In this issue, “25 Years Ago” revisits the article “Iterative Feedback Tuning: Theory and Applications,” by H. Hjalmarsson, M. Gevers, S. Gunnarsson, and O. Lequin in *IEEE Control Systems Magazine*, vol. 18, no. 4, pp. 26–41. Below is an excerpt from the article.

Many control objectives can be expressed in terms of a criterion function. Generally, explicit solutions to such optimization problems require full knowledge of the plant and disturbances, and complete freedom in the complexity of the controller. In practice, the plant and the disturbances are seldom known, and it is often desirable to achieve the best possible performance with a controller of prescribed complexity. For example, one may want to tune the parameters of a PID controller in order to extract the best possible performance from such simple controller.

The optimization of such control performance criterion typically requires iterative gradient-based minimization procedures. The major stumbling block for the solution of this optimal control problem is the computation of the gradient of the criterion function with respect to the controller parameters: it is a fairly complicated function of the plant and disturbance dynamics. When these are unknown, it is not clear how this gradient can be computed.

In fact, the major application field of our method here is for the optimal tuning of low order controllers.

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With the IFT scheme the tuning of the controller parameters for disturbance rejection is driven by the disturbances themselves.

Within the framework of restricted complexity controllers, previous attempts at achieving the minimum of a control performance criterion have relied on the availability of the plant and disturbance model, or on the estimation of a full order model of these quantities, see [22] and [32]. Alternatively, reduced order controllers can be obtained from a full-order controller followed by a controller reduction step [1].

In the context of controllers of simple structure for unknown systems, such as PID controllers, some schemes have been proposed for the direct tuning of the controller parameters. These schemes are based on achieving certain properties for the closed loop system that are found to be desirable in general. These properties can then be translated into constraints on the Nyquist plot (or the Ziegler-Nichols plot) of the controlled system. We refer the reader to [2] for a representative of this family of methods.

Recently, so called iterative identification and control design schemes have been proposed in order to address the problem of the model-based design of controller parameters for restricted complexity controllers, see, e.g., [8, 24, 35, 39], and [40]. These schemes iteratively perform plant model identification and model-based controller update, with the successive controllers being applied to the actual plant. Behind these schemes is the notion that closed loop experiments with the presently available controller should generate data that are "informative" for the identification of a model suited for a new and improved control design, and that controllers based on models that are better and better tuned towards the control objective should achieve increasingly higher performance on the actual system. See [9]–[11] for a presentation of these ideas.

So far, there are very few hard results to support these expectations, except for the ideal (but unrealistic) situation where full-order models (and hence full-order controllers) are used. Following up on the early results of [12], it has been shown in [18] that, for that situation, closed loop identification with a specific controller in the loop yields an estimated controller that achieves the best possible performance on the actual system. In addition, an iterative identification and control design scheme has been proposed that approaches these ideal experimental conditions.

In the case of low-order controllers, there are reported successes, including experimental and industrial ones, of the above-mentioned iterative identification-based controller design schemes [31], but there are also examples where these schemes are known to diverge. Most importantly, with the exception of some examples analyzed in [3], there is no analysis of the performance properties of the closed loop systems to which such schemes converge in the cases where they do so. In [21] it was shown that such iterative identification-based control design schemes do not converge to a controller that minimizes the control performance criterion, except possibly for full order models and controllers. This has also been pointed out in [27].

It is the analysis of [21], and our attempt to understand the convergence/divergence properties of the iterative identification and control design scheme of [3] based on a simple model reference control design, that led us to the idea of reformulating the iterative identification and control design scheme as a parameter optimization problem, in which the optimization is carried directly on the controller parameters, thereby abandoning the identification step altogether. This approach is of course analogous to direct adaptive control, the main difference being that here the complexity of the controller need in no way be related with that of the system; in fact, the major application field of our method here is for the optimal tuning of low order controllers.

In the combined identification/control design schemes, the model is only used as a vehicle towards the achievement of the minimization of a control performance objective. An obvious alternative is to directly optimize the control performance criterion over the controller parameters. However, as stated above, earlier attempts at minimizing the control performance criterion by direct controller parameter tuning had stumbled against the difficulty of computing the gradient of this cost criterion with respect to the controller parameters.

The contribution of [19] was to show that an unbiased estimate of this gradient can be computed from signals obtained from closed loop experiments with the present controller operating on the actual system. For a controller of given (typically low-order) structure, the minimization of the criterion is then performed iteratively by a Gauss-Newton based scheme. For a two-degree-of-freedom controller, three batch experiments are to be performed at each step of the iterative design. The first and third simply consist of collecting data under normal operating conditions; the only real experiment is the second batch which requires feeding back, at the reference input, the output measured during normal operation. Hence the acronym Iterative Feedback Tuning (IFT) given to this scheme. For a one-degree-of-freedom controller, only the first and third experiments are required. No identification procedure is involved. A closely related idea of using covariance estimates of signals obtained on the closed loop system to adjust the controller parameters in the gradient direction was used in an adaptive control context by Narendra and coworkers some 30 years ago, see [29] and [30]. Another related method, in which state-feedback is considered, is presented in [23]. In other optimization-based approaches that have appeared in an adaptive control context, the gradient of the criterion was obtained through the estimation of a full-order model of the plant, see, e.g., [38].

This direct optimal tuning algorithm is particularly well suited for the tuning of the basic control loops in the process industry, which are typically PID loops.

[…]

The optimal IFT scheme of [19] was initially derived in 1994 and presented at the IEEE CDC 1994. Given the simplicity of the scheme, it became clear (and not just to the authors) that this new scheme had wide-ranging potential, from the optimal tuning of simple PID controllers to the systematic design of controllers of increasing complexity that have to meet some prespecified specifications. In particular, the IFT method is appealing to process control engineers because, under this scheme, the controller parameters can be successively improved without ever opening the loop. In addition, the idea of improving the performance of an already operating controller, on the basis of closed loop data, corresponds to a natural way of thinking. Finally, in many process control applications the main objective of the controller design is to achieve disturbance rejection. With the IFT scheme the tuning of the controller parameters for disturbance rejection is driven by the disturbances themselves.

Since 1994, much experience has been gained with the IFT scheme.

- It has been shown to compare favourably with identification-based schemes in simulation examples: see [19].
- Its accuracy has been analyzed in [17].
- It has been successfully applied to the flexible transmission benchmark problem posed by I.D. Landau for ECC95, where it achieved the performance specifications with the simplest controller structure [20].
- It has been tested on the flexible arm of the Laboratoire d'Automatique de Grenoble [7], on a ball-on-beam system [6], for the temperature control of a water tube, and for the control of a suspended plate [28].
- It has been adapted to linear time-invariant MIMO systems [16].
- It has been shown to handle time varying, and in particular periodically time-varying, systems [13].
- It has been applied by the chemical multinational Solvay S.A. to the tuning of PID controllers for a number of critical control loops for which opening the loop or creating limit cycles for PID tuning was not allowed: temperature control in furnaces, in distillation columns, flow control in evaporators, etc. The performance improvements achieved by applying the IFT scheme to the existing PID loops have been rather striking (this is discussed below).

Common to many of the processes in these applications is that they exhibit some kind of nonlinear behaviour and, even if IFT was developed for linear time-invariant systems, it seems to also perform well on many nonlinear systems. The reasons for this and the conditions required from nonlinear systems for IFT to perform well have been analyzed in [14].

Our objective in this article is to first present the IFT scheme, and to then review performances achieved by the scheme at the S.A. Solvay, where it was used for the optimal tuning of PID controllers on a number of control loops, and on a DC-servo with backlash. We shall leave aside the connections with identification-based schemes and all other technicalities that might be of interest to theoretically inclined researchers but that would otherwise distract the reader from the essential ideas of the scheme and its potential applications.

FINAL DISCUSSION

In this article we have examined an optimization approach to iterative control design. The important ingredient is that the gradient of the design criterion is computed from measured closed loop data. The approach is thus not model-based. The scheme converges to a stationary point of the design criterion under the assumption of boundedness of the signals in the loop.

From a practical viewpoint, the scheme offers several advantages. It is straightforward to apply. It is possible to control the rate of change of the controller in each iteration. The objective can be manipulated between iterations in order to tighten or loosen performance requirements. Certain frequency regions can be emphasized if desired.

This direct optimal tuning algorithm is particularly well suited for the tuning of the basic control loops in the process industry, which are typically PID loops. These primary loops are often very badly tuned, making the application of more advanced (for example, multivariable) techniques rather useless. A first requirement in the successful application of advanced control techniques is that the primary loops be tuned properly. This new technique appears to be a very practical way of doing this, with an almost automatic procedure. The application of the method at Solvay, of which we have presented a few typical results here, certainly appears promising.

In comparison with available methods for the tuning of PID controllers, IFT requires typically more data and experiments. However, it offers several advantages: the achieved responses are typically faster than those obtained with other model-free methods based on Nyquist (or Ziegler-Nichols) plot considerations; the control objective is clearly expressed, thereby giving the control engineer a confidence for the tuning of critical loops that he cannot have with some commercially available loop tuners that behave more like "dark grey box" systems (in the words of one control engineer). Perhaps in the long run IFT will prove to have its major potential for the tuning of non-linear controllers or controllers applied to nonlinear systems, for which preliminary analyses and applications seem to indicate great potential.

As a final remark, we should like to emphasize that, even though the industrial applications that we have presented in this article pertain to the tuning of industrial PID controllers, the method is by no means limited to the optimization of PID controllers.

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