Computerized Investigation of Robust Measurement Systems

Nikolay Petkov Kolev, Snejana Todorova Yordanova, and Plamen Marinov Tzvetkov

***Abstract*—This paper deals with the development of software for investigating the robust properties of measurement systems and for their design and tuning in order to improve their robustness. The software constitutes Simulink models and m-files as extensions of the libraries of MATLAB. The investigations on continuous measurement systems (a self-balancing system) and discrete systems (ADCs) with improved robustness by using the internal model controller technique revealed new properties—fast dynamics, high accuracy, and discretization error reduction via multiple measurements.**

***Index Terms*—Computer investigation, measurement systems, robustness.**

I. Introduction

ROBUSTNESS is the property of a system to preserve its characteristics with acceptable tolerance about its desired (nominal) characteristics for a given level of model uncertainties (perturbations due to aging of material, drift of the zero, and ambient influences such as noise, disturbances, temperature, dust, etc.).

All measurement systems are designed to be robust as a rule. A special class is developed to further improve the dynamic response speed and the accuracy of measuring systems through a robustness feedback on the basis of a simplified reference model of the system. Such an approach is an extension of the internal model control for achieving robustness to perturbations, noise, and disturbances [1], [2].

The aim of this paper is to develop software, investigate measurement systems, and improve their robustness.

The software concerns the continuous and the discrete parts of measurement channels, including case studies from these parts (self-balancing systems, ADCs, etc.). It is based on the building of Simulink models, m-files using MATLAB and Control Toolbox [3], and Assembler real-time measurement and control modules.

II. Theoretical Background

The robustness of a dynamic system can be estimated by the robust stability or robust performance criteria [1], [2]. The robust stability ensures preservation of the stability of the system for a given multiplicative system uncertainty, defined as $l(s) = (P(s) - P^0(s))/P^0(s)$, where $P(s)$ and $P^0(s)$ are the transfer functions of the measurement system and of its simplified reference model, respectively. The robust performance criterion requires minimization of the ∞-norm of the error in the measurement system. It is estimated by the transfer function of the system and its sensitivity.

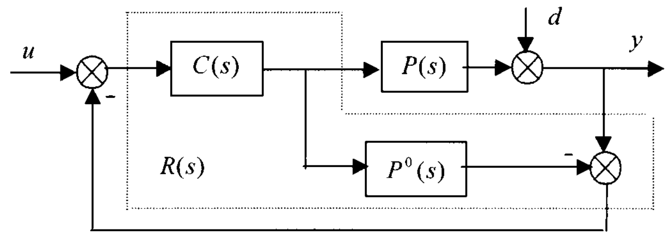

Fig. 1. Block diagram of a measurement system with internal model controller.

The design of high accuracy measurement systems requires the use of various techniques and schemes to achieve the necessary robustness—compensation and protection circuits, thermostats, shielding, etc. [4], [5]. The most effective is the feedback approach. In this case, the robust stability criterion is expressed as $k_s(\omega) = |T(j\omega)l(j\omega)| < 1$, where $T(j\omega)$ is the frequency characteristic of the closed-loop system with nominal parameters, and $\omega \in D_\omega$ with D_ω denoting the significant frequency range [6], [7]. The robust performance criterion takes the form $k(\omega) = |T(j\omega)l(j\omega)| + |S(j\omega)W(j\omega)| < 1$, where $S(j\omega)$ is the sensitivity of the closed-loop system with respect to disturbances and system model uncertainties, and $W(j\omega)$ is the frequency characteristic of a filter that shapes the disturbance d in the Laplace transformation $d(s) = W(s) \cdot 1$ [2]. In the frequency range of interest in most cases of disturbances, $|W(j\omega)|$ is assumed to be within the range [0.3–0.9] [2].

The measurement system with internal model controller is a class of the feedback measurement system, which is based on the introduction of a simplified internal model $P^0(s)$ of the system and a specially designed controller $C(s)$ as shown in Fig. 1. The transfer function of the controller is $C(s) = [P^0(s)]^{-1} \cdot F(s)$, where $[P^0(s)]^{-1}$ is the stable part of the inverse reference model. The filter $F(s)$ is added to make $C(s)$ proper [2], and for step input signals it has the form:

$$F(s) = \frac{1}{(\lambda s + 1)^n}. \tag{1}$$

The equivalent controller has the transfer function

$$R(s) = \frac{C(s)}{1 - C(s) \cdot P^0(s)} = \frac{[P^0(s)]^{-1} \cdot F(s)}{1 - F(s)}. \tag{2}$$

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The free parameter—the time-constant λ is tuned so that the nominal closed-loop system has stable, fast dynamic behavior with high damping and accuracy, and the perturbed and disturbed system retains its performances within an acceptable tolerance by fulfilling either of the criteria for robust stability or for robust performance.

The internal model controller approach turns out to be the most efficient in the design of high-accuracy measurement systems.

III. Computerized Investigations

The general algorithm for computerized investigations of measurement systems is shown in Fig. 2. The algorithm is implemented using the facilities of MATLAB and its toolboxes Control and Simulink. The MATLAB environment supports a procedure-type high-level language for writing of m-files and a block-oriented language, both with rich libraries of modules for simulation of continuous and discrete, linear and nonlinear, deterministic and stochastic dynamic systems in the time, frequency and root domain.

The existing Simulink library is enriched with specific models developed to cover the investigation of typical measurement systems. Some of the models are conventional ADC, ADC with internal model controller, self-balancing system, averaging block for multiple measurements, uncertainty models (discharge circuit model in ADCs), evaluation block for the discretization error in ADCs in multiple measurements [8], etc.

The investigation of time-responses using the Simulink models of the self-balancing systems with and without the ordinary internal model controller (IMC) leads to the establishment of an additional property of the system with IMC, namely, high dynamic accuracy and fast step response as seen in Fig. 3 [1].

New m-files are developed in order to study the frequency characteristics, stability, sensitivity, and robustness of measurement systems as well as to design and tune measurement systems with the IMC. For example, Fig. 4 shows the following characteristics of a self-balancing system with IMC: $T = |T(j\omega)|$, $S = |1 - T(j\omega)| = |S(j\omega)|$, $l = |l(j\omega)|$, and k as functions of the frequency ω. These characteristics can be used to tune the parameter λ in order to satisfy some of the robustness criteria.

The investigation of discrete measurement systems and, particularly, of ADCs with IMC contributed to the development of an approach for discretization error reduction and hence linearization by multiple measurements N_i. The average value of the output code N_R for a certain number m of sample periods is calculated using [7]

$$N_R = \frac{1}{m}\sum_{i=1}^{m} N_i. \tag{3}$$

A Simulink averaging block is developed to relate the number of the multiple measurements to the desired error reduction. The discretization error reduction allows calibration of ADCs for any value of the input signal and number of points [6].

A real-time version of this module is designed to improve the accuracy of existing ordinary ADC systems [8].

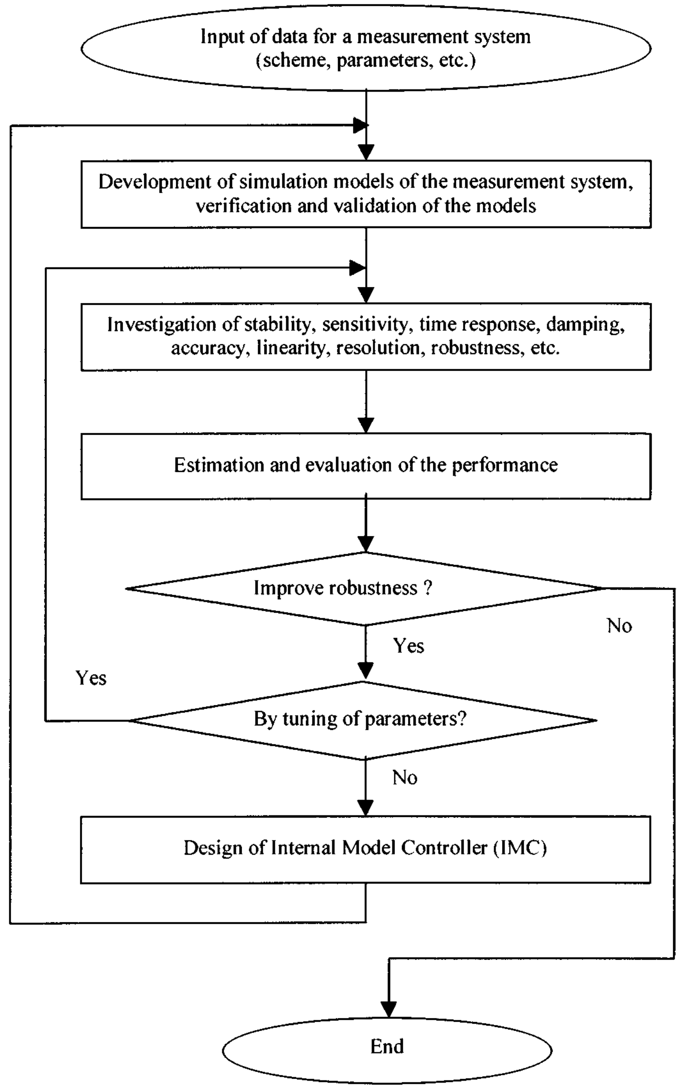

Fig. 2. Flowchart of the general algorithm for computerized investigations.

IV. Example

The generalized model of an ADC in the environment Simulink is shown in Fig. 5. The zero-order hold block stands for the real sample-and-hold element. The drop rate of the analog memory (in most cases, a hold capacitor) is modeled by a reset integrator and a gain block. The Quantizer block represents the quantization determined by the ratio of the range of the ADC to the number of the discrete levels [8]. The unit Delay element corresponds to the delay of the output signal with one sample period that cannot be smaller than the sum of the aperture time of the sample-and-hold circuit and the conversion time [5]. This delay is a basic characteristic of the ADC, so it comprises the linearized simplified reference model. Then, the discrete controller DR is derived according to (1) and (2) in the form

$$R(z^{-1}) = \frac{1}{z^{-1} - z^{-2}}. \tag{4}$$

The tuning parameter λ is obtained equal to the sample period.

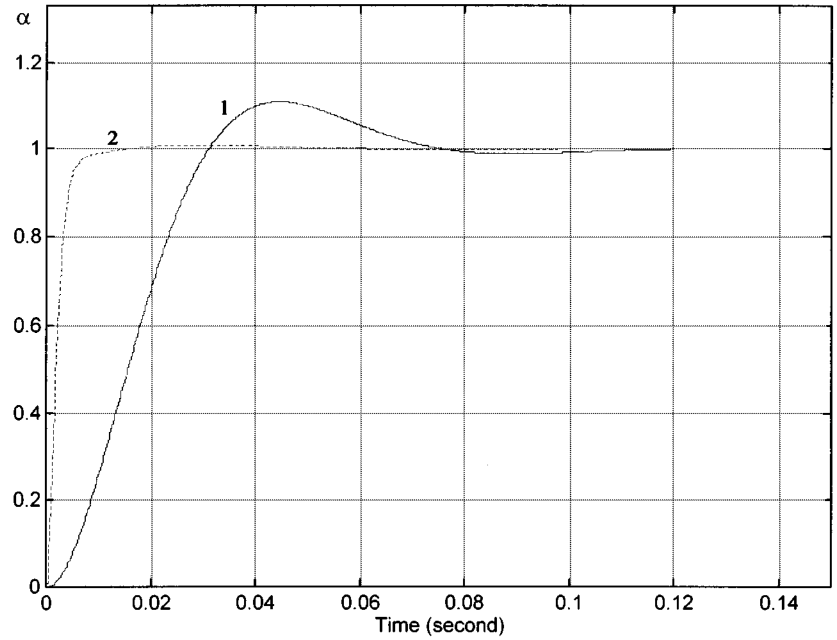

Fig. 3. Step response of an ordinary (1) self-balancing system and a system with IMC (2).

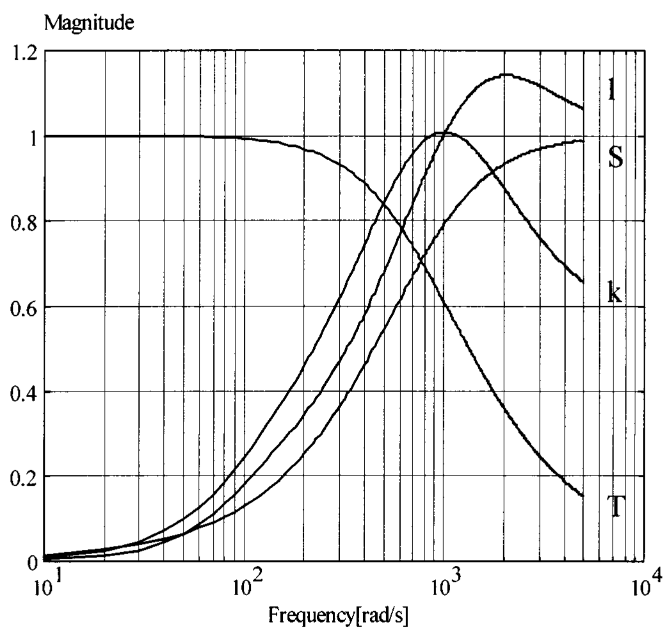

Fig. 4. Magnitude of T, S, k and l of a robust self-balancing measurement system with IMC.

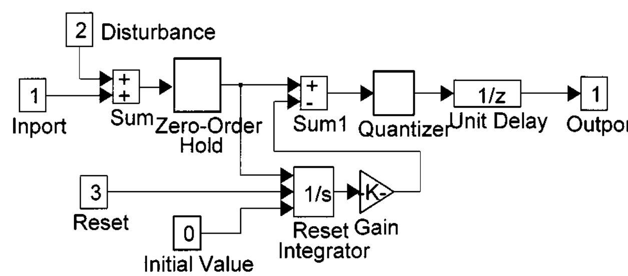

Fig. 5. ADC Simulink model.

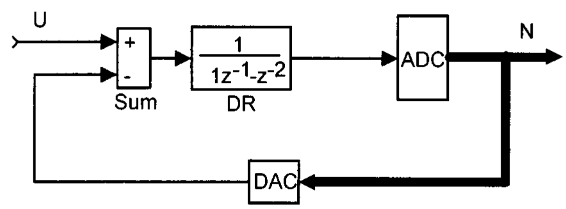

Fig. 6. Robust ADC model with IMC.

The block diagram of the ADC designed with robustness feedback is shown in Fig. 6.

The block DAC is a digital-to-analog converter with the same number of discrete levels, which can be considered a gain.

Fig. 7 shows the relationship between the discretization error and the number of sequential measurements (sample periods) of the ADC with resolution 39 mV. After 39 measurements, the error is reduced 39 times to 1 mV [9].

V. Conclusion

The main contributions can be summarized as follows.

Specialized software is developed in order to study, design, and tune measurement systems with emphasis on the robust properties. The software is an extension to the MATLAB libraries of Simulink models and m-files.

Computerized investigations are carried out on continuous and discrete measurement systems in the time, frequency and root domain. Due to simulation, new features of the designed measurement systems with internal model controller were established—fast dynamics and discretization error reduction.

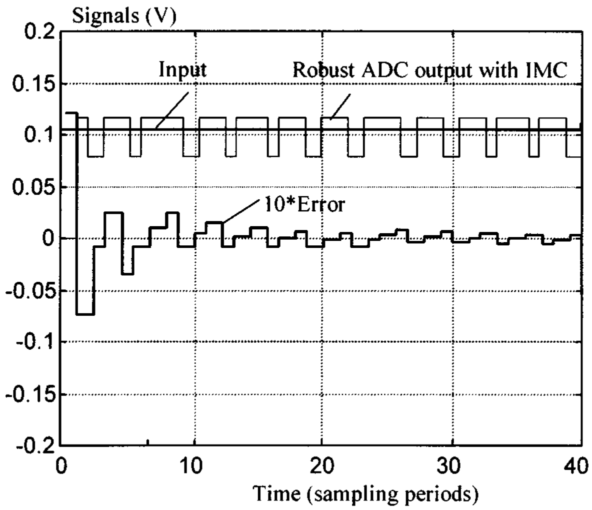

Fig. 7. Evolution of the error of robust ADC with IMC.

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