

**STOCHASTIC SELF- STABILIZATION OF A NON-LINEAR
OPTIMAL CONTROL DELAY DIFFERENTIAL EQUATIONS IN AN
ALMOST SURE EXPONENTIAL SENSE BY - ITO TYPE BROWNIAN
WHITE NOISE .**

Abstract

This study is focused on the application of Brownian white noise in stabilizing deterministic non-linear optimal control delay differential equations which appear to be generally unstable . The technique applied involves the use of Lyapunov sample exponent together with a special partial derivatives equation suggested by Mao (1967) . It was established that if the noise scaling parameter of the stochastically perturbed equation is finite , then the new stochastic optimal control delay differential equations ($SOCDD_S$) is self - stabilized in an almost sure exponential sense . This can never happen in the deterministic optimal control delay differential equations were noise is absence .

1 . Introduction

Delay differential equations are constantly used to model real life situations in various fields such as Economics , physics , chemistry , biology , engineering

mechanics etc, Thus , time lag or delay differential equations occur everywhere in our daily real life situations . In engineering , delay differential equations can be applied in the modeling of the dynamics of control systems , the stability of mechanical structures and the behavior of materials , in biological systems , delay differential equations can be used in the modeling of populations and the spread of diseases , in economics , delay differential equations can be applied to model the dynamics of markets , the effects of taxations and the behavior of consumers and firms . Many dynamic systems not only depend on the present and past states but also involve derivatives with delays . Delay differential systems usually encounter the uncertainties because of the system parameters , modeling error or some factors

A delay differential equation is a differential equation with deviating argument , this means, it is an equation that contains some functions and some of its derivatives to deviating argument values (Kolmanovskii and Myshkis, 1992).

Solutions of linear and nonlinear ODEs and ODDEs usually display certain qualitative properties. These properties include; Oscillation, explosion or blowup, asymptotic behavior as well as stability to mention just a few. When dynamical systems are subjected to performance criteria , aimed at achieving certain targets , the stability of such systems can form an area of interest to research on . Since (1892) when Lyapunov introduced the concept of stability into the study of

dynamic system. Stability means insensitive of the system to little changes in its initial state or parameters of the system .

To understand stability, it is worthy to note that stability is of different types viz: mean square stability, stochastic stability , moment stability, almost sure exponential stability, stability in probability, asymptotic stability, etc. Stamova and Stamov (2013) obtained the stability of the zero solution of differential equations with maximum, by using Lyapunov functions and Razumikhin techniques. Xiao and Zhu (2021) studied the stability of switched stochastic delay differential systems with unstable subsystems . Li et.al (2021) considered the stabilization of multi - weights stochastic complex networks with time delay driven by general Brownian motion . Zhu and Huang (2021) established the stability for the class of stochastic delay nonlinear systems driven by general Brownian motion Ngoc (2021) , established the new criteria for the mean square exponential stability for the neutral stochastic functional differential equations .. For a stable system, the trajectories which were close to each other at a specific instant should therefore remain close to each other at all subsequent instances (Mao 1997) . Shen et al (2021) , established the sufficient condition for the mean square exponential instability of stochastic differential equations by general Levy process with non Lipschitz coefficients , their designed a discrete time feedback control in the drift part and obtained the mean square exponential stability and quasi - sure

exponential stability for the controlled systems . Mao and Mao (2017) , studied the existence and uniqueness of solutions to neutral stochastic functional differential equations with Levy noise or Jumps .Chen et.al (2016) discussed the exponential stability for the neutral stochastic delay differential equations with time -varying delay. Wu et. al (2010) , examined conditions under which the numerical solutions of stochastic delay differential equations may share the almost sure stability of exact solutions for non-linear stochastic delay differential equations

Liu (2017) established a theory about the property of almost sure path-wise exponential stability for a class of stochastic neutral functional differential equations by developing a semi group scheme for the drift part of the systems under consideration and with path-wise stability through a perturbation approach rather than moment stability. Hasminskii (1967) , established the almost sure exponential stability of linear stochastic differential equations . It was established that , by the uses of Lyapunov function and the ideas of generalized moment inequalities as well as borel - Cantelli lemma under certain conditions on the drift and diffusion coefficients, p^{th} - moment, exponential stability implies the almost sure exponential stability , Atonuje (2015). Wei (2019) ,studied the almost sure exponential stabilization of linear and nonlinear stochastic systems by stochastic feedback control with Levy noise from discrete time systems , using the technique to generalized Ito formula for Levy stochastic integral , Borel - cantelli

lemma , Burkholder - Davis - Gundy inequality , Holder inequality , and Gronwall inequality , the almost sure exponential stabilization of the linear and nonlinear stochastic systems was studied and sufficient conditions were provided

We shall consider a nonlinear n - dimensional ordinary delay differential equation of the form ,

$$\dot{x}(t) = f(x(t), x(t - \tau), t); \text{ on } t \geq t_0 \quad 1.1$$

where $f(\cdot)$ is a volterra functional and τ is a constant time lag , for every initial value $x(t_0) = x_0 \in R^n$) there exists a unique global solution which is denoted by $x(t, t_0, x_0)$. Suppose again that $f(0, 0, t) = 0$, for all $t \geq t_0$, equation (1.1) has the solution $x(t_0) = 0$. This solution is called the trivial solution or equilibrium point . If equation (1.1) can be solved explicitly, it would be easier to determine whether the solution is stable. However, equation (1.1) can only be solved implicitly.

The inclusion of a stochastic ordinary delay differential equations . A stochastic delay differential equations have wide varieties of applications in many fields such as science , technology , physics, chemistry, structural (mechanics and optical bi-stability and fatigue cracking) financial mathematics, mathematical biology, radio astronomy and turbulent diffusion etc.

A stochastic differential equation (SDEs) is an equation in which one or more of the terms is a stochastic process, resulting in a solution which is also a stochastic process. Different types of stochastic differential equations have been used to model different phenomena in various fields, such as unstable stock prices in finance (Merton, 1976). That is SDEs contain a variable which represents random white noise calculated as the derivative of Brownian motion or Wiener process.

However, there are other types of random behavior that are possible, such as jump processes. Early work on (SDEs) was done to describe Brownian motion in Einstein's famous paper and at the same time by Smoluchowski. However, one of the earlier works related to Brownian motion is credited to Bachelier (1901) in his thesis theory of speculation. This work was followed up on by Langevin. Later, Ito and Stratonovich put SDEs on more solid mathematical footing. Ito in 1944 laid the foundation of a stochastic calculus known today as the Ito calculus. This represents the stochastic generalization of the classical differential calculus, which models various phenomena in continuous time such as the dynamics of stock prices, physical systems or motion of a microscopic particle subjected to random fluctuations. The corresponding stochastic differential equations (SDEs) generalize the ordinary deterministic differential delay equation (ODDEs). Stochastic

differential equations (SDE_s) are ordinary differential equations perturbed by Brownian noise .

In general, the first order stochastic nonlinear ordinary delay differential equation has the form

$$\left. \begin{aligned} dX(t) &= f(X(t), X(t - \sigma), t)dt + \mu g(X(t))dB(t), t \geq 0 \\ x(t) &= x(t_0) \end{aligned} \right\} \quad 1.4$$

where $f(X(t))$ is called the drift function , $\mu g(X(t))$ is called the diffusion function and $B(t)$ is a Brownian noise , $B = \{B_t, t \geq 0\}$ defines the randomness of the physical systems and it is often called the white noise. The wiener process is the simplest intrinsic noise term that adequately model Brownian motion. The integral form of (1.4) is

$$x(t) = x(t_0) + \int_0^t f(x(s), x(s - \sigma), s)ds + \int_0^t g(x(s))dB(s), t \geq 0 \quad 1.5$$

The first integral in (1.5) is a Volterra integral term and the second integral is an Ito stochastic integral with respect to the Brownian motion $B = \{B(t), t \geq 0\}$.

Let (Γ, ξ, p) be a complete probability space with filtration $\{\xi_t\}_{t \geq 0}$. A standard one dimensional Brownian motion is a real valued continuous $\{\xi\}$ adapted process $\{B(t)\}_{t \geq 0}$ which satisfies the following properties

- (i) . $B_0 = 0$

(ii) . the function $t \rightarrow B(t)$, is continuous

(iii) . for $0 \leq s < t < \infty$, the increment $B_t - B_s$ is normally distributed with mean zero and variance $t - s$

2. Formulation of optimal control delay Equations .

Let (X) be a dynamic system whose state at time t is described by an m –dimensional vector $x(t) = (x_1(t), \dots, x_m(t))$. Assume that the system (X) is controlled by certain controllers ,if these controllers are characterized at time t by an n – *dimensional* vector $v(t) = (v_1(t), v_2(t) , \dots, v_n(t))$. Suppose Q is a compact and convex set in the n – *dimensional* space A^n with points $v = (v_1, \dots, v_n)$,where $v(t)$ is called the control vector or the control function , Q is called the control region .

Admissible Function

A measurable function $v(t)$ defined for $t \in [t_0, t]$, where $t \in [t_1, t_2]$ is called admissible, if their range is in Q .

Let E be the set of all admissible control . Suppose that (X) is the states corresponding to the time interval $I = [\alpha, t_0]$,where $|\alpha|$ is sufficiently large , is described by an n – *dimensional vector*

$$Q(t) \in c([\alpha, t_0], G)$$

where G is a compact region in the set A^n , containing the origin as an interior point. Given an r -dimensional continuous real-valued function, the initial function ϕ , on the interval $\alpha \leq t \leq t_0$ and $\phi(t_0)$, find a function $x(t)$, continuous for $t \geq \alpha$ such that

$$x(t) = \phi(t), \text{ for } \alpha \leq t \leq t_0, \tag{1.6}$$

Let Φ be the set of all allowable initial function $\phi(t)$ and E be the set of all allowable control vector $v(t)$, if \dot{E} is a subset of the n -dimensional space of points with co-ordinates (v_1, v_2, \dots, v_n) , suppose that the vector $v(t) \in \dot{E}$. Then the set \dot{E} is called the control region where \dot{E} is the range of all $v(t) \in E$. Any element $\phi(t) \in \Phi$ is said to be admissible initial function and any $v(t) \in E$ is said to be an admissible control. A pair $\{\phi, u\}$ with $\phi(t_0) \in \Phi$ and $v \in E$ is called admissible pair or admissible policy.

Let $r(t) = r(t, t_0, \phi, v)$ be a trajectory corresponding to an admissible pair

$\{\phi(t_0), u(t)\} \in p$. suppose that .

a. the trajectories $r(t)$ which corresponding to admissible pairs $\{\phi(t_0), v(t)\}$ remain in a given compact region $G \in A^n$ for $r(t) = \phi(t)$, $t \in [\alpha, t_0]$.

b the control region \dot{E} is compact, convex and contains the origin of A^n as an interior point and the members of the set E of all admissible controls consist of

all measurable functions defined for $t \in [t_0, t]$, $[t \in t_1, t_2]$, whose range is contained in \dot{E}

c . the region G is compact ,convex and contains the origin of A^n as an interior point and the set Φ of all admissible initial function which is defined for $\Phi = \{\phi(t) \in c([\alpha, t_0], G)\}$, $\phi(t)$ is admissible , compact ,convex and contains the origin as an interior point .

d . during the evolution of the process ,the integral constraints

$$\int_{t_0}^t r_i(r, v, t)dt \subseteq W_i, i = 1, 2 \dots n .$$

where w_i is a closed subsets of A^n

We shall consider the optimal controlled system (X) which is described by the nonlinear deterministic ordinary delay differential equation of the form

$$\left. \begin{aligned} x'(t) &= f(x(t), v(t), x(t - r), t) \quad t > 0 \\ x(t) &= \phi(t), t \in [-\Gamma, 0] \end{aligned} \right\} \tag{2.1}$$

where $F(.)$ is a volterra functional defined and bounded for $t \in [-\Gamma, 0]$

satisfying the following conditions (a)-(d) for all

$v(t) \in \Phi$ and $\forall x(t) \in c(I[t_0, T], G)$, where G is a compact subset of an n-

dimensional space \dot{E} , F is integrable and continuous for x and v , $r \in (0, 1)$ is a

constant time lag or delay, $v(t)$ is the control vector, defined for

$t \in [-\Gamma, 0]$ and $x(t) = \phi(t), t \in [-\Gamma, 0]$ with $\phi(t_0) \in \phi$ is the initial datum. By the solution of (2.1), we mean a continuous vector function $x(t) = \phi(t)$ such that $x(t)$ satisfies Eq. (4.1) as well as the initial condition $x(t) = \phi(t), t \in [-\Gamma, 0], \phi(t_0) \in \phi$.

The solution of equation (2.1) is said to be unstable on $[-\Gamma, 0]$, if for every $\varepsilon > 0$ and for any $t \geq 0$. Let $x(t, t_0, x_0)$ be the solution of (2.1) satisfying $x(t) = \phi(t)$, where $t \geq t_0$ and $x_0 \in \mathbb{R}$. Then $x(t) = \phi(t)$ is said to be unstable if for any $\varepsilon > 0$ and any $t \geq t_0$, there exists a $\delta = \delta(\varepsilon, t_0) < 0$ such that

$$|x(t_0) - \phi(t)| > 0 \Rightarrow |x(t, t_0, x_0) - \phi(t)| > \varepsilon \quad \forall t \geq t_0$$

We perturbed Eq. (2.1) by an Ito-type Brownian white noise into a stochastic optimal control delay differential equation of the form

$$\left. \begin{aligned} dX(t) &= f(X(t), v(t), X(t-r), t)dt + \mu g(X(t), t)dB(t), t > 0 \\ x(t) &= \phi(t), t \in [-\Gamma, 0] \end{aligned} \right\} \quad (2.2)$$

where $f \in L^1([t_0, T], R^d)$, $g \in L^2([t_0, T], R^{dn})$, $v(t)$ is the control vector, μ is the noise scaling parameter which determine the strength of fluctuation of the system, $f(\cdot)$ is called the drift function, $g(X(t))$ is called diffusion function, $r \in (0, 1)$ is called the constant time lag and $B(t)$ is a Brownian motion, $B = \{B(t), t \geq 0\}$, defined on the probability triple (ϕ, \mathcal{F}, P) with filtration $\{X(t)\}_{t \geq 0}$, defined on $\{\phi, \mathcal{F}, P\}$ satisfying (2.2) together with the initial function which is the same with that of the $OCDDDE_S$ (2.1).

In the present research, we establish that the addition of a multiplicative white noise of an Ito-type represented by the Brownian motion, which resulted in the stochastic optimal control delay differential equation ($SOCDDDE$) that is (2.2), if the average impact of the noise scaling parameter μ is kept finite by making it as large as possible, the $SOCDDDE$ is stable in an almost sure exponential sense, if the noise scaling

parameter can be replaced by a finite value under certain conditions . This happens even when the deterministic equation (2.1) still remains unstable due to the absence of the Brownian white noise .

Definition 1 (The trivial solution of SOCDDE)

Assume that $\{X(t)\}_{t \geq 0}$ is the solution of (2.2) . Suppose that $f(0,0,0, t) \equiv 0, g(0,0,0) \equiv 0 \forall t > 0$. It follows that (2.2) has the solution $X(t) \equiv 0$ corresponding to the initial datum $X(t_0) \equiv 0$ is called the trivial or zero solution of (2.2) .

Definition (2)

The zero solution $X(t, 0,0,0)$ of the SOCDDE (2.2) is said to be almost surely exponentially stable if

$$\lim_{t \rightarrow \infty} \sup \frac{1}{t} \log |X(t, t_0, x_0)| < 0 \quad \forall X_0 \in R^d .$$

The following Assumptions , Lemmas and Theorems are based on the Ito formula is called exponential martingale inequality . it is useful to the proof of the main result .

Assumption (2.1)

H1: we assume that the following hypothesis hold

- (i) $|X^T \Delta f(X, t) + X^T \Delta g(X, t) \leq H |X^T \Delta X|^2|$
- (ii) $\text{Trace} (h^T(X, t) \Delta h(x, t) \leq \pi X^T \Delta X)$
- (iii) $|h^T(X, t) \Delta h(x, t)|^2 \geq \gamma |X^T \Delta X|^2 \quad \forall t > 0, \text{ and } x \in R^d$

H2: There exists a pair of constants $M > 0$ and $\gamma \geq 0$ such that $\|\alpha(t)\| \leq M e^{\alpha t}$

$\forall t \geq 0$, where $\alpha(t)$ is convergence rate function given by $\alpha(t) e^{\alpha t I_{d,d}}$ where $I_{d,d}$ is the $d \times d$ identity matrix

3.Main Results

Lemma (3.1)

Suppose that assumption (H1) hold . Then the solution of equation (2.2) satisfies the property that $p\{x(t, x_0) \neq 0 \forall t \geq 0\} = 1$ provided that $x_0 \neq 0$.

Proof

If lemma (3.1) is false , there exists some $x_0 \neq 0$ such that $p(\gamma < \infty) > 0$, where γ is the time of first reaching state zero that is $\gamma = \inf \{t \geq 0: x(t) = 0\}$ Let $x(t) = x(t, x_0)$. We can find $t^* > 0$ and $\emptyset > 0$, large enough to ensure that $P(B) > 0$, where $B = \{\omega: \gamma \leq t^* \text{ and } |x(t)| \leq \emptyset - 1 \forall 0 \leq t \leq \gamma\}$ for every $0 < \varepsilon < |x_0|$. We have $\gamma_\varepsilon = \inf \{t \geq 0: |x(t)| \leq \varepsilon \Rightarrow |x(t)| \geq \emptyset\}$. By Ito formula we have , for every $0 \leq t \leq t^*$,

$$E[|x^T(t \wedge \gamma_\varepsilon)Hx(t \wedge \gamma_\varepsilon)|^{-1}] \leq x_0^T H x_0 2E \int_0^{t \wedge \gamma_\varepsilon} |x^T(s)Hx(s)|^{-1} |x^T(s)Hf(x(s), s)| ds$$

$$+ 4E \int_0^{t \wedge \gamma_\varepsilon} |x^T(s)Hx(s)|^{-3} x^T(s)Hg(x(s), s) |^2 \left(\int_0^s |\beta(u)x(u)|^p du \right)^2 ds$$

from the (H1) above , we have

$$E[|x^T(t \wedge \gamma_\varepsilon)Hx(t \wedge \gamma_\varepsilon)|_1^{-1}] \leq |x_0^T H x_0|^{-1} + \delta E \int_0^t |x^T(s)Hx(s)| ds^{-1}$$

$$\leq |x_0^T H x_0|^{-1} + \delta E \int_0^{t \wedge \gamma_\varepsilon} [|x^T(s \wedge \gamma_\varepsilon)Hx(s \wedge \gamma_\varepsilon)|]^{-1} ds$$

where δ is a constant dependent but independent of ε . By the Gronwall inequality we have

$$E[|x^T(t^* \wedge \gamma_\varepsilon)Hx(t^* \wedge \gamma_\varepsilon)|^{-1}] \leq |x_0^T H x_0|^{-1} e^{\gamma t^*} \tag{3.11}$$

since $\omega \in B$, then $\gamma_\varepsilon \leq t^*$ and $|x(\gamma_\varepsilon)| = \varepsilon$. From the inequality () we have

$$(\varepsilon^2 \|H\|)^{-1} p(\beta) \leq |x_0^T H x_0| e^{\beta t^*} \tag{3.12}$$

as $\varepsilon \rightarrow 0, p(\beta) = 0$, hence contradicts the definition of β .

Theorem(3.2)

Consider the system

$$dX(t) = [f(X(t), V(t), X(t - \tau), t)]dt + \mu g(X(t), t)dB(t) \dots \tag{3.21}$$

suppose that there exists a function $\alpha \in C^{2,1}(R^d \times [0, \infty), R)$, the family of all non negative function $\alpha(x, t)$ define on $R^d \times [0, \infty), R)$ such that they are continuously twice differential in x and t and constants $h > 0, k > 0, k_2 \in R, k_3 \geq 0$ such that $\forall x \neq 0, t \geq 0$, we have

(a) . $k_1|x|^h \leq \beta(x, t)$

(b) . $L\beta(x, t) \leq k_2\beta(x, t)$

(c) . $|\beta_x(x, t)g(x, t)|^2 \geq k_3\beta^2(x, t)$. Then

$$\lim_{t \rightarrow \infty} \sup \frac{1}{t} \log|x(t, t_0, x_0)| \leq -\frac{k_3-2k_2}{2h} \tag{3.22}$$

almost surely $\forall x_0 \in R^d$. If in particular that $k_3 > 2k_2$, the solution of stochastic optimal control delay differential equation (3.21) is almost surely exponentially stable .

proof

if the sample Lyapunov exponents of the solution (4.14) holds for $x_0 = 0$, then $x(t, t_0, x_0) \equiv 0$. We need to show (3.22) for $x_0 \neq 0$. suppose $x(t) = x(t, t_0, x_0)$ for any $x_0 \neq 0$. By Lemma (4.1.1), $x(t) \neq 0 \forall t \geq 0$ almost surely . Apply the Ito formula and by condition (b) and (c), we show that for $t \geq 0$, we have

$$\log f(x(t), t) \leq \log f(x_0, 0) + k_2(t - 0) + N(t) - \frac{1}{2} \int_0^t \left| \frac{\beta_x(x(s),s)g(x(s),s)}{\beta^2(x(s),s)} \right| ds^2$$

where $N(t) = \int_0^t \frac{\beta_x(x(s),s)g(x(s),s)}{\beta(x(s),s)} dB(s)$, is a continuous martingale with initial value $N(0) = 0$. If $\varepsilon \in (0,1)$ is arbitrary and Let $m = 1, 2, \dots$, By the exponential martingale inequality, we have

$$p \left\{ \sup_{0 \leq t \leq m} \left[N(t) - \frac{\varepsilon}{2} \int_0^t \left| \frac{\beta_x(x(s),s)g(x(s),s)}{\beta^2(x(s),s)} \right|^2 ds \right] > \frac{2}{\varepsilon} \log m \right\} \frac{1}{m^2} \dots \tag{3.23}$$

By the Borel-Cantelli Lemma, we observed that almost all $\rho \in \varphi$, there is an integer $m_0 = m_0(\varphi)$ such that $m \geq m_0$

$$N(t) \leq \frac{2}{\varepsilon} \log m + \frac{\varepsilon}{2} \int_0^t \left| \frac{\beta_x(x(s),s)g(x(s),s)}{\beta^2(x(s),s)} \right|^2 ds \dots \tag{3.24}$$

Eq. (4.16) hold $\forall 0 \leq t \leq m$.

$$\log f(x(t), t) \leq \log f(x_0, t_0) - \frac{1}{2} [(1 - \varepsilon)k_3 - 2k_2](t - 0) + \frac{2}{\varepsilon} \log m \dots (3.25)$$

$\forall 0 \leq t \leq m, m \geq 0$ almost surely . For almost all $\rho \in \varphi$,let $m - 1 \leq t \leq m$ and $m \geq 0$, we have

$$\frac{1}{t} \log \beta(x(t), t) \leq -\frac{t-0}{2t} [(1 - \varepsilon)k_3 - 2k_2] + \frac{\log \beta(x_0,0) + \frac{2}{\varepsilon} \log m}{m-1} \Rightarrow$$

$\lim_{t \rightarrow \infty} \sup \frac{1}{t} \log \beta(x(t), t) \leq -\frac{1}{2} [(1 - \varepsilon)k_3 - 2k_2]$, By condition (a) we have

$$\lim_{t \rightarrow \infty} \sup \frac{1}{t} \log |x(t)| \leq -\frac{(1-\varepsilon)k_3 - 2k_2}{2h}$$
 , since $\varepsilon > 0$ is arbitrary . Hence the

stochastic optimal control delay differential system is almost surely exponentially stable .

Conclusion .

In this study , We established the almost sure exponential stability of the one dimensional non-linear stochastic optimal control differential equations (*SOCDDES*) with a constant delay or time lag . In particular , the new theorem were enable us to stabilize unstable deterministic system . The method of Lyapunov sample exponents were used to achieved stability result in an almost sure exponential sense , together with Brownian white noise to stabilized the system of optimal control delay differential equation in an almost sure exponential sense.

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