Control Theory Tech, Vol. 16, No. 4, pp. 314–323, November 2018

Control Theory and Technology

http://link.springer.com/journal/11768

Control Theory and Technology

Active disturbance rejection control: Applications in aerospace

S. E. TALOLE

Department of Aerospace Engineering, Defence Institute of Advanced Technology, Girinagar, Pune-411 025, India

Received 1 June 2018; revised 4 August 2018; accepted 31 August 2018

Abstract

Control of uncertain dynamical systems has been an area of active research for the past several decades and to this end, various robust control approaches have been proposed in the literature. The active disturbance rejection control (ADRC) represents one prominent approach that has been widely studied and applied for designing robust controllers in diverse areas of engineering applications. In this work, a brief review of the approach and some of its applications in aerospace are discussed. The results show that the approach possesses immense potential to offer viable solution to real-life aerospace problems.

Keywords: Active disturbance rejection control, uncertainty and disturbance estimation, extended state observer, robust control

DOI https://doi.org/10.1007/s11768-018-8114-1

1 Introduction

Control performance of practical systems is usually affected by changes in plant parameters, multifarious nonlinearities, modeling errors, and unmeasurable external disturbances and therefore, design of a high performance control system for such plants offers a challenging task. A robust control design promises to deliver satisfactory control performance even in such scenarios. By definition, a controller designed for an approximate plant model and nominal operating conditions is said to be robust if it retains the desired system performance even in the presence of various uncertainties, changes in operating conditions and external disturbances. Therefore, and due to the ever increasing demands on performance, robust control for uncertain systems continues to be an area of active research.

As is well-known, one of the important characteristics of feedback is to reduce the effect of plant uncertainties and external disturbances on the output. However, complete and timely rejection of the effect of the uncertainties and disturbances may not be achieved in every feedback design as the disturbance attenuation takes place passively. To address the issue in active manner, disturbance rejection approaches such as the use of feed forward compensation based on disturbance measurements have been proposed. The approach, however, is applicable only when the disturbance is measurable.

E-mail: setalole@hotmail.com.

One can also find various theories for robust control of uncertain systems, however, many of them require a priory knowledge of some characteristic of the uncertainties and/or disturbances. Naturally, if sufficiently accurate information on the characteristics of the uncertainty is not available, the design may result into unsatisfactory performance.

One viable strategy for robust control design for uncertain system is to estimate the effect of disturbances and uncertainties and compensate the same by augmenting the controller designed for nominal system [1]. Following this line of thinking, various disturbance estimation appoaches such as classical disturbance observer (DOB) [2], nonlinear disturbance observer (NDOB) [3], unknown input observer (UIO) [4], perturbation observer (PO) [5], time delay control (TDC) [6], equivalent input disturbance (EID) approach [7], the uncertainty and disturbance estimator (UDE) [8] among others, have been proposed to estimate the effect of uncertainties and disturbances. The central idea in the designs based on these approaches is to obtain an estimate of the lumped or total disturbance using the input and output measurements of the plant and to augment the control action by using the disturbance estimate to nullify its effect. Owing to its inherent potential to address the issue of uncertainty and disturbances, the disturbance observer based control (DOBC) and related methods have been widely researched in the literature [9–11].

The active disturbance rejection control (ADRC) [12–15] represents one well-known strategy used for design of robust controllers for uncertain systems subjected to external disturbances. The approach has proven to be highly successful due to its feasibility and satisfactory performance in practice. The idea of ADRC is to treat the combined effect of parametric uncertainties, modeling errors/un-modeled dynamics, external disturbances, nonlinearities etc. as a lumped or total disturbance and designate it as an extended state of the system. Having designated the total disturbance as a state, it is estimated by using an extended state observer (ESO) and the estimate is used in the control law to compensate for it in real time. In general, the ADRC consists of tracking differentiator also called as profile generator or reference generator, an ESO and a proportional derivative (PD) controller. Although in the original formulation, the ADRC components are used in the nonlinear set up, its extension with linear ESO and PD control [16] referred to as linear ARDC (LARDC) gained wide popularity in literature and practice. As the general ADRC formulation is nonlinear wherein various design parameters need to be chosen appropriately, a parameterization of the LADRC has been proposed in [17] making the task of controller design and design parameter tuning more efficient and easier. Results on various aspects of the ADRC such as frequency response analysis of linear ADRC [18] and nonlinear ADRC [19, 20], convergence analysis [21–23], and results on time-frequency domain interpretations [24, 25] have appeared in the literature. In [26], analysis of performance of the ESO in tackling fast-varying sinusoidal disturbances is presented and it is shown that increasing the order of ESO results in improved tracking of the disturbances provided that bandwidth of ESO is sufficiently larger than the disturbance frequency and sufficiently smaller than the un-modeled dynamics. The time and frequency domain analysis is carried out and the findings are verified by simulations and experimentation. Various advances have also been reported in the basic framework of the ADRC. For example, an higher order ESO is proposed in [27] to deal with the time-varying disturbance of the form $d(t) = d_0 + d_1 t + d_2 t^2 + \dots$. A formulation of the finite time convergent ESO can be found in [28]. Extension of the ADRC methodology to non affine-in-control uncertain nonlinear systems is proposed [29]. A formulation of ADRC for a system, the dynamics of which is not in integral-chain form and/or subject to mismatched uncertainties can be found in [30] and [31]. The review of the development of ADRC from its early beginning is given in [32].

In ADRC, the ESO [16, 17, 24, 33] is the key element which enables to treat the disturbance observer design problem as the problem of state observer design. The ESO estimates the effect of uncertainties and disturbances along with the plant states in an integrated manner enabling not only disturbance rejection or compensation but also meeting the requirement of availability of system states. Unlike conventional observers, the ESO estimates the effect of plant parametric uncertainties, nonlinearities and external disturbances acting on the system as an extended state of the original plant. As the observer estimates the total disturbance as an extended state, it is designated as extended state observer. A performance comparison study of three well-known state observers, i.e., high gain observer, ESO, and sliding mode observer is presented in [33] and the authors have shown that overall, the performance of the ESO is better than the other designs. Owing to its effectiveness, applications of ESO based controllers in diverse fields have been reported in the literature [34–44].

2 Some applications in aerospace

In general, owing to various real-life issues such as existence of significant uncertainties in aerodynamic parameters, airframe flexibility, un-modeled dynamics, cross coupling effects, external unmeasurable disturbances, nonlinearities and measurement inaccuracies, the problem of designing controller for aerospace systems that can guarantee stability and uniform performance throughout the flight envelope is a highly challenging task. As many of these issues cannot be taken into account explicitly while designing controllers, the considered plant dynamics represents a highly uncertain system from control design point of view. Owing to this, the ADRC framework naturally becomes a desirable strategy for designing robust controllers for such systems and therefore, the framework has been widely applied to variety of robust control design problems in aerospace. Trajectory tracking problem for an unmanned quadrotor [45], micro-electro-mechanical systems (MEMS) gyroscope [34], fault tolerant attitude control for spacecraft [46], trajectory tracking controller for airship [47], attitude control for a spacecraft [41], control of electro-hydraulic system [48], transonic flutter suppression [49], lateral acceleration estimation of maneuverable ballistic targets [50], design of impact angle constrained guidance law [28], online estimation of helicopter mass and center-of-gravity location [51], consensus tracking control problem of the leader–follower spacecraft formation system [52], control of swing nozzle of anti-aircraft missile [53], velocity and altitude tracking control for hypersonic flight vehicle [54], fault-tolerant control for air-breathing supersonic missiles [55], control of quadrotor with obstacle avoidance [56], trajectory tracking controller for a quadrotor unmanned aerial vehicle [57], and attitude control of launch vehicle [58] are some applications to mention. While the expanse of aerospace applications is quite vast, research carried out by the author's group on some ADRC based aerospace applications is briefly discussed in the next section.

2.1 Autopilot design

Conventionally, autopilots for missiles are designed using classical linear control approaches through gain-scheduling. The nonlinear dynamics of missile is linearized about certain number of operating points in the flight envelope and controllers designed using linear theory at these points are gain scheduled. Although the gain scheduling is widely employed strategy, the resulting controller design may not offer satisfactory performance particularly when the dynamics is significantly nonlinear and undergoes large motion. The need for high performance and greater maneuverability necessitates operation of the missiles in regimes of large angles and angular rates where the nonlinearities are prominent. For example, wingless airframe configurations may need to operate at higher angles of attack to have the required lateral acceleration levels. It is well-known that the high angle of attack aerodynamics are difficult to model accurately and therefore, the designer will not have sufficiently accurate mathematical model of the plant for control design purpose. Another drawback of gain-scheduling is the resulting complexity in interpolation of gains of the controllers. The problem is further compounded due to variety of issues the aerospace systems typically face such as significant parametric uncertainties, external disturbances, presence of un-modeled dynamics, cross-coupling effects etc. Owing to this, ADRC offers a promising approach for designing autopilots for missiles. Even when a linear gain scheduled controller is employed, incorporation of ESO in these designs can result into extending the operational range of the controllers [59]. Using the disturbance and state estimation ability of ESO, pitch autopilot design for a tail controlled, roll stabilized missile is presented in [60]. Similarly, an ESO-based robust predictive control formulation for a class of nonlinear system is proposed in [61] and to showcase the efficacy, the approach is applied for missile pitch autopilot design. In both the designs, it is shown that the resulting controllers are robust to plant uncertainties, modeling errors, and external disturbances.

In the case of pitch autopilot design of tail controlled missiles, controllers are often designed by output redefinition due to the non-minimum phase nature of the acceleration dynamics. For example, angle of attack is considered as output in place of the normal acceleration and the commanded acceleration is related to an equivalent angle of attack command. A controller is then designed to track the angle of attack command. Naturally, such designs may not offer satisfactory performance whenever the commanded acceleration is not accurately translated in terms of the desired angle of attack. Addressing this aspect, design of pitch autopilot with acceleration as output for a tail controlled, roll position stabilized missile is presented in [62]. With acceleration as output, continuous time predictive control formulation is used for the design of control law. Since the predictive controller needs accurate plant mathematical model and complete state vector, the issues are addressed by using the generalized extended state observer (GESO) [11, 30]. The GESO provides the estimate of uncertainties and disturbances as well as the plant states and the same are used in the predictive controller to achiev robustness. Important features of the resulting design are: it is robust due to disturbance estimation and its compensation, the controller is acceleration tracking, the design does not need a separate observer for angle of attack estimation as the same is estimated by the GESO and lastly, the predictive control design provides feedback control and disturbance compensation gains simultaneously thus avoiding carrying out separate exercise to obtain them. Stability of the closed-loop controller-observer combination is proved and results are presented by considering uncertainties, external disturbances, un-modeled dynamics and measurement noise to demonstrate efficacy of the approach. On theoretical side, the two approaches have been used in a complementary manner. Since the predictive controller lacks robustness and also requires state vector, use of GESO has addressed both the issues. On the other hand, the GESO based control presented in [30] requires design of feedback control and disturbance compensation gain and the same have been obtained simultaneously by using the predictive control theory. Thus, the techniques have complemented each other in offering a more practical and viable solution.

Another result employing ESO in the design of acceleration tracking robust pitch autopilot for tail controlled missile is presented in [63] wherein the ESO has been used in conjunction with time-scale separation and feedback linearization (FL) approaches. Firstly, using regional Lyapunov exponents, existence of time-scale separation in the two sub-systems, i.e., pitch rate dynamics and acceleration dynamics is established. Exploiting the naturally existing time-scale separation, the missile pitch plane dynamics is divided into the fast pitch rate dynamics and the slow acceleration dynamics giving rise to two separate sub-systems. The feedback linearization theory is then used to design controllers for the sub-systems separately and for the purpose of robustness, an ESO is employed in each of the sub-system. The total disturbance in each of the sub-system is estimated by the respective ESO and the same is used to augment the FL control law designed for the respective sub-system. The effectiveness of the resulting design in meeting the expected performance in command tracking in the presence of uncertainties, un-modeled dynamics, measurement noise, control input and rate saturation and in varying missile velocity and altitude scenario is illustrated. Further, to analyze the performance for different initial conditions and parameter perturbations, Monte Carlo simulation study is carried out and the results are presented. Also, comparison of performance of the design with some existing controllers is presented to showcase the efficacy of the design.

Research has also been carried out in design of ESO based roll autopilots for missiles. In general, missiles have symmetrical configuration of cruciform type to enable them to maneuver accurately and fast enough in any direction. Such configurations lack inherent stability in roll and therefore, they tend to roll owing to various roll disturbance moments acting on them in flight. It is well-known that the rolling motion results into many undesirable effect and therefore, most missiles employ roll autopilots to achieve stabilization in roll position notwithstanding occurrences of the disturbance moments. Thus, the primary objective in roll autopilot design is to ensure roll position stabilization and to this end, it represents an output regulation problem. As the roll dynamics is significantly uncertain, one can robustify the existing design by employing suitable disturbance estimation and compensation strategy. However, use of the controllers designed using modern control theory require availability of complete state vector. Therefore, it becomes necessary to estimate the uncertainties and disturbances along with the plant state vector. These requirement are conveniently met with by use of the ESO which estimates the uncertainties and states in an integrated manner. To this end, a formulation of a roll autopilot that is robust and implementable is proposed in [64]. In this research, a roll autopilot controller based on the linear quadratic regulator (LQR) technique for nominal system is designed and an ESO is used to estimate the total disturbance and plant states. The estimated disturbance is employed for robustification whereas the estimated states are used in the LQR controller to make it implementable. In the LQR based design presented in [65], the authors have reduced the gain crossover frequency by adjusting the LQR controller weightings so as to avoid stability problems resulting due to the un-modeled flexibility dynamics. However, the design remains sensitive to external disturbances. In the work presented in [64], the weightings in the LQR controller are not changed as the effect of the un-modeled dynamics are attenuated significantly by use of the estimated states in the control law. Stability of the closed loop system is proved and simulation results considering external disturbances, plant uncertainties, un-modeled flexibility and sensor dynamics and measurement noise are presented to showcase efficacy of the proposed design.

Extending the work presented in [64] further, performance analysis of the ESO-based roll autopilot design is carried out in [66]. In this work, firstly a more realistic roll dynamics is considered and comparison of performance of the ESO-based design is carried out with various well-known roll autopilot designs. Next, the designs which have performed better are implemented in a nonlinear 6-degree of freedom (DOF) simulation environment by considering practical engagement scenario. Lastly, Monte Carlo simulation under various parameter uncertainties are carried out to visualize the performance of the ESO-based design. The results clearly bring out the superiority of the proposed ESO-based design in offering highly satisfying performance in regulation of the missile roll attitude and its rate notwithstanding the considered disturbances, uncertainties and cross-coupling effects thus offering a feasible methodology for roll autopilot design of high performance missiles.

2.2 Guidance law design

Due to the ever increasing target maneuvering capabilities, designing a robust guidance law for tactical missiles poses a challenging task. For the design, the usual approach adopted is to decouple the missile-target engagement dynamics into two mutually perpendicular planes followed by designing a guidance law for each plane separately by neglecting the cross-coupling effects. However, planar designs offer satisfactory performance only if the elevation angle between the missile and target is considerably small. The assumption, however, may not hold true in engaging highly maneuvering targets and therefore the cross-coupling effects may show up in practice resulting in degraded performance for the planar guidance laws. The problem is more pronounced in the end-game scenario where within the short interception time, the line of sight (LOS) rates are required to converge rapidly to zero to maintain the collision triangle. Further, miss distance needs to be within the lethal radius of warhead for effective operation. The issues have motivated to analyze and design three-dimensional guidance laws wherein the coupling terms are not neglected. To this end, a robust three-dimensional (3D) proportional navigation guidance law based on input-output linearization (IOL) and ESO is proposed in [67]. For the 3D nonlinear missile-target engagement dynamics, the LOS rates in the pitch and yaw plane are considered as outputs and IOL theory is used to design controllers to drive the LOS rates to zero. To achieve robustness for the guidance law, the effect of cross-coupling terms, system nonlinearities, and unknown target maneuver are treated as disturbances and the same are estimated by using the ESO. The efficacy of the design for constant as well as varying missile velocity profiles is demonstrated and it is shown that the proposed guidance law ensures elevation and azimuth LOS rates converge to zero in the presence of significant nonlinearities, uncertainties, unknown target maneuvers and measurement noise. Finally, performance comparison of the proposed design with modified proportional navigation guidance (MPNG) law is carried out to showcase the effectiveness of the proposed formulation.

In [68], design of an optimal and robust guidance law for end game scenario of tactical missiles is presented. Employing the linearized model of missile target engagement dynamics, guidance law is designed using LQR approach with an objective to minimize miss distance. The guidance law implementation, however, requires system states and also information on target acceleration. As the target acceleration represents mismatched uncertainty, various conventional strategies are not applicable for its estimation. To address this aspect, GESO is used in [68] which apart from estimating the unknown target acceleration, also provides plant state estimates enabling implementation and robustification of the LQR based guidance law. Results using the the designed guidance law to nonlinear two-dimensional missile-target engagement dynamics considering highly maneuvering target are presented.

2.3 Integrated guidance and control

Missile guidance and autopilot systems are usually designed separately as two loops with the autopilot forming the inner loop system designed to track acceleration commands computed by the outer loop guidance algorithm. Integration of the subsystems is then carried out and necessary modifications are effected to each of the sub-system to achieve desired performance for the complete system. The approach usually involves carrying out a numerous design iterations. Also the designs do not gainfully utilize the synergistic inter-relationships between these subsystems resulting in overall suboptimal performance. The issue becomes more prominent especially in the end-game scenario because, while the subsystems typically have different bandwidths, the spectral separation may not be valid close to interception owing to the fast changes in the engagement geometry. Due to these issues, integrated design for guidance and control system, usually known as integrated guidance and control (IGC) has attracted attention of researchers and practitioners. In IGC, a control law is designed to generate directly the control surface deflection commands to drive the missile toward successful interception of the target.

Following the philosophy of the IGC, a design based on the continuous-time predictive control is proposed in [69]. In the formulation, as the target acceleration information is not available, the same is treated as a mismatched external disturbance and is estimated along with the states of missile-target engagement dynamics by means of a GESO. The estimates are used in the predictive design to make the latter implementable. Closed-loop as well as stability of the internal dynamics is established and simulation including Monte Carlo simulation are presented to demonstrate the efficacy of the proposed IGC design. The notable features of the design are that it is implementable using conventional seeker measurements; does not require target maneuver information; caters for control input constraints; and gives satisfactory performance for constant as well as varying missile velocities, stable as well as unstable missile configurations, and for variety of target acceleration profiles.

Similarly, in [70], IGC design utilizing the time-scale separation in the missile-target engagement dynamics is presented. The dynamics is split into a fast pitch rate dynamics and the slow LOS rate dynamics. An Input-Output Linearization based controllers are then designed for the sub-systems independently. ESO based disturbance estimation and rejection is employed to cater for the unknown target maneuver and uncertainties in aerodynamic parameters and the effectiveness of the design is illustrated by simulation by using various maneuvering target maneuver profiles.

2.4 Height control system design

In general, the sea-skimming missiles are required to fly at a low altitude above the mean sea level and hence are controlled at designated desired altitude by a height control system (HCS). The HCS needs to be designed to not to have large overshoots in order to avoid ditching of the missile into sea waves. As is well-known, the significant wave height increases as the sea state becomes worse thereby posing a greater difficulty for the missile. When a missile employs radio altimeter, the altitude of the missile above sea surface is measured instead of the altitude above the mean sea level resulting in missile following the sea-wave pattern instead of flying horizontally. Following such trajectory by the sea-skimming missile results in enormous wastage of energy. Further, the missile can follow such trajectory only if the missile system response is sufficiently fast. Normally, missiles have restricted bandwidth and therefore, they may not be able to follow the sea-wave pattern thus increasing the possibility of ditching into sea waves. One approach to handle the issue is to treat the excursions due to the sea waves as disturbance, estimate it and compensate for it. Following this line of thinking, a novel design of height control system using ESO is proposed in [40]. In the design, the ESO provides estimate of the sea-wave disturbances in real time and the same is used to achieve robustness for the HCS and for real-time altitude planning of the skimming missile. Simulation results have shown that the proposed HCS functions quite effectively in the presence of significant sea-wave disturbances.

2.5 Aircraft control

Wing rock motion represents an important phenomena to deal with in flight of many combat aircraft. Unsteady aerodynamic effects at high angle of attack give rise to wing rock motion in slender delta wing aircraft and is a complex phenomenon characterized by self-induced limit-cycle roll oscillations. The motion needs to be suppressed as it can have adverse effects on operational safety, aircraft maneuverability, and tracking accuracy. The operational envelope of an aircraft having this motion gets significantly restricted due to limiting the maximum incidence angle by the onset of wing rock before the occurrence of stall. Since high performance aircraft often need to operate at high angles of attack due to mission requirements, suppression of the wing rock motion is of great importance. The problem can be dealt with various approaches such as reshaping the airframe configuration, by ensuring limited maneuver and by using automatic flight control system of which the last one has been the most effective method for suppressing the wing rock without compromising the maneuver ability of aircraft. However, the dynamics of wing rock motion changes in nonlinear manner with respect to angle of attack, making the task of designing robust controller quite difficult. Following the ADRC approach, a robust control design for wing rock motion suppression is proposed in [71] considering time-varying angle of attack. In the proposed design, the issues of uncertainties and external disturbances are addressed by using an ESO to achieve robustness. Numerical simulations are carried out and the results are presented to showcase efficacy of the design.

2.6 Experimental validation

Real time operations put stringent constraints on the functionality of techniques that otherwise perform ideally in a simulation study. Hence, experimental analysis of the control strategies is indispensable for critically examining the feasibility and merits of any approach. To this end, experimental validation of the ESO based designs have also been carried out. For example, in [39], an FL based controller made implementable using ESO is presented for trajectory tracking control of a flexible joint robotic system and the effectiveness of the design is verified through experimentation on Quanser's flexible-joint module. Similarly, design and experimental validation of an ESO based robust predictive controller for flexible joint system is presented in [72]. Lastly, in [26], performance analysis of ESO in tackling fast-varying sinusoidal disturbances is presented and the findings are validated through simulations as well as conducting experiment on Quanser's motion control module.

3 Possible areas of application in future

From the vast research reported in the literature and due to its history of successful applications, it will not be exaggeration to state that the ADRC possesses a vast potential to offer viable solution to many current as well as futuristic real-life aerospace applications. With the advances in the ADRC framework, the approach has utility in various current, ongoing as well as futuristic uncertain aerospace systems and some of the areas of application are mentioned here.

As is well-known, hypersonic vehicles have great potential for high-speed transportation and space access. However, such vehicles are also subject to unique problems due to the highly complex and uncertain flight environment. Owing to this, the vehicles will need highly integrated and robust flight, propulsion, and thermal control systems and an efficient guidance design to optimize vehicle performance.

The reusable launch vehicles (RLVs) are space vehicles designed to perform multiple missions and due to the fact that they are re-used, RLVs are expected to reduce the cost of access to low earth orbit significantly. However, the technical challenges to fly to orbit and return are significant and among them is the development of a practical, reliable and cost-effective RLV guidance and control technology. The design poses a great challenge due to enormous uncertainties and fast-changing parameters and therefore, it needs to have both rapid adaptability and sufficient robustness.

Interplanetary vehicle guidance and control where the unpredictable and uncertain environment of planets such as Mars offer a great challenge in designing guidance and control for such vehicles.

As airframes are made more and more lighter, aeroelastic effects induced by the interaction among the unsteady aerodynamic load, aircraft structure, and control system are extremely important in aircraft design. Therefore, dealing with aeroservoelasticity in aircraft design involves active vibration and flutter suppression techniques which can be used to avoid flutter instability and thereby enabling reduction in the weight of aircraft structure.

Control and formation flight control of unmanned air vehicles, control of morphing wing aircraft etc. are some more areas to mention wherein the ADRC has potential to play a significant role in the design of robust controllers.

4 Conclusions

In this paper, an overview of the active disturbance rejection control (ADRC) approach is presented. Basic philosophy of ADRC, some theoretical results and advancement in the techniques have been briefly reviewed. An overview of applications of the technique for a number of aerospace applications is presented along with brief discussion of the research carried out by the author's group. Some possible current/futuristic areas where the technique can be highly useful are also highlighted.

Acknowledgements

The author would like to thank all his co-authors and students who have contributed in the research on ADRC briefly presented in this paper.

References

[1] Z. Gao. On the centrality of disturbance rejection in automatic control. *ISA Transactions*, 2014, 53(4): 850 – 857.

[2] E. Sariyildiz, K. Ohnishi. A guide to design disturbance observer. *Journal of Dynamic Systems, Measurement, and Control – Transactions of the ASME*, 2014, 136(2): DOI 10.1115/1.4025801.

[3] W.-H. Chen. Nonlinear disturbance observer-enhanced dynamic inversion control of missile. *Journal of Guidance, Control, and Dynamics*, 2003, 26(1): 161 – 166.

[4] R. H. C. Takahashi, P. L. D. Peres. Unknown input observers for uncertain systems: A unifying approach and enhancements. *Proceedings of the 35th Conference on Decision and Control*, Kobe, Japan: IEEE, 1996: 1483 – 1488.

[5] J. T. Moura, H. Elmali, N. Olgac. Sliding mode control with sliding perturbation observer. *Journal of Dynamic Systems, Measurement, and Control – Transactions of the ASME*, 1997, 119(4): 657 – 665.

[6] K. Youcef-Toumi, O. Ito. A time delay controller for systems with unknown dynamics. *Journal of Dynamic Systems, Measurement, and Control – Transactions of the ASME*, 1990, 112(1): 133 – 142.

[7] J. H. She, M. Fang, Y. Ohyama, et al. Improving disturbance-rejection performance based on an equivalent-input-disturbance approach. *IEEE Transactions Industrial Electronics*, 2008, 55(1): 380 – 389.

[8] Q. C. Zhong, D. Rees. Control of uncertain LTI systems based on an uncertainty and disturbance estimator. *Journal of Dynamic Systems, Measurement, and Control – Transactions of the ASME*, 2004, 126(4): 905 – 910.

[9] W.-H. Chen, J. Yang, L. Guo, et al. Disturbance observer-based control and related methods – an overview. *IEEE Transactions on Industrial Electronics*, 2016, 63(2): 1083 – 1095.

[10] A. Radke, Z. Gao. A survey of state and disturbance observers for practitioners. *Proceedings of the American Control Conference*, Minneapolis: IEEE, 2006: 5183 – 5188.

[11] S. Li, J. Yang, W.-H. Chen, et al. *Disturbance Observer-Based Control: Methods and Applications*. Boca Raton: CRC press, 2014.

[12] J. Han. From PID to active disturbance rejection control. *IEEE Transactions on Industrial Electronics*, 2009, 56(3): 900 – 906.

[13] Z. Gao. Active disturbance rejection control: A paradigm shift in feedback control system design. *Proceedings of the American Control Conference*, Minneapolis: IEEE, 2006: 2399 – 2405.

[14] Z. Gao, Y. Huang, J. Han. An alternative paradigm for control system design. *Proceedings of the 40th IEEE Conference on Decision and Control*. Orlando, Florida, USA: IEEE, 2001: 4578 – 4585.

[15] D. Sun. Comments on active disturbance rejection control. *IEEE Transactions on Industrial Electronics*, 2007, 54(6): 3428 – 3429.

[16] D. Yoo, S. S. T. Yau, Z. Gao. Optimal fast tracking observer bandwidth of the linear extended state observer. *International Journal of Control*, 2007, 80(1): 102 – 111.

[17] Z. Gao. Scaling and bandwidth-parametrization based controller tuning. *Proceedings of the American Control Conference*, Denver: IEEE, 2003: 4989 – 4996.

[18] C. Huang, Q. Zheng. Frequency response analysis of linear active disturbance rejection control. *Sensors & Transducers*, 2013, 157(10): 346 – 354.

[19] J. Li, X. Qi, Y. Xia, et al. Frequency domain stability analysis of nonlinear active disturbance rejection control system. *ISA Transactions*, 2015, 56: 188 – 195.

[20] D. Wu, K. Chen. Frequency-domain analysis of nonlinear active disturbance rejection control via the describing function method. *IEEE Transactions on Industrial Electronics*, 2013, 60(9): 3906 – 3914.

[21] D. Yoo, S. S. T. Yau, Z. Gao. On convergence of the linear extended state observer. *Proceedings of the IEEE International Symposium on Intelligent Control*, Munich, Germany: IEEE, 2006: 1645 – 1650.

[22] B. Z. Guo, Z. L. Zhao. On the convergence of an extended state observer for nonlinear systems with uncertainty. *Systems & Control Letters*, 2011, 60(6): 420 – 430.

[23] B. Z. Guo, Z. L. Zhao. On convergence of the nonlinear active disturbance rejection control for MIMO systems. *SIAM Journal on Control and Optimization*, 2013, 51(2): 1727 – 1757.

[24] Q. Zheng, L. Q. Gao, Z. Gao. On validation of extended state observer through analysis and experimentation. *Journal of Dynamic Systems, Measurement, and Control*, 2012, 134(2): DOI 10.1115/1.4005364.

[25] Q. Zheng, Z. Gao. Active disturbance rejection control: Between the formulation in time and the understanding in frequency. *Control Theory and Technology*, 2016, 14(3): 250 – 259.

[26] A. A. Godbole, J. P. Kolhe, S. E. Talole. Performance analysis of generalized ESO in tackling sinusoidal disturbances. *IEEE Transactions on Control Systems Technology*, 2013, 21(6): 2212 – 2223.

[27] R. Miklosovic, A. Radke, Z. Gao. Discrete implementation and generalization of the extended state observer. *Proceedings of the American Control Conference*, Minneapolis: IEEE, 2006: 2209 – 2214.

[28] S. Xiong, W. Wang, S. Song, et al. Extended state observer based impact angle constrained guidance law for maneuvering target interception. *Proceedings of the IMechE – Part G: Journal of Aerospace Engineering*, 2015, 229(14): 2589 – 2607.

[29] M. Ran, Q. Wang, C. Dong. Active disturbance rejection control for uncertain nonaffine-in-control nonlinear systems. *IEEE Transactions on Automatic Control*, 2017, 62(11): 5830 – 5836.

[30] S. Li, J. Yang, W.-H. Chen, et al. Generalized extended state observer based control for systems with mismatched uncertainties. *IEEE Transactions on Industrial Electronics*, 2012, 59(12): 4792 – 4802.

[31] A. Castillo, P. Garcia, R. Sanz, et al. Enhanced extended state observer-based control for systems with mismatched uncertainties and disturbances. *ISA Transactions*, 2018, 73: 1 – 10.

[32] H. Feng, B. Z. Guo. Active disturbance rejection control: Old and new results. *Annual Reviews in Control*, 2017, 44: 238 – 248.

[33] W. Wang, Z. Gao. A comparison study of advanced state observer design techniques. *Proceedings of the American Control Conference*, Denver: IEEE, 2003: 4754 – 4759.

[34] Q. Zheng, L. Dong, D. H. Lee, et al. Active disturbance rejection control for MEMS gyroscopes. *IEEE Transactions on Control Systems Technology*, 2009, 17(6): 1432 – 1438.

[35] G. Feng, Y. F. Liu, L. Huang. A new robust algorithm to improve the dynamic performance on the speed control of induction motor drive. *IEEE Transactions on Industrial Electronics*, 2004, 19(6): 1614 – 1627.

[36] Y. X. Su, B. Y. Duan, C. H. Zheng, et al. Disturbance-rejection high-precision motion control of a Stewart platform. *IEEE Transactions on Control Systems Technology*, 2004, 12(3): 364 – 374.

[37] R. Zhang, C. Tong. Torsional vibration control of the main drive system of a rolling mill based on an extended state observer and linear quadratic control. *Journal of Vibration and Control*, 2006, 12(3): 313 – 327.

[38] J. Su, W. Qiu, H. Ma, et al. Calibration-free robotic eye-hand coordination based on an auto disturbance rejection controller. *IEEE Transactions on Robotics*, 2004, 20(5): 899 – 907.

[39] S. E. Talole, J. P. Kolhe, S. B. Phadke. Extended-state-observer-based control of flexible-joint system with experimental validation. *IEEE Transactions on Industrial Electronics*, 2010, 57(4): 1411 – 1419.

[40] K. S. Priyamvada, V. Olikal, S. E. Talole, et al. Robust height control system design for sea skimming missiles. *Journal of Guidance, Control, and Dynamics*, 2011, 34(6): 1746 – 1756.

[41] Y. Xia, Z. Zhu, M. Fu, et al. Attitude tracking of rigid spacecraft with bounded disturbances. *IEEE Transactions on Industrial Electronics*, 2011, 58(2): 647 – 659.

[42] Y. Xia, Z. Zhu, M. Fu. Back-stepping sliding mode control for missile systems based on an extended state observer. *IET Control Theory Applications*, 2011, 5(1): 93 – 102.

[43] B. Li, Q. Hu, G. Ma. Extended state observer based robust attitude control of spacecraft with input saturation. *Aerospace Science and Technology*, 2016, 50: 173 – 182.

[44] Z. Zhu, D. Xu, J. Liu, Y. Xia. Missile guidance law based on extended state observer. *IEEE Transactions on Industrial Electronics*, 2013, 60(12): 5882 – 5891.

[45] D. Ma, Y. Xia, T. Li, K. Chang. Active disturbance rejection and predictive control strategy for a quadrotor helicopter. *IET Control Theory & Applications*, 2016, 10(17): 2213 – 2222.

[46] D. Ran, X. Chen, A. de Ruiter, et al. Adaptive extended-state observer-based fault tolerant attitude control for spacecraft with reaction wheels. *Acta Astronautica*, 2018, 145: 501 – 514.

[47] E. Zhu, J. Pang, N. Sun, et al. Airship horizontal trajectory tracking control based on active disturbance rejection control (ADRC). *Nonlinear Dynamics*, 2014, 75(4): 725 – 734.

[48] Q. Guo, Y. Zhang, B. G. Celler, et al. Backstepping control of electro-hydraulic system based on extended-state-observer with plant dynamics largely unknown. *IEEE Transactions on Industrial Electronics*, 2016, 63(11): 6909 – 6920.

[49] Z. Yang, R. Huang, Y. Zhao, et al. Design of an active disturbance rejection control for transonic flutter suppression. *Journal of Guidance, Control, and Dynamics*, 2017, 40(11): 2905 – 2916.

[50] Y. P. Lin, C. L. Lin, P. Suebsaiprom, et al. Estimating evasive acceleration for ballistic targets using an extended state observer. *IEEE Transactions on Aerospace and Electronic Systems*, 2016, 52(1): 337 – 349.

[51] S. Zarovy, M. Costello. Extended state observer for helicopter mass and center-of-gravity estimation. *Journal of Aircraft*, 2015, 52(6): 1939 – 1950.

[52] D. Ye, J. Zhang, Z. Sun. Extended state observer-based finite-time controller design for coupled spacecraft formation with actuator saturation. *Advances in Mechanical Engineering*, 2017, 9(4): 1 – 13.

[53] L. Sun, W. Wang, R. Yi, et al. Fast terminal sliding mode control based on extended state observer for swing nozzle of anti-aircraft missile. *Proceedings of the IMechE – Part G: Journal of Aerospace Engineering*, 2015, 229(6): 1103 – 1113.

[54] Y. Zhang, Z. Jiang, H. Yang, et al. High-order extended state observer-enhanced control for a hypersonic flight vehicle with parameter uncertainty and external disturbance. *Proceedings of the IMechE – Part G: Journal of Aerospace Engineering*, 229(13): 2481 – 2496.

[55] C. Ming, R. Sun, B. Zhu. Nonlinear fault-tolerant control with prescribed performance for air-breathing supersonic missiles. *Journal of Spacecraft and Rockets*, 2017, 54(5): 1092 – 1099.

[56] K. Chang, Y. Xia, K. Huang, et al. Obstacle avoidance and active disturbance rejection control for a quadrotor. *Neurocomputing*, 2016, 190: 60 – 69.

[57] X. Shao, J. Liu, H. Cao, et al. Robust dynamic surface trajectory tracking control for a quadrotor UAV via extended state observer. *International Journal of Robust and Nonlinear Control*, 2018, 28(7): 2700 – 2719.

[58] Q. Wu, M. Sun, Z. Chen, et al. Tuning of active disturbance rejection attitude controller for statically unstable launch vehicle. *Journal of Spacecraft and Rockets*, 2017, 54(6): 1383 – 1389.

[59] A. A. Godbole, S. E. Talole. Extending the operating range of linear controller by means of ESO. *Computational Intelligence and Information Technology*. Berlin: Springer, 2011: 44 – 49.

[60] A. A. Godbole, T. R. Libin, S. E. Talole. Extended state observer-based robust pitch autopilot design for tactical missiles. *Proceedings of the IMechE – Part G: Journal of Aerospace Engineering*, 2012, 226(12): 1482 – 1501.

[61] B. Panchal, J. P. Kolhe, S. E. Talole. Robust predictive control of a class of nonlinear systems. *Journal of Guidance, Control, and Dynamics*, 2014, 37(5): 1437 – 1445.

[62] B. Panchal, S. E. Talole. Generalized ESO and predictive control based robust autopilot design. *Journal of Control Science and Engineering*, 2016, 2016: DOI http://dx.doi.org/10.1155/2016/5741603.

[63] B. Panchal, K. Subramanian, S. E. Talole. Robust missile autopilot design using two time-scale separation. *IEEE Transactions on Aerospace and Electronic Systems*, 2018, 54(3): 1499 – 1510.

[64] S. E. Talole, A. A. Godbole, J. P. Kolhe, et al. Robust roll autopilot design for tactical missiles. *Journal of Guidance, Control, and Dynamics*, 2011, 34(1): 107 – 117.

[65] F. W. Nesline, P. Zarchan. Why modern controllers can go unstable in practice. *Journal of Guidance, Control, and Dynamics*, 1984, 7(4): 495 – 500.

[66] C. V. Sirisha, R. Das, S. E. Talole. Performance investigation of extended state observer based roll autopilot design. *Proceedings of the Institution of Mechanical Engineers – Part G: Journal of Aerospace Engineering*, 2015, 229(12): 2205 – 2220.

[67] S. K. Pandit, B. Panchal, S. E. Talole. Design of three-dimensional guidance law for tactical missiles. *Proceedings of the AIAA Guidance, Navigation and Control Conference*, Kissimmee: AIAA, 2018: AIAA 2018-1323.

[68] N. Mate, B. Panchal, S. E. Talole. GESO based robust optimal guidance. *Proceedings of the IEEE International Conference on Industrial Instrumentation and Control*, Pune, India: IEEE, 2015: 187 – 192.

[69] B. Panchal, N. Mate, S. E. Talole. Continuous-time predictive control-based integrated guidance and control. *Journal of Guidance, Control, and Dynamics*, 2017, 40(7): 1579 – 1595.

[70] B. Panchal, K. Subramanian, S. E. Talole. Robust integrated guidance and control design for tactical missiles. *Proceedings of the AIAA Guidance, Navigation and Control Conference*, Kissimmee: AIAA, 2018: AIAA 2018-1120.

[71] D. K. Kori, J. P. Kolhe, S. E. Talole. Extended state observer based robust control of wing rock motion. *Aerospace Science and Technology*, 2014, 33(1): 107 – 117.

[72] B. Panchal, J. P. Kolhe, S. E. Talole. Experimental validation of robust predictive control. *Proceedings of the IEEE International Conference on Industrial Instrumentation and Control*, Pune, India: IEEE, 2015: 237 – 242.

S. E. TALOLE obtained his B.E. in Electrical Engineering from Govt. College of Engineering, Amravati, M.E. in Aerospace Engineering from Indian Institute of Science Bangalore and Ph.D. from the Indian Institute of Technology Bombay, Mumbai. He worked as a Postdoctoral Research Scholar at the Flight Dynamics and Control Laboratory of the University of California Irvine, U.S.A. In 1989, he joined the Defence Research and Development Organization, India, where currently he is Professor at the Department of Aerospace Engineering, Defence Institute of Advanced Technology (DIAT), Girinagar, Pune. Research interests of Dr Talole include nonlinear control and robust control based on uncertainty and disturbance estimation with applications in flight guidance and control, robotics, and control of marine vehicles. He has published over 115 papers in various international and national journals and conferences. He is recipient of the DIAT Researcher of the Year award in 2007 and Laboratory Scientist of the Year award in the year 2002. In 2010, he was honored with the DRDO Scientist of the Year Award.

Dr Talole is Fellow of The Institution of Engineers (India), The Aeronautical Society of India and The Institution of Electronics & Telecommunication Engineers and Member of Astronautical Society of India and Automatic Control & Dynamics Optimization Society (ACDOS) of India. E-mail: setalole@hotmail.com.