Existence and stability for fractional parabolic integro-partial differential equations with fractional Brownian motion and nonlocal condition

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Abstract: In this paper, a nonlinear fractional parabolic stochastic integro-partial differential equations with nonlocal effects driven by a fractional Brownian motion is considered. In particular, first we have formulated the suitable solution form for the fractional partial differential equations with nonlocal effects driven by fractional Brownian motion using a parabolic transform. Next, the existence and uniqueness of solutions are obtained for the fractional stochastic partial differential equations without any restrictions on the characteristic forms when the Hurst parameter of the fractional Brownian motion is less than half. Further, we investigate the stability of the solution for the considered problem. The required result is established by means of standard Picard’s iteration.

Subjects: Differential Equations; Mathematical Analysis; Stochastic Models & Processes

Keywords: nonlinear fractional integro-partial differential equations; fractional Brownian motion with Hurst parameter less than half; nonlocal Cauchy problem; stability

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PUBLIC INTEREST STATEMENT

Fractional parabolic partial differential equations are found to be an effective tool to describe certain physical phenomena such as diffusion processes, visco-elasticity theories, filtration, phase transition, electromagnetism, acoustics, electrochemistry, cosmology, and biochemistry. However, no work has been reported in the literature regarding the existence and uniqueness of solutions for nonlinear fractional parabolic integro-partial differential equations with nonlocal effects driven by a fractional Brownian motion when the Hurst parameter of the fractional Brownian motion is less than half. Motivated by these facts, in this note, we studied the existence, uniqueness and stability of solutions for the fractional stochastic partial differential equations without any restrictions on the characteristic forms when the Hurst parameter of the fractional Brownian motion is less than half.
1. Introduction

Fractional differential equations has many important applications in several areas of science and engineering. Recently, many researchers have found that it describes several physical phenomena more exactly than differential equations without fractional derivative. On the other hand, the noises arise in mathematical finance, physics, telecommunication networks, hydrology, medicine etc., can be modeled by fractional Brownian motions (Baudoin, Nualart, Ouyang, & Tindel, 2016; Grecksch & Anh, 1999; Nualart & Ouknine, 2002; Maslowski & Nualart, 2003; Tindel, Tudor, & Viens, 2003). More and more work has been devoted to the investigation of fractional differential equations driven by fractional Brownian motions (Arthi, Park, & Jung, 2016; Balasubramaniam, Vemburasan, & Senthilkumar, 2014; Boudaoui, Caraballo, & Ouahab, 2016; Diop, Ezzinbi, & Mbaye, 2015; Hamdy, 2015; Ren, Wang, & Hu, 2017; Sathiyara & Balasubramaniam, 2017; Tamilalagan & Balasubramaniam, 2017a, b). On the other hand, fractional parabolic partial differential equations are found to be an effective tool to describe certain physical phenomena such as diffusion processes, visco-elasticity theories, filtration, phase transition, electromagnetism, acoustics, electrochemistry, cosmology, and biochemistry. However, no work has been reported in the literature regarding the existence and uniqueness of solutions for nonlinear fractional parabolic-integro partial differential equations with nonlocal effects driven by a fractional Brownian motion when the Hurst parameter of the fractional Brownian motion is less than half. Motivated by these facts, in this note, we will consider the following nonlinear fractional parabolic stochastic integro partial differential equations in the form

\[
\frac{\partial^\alpha u(x, t)}{\partial t^\alpha} = Lu(x, t) + f_1(x, t, W(x, t)) + \int_0^t K_1(t, s)f_2(x, s, W(x, s)) \, ds + \int_0^t \int_{\mathbb{R}^n} K_2(x, y, t, s)f_3(y, s, W(y, s)) \, dy \, ds + g(x, t)B_H(t),
\]

with nonlocal initial condition

\[
u(x, 0) = q(x) + \sum_{i=1}^p \zeta_i u(x, t_i),
\]

where \( W = (w_1, \ldots, w_r) \), \( w_j \) is of the form \( D^q u \), for some \( q, \) \(|q| \leq 2m-1, j = 1, \ldots, r, 0 < \alpha \leq 1, L = \sum_{|\alpha| = 2m} q(x)D^\alpha, D^\alpha = D_1^\alpha \cdots D_r^\alpha, D_j = \frac{\partial}{\partial x_j}, x \in \mathbb{R}^n, \mathbb{R}^n \) is the n-dimensional Euclidean space, \( q = (q_1, \ldots, q_r) \) is an n-dimensional multi-index, \(|q| = q_1 + \ldots + q_r, j \in J, J = [0, T], T > 0, B_H(t) \) is a fractional Brownian motion with Hurst parameter \( H \in (0, \frac{1}{2}, B_H(0) = E[B_H(t)] = 0, E[B_H(t)B_H(s)] = \frac{1}{2} (|t|^{2H} + |s|^{2H} - |s-t|^{2H}), \) and \( E(X) \) denotes the expectation of a random variable \( X \). It is well known that if \( H = \frac{1}{2} \), then \( B_H(t) \) coincides with the classical Brownian motion \( B(t) \). For \( H \neq \frac{1}{2} \), \( B_H(t) \) is not a semimartingale, so one cannot use the general theory of stochastic calculs for semimartingale on \( B_H(t) \), (Caraballo, Diop, & Ndiaye, 2014; Decreusefond & Üstünel, 1999; Duncan & Nualart, 2009; Elliott & Van Der Hoek, 2003; El-Borai & El-Nadi, 2017; Ren, Hou, & Sakthivel, 2015). It should be mentioned that the kind of equations given in (1.1)–(1.2) can be used to model a variety of anomalous diffusion in continuum mechanics, particularly in connection with the investigation in turbulence. In Section 2, we shall present some properties of the stochastic solutions of the nonlocal Cauchy problem (1.1), (1.2) using a parabolic transform. In Section 3, we shall prove the existence and uniqueness of solutions for the concerned stochastic equations under suitable conditions. In Section 4, we shall investigate the stability of the solution for the considered problem.

2. Parabolic transform and weak solutions

In this section, we present some basic properties and some suitable solution form for the nonlinear fractional parabolic partial differential equations with nonlocal effects driven by fractional Brownian motion using a parabolic transform. In order to obtain the required result, we impose the following conditions on the functions:
(H1) The given function \( \varphi \) is continuous and bounded on \( \mathbb{R}^n \).
(H2) All the coefficients of \( a_q \) are bounded and satisfy a uniform Holder conditions on \( \mathbb{R}^n \).
(H3) The functions \( f_1, f_2, f_3 \) are continuous on \( \mathbb{R}^n \times J \times J' \).
(H4) The function \( g \) is given and bounded on \( \mathbb{R}^n \times J \), also there exist two positive constants \( m \) and \( M \), such that \( m \leq g(x, t) \leq M \) for all \((x, t) \in \mathbb{R}^n \times J \).
(H5) The operator \( \frac{d}{dt} - L \) is uniform parabolic. This mean that \((-1)^{m-1} \sum_{|\alpha|=2m} a_q(x) y^\alpha \geq c |y|^{2m}

for all \( x, y \in \mathbb{R}^n \), |y|^2 = y_1^2 + \ldots + y_n^2 \), and \( c \) is a positive constant.
(H6) The kernel \( K_2 \) and \( \frac{\partial}{\partial t} K_2 \) are continuous on \( J \times J \).
(H7) The kernel \( K_3 \) and \( \frac{\partial}{\partial t} K_3 \) are continuous on \( \mathbb{R}^n \times \mathbb{R}^n \times J \times J \) and \( \int_{\mathbb{R}^n} |K_3| dy, \int_{\mathbb{R}^n} \frac{\partial}{\partial t} K_3 \) exist and continuous bounded on \( \mathbb{R}^n \times J \times J \).
(H8) The function \( \frac{\partial}{\partial t} G(x, t, W(x, t)) \) is continuous and bounded on \( \mathbb{R}^n \times J \times J' \).

Fractional stochastic nonlinear partial differential Equation (1.1), (1.2) can be transformed to the following problem

\[
\begin{align*}
    u(x, t) &= \int_0^\infty \int_{\mathbb{R}^n} \xi_q(\theta) G(x, y, t^\theta) \varphi(y) + \sum_{i=1}^p \zeta_i u(y, t_i^-) \, dy \, d\theta \\
    &\quad + a \int_0^t \int_{\mathbb{R}^n} \theta(t-s)^{s-1} \xi_q(\theta) G(x, y, (t-s)^\theta) \psi(y, s) \, dy \, d\theta \, ds,
\end{align*}
\]

where \( \psi \) is given by

\[
\begin{align*}
    \psi(x, t) &= f_1(x, t, W(x, t)) + F_2 + F_3 + g(x, t) B(t) \, , \\
    F_2(x, t) &= \int_0^t K_2(t, s) f_2(x, s, W(x, s)) \, ds, \\
    F_3(x, t) &= \int_0^t \int_{\mathbb{R}^n} K_3(t, s, x, y) f_3(y, s, W(x, s)) \, dy \, ds,
\end{align*}
\]

\( G \) is the fundamental solution of the parabolic partial differential equation:

\[
\frac{\partial u(x, t)}{\partial t} = Lu(x, t).
\]

The proof of formula (2.1) and the definition of the function \( \xi_q(\theta) \) can be found in El-Borai, El-Nadi, and El-Akabawy (2010) and El-Borai, El-Nadi, and Fouad (2010). The function \( G \) satisfies the following inequalities,

\[
|D^\rho G(x, y, t)| \leq \gamma t^{-\rho} e^{-\nu_2 t},
\]

where \( \rho = |x-y|^{m_1} t^{m_2}, m_1 = \frac{2m}{2m-1}, m_2 = \frac{1}{2m-1}, \nu_1 = -\frac{\nu_2}{2m} \), \( \gamma \), and \( \nu_2 \) are positive constants. The function \( \xi_q \) is a probability density function defined on \((0, \infty)\). According to the properties of \( G \), we can find a positive constant \( M^* \) such that

\[
|\int_{\mathbb{R}^n} G(x, y, t) f(y) \, dy| \leq M^* \sup_x |f(x)|,
\]

for all bounded continuous function \( f \) on \( \mathbb{R}^n \).

Let us suppose that \( cM^* < 1 \), where \( c = \sum_{i=1}^p |c_i| \). For every \( t \in (0, T) \), we define two operators \( \Lambda(t) \) and \( \Lambda^-(t) \) on the set of all bounded continuous function on \( \mathbb{R}^n \), by

\[
\begin{align*}
    (\Lambda(t)f)(x) &= \int_0^\infty \int_{\mathbb{R}^n} G(x, y, t^\theta) \xi_q(\theta) f(y) \, dy \, d\theta, \\
    (\Lambda^-(t)f)(x) &= a \int_0^\infty \int_{\mathbb{R}^n} \theta^{s-1} G(x, y, t^\theta) \xi_q(\theta) f(y) \, dy \, d\theta.
\end{align*}
\]
According to (2.4), the inverse operator \( \psi = [1 - \sum_{i=1}^{p} c_i \Lambda(t_i)]^{-1} \) exists on the set of all bounded continuous functions on \( \mathbb{R}^2 \). From (2.1), one gets, formally,

\[
\sum_{i=1}^{p} c_i u(x, t_i) = \psi \sum_{i=1}^{p} (c_i \Lambda(t_i) \varphi)(x) + a \psi \sum_{i=1}^{p} c_i \int_{0}^{t_i} (\Lambda(t_i - s) \nu)(x, s) \, ds.
\]

If we can find the stochastic process \( \nu \) in a suitable space, then formulas (2.1) and (2.5) will determine the stochastic process \( u \). Let us now try to study Equation (2.2). By a weak solution of Equation (2.1), we mean a triple of adapted processes \( (\mathcal{B}_t, u, \nu) \) on a filtered probability space \( (\Omega, \mathcal{F}, \mathbb{P}, \{\mathcal{F}_t : t \in J\}) \), such that

(a) \( \mathcal{B}_t \) is an \( F_t \)-fractional Brownian motion,

(b) The norm \( \|\nu(\cdot, t)\| = \sup_x |\nu(x, t)| \) exists,

\( \nu \) satisfies Equation (2.2) and \( u \) satisfies equation (2.1). Let

\[
K_h(t, s) = [\Gamma(H + \frac{1}{2})]^{-1}(t - s)^{H-rac{1}{2}} F(H - \frac{1}{2}, H + \frac{1}{2}, 1 - \frac{t}{s}),
\]

where \( \Gamma \) denotes the gamma function and \( F(a, b, c; z) \) is the Gauss hyper geometric function. Define an operator \( K_h \) by \( (K_h \varphi)(s) = \int_{0}^{s} K_h(t, s) \varphi(t) \, dt \). The operator \( K_h \) is an isomorphism from the space of all square integrable functions \( L_2(J) \) onto \( I_0^{H\frac{1}{2}}(L_2(J)) \), where \( I_0^{H\frac{1}{2}}(L_2(J)) \) is the image of \( L_2(J) \) by the fractional integral operator \( I_0^{H\frac{1}{2}} \), where

\[
(I_0^{H\frac{1}{2}} \varphi)(t) = \frac{1}{\Gamma(\alpha)} \int_{0}^{t} (t-s)^{\alpha-1} \varphi(s) \, ds, \quad 0 < \alpha \leq 1.
\]

The inverse operator \( K_h^{-1} \) exists and can be defined on the set of all functions \( h \in I_0^{H\frac{1}{2}}(L_2(J)) \). It is well known that there exists a Brownian motion \( B(t) \) such that the fractional Brownian motion \( \mathcal{B}_h(t) \) can be represented by \( \mathcal{B}_h(t) = \int_{0}^{t} K_h(t, s) dB(s) \) (Nualart & Ouknine, 2002).

**Theorem 2.1** Let \( H \in (0, \frac{1}{2}) \) and \( \nu \) be a weak solution of Equation (2.2). If \( f_1, f_2, \) and \( f_3 \) are Borel functions on \( \mathbb{R}^n \times J \times \mathbb{R}^p \) and satisfy the linear growth condition:

\[
|f_i(x, t, W)| \leq M_1[1 + \sum_{j=1}^{3} |W_j|], \quad i = 1, 2, 3
\]

for all \( x \in \mathbb{R}^n, t \in J, W \in \mathbb{R}^p \), where \( M_1 \) is a positive constant, then \( f_i(x, t, W) \in L_0^{H\frac{1}{2}}(L_2(J)) \), \( i = 1, 2, 3 \) almost surely for every \( x \in \mathbb{R}^n \) and \( |W| = 2m - 1 \).

**Proof** From (2.1), (2.2), (2.3), (2.5) and conditions (H4), (H6), (H7), one gets,

\[
V(t) \leq M_2 |\mathcal{B}_h(t)| + M_3 \int_{0}^{t} V(s) \, ds + M_2,
\]

for some positive constant \( M_2, V(t) = \sup_x |\nu(x, t)| \).

Thus for some positive constant \( M_3 \), we have

\[
V(t) \leq M_2 |\mathcal{B}_h(t)| + M_2 \int_{0}^{t} e^{M_3(t-s)} |\mathcal{B}_h(s)| \, ds + M_2 e^{M_3 t}.
\]
From (2.6) and (2.7), one gets, for some positive constant $M_3$:

$$
\int_0^T f_i^2(x, s, W) \, ds \leq M_3 [T + \int_0^T B^2_i(s) \, ds + 1].
$$

(2.8)

For some positive constant $M_2$ we have

$$
|I_{0^-}^{H+}_{1} f_i| = \frac{1}{\Gamma(H + \frac{1}{2})} \int_0^1 (t - s)^{H+\frac{1}{2}} f_i(x, s, W) \, ds \leq M_3 \int_0^T f_i^2(x, s, W) \, ds.
$$

(2.9)

Hence the required result. According to the conditions (H6), (H7) and the conditions and results of Theorem 2.1, we can find also that $f_1, f_2$ and $f_3$ are elements of $I_{0^-}^{H+}_{1} (L_2(J))$, for every $x \in \mathbb{R}^n, W \in \mathbb{R}'$. For every $x \in \mathbb{R}^n$, let us define an operator $Q_h$ from $L_2(J)$ onto $I_{0^-}^{H+}_{1} (L_2(J))$, by:

$$(Q_h f)(x, t) = \int_0^t Q_h(x, t, s) f(s) \, ds,$$

where $Q_h(x, t, s) = g(x, t)K_h(t, s)$.

Using conditions (H6), (H7) and that the functions $F_2, F_3$ are elements of $I_{0^-}^{H+}_{1} (L_2(J))$, one gets that $K_h^{-1} F_2$ and $K_h^{-1} F_3$ are defined and can be represented by:

$$(K_h^{-1} F)(x, t) = t^{H+\frac{1}{2}} I_{0^-}^{1-H \frac{1}{2}} tf_i, i = 1, 2$$

where

$$F_2(x, t) = K_h(t) f_2(x, W(x, s)) \, ds,$$

$$F_3(x, t) = \int \int \frac{\partial K_h}{\partial t}(t, s, x, y) f_3(y, W(y, s)) \, dy \, ds.$$

Notice that $F_2$ and $F_3$ are elements of $I_{0^-}^{H+}_{1} (L_2(J))$. Using condition (H4), we can see that $Q_h^{-1}$ exists and is defined on $I_{0^-}^{H+}_{1} (L_2(J))$. Now according to Theorem 2.1 and the last discussions, the weak solution $v$ of Equation (2.2) can be represented by

$$v(x, t) = \int Q_h(x, t, s) d\tilde{B}(x, s) + \varphi^*(x),$$

where $\tilde{B}(x, t) = B(t) + \int_0^t \eta(x, s) \, ds$, $\eta = \eta_1 + \eta_2 + \eta_3$, $\eta_1 = Q_h^{-1} f_1, \eta_2 = Q_h^{-1} f_2, \eta_3 = Q_h^{-1} f_3, i = 2, 3$ and $\varphi^*(x) = f(x, 0, W(x, O))$. Notice that $\eta_1$ exists according to condition (H8).

3. Existence and uniqueness of solutions

Formula (2.10) leads to the fact that two weak solutions of Equation (2.2) must have the same distributions. We can also conclude that if two weak solutions of Equation (2.2) defined on the same filtered probability space must coincide almost surely, (El-Borai & El-Said, 2015).

THEOREM 3.1 If $f_1, f_2$ and $f_3$ are continuous on $\mathbb{R}^n \times J \times \mathbb{R}'$ and satisfy a Lipschitz condition;

$$
|f_i(x, t, W) - f_i(x, t, W^*)| \leq M \sum_{j=1}^3 |W_j - W_j^*|, i = 1, 2, 3
$$

(3.1)

for all $x \in \mathbb{R}^n, W, W^* \in \mathbb{R}'$, $t \in J, W = (w_1, \ldots, w_j), W^* = (w_1^*, \ldots, w_j^*)$, then there is a weak solution of Equation (2.1). Moreover, $E[u^2(x, t)] < \infty$. 
Proof Let us use the method of successive approximations. set,

$$v_k(x, t) = g(x, t)B_0(t) + f_1(x, t, W_k) + \int_0^t K_2(t, s)f_2(x, s, W_k(x, s)) ds$$

$$+ \int_0^t \int_{\mathbb{R}^n} K_3(x, y, t, s) f_3(y, s, W_k(y, s)) dy ds,$$

where $W_k = (w_{1k}, \ldots, w_{nk})$ and every $w_k$ is of the form $D^q w_k$ for some $q, |q| \leq 2m - 1$,

$$u_k(x, t) = \int_0^t \int_{\mathbb{R}^n} \xi_j(s) G(x, y, t - s) \varphi(y) \, dy \, ds$$

$$+ \alpha \int_0^t \int_{\mathbb{R}^n} \theta(t - s) \xi_j(s) G(x, y, t - s) \varphi(y, s) \, dy \, ds,$$

$$\sum_{i=1}^p c_i u_k(x, t) = \psi \sum_{i=1}^p \xi_j(t_i) \varphi(x) + a \psi \sum_{i=1}^p \xi_j(t_i - s) v_k(x, s) ds.$$

Suppose that the zero approximation $v_0(x, t) = 0$. Using (2.3) and (3.1)–(3.4), one gets, for some positive constant $M$.

$$|v_{k+1}(x, t) - v_k(x, t)| \leq \frac{M t^k}{k!} \int_0^t (t - s)^k |B_0(s)| ds.$$

The last inequality leads to the fact that the sequence $(v_k)$ uniformly converges to a stochastic process $v$ on $\mathbb{R}^n \times \mathbb{R}$. It is clear that,

$$E[v^2(x, t)] \leq \frac{1}{(k + 1)!!} \sum_{k=0}^\infty E(k + 1)^2 \{v_{k+1}(x, t) - v_k(x, t)\}.$$

From (3.5) and the fact that $E[B_0^2(t)] = t^{2m}$, we get $E[v^2(x, t)] < \infty$. Using (2.1) and (2.5), we get also $E[u^2(x, t)] < \infty$. This complete the proof of the theorem, (El-Borai, 2002, 2004; El-Borai, El-Nadi, Labib, & Ahmed, 2004; El-Nadi, 2005).

4. Stability of solutions

In order to study the stability results for problem (1.1), (1.2), we shall prove that the weak solutions of the Cauchy problem (1.1), (1.2) depends continuously on the part of the initial condition $\varphi(x)$. Let $u_k, k = 1, 2$ be weak solutions of the equations

$$\frac{\partial^2 u_k(x, t)}{\partial t^2} = Lu_k(x, t) + f_1(x, t, W_k(x, t)) + \int_0^t K_2(t, s)f_2(x, s, W_k(x, s)) ds$$

$$+ \int_0^t \int_{\mathbb{R}^n} K_3(x, y, t, s) f_3(y, s, W_k(y, s)) dy ds + g(x, t)B_0(t),$$

with initial conditions

$$u_k(x, 0) = \varphi_k(x) + \sum_{i=1}^p c_i u_k(x, t_i), k = 1, 2,$$

where $W_k = (w_{1k}, \ldots, w_{nk})$, $w_{jk}$ is of the form $D^q w_k$, for some $q, |q| \leq 2m - 1, j = 1, \ldots, r$. It is supposed that $\varphi_1(x)$ and $\varphi_2(x)$ are given bounded continuous functions on $\mathbb{R}^n$.

**Theorem 4.1** If for sufficiently small positive number $\varepsilon, \sup_{x} |\varphi_1(x) - \varphi_2(x)| \leq \varepsilon$, then $\sup_{x} |u_1(x, t) - u_2(x, t)| \leq M \varepsilon$, for some positive constant $M$.

**Proof** We have
\[ u_k(x, t) = \int_0^\infty \int_{\mathbb{R}^d} \xi_k(\theta)G(x, y, t^\alpha \theta)[\varphi_k(y) + \sum_{i=1}^p c_i u_i(y, t)] \, dy \, d\theta \\
+ \alpha \int_0^1 \int_0^1 \theta(t-s)^{-1} \xi_k(\theta)G(x, y, (t-s)^\alpha \theta)v_k(y, s) \, dy \, d\theta \, ds, \quad k = 1, 2, \]
\[ \sum_{i=1}^p c_i u_i(x, t) = \sum_{i=1}^p (\xi(t_i)\varphi(x) + a\psi \sum_{i=1}^p \Lambda(t_i - s)v_i(x, s)) \, ds, \]
where

\[ v_k(x, t) = g(x, t)B(t) + f_1(x, t, W_k) + \int_0^t K_1(t, s)f_2(x, s, W_k(y, s)) \, ds \\
+ \int_0^t K_2(x, y, t, s)f_3(y, s, W_k(y, s)) \, dy \, ds, \quad k = 1, 2. \]

Using (4.3), (4.4), (4.5) and remembering that \( f_1, f_2, f_3 \) satisfy Lipschitz condition, we get

\[ \sup_x |v_1(x, t) - v_2(x, t)| \leq M \int_0^t \sup_x |v_1(x, s) - v_2(x, s)| \, ds + Me, \]

consequently

\[ \sup_x |v_1(x, t) - v_2(x, t)| \leq Me^{Mt}e. \]

From (4.3) and (4.4), we get the required result.

5. Conclusion
In this paper, we discussed the existence, uniqueness, and stability of solutions for the fractional stochastic partial differential equations without any restrictions on the characteristic forms when the Hurst parameter of the fractional Brownian motion is less than half. Our future work will be focused on investigating the approximate controllability for Hilfer fractional stochastic partial differential equations with fractional Brownian motion and Poisson jumps.

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