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AN INTRODUCTION TO THE SPECIAL ISSUE ON LOOP TRANSFER RECOVERY

LOOP TRANSFER RECOVERY (LTR) DESIGN

Historically, loop transfer recovery (LTR) methods were invented mainly as a heuristic tool for introducing robustness into the LQG design framework. As they were developed, however, a series of appealing features which could be achieved by the methods as side-effects came into focus.

Today, after modern (and postmodern?) control has entered the stage, the original scope of LTR as a means of improving robustness in pure LQG designs has faded somewhat, since this can be achieved now in much easier and more elegant ways. However, the LTR design methods and, in a little broader view, the loopshaping methods still have an important role to play, although the scope is rather different today.

The main features that are significant for the use of LTR methods in contemporary control technology are especially:

- the possibility of complete decoupling in the design process between the design of desirable loop shapes from *any* criterion and the design of an implementable dynamical controller, with specified performance and robustness properties in different frequency regions; this allows for a variety of complex design criteria which cannot be handled by other strategies;
- the capability of designating specific observer and/or controller structures, such as low-order ones, to the resulting closed-loop system; this is in contrast to most other optimization-based methods where specific structures cannot be assigned or can be designed through very tedious procedures only.

LTR is by now a very mature field, and any attempt to cover the complete research history or to give a comprehensive and fair treatment of all recent results in this area would fail. The intention of this special issue, however, is to display a few rather different recent developments in the field, and to give some indication of what the main body of the previous research is.

A HISTORICAL OVERVIEW OF LTR DESIGN

The origin of the LTR concept is usually credited to a paper by Kwakernaak in 1969[4] dealing with stochastic linear regulation and the tracking problem for multivariable systems. The design method provided in this paper was based on the LTR principle without formulating it explicitly. It was not until ten years later that the LTR design technique was explicitly formulated in two papers by Doyle and Stein.[2,3] The LQG/LTR design method was derived here for full-order observers.

Since the appearance of these two papers, a large number of results have been published in the area of LTR dealing with different design methods for different types of observers/controllers.

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One of the next crucial publications was a tutorial paper by Athans[1] presented at a special LTR session in the American Control Conference in 1986. Here, the problem of LTR design of non-minimum phase systems was considered. This LTR design problem was investigated more carefully in a paper by Stein and Athans.[7] A complete analysis of the recovery error obtained when the LQG/LTR methods is used for minimum phase systems was given by Zhang and Freudenberg.[8]

Different design methods were combined with the LTR design methodology, for example, LQG, eigenstructure assignment, $\mathcal{H}_\infty$ etc. It is relevant to mention, that the first $\mathcal{H}_\infty$/LTR design method was derived by Moore and Tay.[5] Since the appearance of their results, a range of papers dealing with different $\mathcal{H}_\infty$/LTR design methods was published.

A recent major contribution to the area of LTR is the appearance of the LTR book by Saberi, Chen and Sannuti.[6] This LTR book gives a fairly complete description of the LTR methodology with respect to both analysis and design.

Today, the LTR design methodology is well established as a standard design method for dynamic controllers. Almost all recent textbooks dealing with optimal and robust controller design have included LTR design methods.

SCANNING THE ISSUE

The special issue on *loop transfer recovery* contains the following four papers.

Loop Recovery via $\mathcal{H}_\infty$ Modified Complementary Sensitivity Recovery for Non-minimum Phase Plants by M. Saeki

The problem addressed in this paper is loopshaping in the presence of non-minimum phase zeros. Whereas the usual strategy for such systems is to recover the desirable loopshapes at some frequency ranges only, the author suggests instead replacing the original loopshape by a modified loopshape which is completely recoverable. This modified loopshape is found by solving a certain $\mathcal{H}_\infty$ optimization problem. The design specifications are expressed in terms of a desirable complementary sensitivity function. A number of numerical design examples are given. Moreover, the method is applied to the control of a turbocharged marine diesel engine.

Loop Transfer Recovery Designs with an Unknown Input Reduced-order Observer-based Controller by M. Zasadzinski, M. Darouach and M. Hayar

In this paper, the unknown input reduced-order observer is introduced and applied in connection with recovery design. In connection with the description of the observer, two parametrizations based on the matrix fraction description (MFD) of all unknown input reduced-order observers in $\mathcal{RH}_\infty$ are derived. Based on these parametrizations, an LTR design method is provided. Under certain conditions, exact recovery is obtained for minimum phase systems. In the non-minimum phase case, approximate recovery is obtained by minimizing the Frobenius norm of a certain constant matrix or by minimizing the $\mathcal{H}_\infty$ norm of the recovery matrix.

Loop Transfer Recovery Design via New Observer-Based and CSS Architecture-Based Controllers by B. M. Chen and Y.-L. Chen

The main purpose of the paper is to establish continuous-time equivalents of the main controller structures known from discrete-time control, while maintaining their appealing features. The result is two versions of a new so-called current-type controller: respectively the observer and CSS based current-type architecture controllers. The first is the continuous-time equivalent of the discrete-time current estimator-based controllers, while the latter turns out to belong to a very general class of controller architectures published recently by Chen, Saberi and Sannuti. Both exact and asymptotic recovery are studied for these two controller types, and necessary and sufficient conditions for achieving this are given in terms of conditions from geometric control theory. The paper deals with general systems, i.e. possibly non-strictly proper and non-minimum phase systems. Finally, a certain balancing property between observer structures for continuous-time and discrete-time systems is demonstrated.

LTR Design of Proportional-integral Observers by H. H. Niemann, J. Stoustrup, B. Shafai and S. Beale

The proportional-integral (PI) observer structure is used in an LTR design of continuous-time systems. Using the PI observer makes it possible to obtain time recovery, i.e. good recovery in steady state. It is shown, that it is possible to obtain time recovery under mild conditions for both minimum phase and non-minimum phase systems. Based on an extension of the LQG/LTR design method for the normal full-order observer, a systematic LTR design method is derived for the PI observer. This recovery design method makes it possible to tune the time recovery and the frequency (normal) recovery independently. An analysis of the nonasymptotic recovery case is also included when PI observers are applied.

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