Controllability of abstract fractional differential evolution equations with nonlocal conditions

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Abstract

In this paper, the controllability of a class of fractional differential evolution equations with nonlocal conditions is investigated. Sufficient conditions which guarantee the controllability of fractional differential evolution equations are obtained. The method used is the contraction mapping principle and Krasnoselskii theorem. A fractional distributed parameter control system is provided to illustrate the applications of our results. ©2017 All rights reserved.

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1. Introduction

Fractional calculus is an area having a long history whose infancy dates back to three hundred years. Later on, with the development of computer technology and fractional calculus theory, fractional differential equations have numerous applications in natural sciences and engineering. For instance, fractional differential equations with nonlocal conditions are often used for modeling various phenomena arising in control, electrochemistry, viscoelasticity, and electromagnetics.

During the past few years, a great deal of interest in existence of solutions to various classes of fractional differential and difference equations has been shown. We refer the reader to the papers [1–11, 14–17] and the references cited therein. In particular, many authors investigated the existence of mild solutions of fractional differential equations in Banach space by semigroup techniques and fixed point theorems; see, e.g., the papers [4, 5, 7, 9–11, 14, 16, 17]. Thereinto, Shu and Wang [14] studied the existence and uniqueness of mild solutions for a differential equation with nonlocal conditions in a...
Banach space $X$

\[
\begin{aligned}
&C^\alpha_D u(t) = A u(t) + f(t, u(t)) + \int_0^t q(t-s) g(s, u(s)) ds, \quad t \in [0, T], \\
u(0) + m(u) = u_0 \in X, \quad u'(0) + n(u) = u_1 \in X,
\end{aligned}
\]

(1.1)

where $C^\alpha_D$ is Caputo’s fractional derivative of order $1 < \alpha < 2$, $A : D(A) \subset X \to X$ is a sectorial operator of type $(M, \theta, \alpha, \mu)$, $f, g : [0, T] \times X \to X$ are continuous functions, and nonlocal maps $m, n : X \to X$ are continuous. The method relies on the fixed point theorems and solution operator theorems. By introducing solution operators, the authors gave a reasonable definition of mild solutions, and they also provided estimates on solution operators which will be needed to study the existence results. Because of the complexity, the analysis of distributed parameter systems is difficult. It is well known that controllability and observability are important for the analysis and design of distributed parameter systems. Under certain assumptions, partial differential equations can be written to ordinary differential equations in a functional space. More precisely, the controllability problem for distributed parameter systems can be transformed into that of lumped parameter systems; see Sakthivel et al. [12, 13].

Inspired by the previous papers and many known results reported in [12–14], we study controllability of a class of fractional differential evolution equations with nonlocal conditions

\[
\begin{aligned}
&C^\alpha_D x(t) = A x(t) + f(t, x(t)) + \int_0^t h(t, s, x(s)) ds + B u(t), \quad t \in I = [0, b], \\
x(0) + g_1(x) = x_0 \in X, \quad x'(0) + g_2(x) = x'_0 \in X,
\end{aligned}
\]

(1.2)

where $C^\alpha_D$ is Caputo’s fractional derivative of order $1 < \alpha < 2$, $A : D(A) \subset X \to X$ is a sectorial operator of type $(M, \theta, \alpha, \mu)$, $f : I \times X \times X \to X$ and $h : \Delta \times X \to X$ are continuous functions, $\Delta = \{(t, s) \in I \times I, 0 \leq t \leq s \leq b\}$, nonlocal maps $g_1, g_2 : X \to X$ are continuous, $B : U \to X$ is a bounded linear operator, control function $u(\cdot) \in L^2(0,1)$, $U$ is a Banach space, and $X$ is a Banach space endowed with the norm $\| \cdot \|$.

Equation (1.2) has a more general form than equation (1.1). Nonlocal conditions $x(0) + g_1(x) = x_0$ and $x'(0) + g_2(x) = x'_0$ are more realistic than the local ones in treating physical problems. The problem considered in this paper has a strong physical background; see, for instance, fractional integrodifferential equations appeared in the study of dynamical systems when the controlled systems are described by fractional equations.

The remainder of this paper is organized as follows. In Section 2, we present some necessary definitions and lemma that will be used to prove our main results, and we also introduce a suitable definition of mild solution of fractional evolution equation (1.2). The main results are given in Section 3. Finally, in Section 4, an example is provided to demonstrate the effectiveness of our results.

2. Preliminaries

We need the following basic definitions and properties from the fractional calculus.

**Definition 2.1.** The fractional integral of order $\gamma$ with the lower limit zero for a function $f$ is defined as

\[
\Gamma^\gamma f(t) = \frac{1}{\Gamma(\gamma)} \int_0^t (t-s)^{\gamma-1} f(s) ds, \quad t > 0, \quad \gamma > 0,
\]

provided that the right side is point-wise defined on $[0, +\infty)$, where $\Gamma(\cdot)$ is the gamma function.

**Definition 2.2.** The Caputo derivative of the order $\gamma$ for a function $f \in C^n[0, \infty)$ is defined by

\[
C^\gamma D f(t) = \frac{1}{\Gamma(n-\gamma)} \int_0^t (t-s)^{n-\gamma-1} f^{(n)}(s) ds = \Gamma^{n-\gamma} f^{(n)}(t), \quad t > 0, \quad n-1 < \gamma < n.
\]
**Remark 2.3.** If $f$ is an abstract function with values in $X$, then integrals which appear in Definitions 2.1 and 2.2 are taken in Bochner’s sense.

**Definition 2.4 ([14]).** Let $A : D(A) \subseteq X \to X$ be a closed linear operator. $A$ is said to be a sectorial operator of type $(M, \theta, \alpha, \mu)$ if there exist $0 < \theta < \pi/2$, $M > 0$, and $\mu \in \mathbb{R}$ such that the $\alpha$-resolvent of $A$ exists outside the sector

$$\mu + S_\theta = \{\mu + \lambda^\alpha : \lambda \in \mathbb{C}, |\text{Arg}(-\lambda^\alpha)| < \theta\}$$

and

$$\|(\lambda^\alpha I - A)^{-1}\| \leq \frac{M}{|\lambda^\alpha - \mu|}, \quad \lambda^\alpha \notin \mu + S_\theta.$$

**Theorem 2.8 (Krasnosel’skii theorem).** Assume that $D$ is a closed convex and nonempty subset of a Banach space $X$. Let $Q_1$ and $Q_2$ be two operators such that

1. $Q_1x_1 + Q_2x_2 \in D$ whenever $x_1, x_2 \in D$;
2. $Q_1$ is a contraction mapping;
3. $Q_2$ is compact and continuous.

Then there exists a $z \in D$ such that $z = Q_1z + Q_2z$. 

**Proposition 2.6.** Operators $S_\alpha(t), K_\alpha(t),$ and $T_\alpha(t)$ have the following properties:

1. there exists a constant $M_1 > 0$ such that

$$\sup_{t \in I} \|S_\alpha(t)\| \leq M_1, \quad \sup_{t \in I} \|K_\alpha(t)\| \leq M_1, \quad \sup_{t \in I} \|T_\alpha(t)\| \leq M_1;$$

2. for all $\epsilon > 0$ and $t_1, t_2 \in (0, b]$, there exists a constant $\delta > 0$ such that for $|t_1 - t_2| < \delta$,

$$\|S_\alpha(t_1) - S_\alpha(t_2)\| \leq \epsilon, \quad \|K_\alpha(t_1) - K_\alpha(t_2)\| \leq \epsilon, \quad \|T_\alpha(t_1) - T_\alpha(t_2)\| \leq \epsilon.$$
3. Main results

In order to demonstrate the main results, we list the following reasonable hypotheses.

\((H_1)\) For any \(u_1, u_2, v_1, v_2 \in X\), there exist three functions \(\mu_1, \mu_2, \nu_1 \in L(I, \mathbb{R}^+)\) such that

\[
\|f(t, u_1, v_1) - f(t, u_2, v_2)\| \leq \mu_1(t)\|u_1 - u_2\| + \mu_2(t)\|v_1 - v_2\|
\]

and
\[
\|h(t, s, u_1) - h(t, s, u_2)\| \leq \nu_1(t)\|u_1 - u_2\|.
\]

\((H_2)\) \(g_1, g_2 : X \to D(\mathcal{A})\) are continuous. For any \(u_1, u_2 \in X\), there exist two constants \(N_1\) and \(N_2\) such that

\[
\|g_1(u_1) - g_1(u_2)\| \leq N_1\|u_1 - u_2\| \quad \text{and} \quad \|g_2(u_1) - g_2(u_2)\| \leq N_2\|u_1 - u_2\|.
\]

\((H_3)\) The linear operator \(W\) from \(L^2(I, U)\) into \(X\) defined by \(Wu = \int_0^b T_\alpha(b - s)Bu(s)ds\) induces an invertible operator \(W^{-1}\) defined on \(L^2(I, U)/\text{Ker}W\), and there exists a constant \(K > 0\) such that \(\|BW^{-1}\| \leq K\).

\((H_4)\) For any \(k > 0\), there exists a function \(\mu_k \in L(I, \mathbb{R}^+)\) such that \(\sup_{\|x\| \leq k} \|f(t, x, (Hx))\| \leq \mu_k(t)\).

**Theorem 3.1.** Suppose that hypotheses \((H_1)-(H_3)\) hold. Then system (1.2) is controllable on \(I\) provided that

\[
\frac{L - KN_1}{K} + M_1Lb < 1,
\]

where

\[
L = KN_1 + KM_1N_1 + KM_1N_2 + KM_1 \left( \int_0^b \mu_1(s)ds + \int_0^b \mu_2(s)ds \times \int_0^b \nu_1(s)ds \right).
\]

**Proof.** Using \((H_3)\), for an arbitrary function \(x(\cdot)\), we define the control \(u\) and operator \(Q : C(I, X) \to C(I, X)\) by

\[
u(t) = W^{-1} \left[ y_0 - g_1(x) - S_\alpha(b)(x_0 - g_1(x)) - K_\alpha(b)(x_0' - g_2(x)) - \int_0^b T_\alpha(b - s)f(s, x(s), (Hx)(s))ds \right](t)
\]

and

\[(Qx)(t) = S_\alpha(x_0 - g_1(x)) + K_\alpha(t)(x_0' - g_2(x)) + \int_0^t T_\alpha(t - s)f(s, x(s), (Hx)(s)) + Bu(s)ds,\]

respectively. For any \(x_1, x_2 \in C(I, X)\), by \((H_1)-(H_3)\) and (3.2), we get

\[
\|Bu_1(t) - Bu_2(t)\| \leq \|BW^{-1}[y_0 - g_1(x_1) - S_\alpha(b)(x_0 - g_1(x_1)) - K_\alpha(b)(x_0' - g_2(x_1)) - \int_0^b T_\alpha(b - s)f(s, x_1(s), (Hx_1)(s))ds](t)
\]

\[
- BW^{-1}[y_0 - g_1(x_2) - S_\alpha(b)(x_0 - g_1(x_2)) - K_\alpha(b)(x_0' - g_2(x_2)) - \int_0^b T_\alpha(b - s)f(s, x_2(s), (Hx_2)(s))ds](t)
\]

\[
\leq K\|g_1(x_1) - g_1(x_2)\| + KM_1\|g_1(x_1) - g_1(x_2)\| + KM_1\|g_2(x_1) - g_2(x_2)\|
\]

\[
+ KM_1 \int_0^b \mu_1(s)x_1 - x_2 ds + KM_1 \int_0^b \mu_2(s)((Hx_1)(s) - (Hx_2)(s))ds
\]

\[
\leq (KN_1 + KM_1N_1 + KM_1N_2)\|x_1 - x_2\|
\]

\[
+ KM_1 \left( \int_0^b \mu_1(s)ds + \int_0^b \mu_2(s)ds \times \int_0^b \nu_1(s)ds \right)\|x_1 - x_2\|
\]

\[
\leq L\|x_1 - x_2\|
\]
and
\[
\|(Q_1 x)(t) - (Q_2 x)(t)\| \\
\leq \|S_\alpha(t)(x_0 - g_1(x_1)) + \mathcal{K}_\alpha(t)(x_0' - g_2(x_1)) + \int_0^t \mathcal{T}_\alpha(t - s)[f(s, x_1(s), (Hx_1)(s)) + Bu_1(s)] ds \\
- \mathcal{K}_\alpha(t)(x_0' - g_2(x_2)) - \int_0^t \mathcal{T}_\alpha(t - s)[f(s, x_2(s), (Hx_2)(s)) + Bu_2(s)] ds \|
\leq \left( \frac{L - KN_1}{K} + M_1 L b \right) \|x_1 - x_2\|.
\]

By virtue of (3.1), the operator Q is a contraction mapping, and so Q has a fixed point. It follows from (H3) that the fixed point is a mild solution of control problem (1.2) and \(x(b) + g_1(x) = y_0\). Therefore, system (1.2) is controllable on I.

**Theorem 3.2.** Let hypotheses (H2)-(H4) be satisfied and suppose that
\[
M_1(N_1 + N_2) < 1
\]
and
\[
M_1\left(\|x_0\| + \|x_0'\| + N_1 r + \|g_1(0)\| + N_2 r + \|g_2(0)\|\right) \\
+ b M_1 \left(\|y_0\| + N_1 r + \|g_1(0)\| + M_1\|x_0\| + M_1 N_1 r + M_1\|g_1(0)\| + M_1\|x_0'\|\right) \\
+ M_1 N_2 r + M_1\|g_2(0)\| + M_1 \int_0^b \mu_r(s) ds < r
\]
for some constant \(r > 0\). Then system (1.2) is controllable on I.

**Proof.** Set \(B_r = \{x \in X : \|x\| \leq r\}\). For \(x \in B_r\), define the operator \(Q = Q_1 + Q_2\), where
\[
(Q_1 x)(t) = S_\alpha(t)(x_0 - g_1(x)) + \mathcal{K}_\alpha(t)(x_0' - g_2(x))
\]
and
\[
(Q_2 x)(t) = \int_0^t \mathcal{T}_\alpha(t - s)[f(s, x(s), (Hx)(s)) + Bu(s)] ds.
\]

Then
\[
\|(Q_1 x)(t)\| \leq M_1\|x_0 - g_1(x)\| + M_1\|x_0' - g_2(x)\| \leq M_1(\|x_0\| + \|x_0'\| + N_1 r + \|g_1(0)\| + N_2 r + \|g_2(0)\|)
\]
and
\[
\|(Q_2 y)(t)\| \leq M_1 \int_0^t \left\|f \left(s, y(s), \int_0^s h(s, \tau, y(\tau)) d\tau \right) \right\| ds + M_1 \int_0^t \|Bu(s)\| ds \\
\leq M_1 \int_0^t \mu_r(s) ds + M_1 \int_0^t \|Bu(s)\| ds \\
\leq M_1 \int_0^b \mu_r(s) ds + b M_1 \left(\|y_0\| + N_1 r + \|g_1(0)\| + M_1\|x_0\| + M_1 N_1 r + M_1\|g_1(0)\| \\
+ M_1\|x_0'\| + M_1 N_2 r + M_1\|g_2(0)\| + M_1 \int_0^b \mu_r(s) ds \right).
\]

Using (3.4), we deduce that \(\|(Q_1 x)(t) + (Q_2 y)(t)\| \leq r\). That is, for any \(x, y \in B_r\), \(Q_1 x + Q_2 y \in B_r\). Next, for any \(x, y \in B_r\), we have
\[
\|(Q_1 x)(t) - (Q_1 y)(t)\| \leq \|S_\alpha(t)(x_0 - g_1(x)) + \mathcal{K}_\alpha(t)(x_0' - g_2(x)) - S_\alpha(t)(x_0 - g_1(y)) - \mathcal{K}_\alpha(t)(x_0' - g_2(y))\| \\
\leq M_1\|g_1(y) - g_1(x)\| + M_1\|g_2(y) - g_2(x)\|
\]
Define \( t \parallel \{ \cdot \} \),\( \parallel \cdot \parallel \), and \( \parallel \cdot \parallel \).

Thus we conclude that

\[
\text{By (3.6) and the Lebesgue dominated convergence theorem, it is easy to see that}
\]

\[
\text{for all } t \in [0, b], \text{ we obtain}
\]

\[
\left\| (Q_2x_n)(t) - (Q_2x)(t) \right\| \leq \left\| BW^{-} \left[ y_0 - g_1(x_n) - S_\alpha(b)(x_0 - g_1(x_n)) - \mathcal{K}_\alpha(b)(x'_0 - g_2(x_n)) \right. \right.
\]

\[
\left. - \int_0^t \mathcal{J}_\alpha(b)f(s, x_n(s), (Hx_n)(s))ds + Bu_n(s) \right] ds
\]

\[
- BW^{-} \left[ y_0 - g_1(x) - S_\alpha(b)(x_0 - g_1(x)) - \mathcal{K}_\alpha(b)(x'_0 - g_2(x)) \right. \right.
\]

\[
\left. - \int_0^t \mathcal{J}_\alpha(b)f(s, x(s), (Hx)(s))ds \right] (t)
\]

\[
\leq K\|g_1(x) - g_1(x_n)\| + K\|S_\alpha(b)g_1(x) - S_\alpha(b)g_1(x_n)\|
\]

\[
+ K\|\mathcal{K}_\alpha(b)g_2(x) - \mathcal{K}_\alpha(b)g_2(x_n)\|
\]

\[
+ K\int_0^b \mathcal{J}_\alpha(b - s)\|f(s, x(s), (Hx)(s)) - f(s, x_n(s), (Hx_n)(s))\|ds
\]

\[
\leq KN_1\|x_n - x\| + KM_1N_1\|x_n - x\| + KM_1N_2\|x_n - x\|
\]

\[
+ KM_1\int_0^b \|f(s, x(s), (Hx)(s)) - f(s, x_n(s), (Hx_n)(s))\|ds.
\]

By (3.6) and the Lebesgue dominated convergence theorem, it is easy to see that

\[
\left\| (Q_2x_n)(t) - (Q_2x)(t) \right\| \to 0, \quad n \to \infty.
\]

Thus we conclude that \( Q_2 \) is continuous. In order to present the compactness of \( Q_2 \), we prove that \( \{(Q_2x)(t) : x \in B_r \} \) is relatively compact for all \( t \in I \) and uniformly bounded, respectively. It follows from (3.5) that \( \|(Q_2x)(t)\| \leq C \), where \( C \) is a constant. For \( 0 < t_1 < t_2 \leq b \), we obtain

\[
\left\| (Q_2x)(t_1) - (Q_2x)(t_2) \right\| = \left\| \int_0^{t_1} \mathcal{J}_\alpha(t_1 - s) [f(s, x(s), (Hx)(s)) + Bu(s)]ds
\]

\[
+ \int_{t_1}^{t_2} \mathcal{J}_\alpha(t_1 - s) [f(s, x(s), (Hx)(s)) + Bu(s)]ds
\]

\[
- \int_0^{t_2} \mathcal{J}_\alpha(t_2 - s) [f(s, x(s), (Hx)(s)) + Bu(s)] ds \right\|
\]

\[
\leq \int_0^{t_2} \| \mathcal{J}_\alpha(t_1 - s) - \mathcal{J}_\alpha(t_2 - s) \| \| f(s, x(s), (Hx)(s)) + Bu(s) \| ds.
\]
where
\[ I_1 = \int_0^{t_1} \|T_\alpha (t_1 - s)\| f(s, x(s), (Hx)(s)) + Bu(s) \|ds \]
\[ \leq I_1 + I_2, \]

and
\[ I_2 = \int_{t_2}^{t_1} \|T_\alpha (t_1 - s) - T_\alpha (t_2 - s)\| f(s, x(s), (Hx)(s)) + Bu(s) \|ds. \]

Noting that the continuity of the function \( t \to \|T_\alpha (t)\| \) for \( t \in (0, b) \), we have \( \lim_{t_2 \to t_1} I_1 = 0 \). Hence, by the Arzelà–Ascoli theorem, \( Q_2 \) is compact. Then Definition 2.7 and Theorem 2.8 allow us to conclude that (1.2) is controllable on 1.

4. Example

In order to demonstrate applications of our main results obtained in Section 3, we consider the following fractional order distributed parameter control system
\[
\begin{align*}
\frac{\partial^\alpha u(t, x)}{\partial t^\alpha} &= \frac{\partial^2 u(t, x)}{\partial x^2} + f \left( t, u(t, x), \int_0^t h(t, s, u(s, x)) ds \right) + Bu(t, x), \\
u(t, 0) &= u(t, \pi) = 0, \quad u'(t, 0) = u'(t, \pi) = 0, \\
u(t, 0) + \sum_{i=1}^k a_i u(t_i, x) &= u_0(x), \quad u'(t, 0) + c_1 u(t_1, x) = u_1(x),
\end{align*}
\]
where \( t \in I = [0, b] \), \( t_i \in (0, b) \), \( i = 1, 2, \ldots, k \), \( x \in [0, \pi] \), \( 1 < \alpha < 2 \), and \( B : U \to X \) is a bounded linear operator. Let \( X = L^2([0, \pi]) \) and define the operator \( A : D(A) \subseteq X \to X \)
\[
A(u) = \frac{\partial^2 u}{\partial x^2}, \quad D(A) = \left\{ u \in X : \frac{\partial u}{\partial x} \frac{\partial^2 u}{\partial x^2} \in X \right\}.
\]
Obviously, \( A \) is densely defined in \( X \) and is the infinitesimal generator of a resolvent family \( \{T_\alpha (t)\}_{t \geq 0} \) on \( X \). For \( u, v \in C(I, X) \), define
\[
f(t, u, Hu) = \frac{|u(t, x)|}{(6 + e^t)(1 + |u(t, x)|)} + \frac{1}{10 + e^t} \int_0^t \frac{e^{2s}}{2 \sqrt{2 + |u(s, x)|}} ds,
\]
\[
f(t, v, Hv) = \frac{|v(t, x)|}{(6 + e^t)(1 + |v(t, x)|)} + \frac{1}{10 + e^t} \int_0^t \frac{e^{2s}}{2 \sqrt{2 + |v(s, x)|}} ds,
\]
\[
g_1(u)(x) = \sum_{i=1}^k a_i u(t_i, x), \quad \text{and} \quad g_2(u)(x) = c_1 u(t_1, x).
\]
Then we conclude that fractional integrodifferential equation (1.2) serves as an abstract formulation of fractional distributed parameter control system (4.1),
\[
\|f(t, u, Hu) - f(t, v, Hv)\| \leq \frac{\|u - v\|}{6 + e^t} + \frac{\|v(t, x)\|}{10 + e^t} \int_0^t \frac{e^{2s}}{2 \sqrt{2 + |u(s, x)|}} ds - \int_0^t \frac{e^{2s}}{2 \sqrt{2 + |v(s, x)|}} ds + \frac{1}{6} \|u - v\| + \frac{1}{10} \|Hu - Hv\|,
\]
\[
\leq \|u - v\| + \frac{1}{6} \|Hu - Hv\|.
\]
and
\[
\|h(t, s, u) - h(t, s, v)\| \leq e^{2t} \left\| \frac{1}{2\sqrt{2} + |u(t, x)|} - \frac{1}{2\sqrt{2} + |v(t, x)|} \right\| \leq \frac{e^{2t}}{8} |u - v| \leq \frac{e^{2t}}{8} |u - v|.
\]

Hence, we can choose \( \mu_1(t) = 1/6 \), \( \mu_2(t) = 1/10 \), \( \nu_1(t) = e^{2t}/8 \), \( N_1 = \sum_{i=1}^{k} a_i \), and \( N_2 = c_1 \). Assume now that (H3) holds. With the choices of \( b, K \), and \( M_1 \), inequality (3.1) can be satisfied. Therefore, by Theorem 3.1, system (1.2) is controllable on \( I \), and thus fractional distributed parameter control system (4.1) is controllable on \( I \).

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