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A NOTE ON
THE COMPUTATIONAL SOLUTION OF
A SYSTEM OF DIFFERENTIAL EQUATIONS
WITH VARYING TIME-LAGS

Richard Bellman and Bella Kotkin

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PREPARED FOR:
NATIONAL INSTITUTES OF HEALTH

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This investigation was supported in part by Public Health Service Research Grant Number GM-09608-02, from the Division of General Medical Sciences, National Institutes of Health.

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PREFACE

Part of the RAND research program consists of basic supporting studies in mathematics. The mathematical research presented here concerns techniques for the solution of differential equations with time-lags. This method is of importance in connection with the study of more realistic models of chemotherapy, of the type being studied under GM-09608.

SUMMARY

In this paper we briefly indicate how a technique for the reduction of the solution of differential-difference equations with one time-lag to the solution of systems of ordinary differential equations can be extended to the more complex situation involving different time-lags.

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A NOTE ON THE COMPUTATIONAL SOLUTION OF A SYSTEM OF
DIFFERENTIAL EQUATIONS WITH VARYING TIME-LAGS

1. INTRODUCTION

In this paper we wish briefly to indicate how a technique for the reduction of the solution of differential-difference equations with one time-lag to the solution of systems of ordinary differential equations can be extended to the more complex situation involving different time-lags. This method is of some importance in connection with the study of more realistic models of chemotherapy, of the type studied in [5], [6].

2. DESCRIPTION OF METHOD

Consider a system of two differential-difference equations with different, but commensurable, time-lags, as and bs , where $s > 0$ and a and b are positive integers:

$$(2.1) \quad \begin{aligned} y'(t) &= f(t, y(t), y(t - as), z(t), z(t - bs)), \\ z'(t) &= g(t, y(t), y(t - as), z(t), z(t - bs)), \end{aligned}$$

with the initial conditions $y(t) = z(t) = 0$, $t \leq 0$.

Let us now present an algorithm which obtains the numerical solution of (2.1) by means of the solution of sequences of ordinary differential equations of increasing order. The case of one time-lag was treated in [1], [2].

Introduce the functions

$$(2.2) \quad y_n(t) = y(t + ns),$$

$$z_n(t) = z(t + ns),$$

with $n = -b, -b + 1, -b + 2, \dots, 0, \dots, N$, where N is determined by the range of integration, and

$$0 \leq t \leq s.$$

To begin with, we solve numerically the following system of ordinary differential equations:

$$(2.3) \quad \begin{array}{ll} y'_{-b} = 0, & z'_{-b} = 0, \\ y'_{-b+1} = 0, & z'_{-b+1} = 0, \\ \vdots & \vdots \\ y'_{-1} = 0, & z'_{-1} = 0, \\ y'_0 = f(t, y_0, y_{-a}, z_0, z_{-b}), & z'_0 = g(t, y_0, y_{-a}, z_0, z_{-b}), \end{array}$$

in the range $0 \leq t \leq s$, with the initial values

$$y_i(0) = z_i(0) \quad \text{for all } i.$$

Note that

$$(2.4) \quad y_1(0) = y_0(s), \quad z_1(0) = z_0(s).$$

In the next round, we adjoin to the system in (2.3) the equations

$$\begin{aligned}
 (2.5) \quad y_1^i &= f(t + s, y_1, y_{-a+1}, \dots, z_1, z_{-b+1}), \\
 & y_1(0) = y_0(s), \\
 z_1^i &= g(t + s, y_1, y_{-a+1}, \dots, z_1, z_{-b+1}), \\
 & z_1(0) = z_0(s).
 \end{aligned}$$

Integrating this larger system over the interval $[0, s]$, we obtain two more initial values

$$(2.6) \quad y_2(0) = y_1(s), \quad z_2(0) = z_1(s).$$

Generally, in the $(i + 1)$ -st round of iteration, we add to the i -th system the equations

$$\begin{aligned}
 (2.7) \quad y_1^i &= f(t + is, y_1, y_{-a+1}, z_1, z_{-b+1}), \quad y_1(0) = y_{i-1}(s), \\
 z_1^i &= f(t + is, y_1, y_{-a+1}, z_1, z_{-b+1}), \quad z_1(0) = z_{i-1}(s).
 \end{aligned}$$

3. DISCUSSION

In many cases the time-lags, λ_1 and λ_2 , will not be commensurable. If we do not wish to use the usual storage technique for the numerical integration of (2.1), we can approximate to λ_1 and λ_2 by rational fractions p_1/q , p_2/q in such a way that

$$(3.1) \quad \left(\lambda_1 - \frac{p_1}{q}\right)^2 + \left(\lambda_2 - \frac{p_2}{q}\right)^2$$

is as small as possible, with $q \leq N$. If q is too large, the systems of equations described in Sec. 2 become unwieldy.

In general, we can cut down on the dimension of these differential equations by applying the preceding technique over an interval $[0, T_1]$ and then using the technique of differential approximation [3], [4] to replace storage of the "initial values" over $[T_1, T_1 + s]$.

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