Addendum to “Seeking a Unique View to Control of Simple Systems”

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Abstract. This article extends the spectrum of basic structures with disturbance reconstruction and compensation considered in the paper from IFAC ACE’19 symposium and discusses problems met in their application, interpretation, teaching and learning. The objective is to foster a comprehensive understanding of basic control problems wrapped around the simplest first order plant models, which may be useful in dealing with their generalization to more complex tasks. Also included are remarks to some of the results and comments in the IFAC pilot survey on the introductory control course content.

Keywords: PI control · Disturbance observer · ESO · IMC · ADRC

1 Introduction

In the paper [12], an introduction to a learning object focussed on controllers with integral (I) action for compensating input and output disturbances related to the simplest first order plant models has been given. It started with discussing pole assignment 2DOF proportional (P) control of first order plants with possible feedforwards from measurable input and output disturbances. This core structure has then been used in more advanced controllers with I action, as:

- Input disturbance \(d_i\) reconstruction by FIR filters yielding the simplest structure of the Model Free Control (MFC) denoted as Intelligent P control [2];
- State-space reconstruction of \(d_i\) by extended state observer ESO; Its application to first order plant yields identical (Luenberger) observer; In combination with integrative first order models it yields structure typically used in active disturbance rejection control (ADRC) [3].
- ESO based approaches may be shown as special case of transfer functions based disturbance observer (DOB) for \(d_i\) reconstruction with inverse plant model considering loop stabilization by the setpoint tracking channel [18, 19].
- State-space reconstruction of the output disturbance \(d_o\) shows to lead for integral plant models to unobservable situation which requires special elimination
of the unobservability impact [6]. In a structure considered typically within internal model control (IMC) with a parallel plant model based reconstruction of $d_o$ for time delayed integrative plants it may lead to modification of the Smith Predictor [27] named as filtered Smith Predictor (FSP) considering stabilizing controller in the disturbance compensation channel [16].

Finally, different tuning approaches to traditional PI control have been treated to illustrate differences in dealing with stable, integrative, or unstable plants.

To explain success of the simplified plant modeling and control considered firstly in [33] and exploited today by ADRC and MFC, all structures have been applied twice by using two types of linear models - the “ultra local” integrative models ($a = 0$) and the “usual - local” first order models including an internal feedback characterized by a coefficient $a \neq 0$ of the transfer function

$$\frac{S(s)}{U(s)} = \frac{K_s}{s + a}$$

With respect to limited space offered by standard conference publication it was not possible to include also the structure [15,24,28,30–32] with “decoupled” setpoint and disturbance responses based on stabilizing DOB (SDOB) with inverse plant model. Therefore, it was left to next contributions. Of course, as several comments on our article have recalled, there are numerous other interesting approaches to control based on simple models - let’s just mention unstable systems control, for which many traditional approaches are inappropriate, and therefore cascading solutions are used. Or a dynamic setpoint feedforward which requires application of reference model control [29]. But, from the point of view of the introduction to the most common structures and the development of block diagram manipulation skills, we consider the introduction to be sufficient. As already mentioned above, besides of adding SDOB control structure, this paper continues in the unified introduction to the most common controllers with I action used for regulation and tracking of simple first order plants (equivalents of PI control) by extending discussion of the educational and the scientific framework. In this context, it also notes, at least in part, the problems raised within the framework of IFAC pilot survey devoted to the needs of a single subject on automatic control included in the bachelor study (see e.g. [22,23], or http://iolab.sk/ifac/results.php).

2 Decoupled Setpoint and Disturbance Response

The DOB based control with inverse plant model [18,19] and its modification to integrator plus dead time (IPDT) plant [5] have been reported for situations with the stabilizing controller located in the setpoint tracking channel. The subsequent decoupled setpoint and disturbance responses for IPDT systems have been proposed in [15,30–32] without explaining shift of the stabilizing controller to the disturbance compensation channel and with a baffling comment [32] “The
original structure is not causal and sometimes is not internally stable”. Since it
required implementation by a modified equivalent scheme, we decided to analyze
firstly the situation without a dead time.

2.1 Model Uncertainties and Constrained Setpoint Feedforward

For a piece-wise constant reference setpoint \( w \) filtered with a first order low-pass
filter \( Q_w(s) \), simple feedforward control may be accomplished according to

\[
F_{ff}(s) = \frac{U_{ff}(s)}{W(s)} = \frac{s + \bar{a}}{K_s} Q_w(s); \quad Q_w(s) = \frac{1}{1 + T_c s}
\]  

Obviously, for a model uncertainty expressed as \( \bar{a} = a + \Delta a, \) \( K_s = K_s \)

\[
Y(s) = \frac{s + a + \Delta a}{s + a} Q_w(s) W(s) = (1 + \frac{\Delta a}{s + a}) Q_w(s) W(s)
\]  

The model uncertainty is equivalent to an equivalent external input disturbance

\[
d_{ie} = \frac{\Delta a Q_w(s) W(s)}{K_s}
\]  

which, in the case of unstable systems, leads to an unrestricted output increase
and prevents the concept from being usable.

Fig. 1. Constrained setpoint and \( d_i \) feedforward

Furthermore, already for \( \bar{a} = a = 0 \), constraints put on the applied control
\( u_{ff} \) lead to a permanent control error also in nominal systems without
disturbances. For stable plants, effect of control constraints may be eliminated
by implementing the feedforward (instead of using just the transfer function
\( F_{ff}(s) \)), by a primary loop (Fig. 1) with

\[
K_P = \frac{1}{T_c - \bar{a}} / \bar{K}_s
\]  

Of course, in situations with acting disturbances and \( a \leq 0 \), such a control is not
able to guarantee stable responses with zero permanent error. A feedback stabi-
лизation needs to be used. In [7–10] it has been located into the setpoint tracking
channel. Later appearing papers on FSP, or SDOB introduced the disturbance
response stabilization via the disturbance rejection channels.
2.2 Stabilizing Disturbance Feedforward by SDOB

In the setpoint tracking channel, unstable plants may be stabilized by simple P control. However, stabilization via the DOB channel requires a proportional-derivative (PD) controller. $Q_d(s)$ (Fig. 2) has to be composed (as in [15]) as

$$Q_d(s) = \frac{1 + \beta s}{(1 + T_f s)^2}$$  \hspace{1cm} (6)

![Fig. 2. Decoupled setpoint and disturbance feedforward](image)

Its time constant $\beta$ has to guarantee stable disturbance response

$$F_{iy}(s) = \frac{Y(s)}{D_i(s)} = \frac{s(2T_f - \beta + T_f^2 s)K_s}{s(2T_f - \beta + T_f^2 s)(s + \alpha) + (s + \alpha)(1 + \beta s)K_s/K_s}$$  \hspace{1cm} (7)

For $\alpha = a = 0$, $K_s = K_z$ and $T_c = T_f$, under requirement of zero steady-state error $F_{iy}(0) = 0$, the plant pole $s = 0$ may be cancelled by a numerator zero for

$$\beta = 2T_f$$  \hspace{1cm} (8)

$$F_{iy}(s) = \frac{sK_s T_f^2}{(1 + T_f s)^2}; \quad F_{uy}(s) = \frac{Y(s)}{U(s)} = \frac{K_s}{s}; \quad I E_{w0} = T_c; \quad I AE_i = K_s T_c^2$$  \hspace{1cm} (9)

It means that with respect to $u$ the plant block with SDOB behaves as a single integrator. On the other hand, with respect to disturbances, it keeps zero total disturbance $d_i - d_i f$ whereby it guarantees stable $d_i$ responses. Simple feedforward control might thus be expected to guarantee precise setpoint tracking also in presence of disturbances and uncertainties. For $\alpha = 0, a \neq 0, T_f = T_c$ with (8)

$$F_{iy}(s) = \frac{sK_s T_f^2}{(1 + T_f s)^2 + s a T_f^2}; \quad F_{uy}(s) = \frac{K_s}{s} \frac{(1 + T_f s)^2}{(1 + T_f s)^2 + s a T_f^2}$$  \hspace{1cm} (10)

$$I E_{w0} = T_c(1 + a T_c); \quad I AE_i = K_s T_c^2; \quad T_c = T_f$$

These results are the same as for DOB with stabilizing P controller in the setpoint tracking channel [12] with the first order filter. The disturbance response remains
stable for $2T_f + aT_f^2 > 0$, i.e. $2 + aT_f > 0$. For $a < 0$ $T_f$ may not be chosen arbitrarily large. For $\bar{a} = a \neq 0$, from zero steady-state error $F_{iy}(0) = 0$ and from cancellation of the unstable pole $s = -a$ expressed by $F_{iy}(-a) = 0$ follows

$$\beta = T_f(2 - aT_f); \quad F_{iy}(s) = \frac{sK_sT_f^2}{(1 + T_f s)^2}; \quad F_{uy}(s) = \frac{K_s}{s + a}$$

(11)

From comparison of these results with [12] follows that no new performance appeared. When simulating transients for various model and plant parameters, students may encounter situations where the proposed structures work perfectly. However, when attempting longer transients with unstable systems, they discover collapsing responses with signals growing above all limits. The moment of collapse can be influenced by choice of the simulation parameters and the numerical integration method, but only partially. After trying all possible solutions to eliminate the problem, students are more receptive to following its explanation - stabilizing the disturbance responses does not mean stabilizing the state of the system. The aim of SDOB, by introducing feedback to follow dynamics given by the parameter $\bar{a} < 0$ even in the presence of uncertainties and disturbances [25], may not guarantee permanently stable loop behavior for unstable plants. Thus, achieving an ideally matching model and system dynamics leads here to a conflicting requirement in terms of overall stability. The task formulated in this way is meaningless and it is always necessary either to worsen the dynamics of transients by choosing a stable model with $\bar{a} > 0$, or to add a regulator ensuring stabilization of the plant state. Due to the decoupled setpoint tracking and disturbance compensation, this moment may here be easier understood than for the stabilizing disturbance feedforward of the IMC like structures (as e.g. in [12]).

The final lesson of the experiment for students is to critically examine all claims, even if they are published in the top journals and books. The different effects of the experts’ opinions on the solution of unstable process control can also be nicely illustrated by the results of the corona virus pandemic control in different countries, which is an example of unstable time-delayed dynamics. Since such untreated problems, together with limitations of the control action, significantly influence usability of the SDOB concept, they could explain reasons for the above-mentioned unintelligible remark “The original structure is not causal and sometimes is not internally stable”.

3 Educational Framework of the Complete Batch

The impulses for writing this article come from several sources. They include curiosity that forces us to ask what, how, whom and why we teach, whether students are interested and what it gives them, etc. Since such questions have been addressed since the 1980s, the answers to them include much of the development of the theory of automatic control. Recently, numerous similar questions appeared also in preparing and conducting the IFAC pilot survey devoted to the
needs of a single subject on automatic control included in the bachelor study. Although education in areas dominating our courses is certainly not enough with a single semester, the essence of the questions to be answered remains the same. And we do not avoid situations when, forced by the environment changes, long-term stabilized blocks of education and knowledge need to be broken first and then picked up from them isolated stones that fit into a newly created mosaic.

3.1 Plant Modeling, Block Diagrams and Content Flipping

Most traditional control curricula start from rigorous mathematical models, then go through simplifications (e.g., linearization), then Laplace and transfer functions, to arrive at the simple models. It typically takes a few weeks and all that time students are asking “Where is the control?” Students lose motivation and fail to see the connection to real world practice. In their minds control is just another applied math class. Project-based learning [14,20] allows us to flip this progression backwards. Start with the simplified model (do not derive, just make them axioms) and build control concepts from there. Let students do trial and error tuning and controller design. Let them experience firsthand what set-point tracking and disturbance rejection is. Let them get frustrated and fail a few times... Then, show how mathematical analysis can streamline the process. Thus, as the first priority of our course, the ability to work with block diagrams in Matlab/Simulink has been defined. This is crucial for both control analysis and synthesis and also for system modeling. While in the distant past students tested their skills while working with some “artificial” schemes, by considering all the basic approaches to designing integrating controllers, we gained a wide range of schemes interesting both from the point of their functionality and for developing the simulation skills. Work with them includes experimenting, watching lectures, attentive listening and team work including writing and presenting reports. Considered problems also enable to illustrate historical development of control technology, including simple application examples and relevant terminology (aspects neglected in the running survey).

Lecture, or classroom flipping represent an instructional strategy used also in the control area [11,21]. In principle, it shifts instructions from a teacher-centered to a learner-centered model. It may also be extended to content flipping, when some its items are treated in an inverse order. Due to the recently decreased ability of students to study mathematically oriented courses (including low motivation for such a study), we may use control experiments to encourage their motivation and to show the practical needs of math study. From the Kolb’s learning cycle [13] follows that it may favor different type of student than the traditional study. As e.g. reported in [11], such control course may start with much lower student knowledge from the math area covering just work with exponential functions. By assuming solutions of differential equations in form \( y(t) = ce^{st} \) it is possible to interpret “\( s \)” as an operator of differentiation, or “\( z^{-1} \)” as a shift operator, which opens the way to using the Simulink blocks, to introduce the closed loop pole as quotient of signal increase/decrease, block algebra, etc. A detailed interpretation of some steps relevant for the Laplace, or Z transforms may be
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shifted to later stages, when students have already advanced in a parallel running math course and due to increased motivation they better understand the overall context. One comment received to the paper was: “Is not the 2-parameter model too big simplification of reality?” Another note to this point claims that “even the system has 1 dominant time constant and exhibits open loop time domain behavior close to first order model, the frequency response could be significantly different and closing loop may cause instability when higher order are neglected. Then, from controller perspective the system is of higher order, although has a dominant time constant. Also small dead-time caused by sampling and signal processing could cause problems when moving from virtual space to real plant.” These comments are appreciated, because they bring up highly important and for a long time neglected questions. As shown by our analysis, all disturbance responses do not depend on the plant parameter $a$. This allows for the possibility of a simplified plant identification, which has already been used by Ziegler and Nichols way back in 1942. Also MFC and ADRC use this simplification which is significant especially in dealing with nonlinear systems, where the linear plant approximations change with the operating point and require application of gain-scheduling. By experimenting on real plant with different values of $T_c$, students see when the used plant model becomes inadequate (evidenced by increasingly oscillatory transients with growing shape-related performance measures). With respect to the level of their preparation, detailed traditional analysis and design in the frequency domain is out of the possibilities. However, several structures from the batch have been included especially as a preparation to design of dead-time compensators (DTCs) for the time delayed systems. Above approach shows to be consistent with the results from the survey question [22,23]: “A first course should focus more on concepts, philosophy and motivation-reasons to use control, illustrating principles such as uncertainty handling with case studies but not get drawn into mathematics too quickly”. But, without showing, how, such statements turn to be more or less just political slogans. A bit more specific is the sentence: “A first course should focus on classical tools such as Laplace, closed-loop transferences and lead/lag/PID design.” Basically, it is to agree also with other similar statement “PID analysis and tuning is essential for all students.” However, without a rigorous definition it is not clear, what should be understood under the notion PID (see e.g. different types of PIDs considered in standard textbooks [1,29]). And numerous authors extend this notion, under denotations as IMC-PID, DOB-PID, or iPID, to a much broader context including several structures of our test set. As noted by [17], design of PID controllers is most frequently accomplished using FOTD and IPDT models. Most of the existing DTCs follow from generalization of the approaches discussed in our case study, based on the same plant models as PID control. Furthermore, also PID has been shown as a special case of a model based approach with dead-time approximated by Padé or Taylor series expansions [26]. From this point of view, better performance could be expected from more precise methods not requiring such approximations. Of course, historically, the use of transport delays was a problem for analogue-based controllers, but this is no longer the case for
modern digital controllers. Thus, when seeing doubts regarding use of DTCs [4], something must be wrong in the approaches used. And when the preliminary survey shows relatively low interest regarding development of the last 60 years, this suspicion is yet increasing.

### 3.2 Non Multa Sed Multum Versus Non Multum Sed Multa

Some comments expressed doubts, whether the chosen design methods fit well to the introductory control course and if they can be considered as the most common approaches to control system design. Traditional control curricula usually begin with classical methods such as root-locus or loop-shaping which require iterative “hand-tuning” but allow the students to develop deeper understanding of how the feedback loop affects the overall system behavior... Exactly these aims may be achieved by individual experimenting on laboratory plant models, produced in large numbers, given to every student and adjusted the course topics, enabling students to play, iterate and to develop deeper understanding. The presented structures may seem too complex for bachelor students and cause confusion and misunderstanding. But, at the same time, other comments appeared that “the complexity of choices the designer must make grows considerably for higher order models and the results achieved for the first order plant cannot be extrapolated simply. Also the interpretation of robustness becomes much more involved than presented.” When discussing inflation of different approaches, it is just to remind that it started long time ago - see e.g. the arguments given by introducing the Modern Control Theory, IMC, ADRC, MFC, etc. Which of these approaches should be omitted? Should we deal just with the “traditional” PID control (do we know its definition?) and let all the alternatives untouched? The result would be that many students, upon discovering some of these “revolutionary” alternatives, would start complaining about the obsolescence of our education and full of enthusiasm continue disseminating unfounded optimistic information on their use. However, as shown by the analysis, nominally all discussed structures may be included into few equivalent classes. No matter how “attractive” and “trendy” titles they use.

### 4 Conclusions and Future Work

As concluded already in the source paper [12], mastering of the presented structures and tuning procedures opens the door to deeper and rigorous study of more complex tasks as, for example: control of first order time delayed systems, or control of (time delayed) systems with higher (2nd) order dominant dynamics with possibly constrained control and the discrete time implementation. The analysis also pointed to the need for a fundamental revision of several conclusions regarding the control of unstable systems.

In view of the ongoing survey, it can be stated that one cannot expect from it straightforward and unambiguous instructions for optimal design of his course. Therefore, it will be appropriate to discuss a number of possible approaches, including their detailed syllabi.
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