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A note on existence and uniqueness of solutions of neutral functional-differential equations with state-dependent delays

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Abstract. Existence and uniqueness theorem for state-dependent delay-differential equations of neutral type is given. This theorem generalizes previous results by Grimm and the author.

Keywords: functional-differential equation, existence and uniqueness of solutions

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Consider the scalar initial-value problem for state-dependent delay-differential equations of neutral type

$$(1)\qquad \begin{aligned} y'(t) &= f(t, y(t), y(\alpha(t, y(t))), y'(\beta(t, y(t)))), && t \in [a, b],\\ y(t) &= g(t), && t \in [\gamma, \alpha], \end{aligned}$$

$\gamma \leq a < b$, where $\gamma \leq \alpha(t, y) \leq t$, $\gamma \leq \beta(t, y) \leq t$, and g is a given initial function. We assume the following:

(i) g and g' are Lipschitz-continuous with constants L_g and $L_{g'}$ respectively;
(ii) $f(a, g(a), g(\alpha(a, g(a))),\ g'(\beta(a, g(a)))) = g'(a)$, where $g'(a)$ denotes the left hand side derivative.

Moreover, suppose that in their respective domains f, α and β satisfy the following conditions with nonnegative Lipschitz constants:

(iii) $|f(t_1, y_1, u_1, z_1) - f(t_2, y_2, u_2, z_2)|$
$\leq L_1(|t_1 - t_2| + |y_1 - y_2| + |u_1 - u_2|) + L_2|z_1 - z_2|$, $L_2 < 1$;
(iv) $|\alpha(t_1, y_1) - \alpha(t_2, y_2)| \leq A_1|t_1 - t_2| + A_2|y_1 - y_2|$;
(v) $|\beta(t_1, y_1) - \beta(t_2, y_2)| \leq B_1|t_1 - t_2| + B_2|y_1 - y_2|$.

The problem (1) with $\gamma = a$ was studied by Grimm [1]. He proved an existence result for (1) assuming that f is bounded by some constant M, $L_2 < 1$, and $B_1 + B_2M \leq 1$. He also proved a uniqueness result when β is independent of y. In the recent paper [2] the author relaxed this very restrictive assumption at the expense of the additional condition $L_2(1 + B_1 + B_2G) < 1$, where G is some constant depending on f and g. This condition means that the dependence of f on the last argument is not too strong. It is the purpose of this note to improve further the results given in [1] and [2]. We prove the existence and uniqueness theorem for (1) (with β depending both on t and y), where the inequality $L_2(1+B_1+B_2G)<1$ is replaced by the weaker conditions $L_2<1$ and $B_1+B_2G\le 1$.

For any continuous functions y and z on $[\gamma,b]$, put

$$F(t,y,z):=f(t,y(t),y(\alpha(t,y(t))),z(\beta(t,y(t)))),$$

and define

$$M:=\sup\{|F(t,0,0)|:t\in[a,b]\};\qquad C_1:=(g'_{[\gamma,a]}+M)/(1-L_2);$$
$$C_2:=2L_1/(1-L_2);\qquad Y:=(g_{[\gamma,a]}+C_1/C_2)\exp((b-a)C_2);$$
$$Z:=\max\{C_1+C_2Y,(M+2L_1Y)/(1-L_2)\};\qquad G:=\max\{L_g,Z\};$$
$$D:=\max\{L_{g'},L_1(1+G(1+A_1+A_2G))/(1-L_2(B_1+B_2G))\}.$$

Here $x_{[c,d]}:=\sup\{|x(t)|:t\in[c,d]\}$ for any function x. We have the following:

Theorem. *Assume that* (i)–(v) *hold,* $L_2<1$, *and* $B_1+B_2G\le 1$. *Then* (1) *has a solution* y *whose derivative is Lipschitz-continuous. Moreover, this solution is unique in the space of continuously differentiable functions on* $[\gamma,a]$.

Proof: For $h\in J:=\{h\mid h=(b-a)/n,\ n\ge n_0\}$, where n_0 is a positive integer, put $t_i=a+ih$, $i=0,1,\dots,n$, and as in [2] define the modified Euler sequences $\{y_h\}_{h\in J}$ and $\{z_h\}_{h\in J}$ by

$$\begin{aligned}y_h(t_i+rh)&=y_h(t_i)+rhz_h(t_i),\\ z_h(t_i+rh)&=(1-r)z_h(t_i)+rz_h(t_{i+1}),\\ z_h(t_{i+1})&=F(t_{i+1},y_h,z_h),\end{aligned}\tag{2}$$

$i=0,1,\dots,n-1$, $r\in(0,1]$, where $y_h(t)=g(t)$ and $z_h(t)=g'(t)$ for $t\in[\gamma,a]$. Note that (2) is, in general, implicit in z_h, but in view of $L_2<1$ it has a unique solution (y_h,z_h) for any $h\in J$. We will first show that $\{y_h\}_{h\in J}$ and $\{z_h\}_{h\in J}$ are relatively compact in the space $C[\gamma,b]$ of continuous functions on $[\gamma,b]$. Proceeding as in [2] it follows that $\{y_h\}_{h\in J}$ and $\{z_h\}_{h\in J}$ are uniformly bounded by Y and Z, respectively, and that $\{y_h\}_{h\in J}$ are uniformly Lipschitz-continuous with the constant G. The proof that $\{z_h\}_{h\in J}$ are also uniformly Lipschitz-continuous is more delicate than in [2]. The proof is by induction. Assume that

$$|z_h(t_1)-z_h(t_2)|\le D|t_1-t_2|,\qquad t_1,t_2\in[\gamma,t_i],\tag{3}$$

and we will show that this inequality is also true for $t_1,t_2\in[\gamma,t_{i+1}]$ (obviously (3) holds for $t_1,t_2\in[\gamma,t_0]$). Define on $[\gamma,t_{i+1}]$ the iterations $z_h^{[\nu]}(t)=z_h(t)$ for $t\in[\gamma,t_i]$, $\nu=0,1,\dots$, and

$$\begin{aligned}z_h^{[0]}(t_i+rh)&=z_h(t_i),\\ z_h^{[\nu+1]}(t_{i+1})&=F(t_{i+1},y_h,z_h^{[\nu]}),\\ z_h^{[\nu+1]}(t_i+rh)&=(1-r)z_h(t_i)+rz_h^{[\nu+1]}(t_{i+1}),\end{aligned}$$

$r \in (0,1]$, $\nu = 0,1,\ldots$. It follows by the induction with respect to ν that $\{z_h^{[\nu]}\}_{\nu=0}^{\infty}$ are uniformly bounded by Z and uniformly Lipschitz-continuous on $[\gamma, t_{i+1}]$ with the same constant D. Indeed, this is true for $\nu = 0$ and, assuming that it is true for ν, routine manipulations yield

$$|z_h^{[\nu+1]}(t_{i+1})| \le M + 2L_1Y + L_2Z \le Z,$$

and

$$|z_h^{[\nu+1]}(t_{i+1}) - z_h^{[\nu+1]}(t_i)| \le L_1(1 + G(1 + A_1 + A_2G))h + L_2D(B_1 + B_2G)h \le Dh.$$

The last inequality follows from the definition of D. In view of the Ascoli-Arzela theorem the sequence $\{z_h^{[\nu]}\}_{\nu=0}^{\infty}$ is relatively compact in $C[\gamma, t_{i+1}]$ and since the solution (y_h, z_h) of (2) is unique, we have $z_h^{[\nu]} - z_{h[\gamma,t_{i+1}]} \to 0$ as $\nu \to \infty$. Therefore, $\{z_h\}_{h\in J}$ are uniformly Lipschitz-continuous on $[\gamma, t_{i+1}]$ with the same constant D. By induction with respect to i, this is also true on $[\gamma, b]$. Consequently, $\{y_h\}_{h\in J}$ and $\{z_h\}_{h\in J}$ are relatively compact in $C[\gamma, b]$ and from this point the proof is exactly the same as the proof of Theorem 2 in [2]. We prove the existence by showing that there is a subsequence of $\{y_h\}_{h\in J}$ convergent to the solution y of (1) and we prove the uniqueness by contradiction. □

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