Journal of Computer and Systems Sciences International, Vol. 43, No. 2, 2004, pp. 278–287.
Translated from Izvestiya Akademii Nauk. Teoriya i Sistemy Upravleniya, No. 2, 2004, pp. 126–136.

CONTROL SYSTEMS FOR MOVING OBJECTS

Trends in the Automatic Control in Aerospace

B. R. Andrievskiĭ and A. L. Fradkov

Institute for Problems of Mechanical Engineering, Russian Academy of Sciences, Vasil'evskii Ostrov, Bolshoi pr. 61, St. Petersburg, 199178 Russia

Received July 11, 2003; in final form, November 4, 2003

Abstract—In this survey, the analysis of papers of the 15th IFAC World Congress devoted to the theory and systems of control of aircraft is given. Certain other papers presented at other international conferences and recent publications in journals are also analyzed.

INTRODUCTION

Russia remains among the world's leading countries in the field of aviation and space research. However, the share of Russian participants in scientific conferences on this theme which are held abroad has substantially decreased in recent years. Obviously, in such a situation, the preparations of surveys of papers and papers submitted at large international conferences is especially important for the preservation of the leading position of the national science in the aerospace field.

The aforementioned is completely relevant to problems of designing control systems for aircraft; the solution of these problems is substantially science-consuming and exerts a fundamental effect on the competitiveness of new development works.

The World Congresses of the International Federation on Automatic Control (IFAC) are the most representative forums in the field of control theory and control systems; all specialists actively working in this field seek to present their papers at these forums.

The largest international meetings of specialists completely devoted to the control of aircraft are the IFAC symposia. The last such symposium (15th IFAC Symposium on Automatic Control in Aerospace) was held in 2001 in Bologna (Italy) and gathered about 100 participants. Out of 95 papers, Russia's achievements were represented by 11 papers which demonstrated the growing interest of Russian scientists and engineers in the aerospace theme.

Unfortunately, a detailed survey of the materials of the mentioned symposium and the IFAC Congress was absent from domestic scientific publications, thereby limiting the knowledge of Russian specialists of foreign achievements in the field.

In the present survey, an attempt is made to fill the indicated gap, and an analysis of papers of the 15th IFAC World Congress devoted to the theory and systems of control of aircraft is given. As the necessity arises, certain other papers which were presented at other international conferences and recent publications in journals are also analyzed.

The 15th IFAC World Congress was held in Barcelona, Spain, July 21–26, 2002. The program of the congress contained 1757 papers, including about 60 papers devoted to the problems of control, guidance and navigation in the aerospace. Thirty-five papers were presented at sessions devoted exclusively to the following themes:

Aircraft control;

Nonlinear, robust and fault-tolerant aerospace control systems;

Recent MIMO design approaches for aerospace application;

Spacecraft and missiles control;

Advances in missiles guidance and control;

Flight, hovering, and unmanned vehicle control.

Other papers were considered as posters at the section "Posters on Transportation and Vehicles" and also included in other sections. Below, we present the survey of papers in accordance with corresponding sessions.

1. AIRCRAFT CONTROL

One of the most important problems of the control of motion of an aircraft in the atmosphere is the problem of path planning a trajectory. In the paper [1] presented by the researchers from the California Technological Institute of the United States (Caltech), the problem of determining an optimal trajectory of motion of an aircraft with regard for the possibility of its implementation under the given aerodynamic characteristics of the aircraft is examined. Major emphasis is put on the development and implementation of the computational methods allowing one to solve the problem of real-time generation of the trajectory. The authors use a software package for synthesizing trajectories (trajectory generator) which allows one to obtain feasible feedforward and reference trajectories under the presence of restrictions characteristic of the control plant and the environment. The paper does not contain the description of computational algorithms; the main attention is paid to the results of computer simulation and laboratory experiments on the Caltech Ducted Fan Testbed. The ducted fan is considered as the scaled model of the highly maneuverable Uninhabited Combat Air Vehicle (UCAV). The UCAV can follow the commands of the operator or maintain the given flight program without the operator's interference. The task of trajectory generation can consist in attacking a target in a dynamically changing environment or in obtaining the trajectory under which the cross section of the UCAV is minimized for evasion from radar detection in reconnaissance flights. The trajectories with minimal time are calculated for hover-to-hover flight and maneuvers. The sudden changes in trajectory restrictions as a result of the appearance of obstacles and dangerous situations are also taken into account. The results of experiments obtained by the use of the software package called the Nonlinear Trajectory Generation and substantiating the high quality of the closed system for all the maneuvers considered are described in the paper. As was noted in the paper, the real-time construction of trajectories was achieved despite the essentially nonlinear and nonconvex character of the problem being solved. Note that no assertions or proofs of the fact that the obtained solutions are optimal were given in the paper. Nevertheless, the presented illustrations and the video film, which was demonstrated during the presentation, showed that the model system under consideration in fact meets the requirements set.

Paper [2], whose content is partially reflected in the works [3–6] published earlier, is devoted to the problems of control of "undisplacement vessels" (to which hovercraft, ekranoplanes (wing-in-ground-effect vehicles), and controlled hydrofoil belong). These problems are close to problems of aircraft control. Of special importance is to ensure the high accuracy of the altitude of flight relative to the disturbed sea surface. In [2], the description of this problem is presented, and the main ways of its solution are outlined. Examples of algorithms for processing data incoming from measurement equipment are also presented; a phase radio altimeter developed with the participation of the author for use on the experimental model of the ekranoplane (wing-in-ground-effect aircraft) is described.

One of the trends in the research in recent years is the use of modern methods of nonlinear dynamics and control, in particular, the bifurcation theory and the theory of chaotic systems. This direction is developed at the Chair of Aerospace Research of the University of Bristol in Great Britain. A paper [7] presented by this university is devoted to the so-called bifurcation tailoring whose use is demonstrated for the nonlinear second-order model of a highly maneuverable aircraft. According to this method, the behavior of the system is regulated by means of changing its bifurcation diagram. The bifurcation tailoring method consists in generating an appropriate control action under which the closed system has the required bifurcation diagram. In the paper, the task of obtaining the given bifurcation diagram of the dependence of the angle of attack α on the elevator deflection δ_{el} is set. For this purpose, in the process of control it is proposed to solve the system of nonlinear equations for the generation of the command signal in the feedforward circuit (online feedforward scheduling). In the solution of equations, the Newton method is applied. The bifurcation tailoring method is described in more detail in the other paper [8] of authors at the IFAC Congress where its application was illustrated by the example of the Duffing system. The additional information can be found in [9, 10] and on the website Aero-Chaos Group-Systems Engineering of the University of Bristol (http://www.men.bris.ac.uk/chaos/). The idea of the method consists in using certain components of the control vector for obtaining the required dynamics of the closed system under different values of the bifurcation parameter. In [7], an aircraft is considered for which the jumplike change of the angle of attack, α, in a certain domain (in the neighborhood of –20°) of angles of deflection of elevators δ_{el} is characteristic. To obtain a smooth statical dependence $\alpha = \alpha(\delta_{el})$, it is proposed to use an additional control: the change of the thrust vector δ_{tp}. Note that in [7–10], no theoretical analysis of the stability of the closed-loop system with the proposed method of control was given. Furthermore, it is assumed that the bifurcation parameter is slowly changing. This assumption may be justified for the illustrative example of the Duffing system considered in [8], but it is not justified in respect of the deflection of the elevator of the aircraft (δ_{el}). This problem is bypassed in [7]; moreover, in the numerical example, it is assumed that the elevator changes its position at the constant rate 10^{-3} deg/s. It is not clear from the paper how the system will behave under actual variation in the angle $\delta_{el}(t)$. In addition, the design of the stable adaptive controller with the standard model for a nonlinear control plant is a complex independent problem whose solution in the case of maneuverable aircraft is still far from the practical application. The simplicity of the result described in [7] is by all means a consequence of the fact that the extremely simplified model (of the second order) of the dynamics of an aircraft was used.

In a paper [11], the problems of design of an autopilot for an asymmetric missiles (in other words, missiles with the aircraft design of the airframe, i.e., cruise missiles (CM)) were considered. In an earlier paper by the same authors [12], the problem of an autopilot for the coordinated turn of a CM (the execution of the bank-to-turn (BTT) maneuver) was considered. The solution was obtained by the use of a linear parameter varying model of a CM and the method of the construction of feedbacks extended to the "parameter varying polytopic plants" whose uncertain parameters change within parallelepipeds (polytopes). In [11], the procedure of the H_∞-synthesis is used in the construction of a controller. In the presented numerical example, the MIMO H_∞-optimal control law in the feedback is obtained for two characteristic flight modes (for the Mach number $M = 2$ and the altitudes $h = 5$ and 10 km). The control laws are obtained both for the banked turn and for the flat turn (the skid-to-turn (STT)). The closed-loop attitude control system behavior is studied by simulating an adequately complete nonlinear model of a CM in which the dynamics of actuators, sensors, the elastic vibrations of the airframe, the measurement noises and the cross-couplings between the channels of motion are taken into account. Based on the numerical results, it is shown that the quality of the control process exceeds the quality which is obtained under the programmed change of the parameters of the autopilot and the polytopic parameter varying model of the plant (gain-scheduled LPV control).

A paper [13] was devoted to the design of an automatic piloting system for landing an aircraft with the use of the nonlinear energy approach. The application of this method for the automatic landing control is demonstrated for the twin-engine research civil aircraft model (RCAM) developed by the Group for Aeronautical Research and Technology in Europe (GARTEUR). In this paper, the longitudinal motion of the aircraft was considered. It is assumed that all states of the aircraft dynamics are measurable. To simplify the synthesis of the complete control system, the method of singular perturbations is used; this method makes it possible to take into account the characteristic rates of processes and to reduce the order of the model. The nonlinear energy controller is constructed in such a way that, acting on control surfaces and the thrust force of the engine, one can change the energy characteristics of the motion of the aircraft and to ensure the required flight characteristics as a result. The controller, on the whole, is a nonlinear energy controller intended for tracking the assigned velocity and the trajectory of flight under the pitch stabilization of the aircraft. The controller comprises the following three components: an internal loop, an energy loop and a PID controller (PID component). The PID controller is introduced in order to eliminate the static error of tracking on the basis of the aircraft center of gravity (COG) position. The errors of the aircraft model are also taken into account in the simulation. These results make it possible to evaluate the roughness (robustness) of the controller with respect to the changes of parameters and dynamic perturbations, such as wind gusts, wind drifts, and inaccuracies of the aircraft model. Note that the idea of using the energy approach in the synthesis of control algorithms was developed by many authors [14–17] including the works devoted to the problem of automatic piloting [16]. The paper [13] is an intermediate step between the theoretical studies and the practical applications of the method. Despite a number of simplifications, a sufficiently complete model of the dynamics of the motion of an aircraft, which is adequate to the preliminary synthesis of the landing control system, is used in this work. Note that the proposed control laws can be sufficiently easily implemented and, in addition, the structure of the obtained controller does not have essential distinctions from the traditional one.

2. NONLINEAR, ROBUST AND FAULT-TOLERANT AEROSPACE CONTROL SYSTEMS

A paper [18] was devoted to the development of the methods for synthesizing a stabilization system for a launch vehicle (LV) during the atmospheric flight. As a consequence of the change of the parameters of the launch vehicle on the booster phase of flight, it is required to change the coefficients of the autopilot as well. The gain-scheduled tuning of coefficients is used in the paper; this is the traditional approach to the problem under consideration. Emphasis is put on the method of interpolation of the controller's coefficients, which would guarantee the stability not only of the set of systems with "frozen" parameters, but that of a parameter varying system as well. To ensure the stability of the linear parameter varying systems, the conditions which have the form of linear matrix inequalities (LMI) for the solution of which efficient software packages [19] are available at present are used. Thus, in the paper, an attempt is made to depart from the "hypothesis of quasistationariness" of the aircraft, which is usually used in such problems, and to directly ensure the stability of the *linear nonstationary model* which reflects the launch vehicle's dynamics more adequately. Thereby, the authors think that it is possible to do without the analysis of the stability of the parameter varying system (for example, by means of simulation) at the ensuing stages of design. Note that the method of frozen coefficients is widely applied in practice control law design for launch vehicles and its capabilities are sufficiently well known both to theorists and practical specialists in the field of automatic control of aircraft. The possibility to avoid the study of the stability of the designed nonstationary system leaning exclusively on the theoretical analysis will hardly be called for by aerospace control practitioners.

A paper [20] was devoted to the problems of control of highly maneuverable missiles for which nonlinear aerodynamic effects caused by a wide range of variation in the angle of attack are characteristic. In the paper, the method for synthesizing a discrete linear controller with variable parameters for the nonlinear system whose equations are represented through the linear fractional transformation (LFT) was presented. This method of synthesis can be applied to the feedback control loop design of a parameter varying system in order to obtain an algorithm of discrete control with the parameters of the controller varying depending on the flight conditions (discrete gain-scheduled control law). As an example, the problem of tracking the command signal by the normal overload through the action on the elevator is considered. The nonlinear model of the longitudinal motion of a missile described in [21] is used in the paper. Note that the model problem which is presented in the paper is sufficiently adequate in order to judge the practical applicability of the method developed on its basis. The control law used in the work has a classical form, in which the feedbacks with respect to measured variables are supplemented by the PI controller in the acceleration channel in order to impart astatism on the system. The obtained nonlinear system is studied by simulation under substantial changes of the angle of attack, and, for the system with frozen parameters (on the basis of the frequency criterion (the Nikols plots)), the stability study is carried out for various reference values of the attitude of an aircraft. All this, taken together, substantiates the applicability of this approach to the synthesis of the aircraft control system. Note also that, in [20], only the general form of the controller is given, without detailed representation of the procedure of synthesis of an autopilot and the equations of the controller. The given nonstationary controller is described by eighth-order equations and contains a second-order parametric block. The total order of the equations of the controller is rather high for the considered control problem for the plant of the fourth order (with the dynamics of the actuator taken into account).

In a paper [22] (presented at the meeting of the Application of Nonlinear Methods of Control section), the synthesis of an autopilot for controlling the angle of pitch of a missile is carried out on the basis of the method of control of nonlinear systems. On the whole, work [22] contains the description of the method in the general form. The example of the synthesis of an autopilot with variable coefficients (gain-scheduled autopilot) is presented. In this example, the same control problem as in [20] is considered (up to the model of the aircraft and the form of the command signal). The quality of the obtained system, as can be judged from the material presented, turns out to be the same. Note that the same quality of the closed-loop control system of an aircraft for this example can be easily attained by using the traditional method of restructuring the parameters of an autopilot on the basis of the linearized (with respect to different values of angles of attack and control surfaces) model of an aircraft, which, however, does not belittle the significance of the proposed synthesis methods.

A paper [23] is devoted to the problem of stabilization of the lateral motion of an aircraft upon the landing of a moving ekranoplane (wing-in-ground-effect aircraft). In such problems, the accuracy of control of the position of a flying vehicle is of special importance from the point of view of safety. In the paper, it is proposed to ensure the accuracy by means of the optimization of the parameters of the control law on the basis of estimates of current static properties of wind perturbations. It is proposed to estimate the wind characteristics via the remote estimation unit located on the ekranoplane. This system must perform the measurements of the wind distribution and calculate its upper boundaries. The use of the method of majorizing polynomials developed by the author is recommended for ensuring the required accuracy of landing. Note that the paper under consideration, like earlier works [3, 4, 6], contains the general sketch of a possible adaptive system on a moving ekranoplane for the control of landing an aircraft. Certain results presented in [23] are also published in Russian editions, for example, in [24, 25].

3. RECENT MIMO DESIGN APPROACHES FOR AEROSPACE APPLICATION

In the agenda of the Congress, there were a number of special sessions (invitation sessions) organized by leading specialists in the corresponding fields.

Professor Shunji Manabe from Tokai University (Hiratsuka, Japan) organized a session Recent MIMO Design Approaches for Aerospace Application.

A paper [26] is devoted to the coefficient diagram method developed by Manabe [27–29]. This method is intended for the choice of the parameters of the controller in linear stationary systems. It consists of the following two stages: the assignment of the desired duration of the transient process by choosing the corresponding parameters (α_i, τ) and the determination of coefficients of the controller that ensure the coefficients of the characteristic polynomial obtained at the first stage. The paper [26] generalizes the recent results of the author pertaining to the main properties of the set of parameters (α_i, τ) and shows how one can obtain the coefficients of the desired characteristic polynomial. In [28], the application of the Manabe's method is demonstrated by the example of the MIMO problem of control of the angular longitudinal motion of a fighter. The model of an aircraft is taken from the demonstrative example on the robust control in Robust Control Toolbox of MATLAB. The aircraft under consideration has a canard aerodynamic configuration with two aerodynamic control surfaces, canard controls and elevons. Control actions are input signals of the corresponding actuators; the controlled variables care the angle of pitch and the angle of attack. The source model is of sixth order with regard for aperiodic blocks with fast time constants (33 ms) describing the actuator dynamics. The model also takes into account the change of the velocity of flight of the aircraft. The problem of tracking the command actions in the angles of pitch and attack (simultaneously) is considered. It is required that one ensures the independence of the control and the identity of the dynamic properties in each channel, as well as satisfies the constraints on the form of the auxiliary sensitivity functions (see [30, 31] in this connection). In the synthesis of an autopilot, a simplified model is used in which the velocity of flight is assumed to be constant. In addition, the actuators are assumed to be inertia-free blocks and their dynamics is suppressed by the introduction of the forcing blocks into the controller. The result of the application of this method is the synthesis of the PI and PID control laws for each channel. The form of the transient processes in the system is shown, the sensitivity functions (in the frequency domain) are presented, and also the properties of the system are compared with the results of application of the H_∞- and H_2-criteria for the given problem. Note that this method is one of the variations of the *method of standard coefficients* which is widely used and has practical application. Under this method, the parametric synthesis of a controller is carried out so as to obtain given values of the coefficients of the characteristic polynomial of the closed system and, thereby, the required set of its roots. In the state space framework, this method is also called the *method of modal control.* A large number of ways of choosing the desired coefficients of the characteristic polynomial is proposed by many authors. The common drawback of these approaches connected with the complexity of obtaining the given set of the coefficients of the characteristic polynomial by means of the output feedback. This drawback is especially evident in systems with a large range of fundamental frequencies of the plant which is characteristic for the problems of control of angular and spatial motion of an aircraft in which the sluggishness of the actuators, the elasticity of the construction, and vibrations of the liquid in fuel tanks are taken into account.

The synthesis on the basis of mixed-sensitivity functions (Mixed-sensitivity design) for linear MIMO control systems is exposed in papers [30, 31]. This method makes it possible to ensure the assigned form of the sensitivity functions for achieving the required accuracy characteristics and transient responses of the closed system with regard for the robustness property. The mixed sensitivity design is based on the optimization according to the criterion that includes two or more sensitivity functions. In the paper, the matrix transfer function from disturbances to the output of the plant S and the complementary sensitivity function T are used. It is indicated that to solve the posed problem, one can use the methods of optimization according to both the H_∞-criterion and the H_2-criterion. The approach presented in the paper makes it possible to obtain the given form of the frequency characteristics in the high- and low-frequency domains and also to perform a partial assignment of the poles of the closed system. In particular, in [31], it was shown that the linear quadratic Gaussian optimization problem falls in the category of mixed sensitivity design problems. The mixed sensitivity design method is illustrated in the accompanying paper [30] by the example of the synthesis of the system of damping (stability augmentation) of the longitudinal motion of a fighter. In [30, 31], the methods of synthesis known to a wide range of specialists from the monograph [32] are developed. Note that the transformation of the structural scheme of the system recommended in the paper for ensuring the astatism of the closed system is somewhat doubtful because it leads to the degeneracy (to the loss of the controllability/observability of the extended control plant). This circumstance is implicitly admitted in [31], where it is written that a shortcoming of this method is the fact that usually the cancellations of the cofactors in K_0 and W_1 appear, which is unattractive from a computational point of view. The method presented in [31] is illustrated in detail by an example of the test problem on the control of the longitudinal motion of a fighter in paper [30]. Note that the numerical results demonstrate the high quality of the synthesized system; however, the flight control problem considered in the example is not very complex and the appropriate control law can be obtained by traditional means without making substantial efforts. Note also that the mixed-sensitivity design is successfully used for the problem of controlling helicopters [33].

A survey [34] is carried out in the framework of the activity of the European Space Agency (ESA) on the study of the stability of control systems with fuzzy-logic controllers (FLC). Emphasis is made on the possibility of the potential application of FLCs for aerospace systems. The works on the study of the stability of control systems with fuzzy logic in which both time and frequency representations are used are listed rather cursorily. Certain methods of ensuring the stability of such systems are also considered. Note that the fuzzy logic control is a direction in the field of automatic control that is being intensively developed. As was noted in one of the milestone papers of the congress [35], FLCs attracted substantial attention in industry and in a number of academic institutions several years ago, but now this attention has substantially decreased. Since the control in aerospace applications must be especially reliable, it is important to guarantee the efficiency of FLCs in order for them to be applicable in flight control problems. In the paper [34], major attention is paid to the question of stability. The methods for testing the systems with FLCs proposed by the authors are presented in this paper. From the point of view of aerospace applications, in the survey [34], attention is paid to the following three main problems: altitude control, rendezvous, and reentry. The list of publications on aerospace systems presented in [34] is rather broad, but all examples presented are of model character.

4. CONTROL OF SPACECRAFT AND MISSILES

In a paper [36], a method of synthesis of control systems by the overload under the skid-to-turn maneuver for tail-controlled missiles is proposed. In this problem, it is proposed to use a nonlinear observer estimating the angle of attack and the skid angle. For the synthesis of the observer, the nonlinear model of a missile affine in its parameters is used. The stability and the quality of the behavior of the proposed observer are studied. As was shown by the simulation results, the proposed method makes it possible to provide good dynamic characteristics of the control system. Note that the estimation of angles of attack and skid angles on the basis of current measurements of accelerations and angular velocities is a possible (but not unique) method for the determination of the incident flow; these angles (for a quiet atmosphere) can also be calculated on the basis of trajectory measurements from the data of the navigation system. The paper [36] contains the convincing justification of studies on the basis of recent publications in the given field, and leans upon the method of synthesis of nonlinear observers. The numerical results in [36] are of illustrative character; for example, the effect of the wind fluctuations and measurement noise are not taken into account.

A paper [37] presented by the Laboratory of Self-Adjustable Control Systems of the Trapeznikov Institute of Control sciences, Russian Academy of Sciences, is devoted to the development of the combined energy-economic control of a space robotic module (SRM) which is in a free flight and is used as a transportation vehicle in its flight near an inhabited orbital space station. The SRM consists of a rigid platform to which one or more multilink manipulators are attached. This is a complex mechanical system subjected to the action of a large number of nonlinear control actions and disturbances, and is also characterized by substantial variations in mass and geometric characteristics. In [37], the approach to the synthesis of the energy-economic control when the SRM is moving within a safety corridor is presented; this approach belongs to the hybrid methods of control. The concrete control algorithms and the results of the study of the dynamics of functioning of all mutually connected modules are presented. The paper [37] is the last from the series of the works published by this group of authors and is devoted to the control of an SRM near an orbital space station [38–41]. In the work under consideration, a detailed description of the model of an SRM is given, including the manipulators and actuators. The applicability of proposed algorithms is verified by means of computer simulation for the nonlinear test model of an SRM. In [37], there are no especially important theoretical results, but the paper can serve as an example of a carefully prepared research work.

In [42], the main results on the development of methods and the software for the study of nonlinear dynamic properties are presented, along with the development of the robust gyromoment fault tolerant control system for the information satellite (intended, for example, for space photography, communication, navigation and geodesy) jointly developed by the Research Institute of Mechanical Systems Reliability (NII PNMS), Research and Production Association "Applied Mechanics" (NPO PM), State Research and Production Rocket–Space Center "TsSKB–Progress" of the Russian Space Agency (RKA). In [42], the 30-year experience of the authors on the development of systems for the control of satellite attitude possessing a high fault tolerance, survivability and autonomy is generalized.

A paper [48] is devoted to the problem of control of a rigid spacecraft. To solve this problem, the theory of port-controlled Hamiltonian systems which has been developed in recent years by the French-Dutch scientific school under the guidance of Ortega and Shaft (see, e.g., [49]) is invoked. The proposed nonlinear control algorithm is compared with the algorithm on the basis of the structure of eigenvalues which was earlier proposed by the author of the paper. The paper [48] complements the paper [50]. Note that the results of the works [48, 50] demonstrate the efficiency of the energy-based methods for the synthesis of nonlinear control laws described earlier in Russian literature [16, 51, 52] (see also [13, 17]). However, one should bear in mind that the control law proposed in [48, 50] presupposes the possibility of smooth (continuous) variation of the control moment while the control of the spacecraft attitude is often performed by jet (gas) control engines and is bang–bang in its nature. Note also that, in [48, 50], only the problem of damping a spacecraft (rotation suppression) is considered, while a more typical problem is that of attitude control.

5. ADVANCES IN MISSILE GUIDANCE AND CONTROL

Among the papers devoted to the modern methods of control and guidance of aircraft (usually, highly maneuverable missiles) in the atmosphere, an important position is held by the works presented by the Department of Aerospace, Power and Sensors of the Royal Military College of Science, Cranfield University, Great Britain. Let us consider some of them.

In [53], for the problem of tracking the reference signal, an autopilot is designed on the basis of a nonlinear model of an aircraft in which the method of *indirect adaptive control* is combined with the approximate linearization by the feedback. The adaptation is applied for enhancing the robustness of the closed system and the linearization by the feedback is used to eliminate the problems arising as a result of the instability of the zero dynamics of the plant.[1] As the results of the simulation demonstrate, the proposed method makes it possible to obtain the desired properties of the control system with regard for the nonlinearity of the missile model under conditions of its parametric uncertainty. Note that aerospace applications have practically been the primary impetus that generated studies in the field of adaptive systems. In the past 50 years, a great number of adaptation algorithms for the control of aircraft have been proposed and a multitude of works on this theme have been published. However, up until now, the

[1] For linear systems, the instability of the zero dynamics means the nonminimal phase property. As is known, a tail-controlled flying vehicle is a nonminimal phase plant with respect to the overload. See [54] for the nonminimal phase property for nonlinear systems.

practical achievements have been substantially more modest. (As was noted in [55], the ability of control theorists to influence industry adaptation of new control techniques is somewhat analogous to that of an individual attempting to push a rope. It's much easier if the individual holding the other end of the rope is willing to pull.) At the same time, in the summary paper [35], it is noted that, in aeronautical industry, the use of high angle maneuvers and thrust vector control means that nonlinear aerodynamic phenomena increase in importance. ...In this design problems, nonlinear control techniques, are finding increasing applications in the development of control systems for such plants. The paper under consideration, like the preceding works of the same authors (for example, [57, 58]), uses the adaptive control in combination with the method of feedback linearization for the nonlinear model of a missile. The indirect adaptive control, which is applied in [57, 58], consists in the adaptive (performed in real time) identification of parameters of a missile with the corresponding recalculation of the coefficients of an autopilot on the basis of the obtained estimates. This method is also known as the *identification approach to the adaptive control problem* [59]. Note that this approach, like the assumption in respect of the parameters of the model (the quasistationariness hypothesis), is rather typical of works devoted to adaptive control.

Papers [53, 57, 58] are instructive examples of the application of modern methods for the synthesis of flight control systems, but the identification process (a kind of an adaptive observer is used in the papers under consideration) can be violated because of the measurement noise or because the dynamic properties of the elements of the system are not taken into account. Thus, in order to judge the practical applicability of the proposed control laws, it is first of all necessary to test them on a more realistic model of the plant.

In [60], it is noted that although the gain-scheduled control is a very useful and widely used method, it has a number of essential drawbacks connected with the lack of theoretical justification of the stability of a nonstationary system in the whole operating domain and also with the difficulty of the interpolation when the number of parameters is large. In [60], an approach to the improvement of controllers of this type is proposed. It consists in using methods of fuzzy logic for the description of a nonlinear dynamic model of a missile and the synthesis of a control. The expedience of such an approach is not yet evident from the results of [60].

The application of the adaptation methods with a tunable model of the plant for the control of an aircraft under various flight conditions is also considered in [52, 61, 62]. In these works, in order to avoid the measurement of the angular velocity of the aircraft, a shunting block (feedforward compensator) is applied. The tuned filter plays the role of a sequential reference model. Its coefficients depend on the estimates of the parameters of a model of the aircraft generated in real time. The variable structure controller ensures ideal tracking in the internal loop. The obtained structure is called a combined adaptive controller. In its synthesis, the linearized model of the dynamics of the angular motion of the aircraft is used. The domain of applicability of the controller is constructed in [52] for this model and the numerical results of the study in the form of transient processes for various flight conditions are presented. The application of the combined adaptive controller with regard for the nonlinear dynamics of the aircraft is shown in [61], and in [62] the results of the study of the adaptive controller in the internal loop of the homing system are described.

6. FLIGHT, HOVERING, AND UNMANNED VEHICLE CONTROL

The paper [33] presented by the authors from the University of Leicester, Great Britain, is devoted to the control of a helicopter. In this paper, the detailed exposition of the method of synthesis on the basis of the H_∞-optimization is given and the results of simulation and flight tests of the developed systems are presented. The model of the plant complemented with the time lags, smoothing filters, velocity constraints and time quantization is used. The amplitude quantization of the control process with digital controller is also taken into account. For this purpose, the control signal was truncated by up to 6–8 decimal points. The nonlinear model of the mechanics of the flight of the Bell 205 helicopter having the order 32 was taken as the basis for the control law design. Note that paper [33] is a cursory exposition of the complete and detailed research work whose results were used in the practical synthesis of helicopter control systems. These results are also partially presented in [63].

One can also familiarize himself with the studies of this group of authors from paper [64], in which the development of the switching control algorithm in the integrated flight and propulsion operation control system for vertical-takeoff and landing aircraft is described. The perspectives of the bumpless transfer technique developed earlier are demonstrated and the methodology of the control switching between the set of controllers under the limitation of computational efforts connected with the necessity of functioning on a real-time basis are developed. The paper is illustrated by the results of modeling a control system for an aircraft with nonlinear dynamics.

In [65], the control law for the rotorcraft-based aerial vehicle (RUAV) is described. The hierarchical flight management system (FMS) for the group of RUAVs is synthesized. This system ensures both the autonomy and the coordinated behavior of individual RUAVs in a group. The results of the experiment have shown a good quality of the multifunctional FMS developed for RUAVs at the University of California at Berkeley, in the United States, in the following examples: waypoint navigation, pursuit–evasion games, and tracking of a moving target.

In [66], the control algorithm on the basis of the Lyapunov method for the tandem rotor helicopter is obtained on the basis of the backstepping techniques. In this work, a simplified model of the dynamics of a helicopter in a mode close to hovering is presented. The behavior of the system with the proposed control law is substantiated by the numerical simulation.

A paper [67] demonstrates the application of the method of integrated synthesis for the control of the rate of variation in the angle of pitch of a twin-fin combat aircraft. The procedure is designed for the synthesis of a controller that ensures both good control of an aircraft as a rigid body and the suppression of its own vibrations. In the paper under consideration, the difficulties of damping the dynamics of a flexible aircraft and the traditional structure of the autopilot (a pitch rate stabilizer) that includes the rejection filters are presented. It is assumed that the sensors of angular velocity can be located at different (selected) points of the body of the aircraft. The method of H_∞-optimization is used in the work for the determination of the best points of location of sensors. Note that in addition to a number of drawbacks and restrictions which are indicated in the text of the paper, this method is inapplicable to aircraft that have physical restrictions on the location of the measurement unit. On the other hand, if no such restrictions exist, such methods of construction may turn out to be effective.

In [68], the results of the development and modeling of a flight control system for the micromechanical flying insect (MFI) are presented. An MFI is a device 10×25 mm in size which is capable of sustained autonomous flight. The unmanned flying vehicles of this such have a number of advantages over ordinary unmanned flying vehicles and the possibilities of their application are rather wide. The paper [68] is devoted to the perspectives and problems of control of flying vehicles with nontraditional models of dynamics. The results presented in [68] are rather interesting and important, especially if we take into account the very small number of publications on this topic.

7. OTHER SECTIONS

Below, we consider certain papers presented as posters at the Transportation and Vehicles session, and also at the other sessions.

A paper [69] is devoted to the problems of navigation and control for a large helicopter. Based on physical experiments and further processing of the data obtained, the parameters of the model of the RoboCopter helicopter are identified. The hybrid GPS/INS navigation system and also the laws of control of the helicopter's attitude and velocity are developed. The latter are based on the application of the H_∞-optimization method. The experiments on the control of the helicopter's attitude demonstrate the efficiency of the proposed approach and its practical applicability.

In a paper [70], the application of the neural network approach for the control of the flight of a commercial flying vehicle is demonstrated. The neural network control system is used for changing the parameters of the gain-scheduling autopilot without the identification of the plant in the explicit form. The neural network control system uses the *reference model* for the assignment of the required flight characteristics. The paper is illustrated by the simulation results. Note that in the resolution of the paper rather ambitious goals are set; they consist of ensuring the required flight characteristics for various flight modes and aircraft configurations, but the results of the numerical experiments are too cursory for judging to what extent the set goals are achieved. A substantial part of the paper [70] contains commonplace information. Nevertheless, the neural network approach seems to be promising for the problems under consideration and the principles exposed in [70] seem quite reasonable.

In [71], a stabilization algorithm for the planar vertical takeoff and landing (PVTOL) aircraft is proposed. The stability of the closed system is proved and the simulation results are presented.

The model of the dynamics of the four-rotor flying vehicle called the X4-flyer is proposed in the paper [72]. The X4-flyer is an autonomous flying vehicle capable of performing vertical takeoffs and landings and also of maintaining a quasistationary hovering mode (or a mode close to it). This system consists of four electric fans located on a rigid cross-shaped frame. Controller design is carried out by the backstepping method. This paper may be applied to problems of synthesis of aircraft capable of vertical takeoff and landing. It is also interesting from the point of view of the application of modern methods of control of nonlinear plants. Unfortunately, the paper is not accompanied by a numerical example.

ACKNOWLEDGMENTS

This work was partially supported by the Russian Foundation for Basic Research (project no. 02-01-00765), the Scientific Program of the Presidium of Russian Academy of Sciences no. 19, project 1.4, and the *Integration* Federal Program.

REFERENCES

1. M. B. Milam, R. Franz, and R. M. Murray, in *Proceedings of 15th Triennial World Congress of IFAC, Barcelona, Spain, 2002.*
2. A. V. Nebylov, in *Proceedings of 15th Triennial World Congress of IFAC, Barcelona, Spain, 2002.*
3. V. N. Kalinichenko, A. V. Nebylov, and N. Tomita, in *Proceedings of 5th IFAC Symposium NOLCOS'01, St. Petersburg, Russia, 2001.*

4. A. V. Nebylov, in *Proceedings of 15th IFAC Symposium on Automatic Control in Aerospace, Bologna, Italy, 2001.*
5. A. V. Nebylov, in *Proceedings of 8th International Conference on Integrated Navigation Systems, St. Petersburg, Russia, 2001.*
6. A. V. Nebylov, in *Proceedings of 9th International Conference on Integrated Navigation Systems, St. Petersburg, Russia, 2002.*
7. G. A. Charles, M. H. Lowenberg, M. G. Stoten, *et al.*, in *Proceedings of 15th Triennial World Congress of IFAC, Barcelona, Spain, 2002.*
8. X. F. Wang, M. Di Bernardo, M. H. Lowenberg, *et al.*, in *Proceedings of 15th Triennial World Congress of IFAC, Barcelona, Spain, 2002.*
9. G. A. Charles, M. Di Bernardo, M. H. Lowenberg, *et al.*, Latin Amer. Appl. Res. J. **31** (3), (2001).
10. M. H. Lowenberg, and Th. S. Richardson, in *Proceedings of AIAA Guidance. Navigation & Control Conference, 2001.*
11. E. Prempain, Postlethwaite, I., and D. Vorley, in *Proceedings of 15th Triennial World Congress of IFAC, Barcelona, Spain, 2002.*
12. E. Prempain, I. Postlethwatie, and D. Vorley., in *Proceedings of the European Control Conference (ECC'01), 2001.*
13. R. Akmeliawati and I. Mareels, in *Proceedings of 15th Triennial World Congress of IFAC, Barcelona, Spain, 2002.*
14. V. I. Matyukhin, *Universal Control Laws for Mechanical Systems* (MAKS, Moscow, 2001) [in Russian].
15. A. L. Fradkov, Int. J. Control **64** (6), 1996.
16. V. G. Borisov, G. N. Nachinkina, and A. M. Shevchenko, Avtom. Telemekh., No. 6, (1999) [Automat. Remote Contol **59** (6), (1999)].
17. A. A. Lambregts, AIAA Paper., No. 2239, (1983).
18. B. Clement, G. Duc, S. Mauffrey, *et al.*, in *Proceedings of 15th Triennial World Congress of IFAC, Barcelona, Spain, 2002.*
19. B. T. Polyak and P. A. Shcherbakov, *Robust Stability and Control* (Nauka, Moscow, 2002).
20. D. Farren, G. Duc, and J. P. Harcaut, in *Proceedings of 15th Triennial World Congress of IFAC, Barcelona, Spain, 2002.*
21. R. T. Reichert, IEEE Control Syst. Magazine **1**, (2002).
22. P. C. Pellanda, P. Apkarian, H. D. Tuan, *et al.*, in *Proceedings of 15th Triennial World Congress of IFAC, Barcelona, Spain, 2002.*
23. A. V. Nebylov, V. N. Kalinichenko, and N. Tomita, in *Proceedings of 15th Triennial World Congress of IFAC, Barcelona, Spain, 2002.*
24. A. V. Nebylov, *Measurement of Flight Parameters Close to the Sea Level* (SPbGAPP, St.Petersburg, 1990) [in Russian].
25. A. V. Nebylov, *Guaranteed Control Accuracies* (Nauka, Moscow, 1998).
26. Y. Ch. Kim, L. H. Keel, and Sh. Manabe, in *Proceedings of 15th Triennial World Congress of IFAC, Barcelona, Spain, 2002.*
27. Sh. Manabe, in *Proceedings of 14th IFAC Symposium on Automatic Control in Aerospace, Seoul, Korea, 1998.*
28. Sh. Manabe, in *Proceedings of 15th Triennial World Congress of IFAC, Barcelona, Spain, 2002.*
29. Sh. Manabe, *Proceedings of 15th IFAC Symposium on Automatic Control in Aerospace, Bologna/Forli, Italy, 2001.*
30. H. Kwakernaak, in *Proceedings of 15th Triennial World Congress of IFAC, Barcelona, Spain, 2002.*
31. H. Kwakernaak in *Proceedings of 15th Triennial World Congress of IFAC, Barcelona, Spain, 2002.*
32. H. Kvakernaak and R. Sivan, *Linear Optimal Control Systems* (Wiley, New York, 1972; Mir, Moscow, 1977).
33. I. Postlethwaite, E. Prempain, E. Turkoglu, *et al.*, in *Proceedings of 15th Triennial World Congress of IFAC, Barcelona, Spain, 2002.*
34. J. M. Giron-Sierra and G. Ortega, in *Proceedings of 15th Triennial World Congress of IFAC, Barcelona, Spain, 2002.*
35. A. Isidori, R. Bars, J.-M. Dion, *et al.*, in *Proceedings of 15th Triennial World Congress of IFAC, Barcelona, Spain, 2002.*
36. D. K. Chwa, J. Y. Choi, and J. H. Seo, in *Proceedings of 15th Triennial World Congress of IFAC, Barcelona, Spain, 2002.*
37. V. Yu. Rutkovsky, V. M. Sukhanov, V. M. Glumov, *et al.*, in *Proceedings of 15th Triennial World Congress of IFAC, Barcelona, Spain, 2002.*
38. V. M. Glumov, S. D. Zemlyakov, A. M. Puchkov, *et al.*, Izv. Ross. Akad. Nauk, Teor. Sist. Upr., No. 1, (2000) [J. Com. Sys **64** (1), 114 (2000)].
39. V. M. Glumov, S. D. Zemlyakov, V. Yu. Rutkovskii, *et al.*, Avtom. Telemekh., No. 3, (2001) [Automat. Remote Control **62** (3), (2001)].
40. V. Yu. Rutkovskiĭ and V. M. Sukhanov, Avtom. Telemekh., No. 5, (2000) [Automat. Remote Contol **61** (5), (2000)].
41. V. Yu. Rutkovksy and V. M. Sukhanov, in *Proceedings of 15th IFAC Symposium on Automatic Control in Aerospace, Bologna/Forli, Italy, 2001.*
42. Ye. I. Somov, A. G. Kozlov, V. A. Rayevsky, *et al.*, in *Proceedings of 15th Triennial World Congress of IFAC, Barcelona, Spain, 2002.*
43. Ye. Somov, *Proceedings of 15th IFAC Symposium on Automatic Control in Aerospace, Bologna/Forli, Italy, 2001*
44. Ye. I. Somov, S. A. Butyrin, G. P. Anshakov, *et al.*, in *Proceedings of 15th IFAC Symposium on Automatic Control in Aerospace, Bologna/Forli, Italy, 2001.*
45. Ye. I. Somov, S. A. Butyrin, V. A. Rayevsky, *et al.*, *Proceedings of 5th IFAC Symposium NOLCOS'01, St. Petersburg, Russia, 2001.*
46. Ye. I. Somov, V. A. Rayevsky, A. G. Kozlov, *et al.*, *Proceedings of 5th IFAC Symposium NOLCOS'01, St. Petersburg, Russia, 2001.*
47. A. V. Sorokin, N. I. Bashkeev, V. V. Yaremenko, *et al.*, in *Proceedings of 9th St. Petersburg International Conference on Integrated Navigation Systems. St. Petersburg, Russia, 2002.*
48. H. Siguerdidjane, in *Proceedings of 15th Triennial World Congress of IFAC, Barcelona, Spain, 2002.*

49. R. Ortega, A. van der Schaft, I. Mareels, *et al.*, IEEE Control Syst. Magazine **21** (2), (2001).
50. H. Siguerdidjane and H. Rodriguez, in *Proceedings of 15th IFAC Symposium on Automatic Control in Aerospace, Bologna/Forli, Italy, 2001.*
51. B. R. Andrievskiĭ, P. Yu. Guzenko, and A. L. Fradkov, Avtom. Telemekh. **57** (6), (1996).
52. B. R. Andrievskiĭ, and A. L. Fradkov, *Selected Chapters of Automatic Control Theory with Examples in MATLAB* (Nauka, St. Petersburg, 1999) [in Russsian].
53. A. Tsourdos and B. A. White, in *Proceedings of 15th Triennial World Congress of IFAC, Barcelona, Spain, 2002.*
54. A. L. Fradkov, I. V. Miroshnik, and V. O. Nikiforov, *Nonlinear and Adaptive Control of Complex Systems* (Kluwer Academic Publishers, 1999).
55. Th. Ting, IEEE Control Syst. **19** (6), (1999).
56. A. R. Teel, IEEE Trans. Autom. Control **41** , (9), (1996).
57. A. V. Blumel, A. Tsourdos, and B. A. White, in *Proceedings of 15th IFAC Symposium on Automatic Control in Aerospace, Bologna/Forli, Italy, 2001.*
58. A. Tsourdos and B. A. White, *Proceedings of 5th IFAC Symposium NOLCOS'01, St. Petersburg, Russia, 2001.*
59. A. L. Fradkov, *Adaptive Control of Complex Systems* (Nauka, Moscow, 1990).
60. E. J. Hughes, A. Tsourdos, and B. A. White, in *Proceedings of 2002 IEEE International Conference on Control Applications, Glasgow, Scotland, U.K., 2002.*
61. B. R. Andrievsky and A. L. Fradkov, in *Proceedings of 2002 IEEE International Conference on Control Applications, Glasgow, Scotland, U.K., 2002.*
62. A. L. Fradkov and B. R. Andrievsky, in *Proceedings of 9th St. Petersburg International Conference on Integrated Navigation Systems, St. Petersburg, Russia, 2002.*
63. N. Aouf, D. G. Bates, and I. Postlethwaite, Control Eng. Practice., No. 6, (2002).
64. M. C. Turner, N. Aouf, D. G. Bates, *et al.*, in *Proceedings of 2002 IEEE International Conference on Control Applications, Glasgow, Scotland, U.K., 2002.*
65. D. H. Shim, H. Jin Kim, and Sh. Sastry, in *Proceedings of 15th Triennial World Congress of IFAC, Barcelona, Spain, 2002.*
66. A. Dzul, T. Hamel, and R. Lozano, in *Proceedings of 15th Triennial World Congress of IFAC, Barcelona, Spain, 2002.*
67. Ch. Papageorgiou and K. Glover, in *Proceedings of 15th Triennial World Congress of IFAC, Barcelona, Spain, 2002.*
68. L. Schenato, X. Deng, and Sh. Sastry, in *Proceedings of 15th Triennial World Congress of IFAC, Barcelona, Spain, 2002.*
69. S. Hashimoto, Sh. Adachi, Y. Segawa, *et al*., in *Proceedings of 15th Triennial World Congress of IFAC, Barcelona, Spain, 2002.*
70. M. Haouani, M. Saad, and O. Akhrif, in *Proceedings of 15th Triennial World Congress of IFAC, Barcelona, Spain, 2002.*
71. I. Fantoni, R. Lozano, and P. Castillo, in *Proceedings of 15th Triennial World Congress of IFAC, Barcelona, Spain, 2002.*
72. T. Hamel, R. Mahony, R. Lozano, *et al.*, in *Proceedings of 15th Triennial World Congress of IFAC, Barcelona, Spain, 2002.*