

Disturbance-Observer-Based Control and Related Methods—An Overview

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Abstract—Disturbance-observer-based control (DOBC) and related methods have been researched and applied in various industrial sectors in the last four decades. This survey, at first time, gives a systematic and comprehensive tutorial and summary on the existing disturbance/uncertainty estimation and attenuation techniques, most notably, DOBC, active disturbance rejection control, disturbance accommodation control, and composite hierarchical antidisturbance control. In all of these methods, disturbance and uncertainty are, in general, lumped together, and an observation mechanism is employed to estimate the total disturbance. This paper first reviews a number of widely used linear and nonlinear disturbance/uncertainty estimation techniques and then discusses and compares various compensation techniques and the procedures of integrating disturbance/uncertainty compensation with a (pre-designed) linear/nonlinear controller. It also provides concise tutorials of the main methods in this area with clear descriptions of their features. The application of this group of methods in various industrial sections is reviewed, with emphasis on the commercialization of some algorithms. The survey is ended with the discussion of future directions.

Index Terms—Disturbances, estimation, linear systems, motion control, nonlinear systems, robustness, uncertainties.

ACRONYMS

| | |
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| ADRC | Active disturbance rejection control. |
| CHADC | Composite hierarchical antidisturbance control. |
| DAC | Disturbance accommodation control. |
| EHGSO | Extended high-gain state observer. |

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| EID | Equivalent input disturbance. |
| ESO | Extended state observer. |
| GPIO | Generalized proportional integral observer. |
| (L/N)DOB | (Linear/nonlinear) disturbance observer. |
| (L/N)DOBC | (Linear/nonlinear) disturbance-observer-based control. |
| (L/N)DUE | (Linear/nonlinear) disturbance and uncertainty estimation. |
| (L/N)DUEA | (Linear/nonlinear) disturbance and uncertainty estimation and attenuation. |
| UDE | Uncertainty and disturbance estimator. |
| UIO | Unknown input observer. |

I. INTRODUCTION

A. Motivation and Background

DISTURBANCES and uncertainties widely exist in all industrial systems and bring adverse effects on performance and even stability of control systems [1]–[3]. Not surprisingly, disturbance and uncertainty rejection is a key objective in control system design. When a disturbance is measurable, it is well known that a feedforward strategy could attenuate or eliminate the influence of disturbance. However, quite often, the external disturbance cannot be directly measured or is too expensive to measure. One intuitive idea to deal with this problem is to estimate the disturbance (or the influence of the disturbance) from measurable variables, and then, a control action can be taken, based on the disturbance estimate, to compensate for the influence of the disturbance. This basic idea can be intuitively extended to deal with uncertainties where the influence of the uncertainties or unmodeled dynamics could be considered as a part of the disturbance. Consequently, in a similar fashion, the influence of the uncertainties could be suppressed, and system robustness could be improved [4], [5]. This motivates the development and application of a wide variety of disturbance/uncertainty attenuation algorithms *independently* by researchers and practitioners working in different industrial sectors. Although under different names and developed from different prospects, those algorithms/methods share a similar fundamental idea, i.e., an observation mechanism is designed to estimate disturbances or uncertainties (or both of them), and corresponding compensation is then generated by making use of the estimate. In this setting, the disturbances do not only refer to that from the external environment of a control system but also uncertainties of the controlled system including

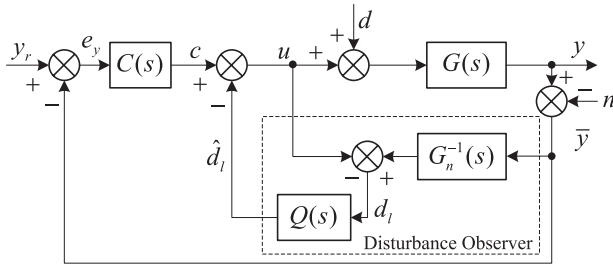


Fig. 1. Conceptual diagram of DOBC.

unmodeled dynamics and parameter perturbations [2], [3], [6]. For the sake of convenience, we refer this kind of technique as *disturbance/uncertainty estimation and attenuation* (DUEA) in this paper.

To a large extent, the influence of disturbances and uncertainties may be dealt with by a classic feedback control system design. Indeed, attenuation of the influence from uncertainties and unmeasurable disturbances is the primary driving force for developing and employing a feedback strategy [1]. However, there are a number of (quite often conflicting) requirements for control systems, e.g., stability, performance, tracking, regulation, disturbance rejection, and robustness. It is well known that there are a number of intrinsic design constraints in the traditional feedback diagram, which is also referred to as single degree of freedom control structure. Among others, the most notable ones are tracking versus disturbance rejection and nominal performance versus robustness. DUEA techniques provide a promising approach to address these constraints. In this paper, *disturbance-observer-based control* (DOBC) is selected to explain the concept of DUEA and as a benchmark method for comparisons and discussion. Choosing DOBC to facilitate the discussion does not imply that this method is necessarily better than other DUEA methods, but for the following reasons: 1) it is one of the most widely accepted and applied DUEA methods; 2) it is easy to understand and quite intuitive; and 3) compared with others, more rigorous results about stability analysis and other properties of DOBC are available (e.g., [3]).

B. Basic Idea and Features

The basic idea behind DUEA can be illustrated by a conceptual diagram of a simple linear DOBC system as Fig. 1, where $G(s)$ represents the real physical plant, $G_n(s)$ is the nominal model used for the controller design, $Q(s)$ is a stable filter, c is the feedback controller output, u is the control input, y is the system output, y_r is the reference signal, \bar{y} is the measured output, n is the measurement noise, d is the external disturbance, d_l is the *lumped disturbance*, and \hat{d}_l is the estimate of the lumped disturbance.

It can be shown from Fig. 1 that, in the absence of the disturbance d and uncertainty (i.e., the nominal plant $G_n(s)$ is the same as the real physical system $G(s)$), the inner loop with the disturbance estimation and compensation mechanism is not activated. Therefore, the baseline controller $C(s)$ can be designed according to tracking performance specifications and stability, while the inner loop is designed to reject disturbance

and suppress uncertainty. These two conflicting requirements can be met by separately designing the normal feedback loop and the inner disturbance attenuation loop (e.g., $Q(s)$ in Fig. 1). This distinguishes it from some other control techniques. For instance, the integral action is introduced in traditional PID to improve the disturbance rejection and robustness, but it also increases overshoot in tracking and degrades the system stability. Furthermore, most of the existing robust control methods are the worst case based design, where the nominal performance is sacrificed to achieve better robustness. As shown in Fig. 1, the nominal performance is preserved in the absence of uncertainty since the inner loop is not activated, so it reduces to a classic feedback loop with the controller $C(s)$. However, the inner loop is activated in the presence of the uncertainty, so the influence of uncertainty can be suppressed.

As the basic idea described previously is quite intuitive and effective, it is not surprising that various DUEA methods have been *independently* proposed and practiced by many researchers and engineers (for example, see the history note [7]). Since the 1960s, a number of DUEA techniques have been proposed, such as *unknown input observer* (UIO) in *disturbance accommodation control* (DAC) [8], [9], *perturbation observer* [10], *equivalent input disturbance* (EID) based estimator [11], [12], *extended state observer* (ESO) [13], [14], *uncertainty and disturbance estimator* (UDE) [15], *disturbance observer* (DOB) [4], [16]–[18], and *generalized proportional integral observer* (GPIO) [19]. Among those disturbance estimation approaches, DOB, UIO, and ESO are most extensively investigated and applied. DOB was initiatively put forward by Ohnishi and his colleagues in the early 1980s to improve torque and speed control by estimating load torque [20]. ESO was first proposed by Han in the 1990s [13] in his effort to develop an alternative practical control method to classic PID. ESO is generally regarded as a fundamental part of the so-called active disturbance rejection control (ADRC) [5], which was developed to estimate the lumped disturbances consisting of both unknown uncertainties and external disturbances.

For most of the methods/techniques in modern control engineering, the theoretical developments and analysis are more advanced than engineering applications, and the theoretical research leads the advances and the developments of the methods. In contrast, to a large extent, the theoretic study is behind the practical applications in DUEA methods. Experience and empirical guidance still play a major role in successfully designing disturbance/uncertainty estimators and compensation to attenuate the disturbances or uncertainties for specific classes of systems, although a significant progress has been made recently in developing rigorous tools for analyzing theoretic properties such as stability [21], [22]. On the other side, there is a lack of *synergy and understanding* of different DUEA algorithms/methods (e.g., the inappropriate statement in [23] that the DOBC is a special kind of PID). Furthermore, these methods have been motivated and developed by researchers and engineers working on different applications in different industrial sectors and in different countries. Their papers are scattered in different journals and conferences. There is no adequate attention in general academic community. As such, similar ideas are still being proposed.

C. Organization of the Survey

Disturbance and uncertainty attenuation is a very broad subject, and numerous methods including various robust and adaptive control methods have been proposed. It is impossible to review all of the methods on this subject. This survey mainly focuses on the methods where a DOB or a similar mechanism is explicitly used to estimate the influence of disturbances/uncertainties. It is no doubt that some DUEA methods shall be included but not due to the scope and length limit. For example, inspired by the work of designing robust observers using the sliding mode concept, a nonlinear DOB (NDOB) for linear minimum phase systems has been proposed in [24].

II. LDUE TECHNIQUES

As mentioned in Section I, there are several linear disturbance and uncertainty estimation (LDUE) techniques. This section will first review the frequency domain LDUE design, followed by a number of time domain design methods.

A. Frequency Domain DOB Design

The basic diagram of DOB in frequency domain was proposed by Ohnishi and his colleagues (e.g., [4] and [20]) as shown in Fig. 1 by ignoring the outer feedback loop. Under the assumption that the controlled plant is of minimum phase, a simple calculation indicates that the “lumped disturbance” d_l in Fig. 1 consists of three items as

$$d_l(s) = [G(s)^{-1} - G_n(s)^{-1}] y(s) + d(s) - G_n(s)n(s). \quad (1)$$

The first item relates to the mismatching between the physical system $G(s)$ and the nominal model $G_n(s)$, the second relates to the external disturbance $d(s)$, and the last relates to the measurement noise $n(s)$. Therefore, d_l captures all of the disturbance and uncertainty influence. After letting it pass a filter $Q(s)$, the estimate of the lumped disturbance in DOB is given by

$$\hat{d}_l(s) = G_{ud}(s)u(s) + G_{yd}(s)\bar{y}(s). \quad (2)$$

If the estimate of the disturbance is fed back to compensate the influence of the lumped disturbance as in Fig. 1, the output of the equivalent system can be expressed as

$$y(s) = G_{cy}(s)c(s) + G_{dy}(s)d(s) + G_{ny}(s)n(s). \quad (3)$$

In the frequency range of $Q(j\omega) \approx 1$, (3) reduces to [4], [25]

$$y(j\omega) \approx G_n(j\omega)c(j\omega) + n(j\omega). \quad (4)$$

It can be observed from (4) that the real physical system $G(s)$ under the disturbance d is forced to behave like the nominal system $G_n(s)$ without disturbance in the frequency range of $Q(j\omega) \approx 1$.

It is obvious that the design of the filter $Q(s)$ plays a central role in DOB. Ideally, to estimate the influence of

disturbance/uncertainty, the $Q(s)$ filter shall be designed to be close to 1 in all of the frequency range. However, this may amplify the sensor noise and also makes the DOB not implementable due to the requirement of the inverse of the nominal plant $G_n(s)$. Normally, the filter $Q(s)$ shall be designed as a low-pass filter with its relative degree (i.e., the order difference between the denominator and the numerator of its transfer function) higher than that of the nominal plant $G_n(s)$. The latter is to ensure that the transfer function $Q(s)G_n(s)^{-1}$ is implementable. The choice of a low-pass filter is because the disturbance d to be estimated is usually of low or medium frequency, whereas the sensor noise n is of medium or high frequency. Therefore, the DOB is able to estimate the disturbance and uncertainty in a low and medium frequency range but filter out the high-frequency measurement noise. This choice can be further justified by two engineering implications: 1) if the controlled plant might be subject to a high-frequency disturbance, the influence of the high-frequency components normally is filtered out by the inertia of the physical system, and 2) even if the high-frequency disturbance could be estimated, it would be quite difficult to attenuate its influence due to the bandwidth constraints of actuators. The cutoff frequency of the low-pass filter $Q(s)$ is vital in trading off between different factors (e.g., stability and performance requirements, frequency characteristic of the external disturbance d and measurement noise n , and size and characteristic of the uncertainties). In general, a high cutoff frequency increases the disturbance attenuation and robustness but demands large control action and increases sensitivity to the sensor noise. Guide and methods for designing the filter $Q(s)$ can be referred to [4] and [17] to name but only a few. Despite three decades have passed after the birth of frequency domain DOB, a great deal of dedicated results is still popping out for further guidelines on tuning, stability, and robustness analysis in DOB [26].

Note that the scheme sketched in Fig. 1 is only applicable to minimum phase systems due to the inverse of the nominal plant; however, DOB for nonminimum phase and (or) unstable systems has been proposed (e.g., [27]), and other developments and relevant references can be found from [3] and [26].

B. ESO in ADRC

Considering a single-input–single-output (possibly nonlinear) system with disturbance, depicted by

$$y^{(n)}(t) = f\left(y(t), \dot{y}(t), \dots, y^{(n-1)}(t), d(t), t\right) + bu(t) \quad (5)$$

where $y^{(l)}$ denotes the l th derivative of the output y and u and d denote the input and the disturbance, respectively. This description represents a wide range of systems, which could be linear or nonlinear and time invariant or time varying. To simplify the notation, the time variable will be dropped if no confusion is caused. Letting $x_1 = y, x_2 = \dot{y}, \dots, x_n = y^{(n-1)}$, one has

$$\begin{cases} \dot{x}_i = x_{i+1}, i = 1, \dots, n-1 \\ \dot{x}_n = f(x_1, x_2, \dots, x_n, d, t) + bu. \end{cases} \quad (6)$$

Choose a new state as

$$\begin{cases} x_{n+1} = f(x_1, x_2, \dots, x_n, d, t) \\ \dot{x}_{n+1} = h(t) \end{cases} \quad (7)$$

with

$$h(t) = \dot{f}(x_1, x_2, \dots, x_n, d, t). \quad (8)$$

ESO is designed to estimate all of the states and lumped disturbance term f , given by [5], [13]

$$\begin{cases} \dot{\hat{x}}_i = \hat{x}_{i+1} + \beta_i(y - \hat{x}_1), \quad i = 1, \dots, n \\ \dot{\hat{x}}_{n+1} = \beta_{n+1}(y - \hat{x}_1). \end{cases} \quad (9)$$

It is obvious that both the influences of model dynamics (including unmodeled dynamics and uncertainty) and external disturbance are estimated in the ESO. Only the relative degree of the system under consideration is required in the ESO design. Therefore, the significant feature of ESO is that it requires minimum information about a dynamic system. Various extensions have been made to extend the basic ESO design to a wider range of dynamic systems. For more information about ESO and related ADRC, please refer to the recent survey paper [28].

C. UIO in DAC

Since the advent of modern control theory, state space framework has proven to be very powerful in system analysis and design such as controllability and observability. However, in the early days, it was not clear how to deal with unknown external disturbance (and uncertainties) in this framework. Motivated by this fact and funded by NASA in later 1960s, research has been initiated to develop a similar function in the modern state space framework as an integral action in the classic control approach for dealing with unknown disturbance (and uncertainties) [7]. Utilizing the newly formed state observer technique, joint state and disturbance estimation was first developed for unknown constant disturbance by Johnson [8]. Integrating this UIO with a state feedback automatically produces a controller with integral effect which is referred to as DAC. This work was extended to deal with a general class of disturbances, e.g., external disturbance that can be modeled by a set of differential equation in [29]. This concept is further extended to deal with the influence of system uncertainties which was regarded as a kind of “adaptive control” [30]. It shall be mentioned that there are a number of alternatives of UIOs, and they may have different meanings. For example, in fault diagnosis and isolation [31], the UIO technique is to design an observer such that the fault residual does not depend on unknown input (i.e., disturbances).

A state space realization of the dynamic system $G(s)$ in Fig. 1 is written as

$$\begin{cases} \dot{x} = Ax + B_u u + B_d d \\ y = Cx. \end{cases} \quad (10)$$

The disturbances are supposed to be generated by the following exogenous system [29], [32]:

$$\dot{\xi} = W\xi, \quad d = V\xi \quad (11)$$

where $\xi \in \mathbb{R}^q$. UIO is to jointly estimate both state and disturbance if the state is not available. The state observer for system (10) could be constructed to estimate the state, and then, a DOB is designed to estimate the disturbance simultaneously [29]. That is,

$$\begin{cases} \dot{\hat{x}} = A\hat{x} + B_u u + L_x(y - \hat{y}) + B_d \hat{d} \\ \hat{y} = C\hat{x} \end{cases} \quad (12)$$

$$\begin{cases} \dot{\hat{\xi}} = W\hat{\xi} + L_d(y - \hat{y}) \\ \hat{d} = V\hat{\xi} \end{cases} \quad (13)$$

where \hat{x} and L_x are the estimates of the state vector x and the state observer gain to be designed. \hat{d} is the estimate of the disturbance d , $\hat{\xi}$ is the estimate of ξ , and L_d is the observer gain to be determined. It can be shown that the estimate yielded by (12) and (13) can asymptotically track both the state of system (10) and the unknown disturbance governed by (11) if the observer gains L_x and L_d are chosen such that the observer error dynamics is stable.

Remark 1: Letting $x_{n+1} = d(t)$, a simple calculation reveals that the dynamics of ESO (9) are the same as those of the UIO in (12) and (13) in the case of $W = 0$ and $V = I$. There are important points that shall be highlighted about ESO in ADRC: 1) Although there may be other similar observers, the ESO of (9) was explicitly developed to estimate the influence of uncertainties (or deliberately ignored dynamics). This was inspired by Han’s vision in developing a powerful and versatile control strategy that is similar to PID with less requirement on the model information but with much better performance; 2) in the original design of ESO, all of the observer gains β_i are nonlinear in order to achieve better performance [5], [13].

D. UDE

UDE was developed from a different origin. Aiming at developing an alternative to time delay estimation in time delay control, Zhong and his collaborators [15] proposed UDE to estimate the combined influence of disturbance and uncertainty. The basic design philosophy is intuitive and illustrated as follows. Consider a linear uncertain system as

$$\dot{x} = Ax + B_u u + \Delta Ax + \Delta Bu + d. \quad (14)$$

Let the lumped disturbance (called equivalent disturbance in UDE) be

$$d_l = \Delta Ax + \Delta Bu + d. \quad (15)$$

It can be estimated by

$$d_l = \dot{x} - Ax - B_u u. \quad (16)$$

However, \dot{x} is not measurable. The so-called UDE proposed in [15] is to circumvent this problem by approximating its estimate through a filter, given by

$$\hat{d}_l = d_l \star q \quad (17)$$

where \star represents the convolution operator and q is the impulse response of the filter $Q(s)$. Consequently, the closed-loop control is generated based on the uncertainty and disturbance estimate. The filter $Q(s)$ is chosen such that \hat{d}_l in (17) is

implementable. The basic idea in UDE is quite similar to DOB. It shall also be noticed that the full state of the dynamic system shall be available in this approach [15].

E. EID Estimator

Consider a dynamic system described as in (10) but with $B_u = B_d$. The EID approach proposed in [11] and [12] looks quite complicated and different from the ESO, UIO, or UDE approaches described previously, but carefully examining, it actually reveals that it is closely related to the others. The disturbance estimate in the EID approach is obtained by passing the modified output estimate error \tilde{d} through a filter $Q(s)$, i.e.,

$$\hat{d} = Q(s)\tilde{d} \quad (18)$$

where $Q(s)$ is given by

$$Q(s) = \frac{1}{T_q s + 1}. \quad (19)$$

The modified output estimate error was suggested to calculate through a least square solution, given by

$$\tilde{d} = B_u^+ L(y - \hat{y}) + \hat{d} \quad (20)$$

with $B_u^+ = (B_u^T B_u)^{-1} B_u^T$ and the gain L to be designed (it shall be noted that there is a typo in [12, eq. (21)]). The disturbance/uncertainty attenuation ability of the EID approach has been analyzed in [12].

As no internal dynamics are used in the disturbance estimation equation, this method is quite close to the ESO described in Section II-B. Indeed, when $Q(s)$ is chosen as a low-pass filter as suggested in [12], combining (18) and (19) gives

$$T_q \dot{\hat{d}} + \hat{d} = \tilde{d} \quad (21)$$

which, after involving (20), leads to

$$\dot{\hat{d}} = \frac{1}{T_q} B_u^+ L(y - \hat{y}). \quad (22)$$

The disturbance estimate \hat{d} is driven by the error between the measurement and its estimate, which is similar to the disturbance estimate in ESO (see the last equation of (9) with $\hat{y} = \hat{x}_1$). In other words, a similar disturbance estimation is obtained by choosing $\hat{B}_{n+1} = (1/T_q) B_u^+ L$.

F. GPIO

For the system described in (6), an enhanced version of the disturbance estimator called GPIO has been proposed for time-varying disturbance and possibly uncertainty estimation. The GPIO proposed is designed [19], [33] as

$$\begin{cases} \dot{\hat{x}}_i = \hat{x}_{i+1} + \beta_i(y - \hat{x}_1), i = 1, \dots, n-1 \\ \dot{\hat{x}}_n = bu + \hat{\xi}_1 + \beta_n(y - \hat{x}_1) \\ \dot{\hat{\xi}}_i = \hat{\xi}_{i+1} + \lambda_i(y - \hat{x}_1), i = 1, \dots, q-1 \\ \dot{\hat{\xi}}_q = \lambda_q(y - \hat{x}_1). \end{cases} \quad (23)$$

where \hat{x}_i is the estimate of the state x_i and $\hat{\xi}_i$ is the estimate of the lumped disturbance term $f^{[i-1]}(x, d)$.

Similar to the design philosophy of ESO, the convergence of GPIO can be achieved by chosen appropriate observer gains β_i and λ_i . It has been reported that the GPIO is a generalized version of ESO since, by setting $q = 1$, the GPIO (23) reduces to the linear ESO (9). The GPIO shall provide higher estimation accuracy in the presence of higher order time-varying disturbances. In particular, it could achieve an offset-free estimation for disturbance with a time series polynomial form, i.e., $f^{[q]}(x, d) = 0$.

The essential principle for GPIO to achieve higher precision disturbance estimation lies in that more information (the integral chain characteristics) of the disturbance is utilized in the observer design. This indicates that the internal model of the disturbance has been implicitly embedded in the observer design for disturbance reconstruction. For this matter, the GPIO possesses a very similar structure as many disturbance-model-based estimation techniques (for example, see DOBC [34], [35] and output regulation control [36]).

III. NDUE TECHNIQUES

The nonlinear part of a nonlinear system can be deliberately ignored so treated as a part of “lumped” disturbances in DUE. Then, the LDUE techniques described in Section II can be applied to estimate the influence of the ignored nonlinearities, so an appropriate action can be generated to compensate for that [5], [37], [38]. This is the motivation behind some DUEA techniques such as ADRC, where a dynamic system, no matter being linear or nonlinear, is simplified as an integrator chain and all of the ignored dynamics including linear and (or) nonlinear terms are estimated by the ESO. However, for most of the physical systems, the nonlinear dynamics may be known or at least partially known. The estimation and attenuation of real external unknown disturbance and uncertainty (or unmodeled dynamics) can be significantly improved if the (known) nonlinear dynamics could be exploited in design. This motivates the development of the nonlinear disturbance/uncertainty estimation (NDUE) techniques for general nonlinear systems. It is obvious that the frequency domain analysis and design techniques of DUEA are not directly applicable to nonlinear systems. Various NDUE techniques have been developed in the last two decades.

Despite some early works of NDUE, a theoretically sound NDOB was first proposed in [16] to estimate disturbance torques caused by unknown friction in nonlinear robotic manipulators. By the use of Lyapunov stability theory, it was shown that the disturbance estimation error exponentially converges to zero. This work was further extended to deal with uncertainty in nonlinear aerodynamics for dynamic-inversion-based autopilot design, and a significant improvement of the performance robustness has been observed [39]. To relax the restriction that the external disturbance and the influence of uncertainties are modeled by unknown constant disturbances, for a class of affine nonlinear systems subject to disturbances governed by an exogenous system, an NDOB was put forward to estimate the disturbances with an exponentially convergent

rate by constructing a nonlinear observer gain function in [34]. An NDOB was proposed in [40] to estimate the harmonic disturbances for a class of single-input–single-output nonlinear systems. In [35], an NDOB was proposed for a class of multi-variable nonlinear systems subject to disturbances governed by exogenous linear systems. Recently, a generalized NDOB has been presented in [41] to estimate higher order disturbances. In addition, by integrating the ideas of disturbance estimation and the intelligent control, intelligent DOBs are also widely investigated, such as fuzzy DOBs [42] and neural network DOBs [43].

A. Basic NDOB

Consider a class of affine nonlinear system, depicted by

$$\begin{cases} \dot{x} = f(x) + g_1(x)u + g_2(x)d \\ y = h(x) \end{cases} \quad (24)$$

where $x \in \mathbb{R}^n$, $u \in \mathbb{R}^m$, $d \in \mathbb{R}^q$, and $y \in \mathbb{R}^s$ are the state, the control input, the disturbance, and the output vectors, respectively. It is assumed that $f(x)$, $g_1(x)$, $g_2(x)$, and $h(x)$ are smooth functions in terms of x .

1) Unknown Constant Disturbance Case: An NDOB was proposed in [16] and [44] to estimate the unknown slow time-varying disturbance for system (24) as

$$\begin{cases} \dot{z} = -l(x)g_2(x)z - l(x)[g_2(x)p(x) + f(x) + g_1(x)u] \\ \hat{d} = z + p(x) \end{cases} \quad (25)$$

where $z \in \mathbb{R}^q$ is the internal state of the nonlinear observer and $p(x)$ is the nonlinear function to be designed. The NDOB gain $l(x)$ is determined by

$$l(x) = \frac{\partial p(x)}{\partial x}. \quad (26)$$

It has been shown in [16] that the NDOB asymptotically estimates the disturbance if the observer gain $l(x)$ is chosen such that

$$\dot{e}_d = -l(x)g_2(x)e_d \quad (27)$$

is asymptotically stable regardless of x , where $e_d = d - \hat{d}$ is the disturbance estimation error.

There are many ways to choose the nonlinear gain $l(x)$ such that (27) is stable and (26) is satisfied. A systematic approach was suggested by [34] and [44]. The convergence and the performance of the proposed NDOB have been established for slowly time-varying disturbance and disturbance with bounded rate in [3] and [45]. This allows the wide application of this NDOB, particularly for estimating the influence of uncertainty as long as the observer error dynamics are faster than the closed-loop dynamics, e.g., [39] (see more discussion in Section VI).

2) General Exogenous Disturbance Case: The nonlinear system considered here still has the form depicted by (24). However, the disturbances are supposed to be generated by the exogenous system as described in (11). This model represents a wide range of periodic disturbances.

An NDOB for estimating exogenous disturbance (11) is proposed in [34] and depicted by

$$\begin{cases} \dot{z} = [W - l(x)g_2(x)V]z + Wp(x) \\ \quad - l(x)[g_2(x)Vp(x) + f(x) + g_1(x)u] \\ \hat{\xi} = z + p(x), \quad \hat{d} = V\hat{\xi}. \end{cases} \quad (28)$$

It has been shown in [34] that the NDOB (28) can exponentially estimate the disturbances if the nonlinear observer gain $l(x)$ is selected such that $\dot{e}_\xi = [W - l(x)g_2(x)V]e_\xi$ is globally exponentially stable regardless of x . By the use of a strictly positive real lemma, a systematic method to choose a nonlinear observer gain function satisfying the stability condition has been developed in [34].

B. Higher Order NDOB

Consider a class of nonlinear system, depicted by

$$\dot{x} = f(x, u, t) + Fd(t) \quad (29)$$

where $x \in \mathbb{R}^n$, $u \in \mathbb{R}^m$, and $d \in \mathbb{R}^q$ are the state, the control input, and the disturbance vectors, respectively. $f(x, u, t)$ and the matrix F with $\text{rank}(F) = q < n$ are known. It is assumed that the state variables x are measurable and their initial values $x(0) = x_0$ are known. The reduced-order system of (29) is expressed as

$$F^+ \dot{x} = F^+ f(x, u, t) + d(t) \quad (30)$$

where F^+ denotes the Moore–Penrose pseudoinverse of the matrix F . The disturbance $d(t)$ in (29) is assumed to be higher order ones, given by

$$d(t) = d_0 + d_1 t + \cdots + d_q t^q \quad (31)$$

where d_0, d_1, \dots, d_q are constant but unknown. A higher order DOB for estimating the disturbances in (31) is proposed in [41], given by

$$\begin{cases} \dot{z} = F^+ f(x, u, t) + \Gamma_0 g_0(t) + \cdots + \Gamma_q g_q(t) \\ \hat{d} = \Gamma_0 g_0(t) + \cdots + \Gamma_q g_q(t) \end{cases} \quad (32)$$

with

$$g_k(t) = \begin{cases} F^+ x - z, & (k = 0) \\ \int_0^t g_{k-1}(\tau) d\tau, & (k \geq 1) \end{cases} \quad (33)$$

where $\Gamma_k = \text{diag}\{\gamma_{k1}, \dots, \gamma_{kq}\}$ for $k = 0, 1, \dots, q$.

It shall be noticed that the disturbance in (31) can also be described by the disturbance model in (11). Therefore, in principle, the NDOB described in Section III-A (e.g., [34]) is also applicable for this kind of disturbance; however, more structure information of the higher order disturbance has been exploited in the aforementioned design.

C. EHGSO

The extended high-gain state observer (EHGSO) was proposed in [46] to deal with a class of nonlinear uncertain

systems. Specifically, a SISO nonlinear system in the following normal form [32]

$$\begin{cases} \dot{x} = Ax + B_u [b(x, z) + a(x, z)u + d] \\ \dot{z} = f_0(x, z, d) \\ y = Cx \end{cases} \quad (34)$$

is considered, where $x \in \mathbb{R}^n$ and $z \in \mathbb{R}^m$ are the state variables, $u \in \mathbb{R}$ is the control input, $y \in \mathbb{R}$ is the measured output, and $d \in \mathbb{R}$ is a disturbance. The nonlinear functions $a(\cdot)$ and $b(\cdot)$ are assumed to be continuously differentiable with locally Lipschitz derivatives, $a(\cdot) \geq a_0$ with a known $a_0 > 0$, and $f_0(\cdot)$ is locally Lipschitz. The disturbance $d(t)$ is supposed to belong to a known compact set $W \subset \mathbb{R}$ and $\dot{d}(t)$ is bounded. A , B_u , and C are system matrices, depicted by

$$A = \begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 & 1 \\ 0 & 0 & \cdots & \cdots & 0 \end{bmatrix}, B_u = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix}, C = \begin{bmatrix} 1 \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix}^T. \quad (35)$$

It is also supposed that system (34) is of minimum phase, which implies that the zero dynamics of system (34) are stable. An EHGSO for system (34) is then designed as [46]

$$\begin{cases} \dot{\hat{x}} = A\hat{x} + B_u [\hat{b}(\hat{x}) + \hat{a}(\hat{x})u + \hat{x}_{n+1}] \\ \quad + H(\varepsilon)(y - C\hat{x}) \\ \dot{\hat{x}}_{n+1} = \frac{\beta_{n+1}}{\varepsilon^{n+1}}(y - C\hat{x}) \end{cases} \quad (36)$$

where $\hat{a}(\cdot) \geq a_0 > 0$ and $\hat{b}(\cdot)$ are twice continuously differentiable and globally bounded functions that model $a(\cdot)$ and $b(\cdot)$, respectively. $H(\varepsilon)$ is designed as

$$H(\varepsilon) = \left[\frac{\beta_1}{\varepsilon}, \dots, \frac{\beta_n}{\varepsilon^n} \right]^T$$

where $\varepsilon > 0$ is a small constant. It is interesting to notice that, without the internal dynamics $\dot{z} = f_0(x, z, d)$, system (34) with the corresponding matrices in (35) is actually the same as the system of (6). EHGSO of (36) also uses the added state x_{n+1} to estimate the influence of uncertainty. Hence, it is not surprising that, in this case, EHGSO of (36) almost has the same structure as ESO of (9), except that the information of the nonlinear dynamics such as \hat{a} and \hat{b} is used in EHGSO of (36). This is also the reason why we put EHGSO in the category of NDUE, rather than as ESO in the category of LDUE. The basic idea of EHGSO has been extended to handle nonminimum phase nonlinear systems in [47] and [48] recently.

IV. DISTURBANCE AND UNCERTAINTY ATTENUATION

A. Framework of Constructing a Composite Controller

After the disturbance/uncertainty is estimated, the key issue is now how to make use of the estimate so as to attenuate or even eliminate the influence of the disturbance/uncertainty. A significant feature shared by DOBC and other related techniques is to employ a two degrees of freedom control system configuration

as shown in Fig. 1. The total control in this kind of control scheme consists of two parts as

$$u = u_f + u_d \quad (37)$$

where u_f is generated by a normal feedback based on the measurements (e.g., output feedback in the classic transfer function approach or state feedback in the state space approach) and u_d depends on the estimate of the disturbances or the uncertainties. As a typical example shown in Fig. 1, the normal feedback loop is designed separately from DUE in DOBC, which is important in facilitating the design in meeting (conflicting) the criteria and providing the flexibility in integrating different feedback design methods with different DUE techniques. The former allows a designer to focus on tracking performance and stability when designing the feedback loop and on disturbance rejection and robustness against uncertainties when designing the compensation loop. This “*separation principle*,” somehow similar to the separation principle in linear state-observer-based control where a feedback controller is designed separately from the design of a state observer [49], greatly simplifies the design process of DUEA. The flexibility in integration enables a designer to add a disturbance and uncertainty estimator to an existing control scheme that cannot provide adequate disturbance rejection or robustness against uncertainties.

The key issues in developing a composite controller that is able to make use of the UDE include the following: 1) how to design a compensation action that is able to attenuate or eliminate the influence of disturbance/uncertainty? 2) How to integrate the compensation with the feedback loop and under what conditions could the properties (such as stability) of the whole closed-loop system under the composite controller be established? 3) If the composite control is designed to improve robustness, what kind or what size of uncertainty is a composite controller able to cope with?

After the last four decades of research in DOBC and related methods, progress has been made in addressing these issues. Some questions have been answered fully or partially for some methods, but others require more study and understanding. Basically, in answering these questions, dealing with uncertainty is more difficult than external disturbances, and mismatched disturbance/uncertainty are much more challenging than the matched one. Here, the matching condition refers to that the disturbance/uncertainty enters a system via the same channels as control inputs, or the disturbances can be transformed into the same channels as the control inputs by the change of coordinate [50]. It could be argued that the adverse effects of disturbance or uncertainty can be eliminated only if it can be equivalent to the input channels, so a number of DUEA methods, such as EID [11], [12] and frequency domain DOB [4], [17], [18], only deal with the matched disturbances/uncertainties. However, careful design and selection of compensation action (e.g., the gain of the compensation generated with the disturbance/uncertainty estimate) is able to reduce the influence of mismatched disturbances at least in steady state.

B. Matched Disturbance and Uncertainty Attenuation

When a disturbance and (or) an uncertainty satisfy the matching condition (or more precisely, when it is assumed that the

influence of a disturbance or uncertainty can be equivalent to the input channels in some way), the composite control law (37) reduces to

$$u = u_f - \hat{d}_l \quad (38)$$

where \hat{d}_l is the estimate of the lumped disturbance. That is, the estimate of the lumped disturbance is directly fed forward to counteract the influence of disturbance/uncertainty. This mechanism is adopted in the frequency domain DOBC (see Fig. 1) and in a number of other related schemes including EID and DAC. The feedback controller is developed through the frequency domain methods or the transfer function approaches in classic DOBC. In state-space-based design, the feedback controller could be developed based on all of the state being available (e.g., UDE) or the state being estimated by a state observer (e.g., UIO and ADRC). In the state space model, normally, the matching condition implies that $B_u = B_d$ (or more precisely $B_d = B_u\Gamma$ for some Γ) in (10) for linear systems or $g_1(x) = g_2(x)$ in (24) for nonlinear systems. It shall be pointed out that, although it is claimed that some methods are able to deal with mismatched disturbance/uncertainty (e.g., [28] for ADRC), it is required to transform the mismatched disturbance/uncertainty into the matched one first, and then, the method could be applied.

DAC was developed for a linear system subject to a general class of external disturbances in [29]. Consider the system (10) driven by a disturbance generated from the model described by (11). It is assumed that $\text{rank}(B_d) = q$ and $B_d = B_u\Gamma$ for some Γ , where q is the dimension of the disturbance d . This assumption implies that the disturbance d satisfies the matching condition as it can be transformed to the input channels by a matrix Γ . Under this assumption and in the case that all of the states are available, the DAC is proposed as [29]

$$\begin{cases} u = K_x x + \Gamma V \xi \\ \dot{\xi} = W \xi + E x \end{cases} \quad (39)$$

where

$$\begin{cases} K_x = K - \Gamma V P \\ E = P(A + B_u K) - W P \\ P = -L [B_d^T B_d]^{-1} B_d^T \end{cases} \quad (40)$$

and the matrices (K, L) are designed such that the matrices $A + BK$ and $W + LV$ are Hurwitz stable. The aforementioned result has been generalized to the case that not all of the state is measurable. Although the original results were developed for external disturbance compensation, DAC has been extended to deal with uncertainty and is regarded as an adaptive control method (for example, see [30] and [51]).

C. Mismatched Disturbance and Uncertainty Attenuation

Mismatched disturbance and uncertainty widely exist in practical applications. Examples include the lumped disturbance torques caused by unmodeled dynamics, external winds, and parameter perturbations in flight control systems [39], [52],

and the parameter variations and the change of load torque in a permanent magnet synchronous motor system [53]. In the presence of mismatched disturbance/uncertainty, the composite control law in (38) may not effectively compensate the disturbance/uncertainty. It shall be pointed out that, no matter what kind of control scheme is employed, it may be impossible to completely eliminate the influence of the mismatched disturbance/uncertainty on the system state. For example, an electric driving system has to generate corresponding current in the motor in order to counteract the external load torque. Therefore, a practical consideration aims at removing the effects of any mismatched disturbance/uncertainty from the variables of interests, i.e., the output channel.

Except for a few DUE methods such as frequency domain DOB and EID, most of the DUE methods are ready to estimate mismatched disturbance/uncertainty. The key issue is how to find a compensation action based on the estimate. For example, a pseudoinverse of the control input matrix was suggested in UDE [54]. There are a number of methods in dealing with mismatched disturbance/uncertainty. For instance, the matched disturbances are compensated by DOBC, while the mismatched disturbances are attenuated by a traditional feedback controller such as H_∞ control [55]. Rather than eliminating the influence of the mismatched disturbances on the output, these methods aim to suppress their influence on the output to a certain level.

A systematic approach to design disturbance compensation gain that is able to remove the influence of mismatched disturbance/uncertainty from the output at least in steady state is proposed in [38] and [56]. For a linear system (10), the disturbance compensation gain is given by

$$K_d = -[C(A + B_u K_x)^{-1} B_u]^{-1} C(A + B_u K_x)^{-1} B_d \quad (41)$$

where K_x is the feedback control gain.

If all state variables are measurable, a reduced-order DOBC can be used, and the following composite control law is employed

$$u = K_x x + K_d \hat{d}. \quad (42)$$

In the case that the state variables are unmeasurable, the UIO or ESO can be employed. The composite control law in this case is designed as

$$u = K_x \hat{x} + K_d \hat{d} \quad (43)$$

where \hat{x} and \hat{d} are yielded by state and DOBs.

Now, we consider a single-input-single-output nonlinear system (24). The disturbance can be removed from the output channel in steady state by the following composite control law [56]:

$$u = \alpha(x) + \beta(x)v + \gamma(x)\hat{d} \quad (44)$$

where \hat{d} is the disturbance estimate obtained by any NDOB

$$\alpha(x) = -\frac{L_f^\sigma h(x)}{L_g L_f^{\sigma-1} h(x)}, \quad \beta(x) = \frac{1}{L_g L_f^{\sigma-1} h(x)}$$

and σ is the input relative degree [32]. The disturbance compensation gain is designed by

$$\gamma(x) = - \frac{\sum_{i=1}^{\sigma-1} c_i L_p L_f^{i-1} h(x) + L_p L_f^{\sigma-1} h(x)}{L_g L_f^{\sigma-1} h(x)} \quad (45)$$

$$v = - \sum_{i=0}^{\sigma-1} c_i L_f^i h(x). \quad (46)$$

The aforementioned result has been extended to multivariable nonlinear systems in [57]. By utilizing backstepping design approaches, new NDUEA approaches have been further proposed to address the global mismatched disturbance compensation problem in [58] and finite-time mismatched time-varying disturbance attenuation problem in [59]. A set of dynamic sliding mode surface design approaches has also been investigated to overcome the problem of mismatched disturbance attenuation (see [60] and [61]).

D. CHADC

Many applications may be subject to multiple types of disturbances, e.g., stochastic noises such as Gaussian and non-Gaussian processes; deterministic disturbances such as unknown constants, harmonic, and other periodic disturbances; and noise without any information but bounded in energy, magnitude, or its change rate. Most of the modern control methods focus on dealing with one type of disturbances or treating the multiple disturbances as a single equivalent disturbance. This may result in conservativeness in disturbance rejection in the presence of multiple disturbances. On the other hand, the advances in sensor technology and data processing have dramatically improved the capability in disturbance analysis and modeling. There is a need to develop an advanced disturbance rejection technique that can make full use of the knowledge about multiple disturbances.

As a refined antidisturbance control scheme, composite hierarchical antidisturbance control (CHADC) has recently been proposed to fulfill this need [6]. In a broad sense, the CHADC diagram is similar to the DOBC diagram in Fig. 1. However, multiple loops may exist in CHADC for attenuating different types of disturbances as the system under consideration is subject to multiple types of disturbance. Furthermore, the baseline controller may not be designed for achieving tracking performance but also for disturbance attenuation such as H_∞ or stochastic control theory. Based on an NDOB, the basic idea of CHADC was first proposed for a system subjected to external disturbance and model uncertainty in [35]. For nonlinear systems with multiple disturbances, the H_∞ and variable structure control have been integrated with DOBC in [55], where DOBC was applied to reject the modeled disturbance and robust H_∞ control or variable structure control was used to attenuate the norm-bounded disturbance (unmodeled disturbance). It is worth noting that uncertainties have been included, for the first time, in an exogenous system modeling the disturbance in [55], for which case the internal model principle is no longer applicable. A composite DOBC and an adaptive control approach were proposed [62] for a class of nonlinear systems with uncertain modeled disturbance and the disturbance signal represented by an unknown parameter function. More details of CHADC could

be found in its first monograph published recently [63]. One of the challenges in CHADC is that disturbance attenuation and rejection loops are coupled, thus increasing the complexity of the resulted closed-loop system. More work is also required to build detailed models/knowledge of disturbances and extend the current CHADC to better cope with uncertainties in disturbance models.

V. APPLICATIONS

A. Applications of DUEA in Various Industrial Sectors

As DUEA methods are developed largely driven by application needs in various industrial sectors, it is not surprising that they have found a wide range of applications. Due to the space constraint, it is impossible to have an exhaustive list of all of the main applications. Instead, some typical applications of DUEA are summarized and reviewed as follows.

1) Mechatronics Systems: In mechatronics, there is increasing demand on performance and precision. The tracking precision is generally affected by different external disturbances, such as uncertain torque disturbances, variations of load torque, vibrations of horizontal position of a rail track, and pivot frictions [17], [18], [64], [65]. Moreover, the control performances of these mechanical systems are also subject to the effects of internal model parameter perturbations caused by the changes of operation conditions and external working environments. DOBC and related techniques provide a promising approach in dealing with these internal and external disturbances/uncertainties and have been applied to many different kinds of mechanical and electrical systems, e.g., industrial robotic manipulators [16], [66], motion servo systems [4], [18], maglev suspension systems [65], power converters [67], and disk drive systems [68].

2) Chemical and Process Systems: In the process control community such as petroleum, chemical, and metallurgical industries, production processes are generally influenced by external disturbances such as variations of raw material quality, fluctuations of production load, and variations of complicated production environment. In addition, the interactions between different production processes are sophisticated and may be difficult to analyze precisely. These factors and their combinations usually result in significant degradation of the production quality of these processes. DOBC and related methods have been applied to deal with these problems, e.g., chemical reactors [69], [70], heat exchanger [71], extrusion process [72], and, in particular, ball mill grinding circuits [73], [74].

3) Aerospace Systems: DOBC and related techniques also found a wide range of applications in aeronautic and astronautic engineering, such as missile systems [39], [52], [75], near-space hypersonic vehicles [76], and space satellites [77]. The main purpose in these applications is to cope with disturbance forces and torques caused by external winds, unmodeled dynamics, or uncertainties in aerodynamics [39]. The early development of DAC was driven by the need of NASA, and it was also reported that this method has been studied for improving the pointing accuracy of the Hubble Space Telescope [78], where cyclic thermal expansions and mechanical stiction effects in the solar arrays trigger repeated occurrences of

damped relaxation-type flex-body vibrations of the solar arrays. CHADC has also been tried in Mars' precision landing, attitude control of flexible spacecraft, and initial alignment of inertial navigation systems [79], [80].

B. Commercialization and Industrialization of DUEA

In addition to numerous trials and case studies, compared with other advanced control methods, one significant feature of DUEA is its large-scale commercialization and industrialization. It has been embedded in a number of products in the market. For instance, DOBC techniques have been embedded in the products of Panasonic MINAS A5-series ac servo motors and drivers for a variety of purposes including torque observation and compensation [81]. The ADRC approach has been utilized in the products of Estun EDC-08 APE and EDB-10 AMA series ac servo drivers for inertial moment identification and disturbance/uncertainty attenuation [82].

Most notably, as a default alternative control algorithm, ADRC has been embedded by the Texas Instruments in its new series of motion control chips [83]. ADRC was introduced to the international community largely by Gao [14], [84]. Since then, it has been attracting a good amount of interest from both academic and industrial communities due to its simplicity as an alternative to classic PID controllers. The gains in both the ESO and the associated feedback controller are, in general, nonlinear, in the original ADRC setting (for example, see [5] and [13]). It was acknowledged that, while nonlinear gains may be more effective, they also bring extra complexity in the control algorithm implementation and tuning. In addition, stability of the system becomes more difficult to establish. To address these issues, Gao refined and proposed the linear and parameterized version of ADRC in 2003 [84]. Among many other applications such as resulting in over 50% energy saving per line across ten production lines in a Parker Hannifin Extrusion Plant in North America [85], one of the most successful applications of ADRC is motion control. Texas Instruments has been granted patents in ADRC and is now marketing a number of new motion control chips with embedded ADRC algorithms, i.e., TMS320F28052M, TMS320F28054M, TMS320F28069M, and TMS320F28068M. As claimed in the manual of SpinTAC MOTION Control Suite [83], SpinTAC Control is an advanced speed and position controller featuring ADRC, which proactively estimates and compensates for system disturbance in real time. SpinTAC automatically compensates for undesired system behavior caused by the following: uncertainties (e.g., resonant mode), nonlinear friction, changing loads, and environmental changes. An extensive and rigorous comparison has been carried out by Texas Instruments, which shows a superior performance of ADRC over traditional PI controllers in a number of aspects such as tracking error under drastic changes of disturbance or references, overshoot, and startup error [83].

VI. CONCLUDING REMARKS AND FUTURE DIRECTIONS

A. Concluding Remarks

After the linear and NDUE techniques have been introduced and reviewed, different compensation mechanisms and the

different procedures of integrating a compensation mechanism with a (predesigned) feedback controller are discussed. It has been shown that, although these methods are independently developed by researchers and engineers, some are very similar, while others focus on dealing with different design problems/systems with different emphases. This survey focuses on providing a clear and concise tutorial and overview of the most widely used methods in DUEA (particularly DOBC) with a brief discussion on the features or relationships between them. The latest developments and new research results in this area are summarized. It is particularly useful for researchers and practitioners who are new to the areas. As there are many different DUEA methods developed by different groups or in different industrial applications, although this area is developing quite fast and attracting more and more attention, there are a lot of confusions and misunderstandings in the community, even for researchers who have considerable experience on one or two specific methods. By presenting these methods in a single paper in a clear and concise way, the similarities and differences among these DUEA are clearly identified and described in this paper.

It has been shown that, originated from intuitive practices in a number of different applications, DOBC and related methods have now already penetrated into a wide range of industrial applications, ranging from traditional mechatronics and motion control to biological and process systems to aerospace and space systems. Compared with other advanced control algorithms, it is one of the few that have been commercialized and industrialized. Not only it has been embedded in various products for ac motors and drivers, but it has also been implemented by specially designed microcontroller chips. It is envisaged that more and more applications of the DUEA will be found. Although it is still at its early stage, with all of the efforts of researchers and engineers working in this area, it is confident that DUEA methods will be getting more mature and gradually becoming one of the main stream control design methods.

B. Future Directions

Despite all of the progress and applications, DUEA methods are still far from mature. There are a large number of different methods in this area yet, as shown in this paper, sharing similar features. The research of DUEA is still patchy and scattered in different industrial and academic communities. There is still a lot of confusion and misunderstanding. Although a good amount of applications has shown the potentials of these methods, more research is required to understand the true benefits and shortcomings (or limitations) of these methods. In our view, among many others, here are some topics that required further research in this area.

- 1) *Further Improvement of Design Methods*: There is still a significant room to improve the design and analysis of these methods. For example, it is required that all of the states are available for the nonlinear DOBC, the low-pass filter is still largely designed by tuning (under certain guidance) in frequency domain DOB, and how to select the relative order for nonminimum phase systems is still an open problem in ADRC.

- 2) *Theoretic Research*: Theoretical research is still well behind the applications in this area. The basic idea in disturbance/uncertainty estimation is similar to the well-known and widely applied *observer-based control approach*, where a state observer is designed to estimate unmeasurable state, and as long as the state observer dynamics are (much) faster than the closed-loop dynamics under a controller, the performance of the control system with measurable state can be largely recovered. However, what is the limit of this approach or what kind of uncertainty could not be dealt with by this approach? How to analyze the robust stability and performance for a designed DOBC strategy? Another related question is, for a described level of uncertainty, how to develop a strategy that requires a minimum level of feedback or control bandwidth? A limited progress in this regard has been made in particular for ADRC (e.g., [86]). However, to completely answer these questions, fundamental research has to be carried out. Recent work in feedback limitation (e.g., [1]) provides a promising tool in addressing some of the challenges.
- 3) *New Tools for Analysis, Design, and Implementation*: There is still lack of software packages for supporting analysis and design process of DUEA methods. Toolboxes and design packages are important to facilitate the design and analysis process, making the methods more accessible for engineers. The motion controller chips developed and marketed by Texas Instruments are an excellent example for developing hardware implementation and development environment for DUEA. More software and hardware tools shall be developed to facilitate design and real implementation of these methods.
- 4) *New Applications*: It is expected that more and more applications will be found for DUEA methods due to the wide existence of disturbance and uncertainty. However, it is important to have fair and detailed comparisons such as the work carried by Texas Instruments for ADRC to quantify the true benefits provided by these methods. Furthermore, in addition to disturbance rejection and robustness, these methods could be applied to other areas. For example, current model-based fault detection and isolation is mainly based on residual generation that is calculated based on the system output. DOB techniques provide an alternative approach by considering faults as unknown inputs and estimating the size of faults directly (for example, see [87]). There is also a significant potential in applying DUEA in medicine, health care, and other areas. For example, the concept of communication DOBs has been proposed for real-world haptics and telehaptics (see [88]).

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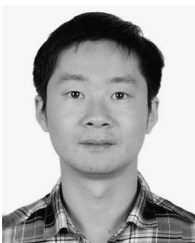


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