for the dynamics control of morphing wings is well-established. In most studies in this area, the Linear Parameter Varying (LPV) approach has been used. Using the LPV approach simplifies the nonlinear dynamic and morphing equations into simpler linear equations. Using the advantages of the LPV method, linear control algorithms are used in the closed-loop control of the dynamics. Apparently, controlling the dynamics necessitates the application of feedback and having a closed-loop strategy. Although the research in this area is still developing, there is no fundamental gap in terms of the diversity of control algorithms for morphing aircraft dynamics control. Though, the existing performance of such linear control algorithms can benefit from recent advancements in control methods from the non-morphing aerospace literature. For example, a real-time identification and tuning approach based on the use of a Deep Neural Network And The Modified Relay Feedback Test (DNN-MRFT) was able to optimally tune PID controllers of a multirotor aircraft in-flight within a few seconds.[119] The DNN-MRFT approach seems to be directly applicable to morphing aircraft where a gain schedule can be efficiently constructed in-flight to address the full flight regime described by the LPV. The application of nonlinear control approaches for dynamics control is less developed in comparison with linear algorithms. Therefore, this area needs more attention. Most studies in the dynamics control are based on simulation and very few on experimental tests. Using experimental tests such as wind-tunnel tests or real-time flight tests to validate the developed control algorithms is a potential area for further investigation.

5.3. Aeroelastic control

Among the studies dealing with the control of morphing aircraft, aeroelastic control received less attention in the literature. In addition to closed-loop strategies,[25,64,113] some studies applied open-loop control approaches for the aeroelastic control of morphing aircraft.[108] Again the PID controller is the dominant controller used in the literature for aeroelastic control of morphing aircraft.[108] Other control methods applied to the linear model have been proposed. [36] A representative example of control for aeroelastic is the study by Prime et al. [36], in which they investigated the limit cycle oscillation suppression of a two degrees of freedom aeroelastic system with a torsional stiffness nonlinearity using a mixed H_2/H_∞ scheduling control scheme with the aid of LFT/LPV gain scheduling controller.[36] The application of nonlinear control algorithms is much less in the area of aeroelastic control and requires much more attention by researchers. From the application point of view, most works are simulation-based although there are some studies concerned with the experimental tests for aeroelastic control. Therefore, employing nonlinear control algorithms and implementing the control algorithms in experimental tests are potential areas that need further studies in the category of aeroelastic control.

5.4. Morphing DOFs

Thickness-to-chord has received the greatest attention compared to other morphing degrees of freedom. The variable thickness-to-chord ratio mentioned in these studies aimed to increase the lift-to-drag ratio by morphing the upper surface of the wing and thereby moving the laminar-to-turbulent transition point to increase the laminar flow region. To achieve the optimal outcome from the aerodynamic studies, the actuation line of the morphing wing with a variable thickness-to-chord ratio must be precisely controlled. Therefore, these works focused to improve shape control using different control systems. Following the thickness-to-chord ratio, sweep morphing wings received significant attention. The purpose of the majority of these works was to study flight dynamics. The focus of these works was to study the effect of the rate of sweep angle change on the developed controller,[52,94] the stability of the controller,[34,52] and the effectiveness of the proposed scheme in controlling the altitude and velocity, [97] etc… After the thickness and sweep morphing concepts, camber morphing wings received the highest attention followed by folding wings. Both span morphing wings and gull wings received the same level of attention. It should be noted that very few studies considered the control of morphing aircraft with twist morphing, and this is one of the areas that require more research. Finally, there are some studies, which focused on morphing wings with multiple degrees of freedom such as span and sweep, sweep and camber, camber and thickness-to-chord ratio, and span, sweep, and chord.

5.5. System dynamics modeling

The majority of research in the literature has employed linear models to simulate the dynamics of the morphing aircraft. In most studies, the nonlinear dynamic model of the morphing aircraft was linearized at specific design points.[16,29,47] Most of the studies that focused on flight dynamics in the literature used the LPV model to establish dynamic modeling as it is capable of capturing the dynamic behavior of the morphing aircraft and matches the nonlinear model. The nonlinear dynamic models of morphing aircraft in these studies were linearized using the LPV method. For instance, Lee et al. [49] linearized a nonlinear parameter-dependent longitudinal dynamic model of a sweep and span aircraft using LPV. Jiang et al. [38] deduced the LPV model with the consideration of the rate of change of the wing sweep angle as the scheduling parameter for a sweep morphing aircraft. Employing nonlinear models for controller design is an area that needs more attention. There is not enough research applying the nonlinear model as the basis for controller design, especially in the area of shape control and aeroelastic control. Very few studies investigated the effect of the controller on the nonlinear behavior of morphing aircraft/wings. For instance, Bai and Dong [16] investigated the effect of a closed-loop switched control system on the nonlinear modeling of a sweep morphing aircraft. The results of this study confirmed the strong control effect of the proposed controller for both linear and nonlinear modeling. In addition, Guo et al. [32] studied the effect of the H_∞ controller on both linear and nonlinear dynamic models of a morphing aircraft with the variable gull. The study showed that in longitudinal movements, the nonlinear dynamics were insignificant, while in lateral movements this cannot be ignored.

5.6. Type of study

Most of the works in the literature were simulations. A representative example is a study by Ma et al. [82] in which they carried out Monte-Carlo simulations to investigate the use of a LPV based gain-scheduled H_∞ robust feedback control system for a morphing UAV with a folding wing. Moreover, a significant number of studies considered both simulations and experiments. An example is a study by Grigorie et al. [109], where they developed an actuation system that can be controlled by an intelligent controller with constant proportional, derivative, and integral coefficients for a variable thickness morphing wing segment. In this study, they conducted both simulation studies and experimental studies through bench tests and wind-tunnel tests to confirm the effectiveness of the controller. Very few studies investigated controllers using experiments alone such as the studies by Jodin[56,57], Popov,[110] and Grigorie,[67] et al.

5.7. 2D airfoil/3D wing/complete aircraft

The studies focused on control algorithms for complete aircraft exceeded those for 3D wing/wing segments and 2D airfoils. The works focused on the complete aircraft are associated with flight dynamics and attitude control. Most of these works concentrated on sweep morphing. 3D models of morphing wings received second attention in the field of controller design for morphing aircraft. The majority of the works of 3D wing segments are on the shape control for thickness-to-chord ratio morphing DOF. Very few studies were focused on the 2D airfoil, which considered camber and thickness-to-chord ratio morphing DOFs.

5.8. Future trends

There is a new trend in the literature to develop polymorphing wings. By definition, a polymorphing wing consists of 2 or more degrees of freedom. Polymorphing wings can significantly increase the functionality of aircraft. For example, consider a polymorphing wing capable of span, twist, and camber morphing. To perform a specific task (a maneuver or alleviate gust loads), multiple combinations of displacement and displacement rates of the three morphing DOFs can be used. Therefore, there is a need to develop control strategies that can determine the optimal combination given the instantaneous flight conditions. These control strategies should not be limited to optimal ways to morph for a specific task but also optimal ways to unmorph from a specific task while taking into account actuation energy/power and potential couplings that can exist. Similarly, there is a huge interest in developing air-vehicles for Urban Air Mobility (UAM) purposes. There exists a large number of UAM air-vehicle concepts and for some of them, morphing technologies can play a pivotal role in improving their capabilities and expanding their flight envelope. Control strategies, which can facilitate realizing the benefits of morphing on UAM air vehicles, must be developed and tested.

Concerning morphing control approaches, the future exploration and enhancement of control algorithms for morphing aircraft are expected to mainly be concentrated around intelligent control methods utilizing various Artificial Intelligence (AI) methodologies. Artificial intelligence techniques offer several potential benefits for the control of morphing aircraft. They can facilitate real-time decision-making, self-learning capabilities, and adaptive responses to varying flight conditions and mission requirements. AI-based control algorithms can exploit the data obtained from sensors and feedback systems to continuously update and refine control strategies, enhancing flight stability, maneuverability, and overall aircraft performance.

5.9. Failure analysis and system reliability

Morphing wings are at least an order of magnitude more complex than conventional wings. The level of synergy in morphing wings is usually high. For example, in a morphing wing, the structure can also be the actuator and the sensor at the same time. This implies that failures in morphing wings can be more catastrophic when compared to conventional wings. From the literature above, it is evident that very little has been done on developing control strategies capable of handling different failure modes without resulting in the catastrophic failure of wing.[52] Failure analysis and system reliability are instrumental in achieving a higher TRL for morphing technologies. Their importance grows in several manifolds when considering polymorphing wings with multiple DOFs. It is worth mentioning that several studies investigated failure analysis and system reliability for morphing wings but not from a control perspective. For example, Dimino et al. [106] conducted a preliminary failure analysis on a morphing winglet as part of the Clean Sky 2 Regional Aircraft IADP program. The mechanical system of the winglet consisted of movable surfaces sustained by a skeleton and completely integrated with an actuation system. The most critical failure modes were assessed to get key requirements for the system architecture consistency. The impact of the morphing outline on the fault hazard analysis was investigated. However, their study (like the majority of other studies on fault hazard analysis of morphing technologies) didn't examine failures from a control strategy perspective but mainly from structural and actuation perspectives. This remains a huge gap that must be filled to mature morphing and increase its Technology Readiness Level (TRL).

6. Conclusions

A comprehensive review of control strategies used for fixed-wing morphing aircraft applications was presented. The review focused on research activities performed since 2005. The main conclusions can be summarized as:

(1) Most studies focused on strategies/algorithms to control the morphing shape and the flight dynamics/handling qualities of morphing aircraft. Aeroelastic control has received secondary attention and this can be due to the complexity of accurately modeling and analyzing the aeroelasticity of morphing aircraft.
(2) The most popular morphing degree of freedom has been the thickness-to-chord ratio. Thickness-to-chord ratio variation belongs to the family of airfoil morphing that can be easily implemented from a structure-actuation perspective. They can have a huge influence on the aerodynamic characteristics of the wing without a significant effect on the inertia and stiffness like other morphing degrees of freedom.
(3) Feedback controllers were the most popular due to their simplicity and robustness. On the other hand, fuzzy logic controllers were the least popular but it was noticed that their implementation is gaining momentum for morphing aircraft applications. Most of the studies that focused on the control of flight dynamics used the LPV model to linearize the dynamic model of morphing aircraft. Very few works studied the effect of the controller on the nonlinear model of the morphing aircraft.
(4) The majority of research activities have focused on simulations, however, a significant number of studies considered both simulations and experiments. With morphing technology, experimental testing is always required to demonstrate the functionality of the pro-

posed concept and increase its readiness level. Pure experimental studies (without simulations) have been very rare. Most of the studies considered models for the complete aircraft especially flight dynamic studies. On the other hand, studies that focused on shape control and aeroelastic control considered models of 3D wings and 2D airfoils.

(5) There is a, trend in morphing aircraft research to develop wings with two or more morphing degrees of freedom. These polymorphing wings expand the design space and allow multiple paths to achieve a certain objective. Control strategies must be developed to determine optimal ways to morph a wing and optimal ways to unmorph while accounting for actuation energy/power and different couplings that might exist.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: [Rafic M. Ajaj reports financial support was provided by Abu Dhabi Education Council.].

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