Perspective

Control Design for Transient Performance

By Qing-Guo Wang

CONTROL systems are everywhere – chemical plants, energy systems, manufacturing, homes and buildings, automobiles and trains, medical devices, cellular telephones and internet, aircraft and spacecraft. Recent developments in these fields bring up the systems with the unprecedented scope, scale and complexity such as cyber-physical and human systems, and the required control task becomes more challenging than ever [1], demanding high performance on the complex systems at low costs. Nowadays, the technical competition has focused on high performance area. High performance products sell in markets in place of low ones. High performance products rely on high performance control in the end.

Transient performance control is significant as it yields incredible benefits to the end users. Transient performance of a dynamic system is commonly measured by speed (rise time, settling time) and accuracy (overshoot, settling error). For a hard disk drive in the presence of eccentricity uncertainties and external disturbances such as vibrations, the higher the track control accuracy, the more tracks/memory the disk has; the faster the control speed from track to track, the shorter time a given data transmission takes. As a comparison, if a control system is stable only, it cannot be used to carry out a job since the response accuracy and speed are unknown. For an assembling robot in face of load and environment uncertainties, the higher the motion control accuracy, higher precision job the robot does; the faster the motion control speed, shorter time the job is done, meaning higher productivity. In process industry, higher control accuracy produces higher-quality products with greater consistency. It allows the products to be nearer the low boundary of the specifications and thus saves raw materials and energy. higher control speed yields high efficiency. In addition, the costs of production can be reduced with performance control for less need for human labors and maintenance. Note however that in the real world today, many systems such as renewable energy and smart grid, waste water processing plants, and techno-social networks lack effective performance control. In other systems such as UAVs in low attitude and low speed, and self-driven cars, autonomous performance control is imperative.

The central issue in modern control theory research reported in the literature since 1960s is system stability and related topics such as asymptotic tracking, regulation, consensus, and synchronization. However, transient performance is demanded in control applications. A stable system with low speed, big transient errors or a very long settling time is obviously unacceptable in practice. In fact, only transient performance specifications matter for real control applications, while asymptotic behavior for infinite future is irrelevant. This theory–practice gap has existed for decades and is one main cause why many control theories have not yet been well adopted in industry. There were insufficient research works on control performance and those on it hardly addressed explicit transient performance specifications (rise-time, overshoot and settling-time). This could be because stability issue is of asymptotic analysis and possible to address with helps of rich mathematical tools, whereas the performance is of transient analysis and hard to do with few tools available. The importance of systems performance cannot be overstated since "performance" attributes are almost always the metrics of interests in R & D investment in any business [2]. Parameters such as speed and accuracy of the system are evaluated and used to claim improvements over the state of the art. In the IFAC survey to assess the industry viewpoint on what is needed for new products and services [2], the industry respondents were asked to rank twelve " key drivers for future improvements for the next generation of product/processes and services", and "Performance" was one top driver. Thus, transient performance control must be addressed for actual control applications in practice. The present perspective promotes transient performance control, and will explore its status, challenges and possible directions in the next section.

I. DESIGN METHODOLOGIES

We begin with definition of transient performance control. Control of a dynamic system is to influence its output by manipulating its input such that it behaves as one wishes. The plant may not behavior as desired, due to its poor dynamics, unknown disturbances, measurement noise and communication errors. A controller is used to change its dynamic behavior. The dynamic behavior means the output transient response to the certain input, and its quality is called transient performance. Conventionally, it is measured based on the output transient response to the unit step input, and typical specifications of transient performance on it include rise time, overshot and settling time. Similar specifications are drawn on the output transient response to a disturbance. Transient performance control is to make the control system meet transient performance specifications, while stability control or stabilization is to make the control system achieve asymptotical stability. Broadly speaking, a control design which can reshape the output transient response falls in transient performance control, unless only the steady-state output response or asymptotic stability is addressed. Specifically speaking according to degree and type of realized transient performance, a control design may be called full transient performance control if all the given transient performance specifications are met, otherwise it is called partial transient performance control.

Transient performance control is more difficult than stability one. The root cause for this difficulty is that there exists no analytical relation between the parameters and transient performance specifications of a general dynamic system except for the special cases such as the standard 2nd-order linear system. Thus, the approximations to the transient performance specifications are usually made in various control designs. These designs are reviewed below according to the approximation types and design techniques.

The **proportional-integral-derivative (PID) control** is most common in the control field. The success that the PID controller has enjoyed in industry (about 90% of industrial control systems with

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PID [3]) is not only because it is relatively simple to implement and easy to tune, but also because its design is judged in the end in terms of transient performance specifications. Note however that the PID design procedures usually do not explicitly take time domain specifications into account but implicitly address them mostly in frequency domain. Hence, the PID design methods cannot ensure the exact performance, resulting in engineers often resorting to their experience when tuning a PID controller in practice. Auto-tuning of PID controllers can largely resolve this issue and has been widely adopted in industry [4]. Note that PID control might fail for coupled multivariable systems [5]. This problem is well recognized in industry. Then, MIMO PID control becomes essential and it deals with multiloop couplings and individual loop transient performance [6]. More research on MIMO PID control is required to consider transient performance and enhance applicability of PID control in complex systems.

The **pole placement** is the most popular design method in modern control engineering. The state feedback law is employed to assign the poles of the closed-loop system according to the desire performance specifications and it keeps the zeros unaltered from the plant's ones. But the system zeros affect the transient response greatly. Two SISO systems with the same poles exhibits drastic different dynamics if one is of minimum phase while other is not. The same poles are not suitable for two loops of a MIMO system if one loop is fast while other is slow.

One might approach the transient problem from the optimization perspective such as the **linear quadratic regulator (LQR)** and **model predictive control (MPC)** by tuning the weights of the cost function. But this would lead to a trail-and-error with no guarantee of satisfying hard performance constraints.

Finite-time stability (FTS) [7] differs from the classical asymptotic stability in that the system state remains in a bounded set over a given finite-time horizon, which could be desirable for the state not to exceed certain bounds during its transient. The definition of finite-time stability (FTS) is refined [8] to allow the time varying confining set for the state, which reflects the common requirement of decaying error transient. It should be pointed out that the existing works on FTS have been on analysis on state stability of a nominal system with unbounded input. The attention should be paid to control design for finite-time stabilization of uncertain systems under input constraints.

Bhat and Bernstein [9] introduced the **finite-time control** which drives the system state to the origin in finite time. The Lyapunov differential inequalities-based approach proposed by Lin and Qian [10] includes a power integrator technique and uses feedback to dominate nonlinearity rather than to cancel it. State consensus and observers in finite-time were developed [11]−[12]. The **terminal sliding mode control** (TSMC) proposed by Venkataraman and Gulati [13] is based on the notion of terminal attractors to ensure finite-time convergence of the state while preserving robustness of the sliding mode control (SMC) against the model error and disturbance. Yu and Man [14] proposed a fast TSMC model that combines the advantages of TSMC and SMC such that fast (finite time) convergence of the state is obtained both at a distance from and at a close range of the equilibrium. The aforementioned finite-time control approaches are continuous at best but non-smooth. Song *et al*. [15] presented the **prescribed-time control (PtC)**, which is smooth control. PtC employs a scaling of the state by a function of time that grows unbounded towards the terminal time and designs a controller that stabilizes the system in the scaled state representation, yielding regulation in prescribed finite time for the original state. In the past three decades, finite-time control had developed rapidly. But there are many challenges which offer potential research directions as follows. The Lyapunov stability theory for PtC is to be further studied. At now, TSMC faces chattering and singularity, unknown relation between the controller parameters and system performance, lack of discrete-time version, and difficulty in implementation. The practical application of finite-time control theory is lacking, and this requires treatment of time delay and input saturations common in practice.

The **model reference adaptive control** (MRAC) designs a reference model with the desired closed-loop performance and makes the control system behavior close to the model. Numerous simulations indicate that the transient response of such adaptive systems may be unacceptable due to large initial swings [16]. To guarantee the transient performance of adaptive control systems is a challenging issue. The major difficulty is that in adaptive control design, either the backstepping approach or the gradient-descent certainty-equivalence method, the transient behavior of the control system could not be quantified directly. The slow estimation of the unknown parameters will also make the transient performance of control system poor. However, large gains in the learning rate of the adaptive laws can enlarge the measure noise and errors, violate the actuator rate and saturation constraints, and excite the unmodeled system dynamics. Therefore, a critical trade-off between system stability and control adaptation rate exists in most adaptive control approaches. With helps of stability analysis of adaptive control systems and the robustness enhancement, several attempts have been made to analyze the transient performance of adaptive control [17]−[20]. One future research is to improve the control architecture of the model reference adaptive control to allow high convergence rate of both parameter estimation and tracking errors. Note that external disturbances deteriorate the transient performance. Therefore, how to attenuate and quantify the effects of disturbances on transient performance as well as the tracking errors is another research direction in robust adaptive control.

The **prescribed performance control** (PPC) proposed by Bechlioulis and Rovithakis in 2008 [21] achieves the reference tracking to a predefined arbitrarily small set, with convergence rate no less than a preassigned value. This is accomplished by recasting the "constrained" system into an equivalent "unconstrained" one via an appropriate transformation, and stability of the latter leads to a solution for the original performance problem. The early results on PPC are based on the specific model information or identification technique. This method was applied with improvements to the SISO pure-feedback systems [22], the SISO cascaded systems [23], and the SISO input-constrained systems [24]. To eliminate the need for the known control directions, an orientation function-based PPC approach was put forward [25]. An extension to output-feedback model-free global PPC was given with the help of the tuning function and the input-driven filter [26]. Decentralized PPC for the interconnected nonlinear systems was achieved [27]. PPC for underactuated systems was studied [28], [29]. PPC can meet a given settling-time. Its solution may have arbitrary fast and large control action. We see the following issues with PPC.

1) Input saturation. According to the current theory of PPC, time for the tracking error to converge to the small set can be arbitrarily chosen by the designer. In practice, however, the settling time of the control system depends on the input size of the plant. A physical system has a finite actuator capacity or limited amplitude of the plant input. PPC may need extremely large control action which cannot be realized due to input saturation. Our simulation shows that instability can occur in such a case, indeed.

2) Time delay. Any engineering system has some time delay. Signal transmission and/or processing can cause time delay even if the physical system is delay-free. PPC needs immediate control action which cannot be realized due to time delay in the signal flow.

3) Discrete-time PPC. The measurement, transmission and computation in modern control systems are in a discrete-time manner. This however challenges the PPC methodology because the continuous behavior of the constrained error close to the performance boundary has to be captured to update the control signal.

The **funnel control** [30] specifies the performance requirements as time-varying constraints (or a "funnel") on the output, and let the control magnitude be proportional to the distance of the output to the funnel boundary. This theory is applicable to dynamical systems of low relative degree with the same number of inputs as outputs [31]. Later works [32], [33] also considered constrained inputs in the formulation. The target tube problem was introduced in [34], where one specifies a time-varying set, called the target-tube, over a finite time horizon and then seeks a control law that keeps the state in this tube.

We would like to point out that the existing methods as surveyed above and many others in the literature treat the transient performance specifications with approximations to facilitate their solutions. They impose certain kinds of symmetric error bounds such as an ellipsoidal target tube and uniform decay rates in place of the performance specifications but cannot explicitly tell or exactly meet time domain performance specifications. There are normally only two types of control tasks: tracking and regulation. For tracking control, the system output needs to track a reference such as a unit-step function. Typically, the output will rise from zero, over-shoot and settle down to one. The uniform bound or delay rate on the output or the output error does not represent such realistic time-domain performance specifications exactly. For regulation control, the output is regulated against the disturbance to settle down at the original value. Typically, the output/error will deviate from zero, increase in magnitude (either positive or negative) and eventually settle down to zero. Once again, the uniform bound or delay rate on the output/errors does not represent such realistic time-domain performance specifications exactly. It is noted that input variables are commonly subjected to upper and lower limits which are polyhedral constraints, while the majority of the literature had been under the assumption of ellipsoidal domains due to their relationship with quadratic functions and linear matrix inequalities which are easy to solve. Moreover, polyhedral sets give independence of variable constraints, whereas ellipsoidal sets introduce conservatism due to variables' couplings.

The **polyhedral tube control** (PTC) proposed by Esterhuizen and Wang [35] can achieve full transient performance control for MIMO uncertain systems. The explicit and exact conversion is made from the transient performance specifications on the outputs into a series of the polyhedral state sets which vary over time with their boundaries matching the performance specifications at any time. A theorem is established that gives necessary and sufficient conditions for the state to evolve from one polyhedral subset of the state-space to another. Then, an algorithm based on Linear Programming is given which constructs a time-varying linear output feedback law which guarantees that the state evolves within a time-varying polyhedral target tube specifying the system's desired transient performance. The generalizations are also made involving constraints on the control signal and a bounded additive disturbance. This formulation is very general and includes the reference tracking with any desired transient performance in the face of disturbances.

PTC is the first feedback controller design method for meeting all the transient performance specifications. The new challenges are to be overcome to further this approach.

1) PTC is a mix of analytical and numerical methods. Whether or not it produces a controller solution depends on the plant dynamics, input size and specifications.

2) In the end of PTC, the controller is computed off line by a numerical algorithm. By nature of off-line design, the controller should work for any unknown initial state which is assumed to be in a prescribed set. The reachable state set under all the possible controls at the next time instant is computed with regards to the above initial set (but not to a particular initial state in real time). This yields significant conservatism as the designed control sequence works for any initial state in the prescribed set while only one initial state occurs in real life.

We propose to resolve those challenges with PTC as follows.

1) Solvability. Use the new advances in the reachable set theory to build the relations between the plant properties (dynamic response speed and input size) and achievable performance (rise time, overshoot, settling time). And find the conditions under which the transient control problem has a solution.

2) On-line Algorithm. One can obtain a tight estimation of the state set in real time. Use the first few output observations to compute the initial state with observability condition and thus use it to initialize a Kalman filter with high accuracy. Run the Kalman filter to estimate the state on line, and obtain the interval state with the estimated state mean and its error bound. This state set is polyhedral and should be much smaller than the one computed from evolution from the initial state region. This new procedure can greatly reduce the conservatism with the current PTC because of the much-reduced state set for which the controller works.

A general and effective approach is sought after in addition to PTC. We think of it from the bottom-up view. Obviously, the full transient performance control is very challenging due to lack of analytical relation between the system parameters and its transient performance specifications in general. Essentially, transient performance involves the characteristics of input-output mapping of the control system. The key issues are how much of the plant mapping can be changed by a realizable controller to meet the desired closed-loop mapping and how this controller can be designed effectively and efficiently. For a linear SISO system, a transfer function can represent the I-O mapping. Its denominator is determined by all its poles and can assigned by feedback control, but it is only a part of the mapping. The full mapping is uniquely determined by all its poles and zeros. But the zeros cannot be altered by state feedback and they can be partially affected by dynamic output feedback. The internal model control reveals that the non-minimum phase part of the plant must remain in any stable feedback control system. The relation between this unchangeable part and transient behavior is unclear as it depends on other part of the system. For MIMO linear systems and nonlinear systems, much less is known so far. Therefore, analytical solution for transient performance control is unlikely to find. Numerical methods should be sought for.

Machine learning and learning control are well developed [36], [37] and potentially useful to develop performance control. This could open a new door. We propose a brand-new approach: Tight Control with Transient Performance Specifications. Consider the conventional feedback system in Fig. 1.

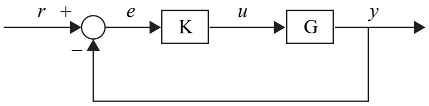

Fig. 1. Conventional control system.

1) Draw the desired output response $y_d(t)$ to meet the given transient performance specifications. Feed this $y_d(t) = r(t)$ as the reference to the control system. The ideal case is to zero the error, $e(t) = y(t) - y_d(t)$ for all $t$in a given time horizon, which is not realizable in general. Practically, tight control is to find the controller K such that $|e(t)| < \varepsilon,\ t = 1, 2, \ldots,\ \varepsilon > 0$, where ε is a small positive number. In contrast, asymptotic tracking control requires $e(\infty) = 0$ only without knowing the error at finite time.

2) Design the initial K with servo control methods so as to obtain stable bounded error and input sequences: $e(t) \triangleq e^0(t)$, $u(t) \triangleq u^0(t)$, $t = 0, 1, \ldots$. Use the iterative learning control to find $u^{(i+1)}(t) \triangleq u^i(t) + \vartriangle u^i(t)$, $t = 0, 1, \ldots$, such that $u^i(t)$ converges and satisfies the error bound for all t. Let the final $u^{i*}(t) \triangleq u^*(t)$, $e^{i*}(t) \triangleq e^*(t)$, $t = 0, 1, 2, \ldots$.

3) Given the data set of $\{e^*(t),\ u^*(t),\ t = 0,\ 1,\ \ldots\}$, use the system identification/machine learning to find the controller K. The controller form could be practical PID, m-th order proper rational function, or neural network.

The iterative learning control and system identification/machine learning are well established in the literature, and there are rich tools to employ. We can handle time delay and input saturation with ILC and also treat single variable, multivariable, linear and nonlinear systems in this framework. Thus, this approach should be general. It has great potentials for theoretical development and practical applications.

II. CONCLUSIONS

Transient performance control is necessary for real applications and it has recently attracted much research attention. But it is in its infancy, and substantial research is demanded to have complete solutions. We believe that transient performance control is well justified from application point of view. We call for effective designs for transient performance control and carry out case studies to demonstrate their effectiveness with actual performance insurance. The advocated transient performance control may impact the control research and applications as follows.

1) A new branch of control theory. The new theory matches actual requirements in control applications, and fills in the control gap mentioned in Introduction. It can change the current stability-central research to the new trend of performance-central research. Thus, it can attract vast interests from the control community, become dominant in this field, and also spread to other close fields such as communication and AI.

2) A new control technology based on this new theory. The new theory can produce a new technology of control design and implementation. The new technology will be very powerful with performance insurance and improvement over the current control technology represented by the conventional controller (PID) and advanced controller (model predictive control), which cannot guarantee transient performance. It may find wide applications in industry.

The technologies with control enhancement must be tested physically to gain real-time experience, detect design or implementation flaws and demonstrate functionality for end users. Thus, we also encourage the case studies and field tests of transient performance control on industrial and social examples in benchmark against the existing control methods. We invite industrial collaborations.

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