CLOSED-LOOP SOLVABILITY OF DELAYED CONTROL PROBLEMS: A STOCHASTIC VOLTERRA SYSTEM APPROACH *

WEIJUN MENG†, TIANXIAO WANG‡, AND JI-FENG ZHANG§

Abstract. A general and new stochastic linear quadratic optimal control problem is studied, where both state delay and control delay can appear simultaneously in the state equation and the cost functional with time-varying coefficients. The closed-loop outcome control of this delayed problem is given by a new Riccati system whose solvability is carefully established. To this end, a novel method is introduced to transform the delayed problem into a control problem driven by a stochastic Volterra integral system without delay. This method offers several advantages: it bypasses the difficulty of decoupling the forward delayed state equation and the backward anticipated adjoint equation, avoids the introduction of infinite-dimensional spaces and unbounded control operators, and ensures that the closed-loop outcome control depends only on past state and control, without relying on future state or complex conditional expectation calculations. Finally, several particular and important stochastic systems are discussed. It is found that the model can cover a class of stochastic integro-differential systems, whose closed-loop solvability has not been available before.

Key words. Stochastic delayed optimal control, time-varying coefficients, closed-loop solvability, Riccati equation

AMS subject classifications. 93E20, 60H10, 34K50, 49N10

1. Introduction.

1.1. Delayed optimal control problems.

Let $(\Omega, \mathcal{F}, \mathbb{F}, \mathbb{P})$ be a complete filtered probability space with filtration $\mathbb{F} = \{\mathcal{F}_t\}_{t\geqslant 0}$ generated by one-dimensional standard Brownian motion $W(\cdot)$. Given $0 \leqslant t_0 < T$, the constant delay time $\delta > 0$ and control $u(\cdot)$, let us consider an optimal control problem where the state equation is described as:

$$
\begin{cases} dx(t) = \big[A_1(t)x(t) + A_2(t)y(t) + A_3(t)z(t) + B_1(t)u(t) + B_2(t)\nu(t) \\ \qquad\quad +B_3(t)\mu(t) + b(t)\big]dt + \big[C_1(t)x(t) + C_2(t)y(t) + C_3(t)z(t) \\ \qquad\quad +D_1(t)u(t) + \sigma(t)\big]dW(t), \quad t \in (t_0, T), \\ x(t) = \xi(t - t_0), \quad u(t) = \varsigma(t - t_0), \quad t \in [t_0 - \delta, t_0], \end{cases} \tag{1.1}
$$

and the cost functional is defined as:

$$
\begin{aligned} J(t_0, \xi(\cdot), \varsigma(\cdot); u(\cdot)) = \mathbb{E}\int_{t_0}^T &\big[x(t)^\top Q_1(t)x(t) + y(t)^\top Q_2(t)y(t) + z(t)^\top Q_3(t)z(t) \\ &+u(t)^\top R_1(t)u(t) + \nu(t)^\top R_2(t)\nu(t)\big]dt. \end{aligned} \tag{1.2}
$$

Here $y(\cdot)$ and $\nu(\cdot)$ are the pointwise delays of the state and the control, respectively, $z(\cdot)$ and $\mu(\cdot)$ are the corresponding (extended) distributed delays which are defined:

$$
y(t) \equiv x(t - \delta), \quad z(t) \equiv \int_{t_0}^t F(t, s)x(s)ds, \quad t \in (t_0, T),
$$

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† School of Mathematics & Statistics, Nanjing University of Science and Technology, Nanjing 210094, China, E-mail: mengwj@njust.edu.cn

‡Corresponding author. School of Mathematics, Sichuan University, Chengdu 610065, China, E-mail: wtxiao2014@scu.edu.cn

§School of Automation and Electrical Engineering, Zhongyuan University of Technology, Zhengzhou 450007; State Key Laboratory of Mathematical Sciences, Academy of Mathematics and Systems Science, Chinese Academy of Sciences, Beijing 100190, and school of Mathematical Sciences, University of Chinese Academy of Sciences, Beijing 100149, China, E-mail: jif@iss.ac.cn

$$\nu(t) \equiv u(t-\delta),\ \mu(t) \equiv \int_{t_0}^{t} \tilde{F}(t,s)u(s)ds, \quad t \in (t_0,T). \tag{1.3}$$

In addition, $\xi(\cdot)$ and $\varsigma(\cdot)$ are called the initial trajectories of the state and the control, respectively. The conditions satisfied by coefficients $F, \tilde{F}, A_i, B_i, C_i, D_1, Q_i, R_1, R_2, b$, σ above will be specified in Section 2, which ensure the well-posedness of the cost functional (1.2), $i = 1,2,3$. The optimal control problem is stated as follows:

Problem (P). To find $u^*(\cdot)$ such that (1.2) is minimized, i.e.,

$$J(t_0, \xi(\cdot), \varsigma(\cdot); u^*(\cdot)) = \inf_{u(\cdot)\in L^2_{\mathbb{F}}(t_0,T;\mathbb{R}^m)} J(t_0, \xi(\cdot), \varsigma(\cdot); u(\cdot)) = V(t_0, \xi(\cdot), \varsigma(\cdot)),$$

where $L^2_{\mathbb{F}}(t_0,T;\mathbb{R}^m)$ is the Hilbert space consisting of $\mathbb{F}$-adapted processes $\phi(\cdot)$ such that $\mathbb{E}\int_0^T |\phi(t)|^2 dt < \infty$. Any $u^*(\cdot) \in L^2_{\mathbb{F}}(t_0,T;\mathbb{R}^m)$ and the corresponding $x^*(\cdot)$ are called an *open-loop optimal pair*. $V(t_0, \xi(\cdot), \varsigma(\cdot))$ is called the value function. In the special case, when $b(\cdot)$ and $\sigma(\cdot)$ vanish, we denote the corresponding delayed linear quadratic (LQ) problem, the cost functional, and the value function by Problem (P_0), $J_0(t_0, \xi(\cdot), \varsigma(\cdot); u(\cdot))$ and $V_0(t_0, \xi(\cdot), \varsigma(\cdot))$, respectively.

As to the above (1.1), it is an extension of the following stochastic differential delay equation (SDDE):

$$\begin{cases} dx(t) = \big[A_1(t)x(t) + A_2(t)y(t) + A_3(t)\widetilde{z}(t) + B_1(t)u(t) + B_2(t)\nu(t) \\ \qquad\qquad +B_3(t)\widetilde{\mu}(t) + \widetilde{b}(t)\big]dt + \big[C_1(t)x(t) + C_2(t)y(t) + C_3(t)\widetilde{z}(t) \\ \qquad\qquad +D_1(t)u(t) + \widetilde{\sigma}(t)\big]dW(t), \quad t \in (t_0,T), \\ x(t) = \xi(t-t_0), \quad u(t) = \varsigma(t-t_0), \quad t \in [t_0-\delta, t_0], \\ \widetilde{z}(t) \equiv \displaystyle\int_{t-\delta}^{t} G_1(t,s)x(s)ds,\ \widetilde{\mu}(t) \equiv \int_{t-\delta}^{t} G_2(t,s)u(s)ds, \quad t \in (t_0,T), \end{cases} \tag{1.4}$$

where $y(\cdot)$ and $\nu(\cdot)$ are defined in (1.3), and G_1, G_2 are bounded. In fact, we have

$$\begin{aligned} &\widetilde{z}(t) = \widetilde{G}_1(t) + \int_{t_0}^{t} \widehat{G}_1(t,s)x(s)ds, \quad \widetilde{\mu}(t) = \widetilde{G}_2(t) + \int_{t_0}^{t} \widehat{G}_2(t,s)u(s)ds, \\ &\widetilde{G}_1(t) \equiv \int_{t-\delta}^{t_0} G_1(t,s)\xi(s-t_0)ds\mathbf{1}_{[t_0,t_0+\delta)}(t),\ \widetilde{G}_2(t) \equiv \int_{t-\delta}^{t_0} G_2(t,s)\varsigma(s-t_0)ds\mathbf{1}_{[t_0,t_0+\delta)}(t), \\ &\widehat{G}_i(t,s) \equiv \big[\mathbf{1}_{[t_0,t_0+\delta)}(t) + \mathbf{1}_{[t_0+\delta,T]}(t)\mathbf{1}_{[t-\delta,t)}(s)\big]G_i(t,s),\ i = 1,2. \end{aligned}$$

Therefore, (1.4) can be seen as a special case of (1.1) with $b = \widetilde{b} + A_3\widetilde{G}_1 + B_3\widetilde{G}_2$, $\sigma = \widetilde{\sigma} + C_3\widetilde{G}_1$, $F = \widehat{G}_1$, $\tilde{F} = \widehat{G}_2$. Based on this fact, we name (1.1) *the (extended) controlled SDDE*. More details about SDDE (1.4) can be referred to [29]. Notice that here we allow $t_0 + \delta \leqslant T$.

1.2. Motivations. In the real world, many challenges across disciplines like economics, finance, aerospace, and network communication can be framed as optimal control problems [8, 9]. Moreover, the evolution of certain phenomena hinges not only on present conditions but also on their historical trajectories. Consequently, the optimal control problem of stochastic control systems containing state delays and control delays, like the above (1.4), is an important issue in control theory. The relevant optimal control problems have attracted enormous attention of the optimization and engineering communities in the last decades. We refer to the monographes by Bensoussan–Da Prato–Delfour–Mitter [5], Meng–Shi–Yong [26].

To motivate the current study, let us make some careful discussions about the existing papers from the viewpoints of frameworks, methodologies, and conclusions.

I. The existing frameworks on stochastic delayed systems seem scattered and decentralized, many of which do not fully cover each other.

• Time-invariant versus time-varying coefficients: Such a difference happens even for deterministic controlled systems. For example, [20, 22, 23, 27, 37] and the relevant papers therein are devoted to the time-invariant case, while [3, 4, 10, 12, 24, 38] and the relevant papers therein are concerned with the time-varying one. The appearance of both cases in the literature is attributed to the complexity of delayed problems and the methodology limitation developed accordingly.

• State delay versus control delay: When only state variables contain the delayed terms, we refer to [12, 14] for the deterministic case and [15, 23, 24] for the stochastic case. When delayed terms are only added to control variables, we refer to [19, 35] for the deterministic case and [22, 23, 33, 37] for the stochastic case. Since the methods for handling state delay or control delay are fundamentally different, the corresponding models are discussed separately in the literature.

• Pointwise delay versus distributed delay: We found that delay types also affect the analogue study. For example, [10, 22, 23, 37] are concerned with the pointwise delay in state or control, while [9, 15] are devoted to the case with distributed delay. The poinwise delay is usually more challenging since the distributed delay can be dealt with using the derivative formula or the Itô formula, but the pointwise delay cannot.

• State (or control) dependence versus constants in diffusion terms: In the literature, we found that whether diffusion terms depend on the state/control variables, or even their delayed terms, brings essential differences. We refer to [15, 22, 37] for the former case while [8, 9] for the simple constant case. In our opinion, the related reason is that this dependence occurs within the stochastic integral terms, rendering the previously used methods for handling the Lebesgue integral terms ineffective.

• Delayed terms in cost functionals or not: Eventually, let us point out the different frameworks caused by the dependence of delayed terms in cost functionals. Even for deterministic controlled systems, pointwise delay in cost functionals makes weight operators unbounded, while distributed delay makes their processing highly dependent on the given weight coefficients (see the Introduction part of [20] for detailed explanations). When cost functionals contain state/control delay terms, we refer to [20, 25, 26, 37], while most other existing studies do not touch this topic.

Based on the above classifications of the models, we pose the first question:

(Q1)*: Is it possible to provide a general framework to cover the above models?*

II. After careful observations of the existing papers, we found that there are several approaches treating LQ problems for stochastic delay systems. We list them out and make some analyses as follows.

• Maximum principle: It is a very natural method [11, 34, 37]. To obtain the explicit forms of optimal controls, the challenging part is to decouple the forward-backward stochastic systems. One successful example is [37], where a class of Riccati equations is established when the system only contains pointwise control delay. The difficulties in general case may lie in that the delay effect disrupts the classical decoupling relation and makes the Itô formula fail to work [4].

• Dynamic programming: This method is very effective in obtaining feedback forms of optimal controls, see [3, 5, 22, 23] for more details. However, the main difficulty for delayed problems is the lack of Markovianity, which obviously forces us to deal with infinite-dimensional HJB equations at the cost of increased complexity.

• State space method: This method is to lift state equations to Banach/Hilbert spaces (depending on the regularity of the data). It is developed in the deterministic case by [12, 19] and then extended in the stochastic case by [15, 27]. This method always comes at a cost of moving problems to infinite dimension. Another limitation in the stochastic case lies in the presence of unbounded operators in state equations [27].

• Variation of constants formula method: By using this method, one can transform the original delayed system into another integral system of Volterra type without delay which is solved by fundamental solution. We refer to [18, 20, 21, 25] for more details. This works well in deterministic controlled systems. However, when diffusion terms contain state delay terms, it becomes unclear to go through the whole procedure since anticipated stochastic integrals may be involved.

Based on the above analysis, different methods are used to handle different models, but each has its own drawbacks. Therefore, we raise the second question:

(Q2): *Is it possible to come up with a new approach to bypass the disadvantages in the existing papers?*

III. Last but not the least, let us make some discussions about the obtained conclusions in terms of feedback controls and Riccati systems in the literature. We separate them into the following cases.

• Riccati systems versus Fredholm systems: To obtain feedback controls, Riccati systems are one of the most popular and important tools. We refer to [3, 8, 11–13, 22, 26, 27, 37] and the related papers therein. On the other hand, according to the works [20,21], Fredholm systems also play important roles. In other words, the helpful systems for establishing the feedbacks are by no means unique.

• The challenges of Riccati systems: This point can be explained in the following manners. Firstly, the successful introduction of Riccati systems only hold in specific settings, e.g., the time-invariant case [19, 22, 27, 37], the only state delay case [11, 23], the only control delay case [8,23,37]. Secondly, even for the papers containing Riccati systems, verifying the coincidences among them seems quite involved and technical, such as [11] and [27], or [22] and [37]. Thirdly, even though Riccati systems are derived, they are quite challenging to further discuss their solvability. Along this line we mention the works of [11, 27] for some progress in the stochastic setting. Fourthly, as to the papers obtaining the solvability, different works require different assumptions [3, 12]. Hence, it seems difficult to give a unified precondition.

• The challenges of feedback controls: In the literature, open-loop optimal controls and closed-loop optimal controls are two main notions for representing the explicit forms. For the former one, there are some relevant papers [27,34,36,38]. Since it is not easy to decouple forward-backward adjoint systems, the closed-loop representations of open-loop optimal controls are not successfully given until some recent works of [11, 27,37]. As to the later one, there are some works treating the closed-loop solvability. We refer to [26,27]. However, their closed-loop solvability depends on the transformed problems, thus lacks generality, and their methods are not applicable to time-varying coefficients.

To sum up the above, different models have different versions of Riccati systems, among which the difference analysis is lacking and the relevant solvability is not obtained. Therefore, we come up with the third question:

(Q3): *Is it possible to derive a unified Riccati system and feedback control for the general model* (1.1) *and* (1.2)*, and verify the consistency with the existing papers?*

Now let us return back to Problem (P) and discuss another special case where $A_2, B_2, C_2, Q_2, R_2 = 0$. Here we then arrive at the LQ optimal control problem for (a class of) stochastic integro-differential systems (or stochastic differential systems with memory). This type of optimal control problems naturally emerges in many different application scenarios, and is particularly common when studying the optimal performances of systems in response to specific inputs. In such cases, the systems' responses do not occur immediately but rather appear after a certain period of time. However, in contrast to the previous discussion on SDDEs, for optimal control problems involving systems with memory, just a few isolated results are available at the moment. We refer to [7] for the finite dimensional case and [6] for the infinite dimensional study. In the LQ framework, [30] studied a simple integro-differential model in the finite-dimensional space and obtained the optimal synthesis via Riccati-type equations for the first time (commented by [2]). Other enhanced results appeared recently in [16, 31]. For the extension to the infinite dimension, we refer to [1, 2]. These results hold in the deterministic controlled system framework. Due to the lack of relevant study on stochastic systems, we raise the fourth question:

(Q4): *It is possible to provide some systematic study in stochastic integro-differen -tial systems to fill the gaps left by the existing literature?*

1.3. Contributions and novelties. In this paper, our goal is to treat the general framework with the state equation (1.1) and the cost functional (1.2) by employing new methodologies, and give positive answers to the aforementioned four questions. To begin with, we propose a general definition of the closed-loop solvability for Problem (P). To show its sufficiency, we separate the procedures into four parts. We firstly adapt the transformation procedures, introduced in [25], into our framework and end up with an LQ problem for a stochastic Volterra integral system without delay. Secondly, by borrowing the ideas developed in [17] and [16], we introduce and discuss a class of Riccati systems and backward stochastic adjoint systems. Then, by the previous Riccati systems, we explicitly construct the desired closed-loop strategy, the resulting closed-loop outcome control, and prove its optimality. Finally, we make detailed comparisons/coincidences with the existing study. The contributions and innovations of this paper are summarized as follows.

- A general yet new stochastic LQ optimal control problem is studied. On the one hand, it covers stochastic differential delay systems where the coefficients are time-varying, both state delay and control delay can appear in the drift terms, the diffusion terms, and the cost functionals. On the other hand, it covers a class of stochastic integro-differential systems where memory terms enter into the drift, diffusion terms, and the cost functionals. This gives a nice response to (Q1), (Q4).
- A new transformation method is employed for the above general framework, and the advantages are shown in three aspects. Firstly, it avoids the complicated decoupling procedures for forward-backward systems. Secondly, it can handle time-varying coefficients case where traditional infinite dimensional lifting methods fail. Thirdly, in our approach there are no unbounded control operators, and there is no need to use infinite-dimensional analysis theories such as operator semigroups. This gives a nice response to (Q2).
- By our main conclusions, we find the following four advantages and new facts. Firstly, we give the solvability of the Riccati system corresponding to Problem (P) and their coincidences with the existing literature in particular cases. Secondly, we explicitly construct the unique closed-loop outcome control, which does not rely on the future state and avoids complex tools of conditional expectations. Then, we only impose integrability conditions on the coefficients of Problem (P), and do not require continuity or even differentiability assumptions. Finally, even for the deterministic control system (1.1), we present, for the first time, results regarding the integro-differential

part and the cost functional (1.2) with pointwise/distributed delays. This gives a nice response to (Q3), (Q4).

The rest part is organized as follows. In Section 2, we formulate the control problem studied in the paper. In Section 3, we transform the original delayed control system into a Volterra integral control system without delay, and then, study the closed-loop solvability of the original delayed optimal control problem. In Section 4, we discuss several important cases to compare our results with the previous ones. In Section 5, we give some concluding remarks. Finally, we provide the proofs of the main results in Appendix.

2. Preliminary. Let $T>0$ be a given finite time duration, define $\triangle_2(0,T)\equiv\Big\{(t,s)\in(0,T)^2\mid T>t>s>0\Big\}$, $\square_3(0,T)\equiv\Big\{(s_1,s_2,t)\in(0,T)^3\mid t<(s_1\wedge s_2)\Big\}$. I is the identity matrix with appropriate dimension. $\mathbb{S}^n$ is the set of all $n\times n$ symmetric matrices. Next we define the following spaces which will be used in this paper. Denote by $L^\infty(0,T;\mathbb{R}^n)$ the Banach space consisting of $\mathbb{R}^n$-valued variables $\phi(\cdot)$ such that $\sup\limits_{0\leqslant t\leqslant T}|\phi(t)|<\infty$, by $L^p(0,T;\mathbb{R}^n)$ the Banach space consisting of $\mathbb{R}^n$-valued variables $\phi(\cdot)$ such that $\int_0^T|\phi(t)|^pdt<\infty$, where p is an integer. Denote by $L^2_{\mathcal{F}_t}(\Omega;\mathbb{R}^n)$ the Hilbert space consisting of $\mathbb{R}^n$-valued $\mathcal{F}_t$-measurable random variables ϕ such that $\mathbb{E}|\phi|^2<\infty$, by $L^2_{\mathbb{F}}(\Omega;C([0,T];\mathbb{R}^n))$ the Banach space consisting of $\mathbb{R}^n$-valued $\mathbb{F}$-adapted continuous processes $\phi(\cdot)$ such that $\mathbb{E}\big[\sup\limits_{0\leqslant t\leqslant T}|\phi(t)|^2\big]<\infty$, by $L^{2,p}_{\mathbb{F}}(\triangle_2(0,T);\mathbb{R}^n)$ the Banach space of $\mathbb{R}^n$-valued and measurable processes ϕ on $\triangle_2(0,T)$ such that $\phi(t,\cdot)$ is $\mathbb{F}$-progressively measurable on $(0,t)$ for each $t\in(0,T)$, and $\mathbb{E}[\int_0^T(\int_0^t|\phi(t,s)|^pds)^{\frac{2}{p}}dt]^{\frac12}<\infty$. For $p=2$, we simply denote $L^2_{\mathbb{F}}(\triangle_2(0,T);\mathbb{R}^n)\equiv L^{2,2}_{\mathbb{F}}(\triangle_2(0,T);\mathbb{R}^n)$. Denote by $\mathscr{L}^2(\triangle_2(0,T);\mathbb{R}^n)$ the set of $\phi\in L^2(\triangle_2(0,T);\mathbb{R}^n)$ satisfying $\operatorname*{ess\,sup}\limits_{t\in(0,T)}\Big(\int_t^T|\phi(s,t)|^2ds\Big)^{\frac12}<\infty$, and for any $\varepsilon>0$, there exists a finite partition $\{a_i\}_{i=0}^m$ of $(0,T)$ with $0=a_0<a_1<\cdots<a_m=T$ such that

$$\operatorname*{ess\,sup}_{t\in(a_i,a_{i+1})}\bigg(\int_t^{a_{i+1}}|\phi(s,t)|^2ds\bigg)^{\frac12}<\varepsilon,$$

for each $i\in\{0,1,\dots,m-1\}$. Denote by $L^{2,2,1}(\square_3(0,T);\mathbb{R}^n)$ the Banach space of $\mathbb{R}^n$-valued deterministic functions ϕ on $\square_3(0,T)$ such that

$$(\int_0^T\int_0^T(\int_0^{s_1\wedge s_2}|\phi(s_1,s_2,t)|dt)^2ds_1ds_2)^{1/2}<\infty.$$

For any $0\leqslant t_0<T$, consider the following SDDE:

$$\begin{cases} d\bar x(t)=[\bar A_1(t)\bar x(t)+\bar A_2(t)\bar y(t)+\bar A_3(t)\bar z(t)+\bar b(t)]dt\\ \qquad\qquad+[\bar C_1(t)\bar x(t)+\bar C_2(t)\bar y(t)+\bar C_3(t)\bar z(t)+\bar\sigma(t)]dW(t),\quad t\in(t_0,T),\\ \bar x(t)=\bar\xi(t-t_0),\quad t\in[t_0-\delta,t_0],\\ \bar y(t)\equiv\bar x(t-\delta),\quad \bar z(t)\equiv\int_{t_0}^t\bar F(t,s)\bar x(s)ds,\quad t\in(t_0,T), \end{cases}\tag{2.1}$$

where $\bar\xi(\cdot)\in C([-\delta,0];\mathbb{R}^n)$ is the initial trajectory, $\delta>0$ is constant delay time. As to the coefficients of (2.1), we impose the following conditions:

(H1) $\bar A_1(\cdot),\bar A_2(\cdot),\bar A_3(\cdot)\in L^2(0,T;\mathbb{R}^{n\times n})$, $\bar C_1(\cdot),\bar C_2(\cdot),\bar C_3(\cdot)\in L^\infty(0,T;\mathbb{R}^{n\times n})$,

$$\bar{F}(\cdot,\cdot)\in L^{2,1}(\Delta_2(0,T);\mathbb{R}^{n\times n}),\ \bar{b}(\cdot)\in L^2_{\mathbb{F}}(\Omega;L^1(0,T;\mathbb{R}^n)),\ \bar{\sigma}(\cdot)\in L^2_{\mathbb{F}}(0,T;\mathbb{R}^n).$$

The following proposition, with proof in [28], guarantees its solvability. In contrast with e.g. [10,11,38] where $\bar{A}_i(\cdot)$ is assumed to be bounded, $i=1,2,3$, we slightly relax them into proper integrable conditions.

Proposition 2.1. *Let* (H1) *hold. Then, SDDE* (2.1) *admits a unique solution* $\bar{x}(\cdot)\in L^2_{\mathbb{F}}\big(\Omega;C([t_0,T];\mathbb{R}^n)\big)$.

Based on the above preparations, let us return back to the state equation (1.1), the coefficients of which satisfy the following assumptions.

(A1) $A_1(\cdot),A_2(\cdot),A_3(\cdot)\in L^2(0,T;\mathbb{R}^{n\times n}),\ B_1(\cdot),B_2(\cdot),B_3(\cdot)\in L^\infty(0,T;\mathbb{R}^{n\times m}),$
$C_1(\cdot),C_2(\cdot),C_3(\cdot)\in L^\infty(0,T;\mathbb{R}^{n\times n}),\quad D_1(\cdot)\in L^\infty(0,T;\mathbb{R}^{n\times m}),$
$F(\cdot,\cdot)\in L^\infty(\Delta_2(0,T);\mathbb{R}^{n\times n}),\ \tilde{F}(\cdot,\cdot)\in L^\infty(\Delta_2(0,T);\mathbb{R}^{n\times m}),\ \xi(\cdot)\in C([-\delta,0];\mathbb{R}^n),$
$\varsigma(\cdot)\in L^2(-\delta,0;\mathbb{R}^m),\quad b(\cdot)\in L^2_{\mathbb{F}}(\Omega;L^1(0,T;\mathbb{R}^n)),\quad \sigma(\cdot)\in L^2_{\mathbb{F}}(0,T;\mathbb{R}^n),$
$Q_1(\cdot),Q_2(\cdot),Q_3(\cdot)\in L^\infty(0,T;\mathbb{S}^n),\qquad R_1(\cdot),R_2(\cdot)\in L^\infty(0,T;\mathbb{S}^m).$

By Proposition 2.1, SDDE (1.1) admits a unique solution, the cost functional (1.2) is well-defined, and hence, it becomes natural to pose Problem (P) in the Introduction.

We are interested in the closed-loop optimal control. To this end, we first look at the closed-loop strategy. For any given $t_0\in[0,T)$, define $\mathbb{L}\equiv L^2(t_0,T;\mathbb{R}^{m\times n})\times L^2(\Delta_2(t_0,T);\mathbb{R}^{m\times n})\times L^\infty(t_0,T;\mathbb{R}^{m\times n})\times L^2(\Delta_2(t_0,T);\mathbb{R}^{m\times m})\times L^2_{\mathbb{F}}(t_0,T;\mathbb{R}^m)$. In the following, for any $(K_1(\cdot),K_2(\cdot,\cdot),K_3(\cdot),\ K_4(\cdot,\cdot),v(\cdot))\in\mathbb{L}$, we call it a *closed-loop strategy* on $[t_0,T]$. Later we will use this closed-loop strategy, which does not depend on the initial data but only the given coefficients, to construct a closed-loop control on $[t_0,T]$. To introduce the closed-loop state, let us consider the SDDE:

$$\begin{cases} dx(t)=\big[A_1(t)x(t)+A_2(t)y(t)+A_3(t)z(t)+B_1(t)u(t)+B_2(t)\nu(t)\\ \qquad\qquad +B_3(t)\mu(t)+b(t)\big]dt+\big[C_1(t)x(t)+C_2(t)y(t)+C_3(t)z(t)\\ \qquad\qquad +D_1(t)u(t)+\sigma(t)\big]dW(t),\quad t\in(t_0,T),\\ x(t)=\xi(t-t_0),\quad u(t)=\varsigma(t-t_0),\quad t\in[t_0-\delta,t_0],\\ u(t)=K_1(t)x(t)+\displaystyle\int_{t_0}^t K_2(t,s)x(s)ds+K_3(t)x(t-\delta)\\ \qquad\qquad +\displaystyle\int_{t_0}^t K_4(t,s)u(s)ds+v(t),t\in(t_0,T). \end{cases} \tag{2.2}$$

We call (2.2) a *closed-loop system* under (K_1,K_2,K_3,K_4,v) corresponding to (t_0,ξ,ς), and call $x(\cdot)$, $u(\cdot)$ the corresponding *closed-loop state* and *closed-loop outcome control*, respectively. The proof of the following result is given in the Appendix.

Proposition 2.2. *Let* (A1) *hold. Then, for any given* $t_0\in[0,T)$ *and* $(K_1(\cdot),K_2(\cdot,\cdot),K_3(\cdot),K_4(\cdot,\cdot),v(\cdot))\in\mathbb{L}$, *the closed-loop system* (2.2) *admits a unique solution* $x(\cdot)\in L^2_{\mathbb{F}}\big(\Omega;C([t_0,T];\mathbb{R}^n)\big)$ *on* $[t_0,T]$, *and there exists a constant* $L>0$ *such that*

$$\begin{aligned}&\mathbb{E}\sup_{t_0\leqslant t\leqslant T}|x(t)|^2+\mathbb{E}\int_{t_0}^T|u(t)|^2dt\leqslant L\bigg\{\sup_{t_0-\delta\leqslant t\leqslant t_0}|\xi(t-t_0)|^2\\ &\qquad+\int_{t_0-\delta}^{t_0}|\varsigma(t-t_0)|^2dt+\mathbb{E}\int_{t_0}^T\big(|b(t)|^2+|\sigma(t)|^2+|v(t)|^2\big)dt\bigg\}.\end{aligned} \tag{2.3}$$

At last, let us introduce the following notions.

Definition 2.3. *For any given* $t_0\in[0,T)$, *the closed-loop strategy* $(K_1^*(\cdot),K_2^*(\cdot,\cdot),K_3^*(\cdot),K_4^*(\cdot,\cdot),v^*(\cdot))\in\mathbb{L}$ *is called an* optimal closed-loop strategy *of Problem* (P) *if*

$$J\big(t_0,\xi,\varsigma;(K_1^*,K_2^*,K_3^*,K_4^*,v^*)\big)\leqslant J\left(t_0,\xi,\varsigma;u\right),$$

for any $(\xi,\varsigma)\in C([-\delta,0];\mathbb{R}^n)\times L^2(-\delta,0;\mathbb{R}^m)$ *and any control* $u(\cdot)\in L^2_{\mathbb{F}}(t_0,T;\mathbb{R}^m)$. *If there (uniquely) exists an optimal closed-loop strategy on* $[t_0,T]$*, Problem* (P) *is said to be* (uniquely) closed-loop solvable on $[t_0,T]$.

Remark 2.4. Inspired by [3, 12, 19, 37], the closed-loop strategy for deterministic Problem (P) was introduced in [26], and then extended to the stochastic setting in [27]. Here our version is more general due to the appearance of $K_3(\cdot)$. Furthermore, the definitions of the closed-loop strategies in [26, 27] rely on the transformed equivalent problems, which are not required for Definition 2.3 in this paper. In (2.2), K_1, K_2, K_3, K_4 represent respectively the gain coefficients of the current state, the distributed state delay, the pointwise state delay and the distributed control delay.

3. The closed-loop solvability of Problem (P).

In this section, we firstly transform the delayed Problem (P) into another optimal control problem driven by a (finite dimensional) stochastic Volterra integral equation (SVIE) without delay. Based on such a transformation, we then introduce and discuss the desired Riccati system for Problem (P). Eventually, we construct an explicit closed-loop strategy and prove its optimality in the sense of Definition 2.3.

3.1. Problem transformation.

To begin with, let us take a closer look at the state $x(\cdot)$. Since $\varsigma(\cdot)$ is the initial trajectory of the control, for either $t\in\big[t_0,(t_0+\delta)\wedge T\big]$ or $t\in\big((t_0+\delta)\wedge T,t_0+\delta\big]$ we get

$$\int_{t_0}^t B_2(s)u(s-\delta)ds=\int_{t_0}^t B_2(s)\varsigma(s-\delta-t_0)ds=\int_{t_0}^{t_0+\delta}\mathbf{1}_{[t_0,t)}(s)B_2(s)\varsigma(s-\delta-t_0)ds.$$

For $t\in\big(t_0+\delta,(t_0+\delta)\vee T\big]$, we have

$$\begin{aligned}\int_{t_0}^t B_2(s)u(s-\delta)ds&=\int_{t_0}^{t_0+\delta}B_2(s)u(s-\delta)ds+\int_{t_0+\delta}^t B_2(s)u(s-\delta)ds\\&=\int_{t_0}^{t_0+\delta}\mathbf{1}_{[t_0,t)}(s)B_2(s)\varsigma(s-\delta-t_0)ds+\int_{t_0}^t\mathbf{1}_{[t_0,t-\delta)}(s)B_2(s+\delta)u(s)ds.\end{aligned}$$

To sum up, for $t\in[t_0,T]$, we have

$$\int_{t_0}^t B_2(s)u(s-\delta)ds=\int_{t_0}^{t_0+\delta}\mathbf{1}_{[t_0,t)}(s)B_2(s)\varsigma(s-\delta-t_0)ds+\int_{t_0}^t\mathbf{1}_{[t_0,t-\delta)}(s)B_2(s+\delta)u(s)ds.$$

As to the $\mu(\cdot)$ term in $x(\cdot)$, by the Fubini theorem, for $t\in[t_0,T]$, we obtain

$$\int_{t_0}^t B_3(s)\mu(s)ds=\int_{t_0}^t B_3(s)\int_{t_0}^s\tilde F(s,r)u(r)drds=\int_{t_0}^t\int_r^t B_3(s)\tilde F(s,r)dsu(r)dr.$$

Thus we deduce

$$\begin{aligned}x(t)=\xi(0)&+\int_{t_0}^{t_0+\delta}B_2(s)\varsigma(s-\delta-t_0)\mathbf{1}_{[t_0,t)}(s)ds+\int_{t_0}^t\Big[A_1(s)x(s)+A_2(s)y(s)\\&+A_3(s)z(s)+\Big(B_1(s)+B_2(s+\delta)\mathbf{1}_{[t_0,t-\delta)}(s)+\int_s^t B_3(r)\tilde F(r,s)dr\Big)u(s)+b(s)\Big]ds\\&+\int_{t_0}^t\big[C_1(s)x(s)+C_2(s)y(s)+C_3(s)z(s)+D_1(s)u(s)+\sigma(s)\big]dW(s),\ t\in[t_0,T].\end{aligned}\tag{3.1}$$

Next let us turn to the term of $y(\cdot)$. For $t\in[t_0+\delta,T]$,

$$\begin{aligned}\int_{t_0}^{t-\delta}B_2(s)u(s-\delta)ds\mathbf{1}_{(t_0+\delta,\infty)}(t)=\Big[\int_{t_0}^{t_0+\delta}\mathbf{1}_{[t_0,t-\delta)}(s)B_2(s)\varsigma(s-\delta-t_0)ds\\+\int_{t_0}^t\mathbf{1}_{[t_0,t-2\delta)}(s)B_2(s+\delta)u(s)ds\Big]\mathbf{1}_{(t_0+\delta,\infty)}(t).\end{aligned}$$

As to the $\mu(\cdot)$ term in $y(\cdot)$, for $t\in[t_0+\delta,T]$, it follows from the Fubini theorem that

$$\begin{aligned}\int_{t_0}^{t-\delta} B_3(s)\mu(s)ds &= \int_{t_0}^{t-\delta} B_3(s)\int_{t_0}^{s}\tilde F(s,r)u(r)drds\\ &= \int_{t_0}^{t-\delta} B_3(r)\int_{t_0}^{r}\tilde F(r,s)u(s)dsdr = \int_{t_0}^{t-\delta}\int_{s}^{t-\delta} B_3(r)\tilde F(r,s)dru(s)ds.\end{aligned}$$

Hence for the pointwise state delay, we have

$$\begin{aligned} y(t) &= \xi(t-\delta-t_0)\mathbf{1}_{[t_0,t_0+\delta]}(t)+\mathbf{1}_{(t_0+\delta,\infty)}(t)\Big\{\xi(0)+\int_{t_0}^{(t_0+\delta)\wedge(t-\delta)} B_2(s)\varsigma(s-t_0-\delta)ds\Big\}\\ &\quad +\int_{t_0}^{t}\mathbf{1}_{[t_0,t-\delta)}(s)\Big(A_1(s)x(s)+A_2(s)y(s)+A_3(s)z(s)+\Big[B_1(s)+B_2(s+\delta)\\ &\quad \times\mathbf{1}_{[t_0,t-2\delta)}(s)+\int_{s}^{t-\delta} B_3(r)\tilde F(r,s)dr\Big]u(s)+b(s)\Big)ds+\int_{t_0}^{t}\mathbf{1}_{[t_0,t-\delta)}(s)\\ &\quad \times\big[C_1(s)x(s)+C_2(s)y(s)+C_3(s)z(s)+D_1(s)u(s)+\sigma(s)\big]dW(s),\quad t\in[t_0,T]. \end{aligned}\tag{3.2}$$

Eventually, let us treat the term of $z(\cdot)$. For $t\in[t_0,T]$,

$$\begin{aligned} z(t) &= \int_{t_0}^{t} F(t,s)x(s)ds = \int_{t_0}^{t} F(t,s)\Big[\xi(0)+\int_{t_0}^{s}\big(A_1(r)x(r)+A_2(r)y(r)+A_3(r)z(r)\\ &\qquad +B_1(r)u(r)+B_2(r)\nu(r)+B_3(r)\mu(r)+b(r)\big)dr\\ &\qquad +\int_{t_0}^{s}\big(C_1(r)x(r)+C_2(r)y(r)+C_3(r)z(r)+D_1(r)u(r)+\sigma(r)\big)dW(r)\Big]ds. \end{aligned}\tag{3.3}$$

By Fubini theorem,

$$\int_{t_0}^{t}\int_{t_0}^{s} F(t,s)B_2(r)\nu(r)drds = \int_{t_0}^{t}\Big[\int_{r}^{t} F(t,s)ds\Big]B_2(r)u(r-\delta)dr.$$

Therefore, for $t\in[t_0,T]$, we obtain that

$$\begin{aligned}\int_{t_0}^{t}\int_{t_0}^{s} F(t,s)B_2(r)\nu(r)drds &= \int_{t_0}^{(t_0+\delta)\wedge t}\Big[\int_{r}^{t} F(t,s)ds\Big]B_2(r)\varsigma(r-\delta-t_0)dr\\ &\quad +\int_{t_0\wedge(t-\delta)}^{t-\delta}\Big[\int_{r+\delta}^{t} F(t,s)ds\Big]B_2(r+\delta)u(r)dr.\end{aligned}\tag{3.4}$$

As to the $\mu(\cdot)$ term in $z(\cdot)$, by the Fubini theorem again, for $t\in[t_0,T]$,

$$\begin{aligned}\int_{t_0}^{t}\int_{t_0}^{s} F(t,s)B_3(r)\mu(r)drds &= \int_{t_0}^{t}\int_{t_0}^{s} F(t,s)B_3(r)\Big[\int_{t_0}^{r}\tilde F(r,\alpha)u(\alpha)d\alpha\Big]drds\\ &=\int_{t_0}^{t}\int_{t_0}^{s}\int_{\alpha}^{s} F(t,s)B_3(r)\tilde F(r,\alpha)u(\alpha)drd\alpha ds=\int_{t_0}^{t}\Big[\int_{\alpha}^{t}\int_{\alpha}^{s} F(t,s)B_3(r)\tilde F(r,\alpha)drds\Big]u(\alpha)d\alpha.\end{aligned}\tag{3.5}$$

Hence, from (3.3)–(3.5) and by adding some indicative functions, we derive

$$\begin{aligned} z(t) &= \int_{t_0}^{t} F(t,s)\Big(\xi(0)+\int_{t_0}^{t_0+\delta} B_2(r)\varsigma(r-\delta-t_0)\mathbf{1}_{[0,s)}(r)dr\Big)ds+\int_{t_0}^{t}\mathcal{E}(t,s)\big[A_1(s)x(s)+A_2(s)y(s)\\ &\quad +A_3(s)z(s)\big]ds+\int_{t_0}^{t}\Big[\int_{s}^{t} F(t,r)\Big(B_1(s)+B_2(s+\delta)\mathbf{1}_{[t_0,r-\delta)}(s)+\int_{s}^{r} B_3(\theta)\tilde F(\theta,s)d\theta\Big)dr\Big]u(s)ds\\ &\quad +\int_{t_0}^{t}\mathcal{E}(t,s)b(s)ds+\int_{t_0}^{t}\mathcal{E}(t,s)\big[C_1(s)x(s)+C_2(s)y(s)+C_3(s)z(s)+D_1(s)u(s)+\sigma(s)\big]dW(s). \end{aligned}\tag{3.6}$$

Here and next, for $T\geqslant t>s\geqslant t_0$, we define $\mathcal{E}(\cdot,\cdot)$ and

$$X(t)\equiv\begin{bmatrix} x(t)\\ y(t)\\ z(t)\end{bmatrix},\qquad \mathcal{E}(t,s)\equiv\int_{s}^{t} F(t,r)dr\mathbf{1}_{[0,t]}(s),\tag{3.7}$$

$$\varphi(t)\equiv\begin{bmatrix} \xi(0)+\int_{t_0}^{t_0+\delta} B_2(s)\varsigma(s-t_0-\delta)\mathbf{1}_{[t_0,t)}(s)ds\\ \xi(t-t_0-\delta)\mathbf{1}_{[t_0,t_0+\delta]}(t)+[\xi(0)+\int_{t_0}^{(t_0+\delta)\wedge(t-\delta)} B_2(s)\varsigma(s-t_0-\delta)ds]\mathbf{1}_{(t_0+\delta,\infty)}(t)\\ \int_{t_0}^{t} F(t,s)[\xi(0)+\int_{t_0}^{t_0+\delta} B_2(r)\varsigma(r-t_0-\delta)\mathbf{1}_{[t_0,s)}(r)dr]ds\end{bmatrix},$$

$$A(t,s)\equiv\begin{bmatrix} A_1(s) & A_2(s) & A_3(s)\\ \mathbf{1}_{(\delta,\infty)}(t-s)A_1(s) & \mathbf{1}_{(\delta,\infty)}(t-s)A_2(s) & \mathbf{1}_{(\delta,\infty)}(t-s)A_3(s)\\ \mathcal{E}(t,s)A_1(s) & \mathcal{E}(t,s)A_2(s) & \mathcal{E}(t,s)A_3(s)\end{bmatrix},$$

$$B(t,s) \equiv \begin{bmatrix} B_1(s)+B_2(s+\delta)\mathbf{1}_{(\delta,\infty)}(t-s)+\int_s^t B_3(r)\tilde F(r,s)dr \\ \mathbf{1}_{(\delta,\infty)}(t-s)[B_1(s)+B_2(s+\delta)\mathbf{1}_{(2\delta,\infty)}(t-s)+\int_s^{t-\delta} B_3(r)\tilde F(r,s)dr] \\ \mathcal{E}(t,s)B_1(s)+\mathcal{E}(t,s+\delta)B_2(s+\delta)+\int_s^t \mathcal{E}(t,\theta)B_3(\theta)\tilde F(\theta,s)d\theta \end{bmatrix},$$

$$C(t,s) \equiv \begin{bmatrix} C_1(s) & C_2(s) & C_3(s) \\ \mathbf{1}_{(\delta,\infty)}(t-s)C_1(s) & \mathbf{1}_{(\delta,\infty)}(t-s)C_2(s) & \mathbf{1}_{(\delta,\infty)}(t-s)C_3(s) \\ \mathcal{E}(t,s)C_1(s) & \mathcal{E}(t,s)C_2(s) & \mathcal{E}(t,s)C_3(s) \end{bmatrix},$$

$$D(t,s) \equiv \begin{bmatrix} D_1(s) \\ \mathbf{1}_{(\delta,\infty)}(t-s)D_1(s) \\ \mathcal{E}(t,s)D_1(s) \end{bmatrix}, \tilde b(t,s) \equiv \begin{bmatrix} b(s) \\ \mathbf{1}_{(\delta,\infty)}(t-s)b(s) \\ \mathcal{E}(t,s)b(s) \end{bmatrix}, \tilde\sigma(t,s) \equiv \begin{bmatrix} \sigma(s) \\ \mathbf{1}_{(\delta,\infty)}(t-s)\sigma(s) \\ \mathcal{E}(t,s)\sigma(s) \end{bmatrix}.$$

Based on (3.1), (3.2) and (3.6), $X(\cdot)$ satisfies the following SVIE:

$$\begin{aligned} X(t) &= \varphi(t) + \int_{t_0}^t \big[A(t,s)X(s)+B(t,s)u(s)+\tilde b(t,s)\big]ds \\ &\quad + \int_{t_0}^t \big[C(t,s)X(s)+D(t,s)u(s)+\tilde\sigma(t,s)\big]dW(s), \quad t\in(t_0,T). \end{aligned} \tag{3.8}$$

Denote

$$Q(t) \equiv \begin{bmatrix} Q_1(t) & 0 & 0 \\ 0 & Q_2(t) & 0 \\ 0 & 0 & Q_3(t) \end{bmatrix}, \quad R(t) \equiv R_1(t) + R_2(t+\delta)\mathbf{1}_{[0,T-\delta)}(t).$$

Then, the cost functional (1.2) becomes

$$\begin{aligned} J(t_0,\xi(\cdot),\varsigma(\cdot);u(\cdot)) &= \mathbb{E}\int_{t_0}^T \big[X(t)^\top Q(t)X(t) + u(t)^\top R(t)u(t)\big]dt \\ &\quad + \mathbb{E}\int_{t_0}^{(t_0+\delta)\wedge T} \varsigma(t-t_0-\delta)^\top R_2(t)\varsigma(t-t_0-\delta)dt. \end{aligned} \tag{3.9}$$

To sum up, we have the following result with proof in the Appendix.

Proposition 3.1. *Let Assumption* (A1) *hold. Then* $u^*(\cdot)$ *is an optimal control of Problem* (P) *if and only if* $u^*(\cdot)$ *minimizes* (3.9) *subject to SVIE* (3.8).

Remark 3.2. The idea of transforming the delayed system into another one without delay is popular in the existing literature.

For example, in [12, 13, 26, 27], they transformed the original delayed systems into infinite-dimensional evolution control systems without delay. However, in some cases they had to treat the unbounded control operator which would bring essential difficulties. More importantly, it seems quite complex to transform the obtained operator-valued Riccati equation into the (finite dimensional) matrix-valued case.

In contrast, in the current paper we put $(x(\cdot), y(\cdot), z(\cdot))$ together to construct a new state $X(\cdot)$ and then transform the original system equivalently to a controlled SVIE. Similar procedure also appeared in [25]. On the one hand, this helps us to utilize the developed LQ theory for SVIEs in [17]. On the other hand, the advantage lies in that $X(\cdot)$ is still finite dimensional which helps us to bypass the complicated operator language.

Another approach to addressing delayed problems is direct decoupling the forward delayed systems and the backward anticipated systems. However, this method requires the application of Itô formula for delayed processes, which constitutes the essential difficulty of delayed problems. In contrast, the method proposed in this paper does not need to tackle such a challenge.

We point out that the transformation to Volterra systems also appeared in e.g. [18, 21] via the constant variation formula. Nevertheless, it is not clear whether such an approach still works when the diffusion term in (1.1) contains the pointwise state delay and distributed state delay.

3.2. The solvability of the new Riccati system. To study the closed-loop solvability of Problem (P), we introduce a new Riccati system based on the above transformation and the existing study in [17]. To this end, we need some preparations.

Firstly, we denote by $\Pi(0,T)$ the set of pairs $P=\big(P^{(1)},P^{(2)}\big)$ with $P^{(1)}:(0,T)\to\mathbb{R}^{(3n)\times(3n)}$ and $P^{(2)}:\square_3\,(t_0,T)\to\mathbb{R}^{(3n)\times(3n)}$ such that

(i) $P^{(1)}\in L^\infty\big(0,T;\mathbb{S}^{3n}\big)$;

(ii) for a.e. $(s_1,s_2)\in(0,T)^2$, $t\mapsto P^{(2)}(s_1,s_2,t)$ is absolutely continuous on $(0,s_1\wedge s_2)$;

(iii) $(s_1,s_2)\mapsto P^{(2)}(s_1,s_2,s_1\wedge s_2)\equiv\lim\limits_{t\uparrow(s_1\wedge s_2)}P^{(2)}(s_1,s_2,t)$ belongs to $L^2\big((0,T)^2;\mathbb{R}^{(3n)\times(3n)}\big)$;

(iv) $(s_1,s_2,t)\mapsto\dot P^{(2)}(s_1,s_2,t)\equiv\frac{\partial P^{(2)}}{\partial t}(s_1,s_2,t)$ belongs to $L^{2,2,1}\big(\square_3(0,T);\mathbb{R}^{(3n)\times(3n)}\big)$;

(v) for a.e. $(s_1,s_2,t)\in\square_3(0,T)$, it holds that $P^{(2)}\,(s_1,s_2,t)=P^{(2)}\,(s_2,s_1,t)^\top$.

Secondly, for later notational usefulness, we define several coefficients as follows:

$$\Pi(s,t,\theta)\equiv\begin{bmatrix}\frac{1}{s-t}I & \frac{1}{s-t}\mathbf{1}_{(\delta,\infty)}(s-t)I & I\\ \frac{1}{s-t}\mathbf{1}_{(\delta,\infty)}(s-t)I & \frac{1}{s-t}\mathbf{1}_{(2\delta,\infty)}(s-t)I & \mathbf{1}_{(\delta,\infty)}(s-\theta)I\\ \frac{1}{s-t}\mathcal{E}(s,t) & \frac{1}{s-t}\mathcal{E}(s,t+\delta) & \mathcal{E}(s,\theta)\end{bmatrix},$$

$$\Upsilon(s,t)\equiv\big(I,\mathbf{1}_{(\delta,\infty)}(s-t)I,\mathcal{E}(s,t)^\top\big)^\top,\quad \mathcal{A}(t)\equiv\big(A_1(t),A_2(t),A_3(t)\big),$$

$$\mathcal{B}(\theta,t)\equiv(B_1(t)^\top,B_2(t+\delta)^\top,(B_3(\theta)\widetilde F(\theta,t))^\top)^\top,\quad \mathcal{C}(t)\equiv\big(C_1(t),C_2(t),C_3(t)\big). \tag{3.10}$$

Given these coefficients, we introduce the following system:

$$\begin{cases}P^{(1)}(t)=Q(t)+\mathcal{C}(t)^\top\mathcal{G}_1(t)\mathcal{C}(t)-\mathcal{C}(t)^\top\mathcal{G}_1(t)D_1(t)\mathcal{R}(t)^{-1}D_1(t)^\top\mathcal{G}_1(t)\mathcal{C}(t), 0<t<T,\\ P^{(2)}(s,t,r)=P^{(2)}(s,t,t\wedge s)-\displaystyle\int_r^{t\wedge s}\int_\tau^T\int_\tau^T\mathcal{G}_3(s,\tau,\theta_1)\mathcal{B}(\theta_1,\tau)\mathcal{R}(\tau)^{-1}\mathcal{B}(\theta_2,\tau)^\top\\ \qquad\qquad\times\mathcal{G}_3(t,\tau,\theta_2)^\top d\theta_1d\theta_2d\tau, 0<r<(s\wedge t)<T,\\ P^{(2)}(\bar s,t,t)=P^{(2)}(t,\bar s,t)^\top=\mathcal{G}_2(\bar s,t)\mathcal{A}(t)\\ \qquad\qquad-\displaystyle\int_t^T\mathcal{G}_3(\bar s,t,\theta)\mathcal{B}(\theta,t)\mathcal{R}(t)^{-1}D_1(t)^\top\mathcal{G}_1(t)\mathcal{C}(t)d\theta, 0<t<\bar s<T,\end{cases} \tag{3.11}$$

where for $0<t<(s\wedge\bar s\wedge\theta)<T$,

$$\mathcal{R}(t)\equiv R_1(t)+R_2(t+\delta)\mathbf{1}_{[0,T-\delta)}(t)+D_1(t)^\top\mathcal{G}_1(t)D_1(t),$$

$$\mathcal{G}_1(t)\equiv\mathcal{G}_1\big(t;P^{(1)},P^{(2)}\big)\equiv\int_t^T\Upsilon(s_1,t)^\top\Big[P^{(1)}(s_1)\Upsilon(s_1,t)+\int_t^TP^{(2)}(s_1,s_2,t)\Upsilon(s_2,t)ds_2\Big]ds_1,$$

$$\mathcal{G}_2(\bar s,t)\equiv\mathcal{G}_2\big(\bar s,t;P^{(1)},P^{(2)}\big)\equiv P^{(1)}(\bar s)\Upsilon(\bar s,t)+\int_t^TP^{(2)}(\bar s,r,t)\Upsilon(r,t)dr,$$

$$\mathcal{G}_3(s,t,\theta)\equiv\mathcal{G}_3\big(s,t,\theta;P^{(1)},P^{(2)}\big)\equiv P^{(1)}(s)\mathbf{1}_{(t,s)}(\theta)\Pi(s,t,\theta)+\int_\theta^TP^{(2)}(s,r,t)\Pi(r,t,\theta)dr. \tag{3.12}$$

In this paper, we name (3.11) the desired Riccati system, explicitly depending on A_i, B_i, C_i, D_1, based on (at least) the following aspects. Firstly, it is consistent with the Riccati system for the stochastic Volterra system in [17]. Secondly, in particular cases we will show in Subsection 4.1, 4.2, 4.5 that it can reduce to the Riccati systems in the existing literature. Thirdly, just like the existing Riccati systems, we will use the above (3.11) to construct the closed-loop control as well. To guarantee its well-posedness, we need the following standard assumption.

(A2) There exists a constant $\lambda>0$ such that for all $t\in(0,T)$, $R_1(t)+R_2(t+\delta)\mathbf{1}_{[0,T-\delta)}(t)\geqslant\lambda I$, $Q_i(t)\geqslant0$, $i=1,2,3$.

The following proposition gives its solvability.

THEOREM 3.3. *Let* (A1)–(A2) *hold. Then, the Riccati system* (3.11) *admits a unique solution* $(P^{(1)}, P^{(2)}) \in \Pi(0,T)$ *such that* $\mathcal{R}(\cdot) \geqslant \beta I$ *for some constant* $\beta > 0$.

Next we introduce the following backward system:

$$
\begin{cases}
d\eta(t,s) = -\Big\{\mathcal{G}_2(t,s)b(s) + \Gamma^*(t,s)^\top\big[D_1(s)^\top\mathcal{G}_1(s)\sigma(s) + \int_s^T\big[D_1(s)^\top\Upsilon(r,s)^\top\zeta(r,s) \\
\quad + \big(\int_s^r\mathcal{B}(\theta,s)^\top\Pi(r,s,\theta)^\top d\theta\big)\eta(r,s)\big]dr\big]\Big\}ds + \zeta(t,s)dW(s), \ 0<s<t<T, \\
\eta(t,t) = \big[\mathcal{C}(t)^\top + \Xi^*(t)^\top D_1(t)^\top\big]\mathcal{G}_1(t)\sigma(t) + \int_t^T\Big\{\big[\big(\int_t^r\Pi(r,t,\theta)\mathcal{B}(\theta,t)d\theta\big) \\
\quad \times\Xi^*(t) + \Upsilon(r,t)\mathcal{A}(t)\big]^\top\eta(r,t) + \big[\mathcal{C}(t) + D_1(t)\Xi^*(t)\big]^\top\Upsilon(r,t)^\top\zeta(r,t)\Big\}dr, \ 0<t<T,
\end{cases}
\tag{3.13}
$$

where $\Xi^*(\cdot)$, $\Gamma^*(\cdot,\cdot)$ are defined by

$$
\begin{aligned}
&\Xi^*(t) = -\mathcal{R}(t)^{-1}D_1(t)^\top\mathcal{G}_1(t)\mathcal{C}(t), \quad 0<t<T, \\
&\Gamma^*(s,t) = -\mathcal{R}(t)^{-1}\int_t^T\mathcal{B}(\theta,t)^\top\mathcal{G}_3(s,t,\theta)^\top d\theta, \ 0<t<s<T,
\end{aligned}
\tag{3.14}
$$

and $\Pi(\cdot,\cdot,\cdot)$, $\Upsilon(\cdot,\cdot)$, $\mathcal{R}(\cdot)$, $\mathcal{G}_1(\cdot)$, $\mathcal{G}_3(\cdot,\cdot,\cdot)$ are defined as (3.10), (3.12). In terms of [17], we name it the Type-II extended backward SVIE in our scenario. To study its well-posedness, we introduce the following space. Denote by $L^2_{\mathbb{F},c}(\triangle_2(0,T);\mathbb{R}^{3n})$ the set of $\eta \in L^2_{\mathbb{F}}(\triangle_2(0,T);\mathbb{R}^{3n})$ such that $s \mapsto \eta(t,s)$ is uniformly continuous on $(0,t)$ with the limits defined by $\eta(t,t) \equiv \lim_{s\uparrow t}\eta(t,s)$ and $\eta(t,0) \equiv \lim_{s\downarrow 0}\eta(t,s)$ for a.e. $t \in (0,T)$, a.s., and $\eta(\cdot,\cdot)$ satisfies $\mathbb{E}(\int_0^T \sup\limits_{s\in[0,t]}|\eta(t,s)|^2 \, \mathrm{d}t)^{\frac{1}{2}} < \infty$.

THEOREM 3.4. *Let* (A1)–(A2) *hold. Then, the Type-II extended backward SVIE* (3.13) *admits a unique solution* $(\eta,\zeta) \in L^2_{\mathbb{F},c}(\triangle_2(0,T);\mathbb{R}^{3n}) \times L^2_{\mathbb{F}}(\triangle_2(0,T);\mathbb{R}^{3n})$.

Remark 3.5. We discuss the solvability results of the above Riccati system.

We firstly make comparisons with that in [27]. In terms of their framework, both the cost functional and the diffusion term can depend on the distributed control delay which is out of our scope. However, to derive the Riccati system they have to assume that $C_2, b, \sigma, R_2, Q_2 = 0$. In addition, to obtain the solvability, they further require that $D_1 = 0$ and all the coefficients are time-invariant or continuous. It is worth mentioning that these assumptions are not needed here. Moreover, the methodologies developed in both papers are essentially different.

Next we turn to a particular case of the state equation (1.1) with $A_2, B_2, C_2, Q_2, R_2 = 0$, and arrive at an LQ problem for a stochastic integro-differential system. Even though there are some positive results of the Riccati system (see [30, 31]) in deterministic scenario, the extension to the stochastic setting is still open. Here we fill this blank in a nice manner.

At last we point out two interesting facts even when (1.1) reduces to the deterministic system. Firstly, in contrast with the relevant literature (e.g. [3, 12, 19, 26]), the corresponding Riccati systems and their solvability appear for the first time since both the pointwise delays and the distributed delays are allowed to appear simultaneously in the cost functional. Secondly, when all the pointwise delayed terms disappear, the corresponding integro-differential system and cost functional can cover those in [30, 31], and thus the corresponding result in the above Theorem 3.3 is also new.

3.3. The closed-loop solvability of Problem (P). In this part we will give an explicit form of the optimal closed-loop strategy and some sufficient conditions for the closed-loop solvability of Problem (P).

Given $\Pi(\cdot,\cdot,\cdot),\Upsilon(\cdot,\cdot),\mathcal{R}(\cdot),\mathcal{G}_1(\cdot),\mathcal{G}_3(\cdot,\cdot,\cdot)$ in (3.10) and (3.12), $P=(P^{(1)},P^{(2)})$ and (η,ζ) being the solutions to (3.11) and (3.13), respectively, we make the following conventions. For $i=1,3$, $t_0\leqslant t\leqslant T$, denote

$$K_i^*(t)=-\mathcal{R}(t)^{-1}\Big\{K_i^{(1)}(t)+\int_t^T\int_t^T\mathcal{B}(\theta,t)^\top\mathcal{G}_3(\alpha,t,\theta)^\top K_i^{(2)}(\alpha,t)d\alpha d\theta\Big\}, \tag{3.15}$$

while for $i=2,4$ and $t_0\leqslant s<t\leqslant T$,

$$K_i^*(t,s)=-\mathcal{R}(t)^{-1}\Big\{K_i^{(1)}(t,s)+\int_t^T\int_t^T\mathcal{B}(\theta,t)^\top\mathcal{G}_3(\alpha,t,\theta)^\top K_i^{(2)}(t,\alpha,s)d\alpha d\theta\Big\}. \tag{3.16}$$

In addition, for $t_0\leqslant t\leqslant T$, let

$$v^*(t)=-\mathcal{R}(t)^{-1}\Big\{v^{(1)}(t)+\int_t^T\int_t^T\mathcal{B}(\theta,t)^\top\mathcal{G}_3(\alpha,t,\theta)^\top v^{(2)}(t,\alpha)d\alpha d\theta\Big\}. \tag{3.17}$$

In the above, each pair of $(K_i^{(1)},K_i^{(2)})$ and $(v^{(1)},v^{(2)})$ have the following representations:

$$\begin{aligned}
&K_1^{(1)}(t)=D_1(t)^\top\mathcal{G}_1(t)C_1(t),\quad K_1^{(2)}(\alpha,t)=\Upsilon(\alpha,t),\quad K_3^{(1)}(t)=D_1(t)^\top\mathcal{G}_1(t)C_2(t),\\
&K_3^{(2)}(\alpha,t)=0,\quad K_2^{(1)}(t,s)=D_1(t)^\top\mathcal{G}_1(t)C_3(t)F(t,s)+\Big(\int_t^T\mathcal{B}(\theta,t)^\top\\
&\times\mathcal{G}_3(s+\delta,t,\theta)^\top d\theta\Big)(0,I,0)^\top\mathbf{1}_{[t-\delta,T-\delta]}(s),\quad K_2^{(2)}(t,\alpha,s)=(0,0,I)^\top F(\alpha,s),\\
&K_4^{(1)}(t,s)=0,\quad K_4^{(2)}(t,\alpha,s)=\Big(I,\mathbf{1}_{(s+2\delta,\infty)}(\alpha)\mathbf{1}_{(0,T-\delta)}(t)I,\int_{s+\delta}^\alpha F(\alpha,\theta')^\top d\theta'\Big)^\top\\
&\times\mathbf{1}_{(s+\delta,T)}(\alpha)B_2(s+\delta)\mathbf{1}_{[t-\delta,T-\delta]}(s)+\Big(\int_t^\alpha\tilde F(\theta',s)^\top B_3(\theta')^\top d\theta',\int_t^{\alpha-\delta}\tilde F(\theta',s)^\top B_3(\theta')^\top d\theta',\\
&\int_t^\alpha\int_t^\beta\tilde F(\theta',s)^\top B_3(\theta')^\top d\theta' F(\alpha,\beta)^\top d\beta\Big)^\top,
\end{aligned} \tag{3.18}$$

and

$$\begin{aligned}
&v^{(1)}(t)=D_1(t)^\top\mathcal{G}_1(t)\sigma(t)+\int_t^T D_1(t)^\top\Upsilon(\alpha,t)^\top\zeta(\alpha,t)d\alpha+\int_t^T\int_\theta^T\mathcal{B}(\theta,t)^\top\Pi(\alpha,t,\theta)^\top\eta(\alpha,t)d\alpha d\theta,\\
&v^{(2)}(t,\alpha)=(0,I,0)^\top\xi(\alpha-\delta-t_0)\mathbf{1}_{[t_0,t_0+\delta]}(\alpha)+\int_{t-\delta}^{t_0}\mathbf{1}_{(\theta'+\delta,\infty)}(\alpha)\Big(I,\mathbf{1}_{(\theta'+2\delta,\infty)}(\alpha)\\
&\qquad\times\mathbf{1}_{(0,T-\delta)}(t)I,\int_{\theta'+\delta}^\alpha F(\alpha,\beta)^\top d\beta\Big)^\top B_2(\theta'+\delta)\varsigma(\theta'-t_0)d\theta'\mathbf{1}_{[t_0,t_0+\delta]}(t).
\end{aligned} \tag{3.19}$$

At this moment, we present the main result of the current section.

Theorem 3.6. *Let* (A1)–(A2) *hold and* $t_0\in[0,T)$ *be given. Then, the five-tuple* $(K_1^*(\cdot),K_2^*(\cdot,\cdot),K_3^*(\cdot),\ K_4^*(\cdot,\cdot),v^*(\cdot))$ *given by* (3.15)–(3.19) *is an optimal closed-loop strategy, and the following* $u^*(\cdot)$ *is the unique optimal closed-loop outcome control of Problem* (P) *on* $[t_0,T]$*:*

$$u^*(t)=K_1^*(t)x^*(t)+\int_{t_0}^t K_2^*(t,s)x^*(s)ds+K_3^*(t)x^*(t-\delta)+\int_{t_0}^t K_4^*(t,s)u^*(s)ds+v^*(t). \tag{3.20}$$

By the above theorem and Theorem 5.4 in [17], we deduce the following result.

Corollary 3.7. *Let* (A1)–(A2) *hold and* $t_0\in[0,T)$ *be given. Then, the five-tuple* $(K_1^*(\cdot),K_2^*(\cdot,\cdot),K_3^*(\cdot),\ K_4^*(\cdot,\cdot),v^*(\cdot))$ *with* $v^{(1)}(\cdot)=0$ *is an optimal closed-loop strategy, and the above* (3.20) *is the unique optimal closed-loop outcome control of Problem* (P_0)*. In addition, the value function is given by*

$$V_0(t_0,\xi,\varsigma)=\int_{t_0}^T\big\langle P^{(1)}(t)\varphi(t),\varphi(t)\big\rangle dt+\int_{t_0}^T\int_{t_0}^T\big\langle P^{(2)}(t_1,t_2,t_0)\varphi(t_2),\varphi(t_1)\big\rangle dt_1dt_2,$$

for any $(t_0,\xi,\varsigma)\in[0,T)\times C([-\delta,0];\mathbb{R}^n)\times L^2(-\delta,0;\mathbb{R}^m)$.

Remark 3.8. We see that Theorem 3.6 gives a sufficient condition of the closed-loop solvability in terms of K_i^* (i=1,2,3,4) which are explicitly and clearly constructed. At this moment, we are not sure about its necessity. However, Lemma A.1 in the Appendix actually gives a new necessary condition in terms of the so-called causal feedback strategy developed in [17]. On the other hand, Theorem 3.6 is also true if the standard assumption (A2) is relaxed properly (see [27]). For simplicity we prefer not to pursue these generalities.

Remark 3.9. To prove Theorem 3.6, we use the equivalence between the original problem (P) and the new control problem associated with the state equation (3.8) and the cost functional (3.9). Even though the dimension of (3.8) and (3.9) is higher than that of the original one, it is still finite dimensional and is essentially different from infinite-dimensional evolution control system method. For this new problem, we borrow some new matrix products notations exemplified by (A.4)–(A.6) from [17]. Then we introduce some computational techniques to convert them into the traditional matrix products, and derive the optimal closed-loop strategy as in Theorem 3.6.

Remark 3.10. There have been lots of works on closed-loop outcome controls of delayed control systems. However, they either contain only state delays [11,20,23,24], or only control delays [19,23,33,37], or work in deterministic systems [19,21], or have time-invariant coefficients [19,21,23,27,33,37], or have no delay in the cost functional [3,12,13,19,34], or have no solvability of the associated Riccati systems [19,21,23,24,33,37]. In this sense, Theorem 3.6 gives a unified treatment of the existing papers with distinctive methods. Moreover, the closed-loop outcome control is explicitly constructed without any continuity or even differentiability assumptions, and does not rely on the future state and avoids complex tools of conditional expectations [34,37].

4. Important cases. In this section, we discuss five special yet important stochastic control systems and make relevant comparisons with the existing literature.

4.1. Case I: Stochastic control systems with control delays only. Consider the state equation

$$\begin{cases} dx(t) = \big[A_1(t)x(t) + B_1(t)u(t) + B_2(t)\nu(t) + B_3(t)\mu(t)\big]dt \\ \qquad\qquad + \big[C_1(t)x(t) + D_1(t)u(t)\big]dW(t), \quad t \in [t_0, T], \\ x(t_0) = \xi_0, u(t) = 0, \quad t \in [t_0 - \delta, t_0], \end{cases} \tag{4.1}$$

along with the cost functional

$$J(t_0, \xi_0; u(\cdot)) = \mathbb{E}\int_{t_0}^T \big[x(t)^\top Q_1(t)x(t) + u(t)^\top R_1(t)u(t)\big]dt.$$

Also for $\theta, \alpha \in [-\delta, 0]$ and $t, \theta', r \in [t_0, T]$ such that $t \leqslant (\theta' \wedge r)$, we define

$$\mathcal{P}_1(t, \theta', r) \equiv \big(I, 0, 0\big)\Big(\int_{\theta'\vee r}^T P^{(1)}(s)ds + \int_r^T\int_{\theta'}^T P^{(2)}(s, \alpha, t)d\alpha ds\Big)\big(I, 0, 0\big)^\top,$$

$$\mathcal{S}_0(t) \equiv \mathcal{P}_1(t, t, t), \tag{4.2}$$

$$\mathcal{S}_1(t, \theta) \equiv B_2(t+\delta+\theta)^\top\mathcal{P}_1(t, t, t+\delta+\theta) + \int_t^T \tilde{F}(\theta', t+\theta)^\top B_3(\theta')^\top\mathcal{P}_1(t, \theta', t)^\top d\theta', \tag{4.3}$$

$$\begin{aligned} \mathcal{S}_2(t, \theta, \alpha) \equiv\ & B_2(t+\delta+\theta)^\top\Big[\mathcal{P}_1(t, t+\delta+\theta, t+\delta+\alpha)^\top B_2(t+\delta+\alpha) + \int_t^T \mathcal{P}_1(t, \theta', t+\delta+\theta) \\ & \times B_3(\theta')\tilde{F}(\theta', t+\alpha)d\theta'\Big] + \int_t^T \tilde{F}(\theta', t+\theta)^\top B_3(\theta')^\top\Big[\mathcal{P}_1(t, \theta', t+\delta+\alpha)^\top B_2(t+\delta+\alpha) \\ & + \int_t^T \mathcal{P}_1(t, \theta', \beta)^\top B_3(\beta)\tilde{F}(\beta, t+\alpha)d\beta\Big]d\theta'. \end{aligned} \tag{4.4}$$

In this part, we will show that for a.e. $t \in [t_0, T], \theta \in [-\delta, 0]$, $\mathcal{S}_0(\cdot)$ and $\mathcal{S}_1(\cdot, \cdot)$ satisfy

(4.5)
$$\begin{cases}\dfrac{d}{dt}\mathcal{S}_0(t)+A_1(t)^\top\mathcal{S}_0(t)+\mathcal{S}_0(t)A_1(t)+Q_1(t)+C_1(t)^\top\mathcal{S}_0(t)C_1(t)-\big[B_1(t)^\top\mathcal{S}_0(t)\\ \quad+\mathcal{S}_1(t,0)+D_1(t)^\top\mathcal{S}_0(t)C_1(t)\big]^\top\mathcal{R}(t)^{-1}\big[B_1(t)^\top\mathcal{S}_0(t)+\mathcal{S}_1(t,0)+D_1(t)^\top\mathcal{S}_0(t)C_1(t)\big]=0,\\ \mathcal{S}_0(T)=0,\end{cases}$$

(4.6)
$$\begin{cases}\Big(\dfrac{\partial}{\partial t}-\dfrac{\partial}{\partial\theta}\Big)\mathcal{S}_1(t,\theta)+\tilde{F}(t,t+\theta)^\top B_3(t)^\top\mathcal{S}_0(t)+\mathcal{S}_1(t,\theta)A_1(t)-\big[\mathcal{S}_1(t,\theta)B_1(t)\\ \quad+\mathcal{S}_2(t,\theta,0)\big]\mathcal{R}(t)^{-1}\big[B_1(t)^\top\mathcal{S}_0(t)+\mathcal{S}_1(t,0)+D_1(t)^\top\mathcal{S}_0(t)C_1(t)\big]=0,\\ \mathcal{S}_1(T,\theta)=0,\ \mathcal{S}_1(t,-\delta)=B_2(t)^\top\mathcal{S}_0(t)+\displaystyle\int_t^T\tilde{F}(\theta',t-\delta)^\top B_3(\theta')^\top\mathcal{P}_1(t,\theta',t)^\top d\theta'.\end{cases}$$

Moreover, for a.e. $t\in[t_0,T],\theta,\alpha\in[-\delta,0]$, $\mathcal{S}_2(\cdot,\cdot,\cdot)$ satisfies

(4.7)
$$\begin{cases}\Big(\dfrac{\partial}{\partial t}-\dfrac{\partial}{\partial\theta}-\dfrac{\partial}{\partial\alpha}\Big)\mathcal{S}_2(t,\theta,\alpha)+\tilde{F}(t,t+\theta)^\top B_3(t)^\top\mathcal{S}_1(t,\alpha)^\top+\mathcal{S}_1(t,\theta)B_3(t)^\top\tilde{F}(t,t+\alpha)\\ \quad-\big[\mathcal{S}_1(t,\theta)B_1(t)+\mathcal{S}_2(t,\theta,0)\big]\mathcal{R}(t)^{-1}\big[B_1(t)^\top\mathcal{S}_1(t,\alpha)^\top+\mathcal{S}_2(t,0,\alpha)\big]=0,\\ \mathcal{S}_2(t,\theta,-\delta)=\mathcal{S}_1(t,\theta)B_2(t)+B_2(t+\delta+\theta)^\top\displaystyle\int_t^T\mathcal{P}_1(t,\alpha,t+\delta+\theta)B_3(\alpha)\tilde{F}(\alpha,t-\delta)d\alpha\\ \quad+\displaystyle\int_t^T\int_t^T\tilde{F}(\alpha,t+\theta)^\top B_3(\alpha)^\top\mathcal{P}_1(t,\alpha,\beta)^\top B_3(\beta)\tilde{F}(\beta,t-\delta)d\beta d\alpha,\\ \mathcal{S}_2(t,-\delta,\theta)=\mathcal{S}_2(t,\theta,-\delta)^\top,\ \mathcal{S}_2(T,\theta,\alpha)=0.\end{cases}$$

In addition, the optimal closed-loop outcome control (3.20) is represented as follows:
(4.8)
$$\begin{aligned}u^*(t)=&-\mathcal{R}(t)^{-1}\Big\{\big[B_1(t)^\top\mathcal{S}_0(t)+D_1(t)^\top\mathcal{S}_0(t)C_1(t)+\mathcal{S}_1(t,0)\big]x^*(t)+\int_{t\vee(t_0+\delta)}^{(t+\delta)\wedge T}\\ &\big[B_1(t)^\top\mathcal{S}_1(t,r-\delta-t)^\top+\mathcal{S}_2(t,0,r-\delta-t)\big]u^*(r-\delta)dr\Big\}+\mathcal{R}(t)^{-1}\Big(\int_{t\vee(t_0+\delta)}^{(t+\delta)\wedge T}-\int_{t_0+\delta}^{t+\delta}\Big)\\ &\times\int_t^T\Big\{B_1(t)^\top\mathcal{P}_1(t,t,\theta')B_2(t+\delta)^\top\mathcal{P}_1(t,t+\delta,\theta')^\top+\int_t^T\tilde{F}(\theta,t)^\top\\ &\times B_3(\theta)^\top\mathcal{P}_1(t,\theta,\theta')^\top d\theta\Big\}B_3(\theta')\tilde{F}(\theta',r-\delta)u^*(r-\delta)d\theta'dr,\end{aligned}$$

where $\mathcal{R}(t)=R_1(t)+D_1(t)^\top\mathcal{S}_0(t)D_1(t)$.

We state the main result of this subsection as follows. For detailed information of its proof, we refer to the Arxiv version of this paper [28].

COROLLARY 4.1. *Let* (A1)–(A2) *hold and* $A_2,A_3,C_2,C_3,Q_2,Q_3,R_2,\ b,\sigma=0$. *Then,* $\mathcal{S}_0$, $\mathcal{S}_1$ *and* $\mathcal{S}_2$*, defined by* (4.2)–(4.4)*, satisfy the coupled Riccati equations* (4.5)–(4.7)*, and the process in* (4.8) *is the optimal closed-loop outcome control.*

Remark 4.2. When Problem (P) contains only control delays, we obtain the optimal closed-loop outcome control (4.8) by (4.5)–(4.7). If the diffusion term disappears in (4.1), then (4.5)–(4.7) essentially reduce to (2.33)–(2.38) in [19]. Compared with [19, 23, 33, 37], we successfully obtain the solvability of the Riccati systems.

4.2. Case II: Stochastic control systems with state delays only. Consider the state equation
$$\begin{cases}dx(t)=\big[A_1x(t)+A_2y(t)+B_1u(t)\big]dt+\big[C_1x(t)+C_2y(t)+D_1u(t)\big]dW(t),\ t\in[t_0,T],\\ x(t)=\xi(t-t_0),\quad t\in[t_0-\delta,t_0],\end{cases}$$
along with the cost functional

$$J(t_0,\xi(\cdot);u(\cdot)) = \mathbb{E}\int_{t_0}^{T}\left[x(t)^\top Q_1 x(t) + u(t)^\top R_1 u(t)\right]dt.$$

Here the coefficients are time-invariant. For $t_0 \leqslant t \leqslant \theta \leqslant T$, we define

$$\begin{aligned}\mathcal{P}_2(t) \equiv& \int_t^T \big(I, \mathbf{1}_{(\delta,\infty)}(s-t)I, 0\big)P^{(1)}(s)\big(I, \mathbf{1}_{(\delta,\infty)}(s-t)I,0\big)^\top ds\\ &+\int_t^T\int_t^T\big(I,\mathbf{1}_{(\delta,\infty)}(s_1-t)I,0\big)P^{(2)}(s_1,s_2,t)\big(I,\mathbf{1}_{(\delta,\infty)}(s_2-t)I,0\big)ds_1ds_2,\end{aligned}\tag{4.9}$$

$$\mathcal{P}_3(t,\theta)\equiv\Big[\big(I,\mathbf{1}_{(\delta,\infty)}(\theta-t)I,0\big)P^{(1)}(\theta)^\top+\int_t^T\big(I,\mathbf{1}_{(\delta,\infty)}(r-t)I,0\big)P^{(2)}(\theta,r,t)^\top dr\Big](0,I,0)^\top.\tag{4.10}$$

In this part, we will show that $\mathcal{P}_2(\cdot)$ and $\mathcal{P}_3(\cdot,\cdot)$ satisfy the following coupled Riccati equations. More precisely, for $t\in(T-\delta,T],\theta\in(t,T]$, we have

$$\begin{cases}-\dot{\mathcal{P}}_2(t) = \mathcal{P}_2(t)A_1 + A_1^\top\mathcal{P}_2(t) + C_1^\top\mathcal{P}_2(t)C_1 + Q_1\\ \qquad -\big(B_1^\top\mathcal{P}_2(t)+D_1^\top\mathcal{P}_2(t)C_1\big)^\top\big(R_1+D_1^\top\mathcal{P}_2(t)D_1\big)^{-1}\big(B_1^\top\mathcal{P}_2(t)+D_1^\top\mathcal{P}_2(t)C_1\big),\\ -\dfrac{\partial\mathcal{P}_3(t,\theta)}{\partial t}=A_1^\top\mathcal{P}_3(t,\theta)-\big(B_1^\top\mathcal{P}_2(t)+D_1^\top\mathcal{P}_2(t)C_1\big)^\top\big(R_1+D_1^\top\mathcal{P}_2(t)D_1\big)^{-1}B_1^\top\mathcal{P}_3(t,\theta),\\ \mathcal{P}_3(t,t)=\mathcal{P}_2(t)A_2+C_1^\top\mathcal{P}_2(t)C_2-\big(B_1^\top\mathcal{P}_2(t)+D_1^\top\mathcal{P}_2(t)C_1\big)^\top\\ \qquad\times\big(R_1+D_1^\top\mathcal{P}_2(t)D_1\big)^{-1}D_1^\top\mathcal{P}_2(t)C_2,\\ \mathcal{P}_2(T)=0,\end{cases}\tag{4.11}$$

while for $t\in[0,T-\delta],\theta\in(t,t+\delta]$,

$$\begin{cases}-\dot{\mathcal{P}}_2(t)=\mathcal{P}_2(t)A_1+A_1^\top\mathcal{P}_2(t)+C_1^\top\mathcal{P}_2(t)C_1+C_2^\top\mathcal{P}_2(t+\delta)C_2+Q_1+\mathcal{P}_3(t,t+\delta)\\ \quad+\mathcal{P}_3(t,t+\delta)^\top-\big(B_1^\top\mathcal{P}_2(t)+D_1^\top\mathcal{P}_2(t)C_1\big)^\top\big(R_1+D_1^\top\mathcal{P}_2(t)D_1\big)^{-1}\big(B_1^\top\mathcal{P}_2(t)\\ \quad+D_1^\top\mathcal{P}_2(t)C_1\big)-\big(D_1^\top\mathcal{P}_2(t+\delta)C_2\big)^\top\big(R_1+D_1^\top\mathcal{P}_2(t)D_1\big)^{-1}D_1^\top\mathcal{P}_2(t+\delta)C_2,\\ -\dfrac{\partial\mathcal{P}_3(t,\theta)}{\partial t}=A_1^\top\mathcal{P}_3(t,\theta)-\big(B_1^\top\mathcal{P}_2(t)+D_1^\top\mathcal{P}_2(t)C_1\big)^\top\big(R_1+D_1^\top\mathcal{P}_2(t)D_1\big)^{-1}\\ \quad\times B_1^\top\mathcal{P}_3(t,\theta)+\mathcal{P}_3(\theta,t+\delta)^\top A_2-\big(B_1^\top\mathcal{P}_3(\theta,t+\delta)\big)^\top\big(R_1+D_1^\top\mathcal{P}_2(t)D_1\big)^{-1}\\ \quad\times D_1\mathcal{P}_2(t)C_2-\displaystyle\int_t^\theta\big(B_1^\top\mathcal{P}_3(s,t+\delta)\big)^\top\big(R_1+D_1^\top\mathcal{P}_2(t)D_1\big)^{-1}B_1^\top\mathcal{P}_3(s,\theta)ds,\\ \mathcal{P}_3(t,t)=\mathcal{P}_2(t)A_2+C_1^\top\mathcal{P}_2(t)C_2-\big(B_1^\top\mathcal{P}_2(t)+D_1^\top\mathcal{P}_2(t)C_1\big)^\top\\ \quad\times\big(R_1+D_1^\top\mathcal{P}_2(t)D_1\big)^{-1}D_1^\top\mathcal{P}_2(t)C_2.\end{cases}\tag{4.12}$$

We state the main result of this subsection as follows. For detailed information of its proof, please refer to the Arxiv version of this paper [28].

COROLLARY 4.3. *Let* (A1)–(A2) *hold with* $A_3,B_2,B_3,C_3,\ Q_2,Q_3,\ R_2,b,\sigma=0$. *Then,* $\mathcal{P}_2(\cdot)$ *and* $\mathcal{P}_3(\cdot,\cdot)$*, defined by* (4.9)–(4.10)*, satisfy the coupled Riccati equations* (4.11)–(4.12)*. In this case, the following process is optimal:*

$$\begin{aligned}u^*(t)=&-\big(R_1+D_1^\top\mathcal{P}_2(t)D_1\big)^{-1}\Big\{\big(B_1^\top\mathcal{P}_2(t)+D_1^\top\mathcal{P}_2(t)C_1\big)x^*(t)+\int_{t\vee(t_0+\delta)}^{(t+\delta)\wedge T}B_1^\top\mathcal{P}_3(t,s)\\ &\times x^*(s-\delta)ds+D_1^\top\mathcal{P}_2(t)C_2x^*(t-\delta)+\int_t^{T\wedge(t_0+\delta)}B_1^\top\mathcal{P}_3(t,s)\xi(s-t_0-\delta)ds\Big\}.\end{aligned}\tag{4.13}$$

Remark 4.4. When Problem (P) contains only state delays, (4.11)–(4.12) are the same as (3)–(12) in [23], the optimal closed-loop outcome control (4.13) coincides with (13) in [23], and Corollary 4.3 is similar to Theorem 1 in [23]. Compared with [21, 23, 24], we give the solvability of the Riccati system. References [12, 13] focus on deterministic systems involving both pointwise delay and distributed delay of state. They not only derive the corresponding optimal control results but also establish the solvability of the Riccati equations. In contrast, the solvability conclusion proposed in this paper only requires the coefficients to be integrable, without the need for differentiability, thus relaxing the constraints imposed by [12, 13].

4.3. Case III: Stochastic control systems with pointwise delays only. Consider the state equation

$$\begin{cases} dx(t) = \big[A_1(t)x(t) + A_2(t)y(t) + B_1(t)u(t) + B_2(t)\nu(t)\big]dt \\ \qquad\qquad + \big[C_1(t)x(t) + C_2(t)y(t) + D_1(t)u(t)\big]dW(t), \quad t \in (t_0, T), \\ x(t) = \xi(t-t_0),\ u(t) = \varsigma(t-t_0),\ t \in [t_0-\delta, t_0], \end{cases}$$

along with the cost functional

$$J(t_0,\xi,\varsigma;u)=\mathbb{E}\int_{t_0}^{T}\big[x(t)^\top Q_1(t)x(t)+y(t)^\top Q_2(t)y(t)+u(t)^\top R_1(t)u(t)+\nu(t)^\top R_2(t)\nu(t)\big]dt.$$

For $0<t<(s\wedge\bar{s})<T$, we define $\mathcal{G}_1(\cdot)$, $\mathcal{G}_2(\cdot,\cdot)$ as in (3.12), and

$$Q(t)=\begin{bmatrix} Q_1(t) & 0 \\ 0 & Q_2(t)\end{bmatrix},\ \mathcal{C}(t)=\big(C_1(t),C_2(t)\big),\ \mathcal{A}(t)=\big(A_1(t),A_2(t)\big),\ \mathcal{B}(t)=\begin{bmatrix} B_1(t) \\ B_2(t+\delta)\end{bmatrix},$$

$$\Upsilon(s,t) = \begin{bmatrix} I \\ \mathbf{1}_{(\delta,\infty)}(s-t)I\end{bmatrix},\quad \mathcal{R}(t) = R_1(t) + R_2(t+\delta)\mathbf{1}_{[0,T-\delta)}(t) + D_1(t)^\top\mathcal{G}_1(t)D_1(t),$$

$$\begin{aligned} \mathcal{G}_3(s,t) &= P^{(1)}(s)\big(\Upsilon(s,t), \mathbf{1}_{(\delta,\infty)}(s-t)\Upsilon(s,t+\delta)\big) \\ &\quad + \int_t^T P^{(2)}(s,r,t)\big(\Upsilon(r,t), \mathbf{1}_{(\delta,\infty)}(r-t)\Upsilon(r,t+\delta)\big)dr. \end{aligned} \tag{4.14}$$

We consider the Riccati system (3.11), where $P^{(2)}(\cdot,\cdot,\cdot)$ satisfies

$$\begin{cases} P^{(2)}(s,t,r) = P^{(2)}(s,t,t\wedge s) - \displaystyle\int_r^{t\wedge s}\mathcal{G}_3(s,\tau)\mathcal{B}(\tau) \\ \qquad\qquad \times\mathcal{R}(\tau)^{-1}\mathcal{B}(\tau)^\top\mathcal{G}_3(t,\tau)^\top d\tau, 0<r<(s\wedge t)<T, \\ P^{(2)}(\bar{s},t,t) = P^{(2)}(t,\bar{s},t)^\top \\ \qquad = \mathcal{G}_2(\bar{s},t)\mathcal{A}(t) - \mathcal{G}_3(\bar{s},t)\mathcal{B}(t)\mathcal{R}(t)^{-1}D_1(t)^\top\mathcal{G}_1(t)\mathcal{C}(t),\ 0<t<\bar{s}<T. \end{cases}$$

With notations in (4.14), we consider the closed-loop strategy

$$\begin{aligned} K_i^*(t) &= -\mathcal{R}(t)^{-1}\Big\{K_i^{(1)}(t) + \mathcal{B}(t)^\top\int_t^T \mathcal{G}_3(\alpha,t)^\top K_i^{(2)}(\alpha,t)d\alpha\Big\},\ i=1,3, \\ K_i^*(t,s) &= -\mathcal{R}(t)^{-1}\Big\{K_i^{(1)}(t,s) + \mathcal{B}(t)^\top\int_t^T \mathcal{G}_3(\alpha,t)^\top K_i^{(2)}(t,\alpha,s)d\alpha\Big\},\ i=2,4, \\ v^*(t) &= -\mathcal{R}(t)^{-1}\Big\{v^{(1)}(t) + \mathcal{B}(t)^\top\int_t^T \mathcal{G}_3(\alpha,t)^\top v^{(2)}(t,\alpha)d\alpha\Big\}, \end{aligned} \tag{4.15}$$

where $t_0\leqslant s<t\leqslant T$, and $K_1^{(1)},K_1^{(2)},K_3^{(1)},K_3^{(2)},K_4^{(1)}$ have the same forms as in (3.18), and

$$\begin{aligned} &K_2^{(1)}(t,s) = \mathcal{B}(t)^\top\mathcal{G}_3(s+\delta,t)^\top(0,I)^\top\mathbf{1}_{[t-\delta,T-\delta]}(s), \qquad K_2^{(2)}(t,\alpha,s) = 0, \\ &K_4^{(2)}(t,\alpha,s) = \big(I, \mathbf{1}_{(s+2\delta,\infty)}(\alpha)\mathbf{1}_{(0,T-\delta)}(t)I\big)^\top\mathbf{1}_{(s+\delta,T)}(\alpha)B_2(s+\delta)\mathbf{1}_{[t-\delta,T-\delta]}(s), \\ &v^{(1)}(t) = 0, \quad v^{(2)}(t,\alpha) = (0,I)^\top\xi(\alpha-\delta-t_0)\mathbf{1}_{[t_0,t_0+\delta]}(\alpha) + \int_{t-\delta}^{t_0}\mathbf{1}_{(\theta'+\delta,\infty)}(\alpha) \\ &\qquad \times\big(I, \mathbf{1}_{(\theta'+2\delta,\infty)}(\alpha)\mathbf{1}_{(0,T-\delta)}(t)I\big)^\top B_2(\theta'+\delta)\varsigma(\theta'-t_0)d\theta'\mathbf{1}_{[t_0,t_0+\delta]}(t). \end{aligned}$$

As a result of Theorem 3.6, we derive the following result.

COROLLARY 4.5. *Let* (A1)–(A2) *hold with* $A_3, B_3, C_3, Q_3, b, \sigma = 0$. *Then, all the strategies in* (4.15) *and the process* $u^*(\cdot)$ *in the same form of* (3.20) *are optimal.*

Remark 4.6. We make some comparisons with the existing literature. Firstly, in contrast to [23, 27], our coefficients are allowed to be time-varying and the cost functional depends on both the pointwise state delay and pointwise control delay. Secondly, even when these features disappear, our framework is still general than that in [23] (except the disappearance of pointwise control delay in the diffusion term), and the solvability issue of the Riccati system is answered. In addition, [27] requires the diffusion term to be independent of the pointwise state delay and control delay, while we drop this assumption here. Thirdly, even though the coefficients in [11] are time-varying, both their state equations and cost functional are still particular cases of ours. Eventually, even for deterministic systems, our coefficients are allowed to be integrable, but not necessarily differentiable as in [12].

4.4. Case IV: Stochastic control systems with distributed delays only.

Consider the state equation

$$\begin{cases} dx(t) = [A_1(t)x(t) + A_3(t)z(t) + B_1(t)u(t) + B_3(t)\mu(t)]dt \\ \qquad\qquad +[C_1(t)x(t) + C_3(t)z(t) + D_1(t)u(t)]dW(t), \quad t \in (t_0, T), \\ x(t) = \xi(t-t_0),\ u(t) = \varsigma(t-t_0),\ t \in [t_0-\delta, t_0], \end{cases}$$

along with the cost functional

$$J(t_0, \xi(\cdot), \varsigma(\cdot); u(\cdot)) = \mathbb{E}\int_{t_0}^T \left[x(t)^\top Q_1(t)x(t) + z(t)^\top Q_3(t)z(t) + u(t)^\top R_1(t)u(t)\right] dt.$$

In this case, we consider the Riccati system (3.11), where for $0 < t < (s \wedge \bar{s} \wedge \theta) < T$,

$$Q(t) = \begin{bmatrix} Q_1(t) & 0 \\ 0 & Q_3(t) \end{bmatrix},\ \mathcal{C}(t) = \big(C_1(t), C_3(t)\big),\ \mathcal{A}(t) = \big(A_1(t), A_3(t)\big),\ \mathcal{B}(\theta, t) = \begin{bmatrix} B_1(t) \\ B_3(\theta)\tilde{F}(\theta, t) \end{bmatrix},$$

$$\Upsilon(s,t) = \begin{bmatrix} I \\ \mathcal{E}(s,t) \end{bmatrix}, \mathcal{R}(t) = R_1(t) + D_1(t)^\top \mathcal{G}_1(t) D_1(t), \Pi(s,t,\theta) = \begin{bmatrix} \frac{1}{s-t}I & I \\ \frac{1}{s-t}\mathcal{E}(s,t) & \mathcal{E}(s,\theta) \end{bmatrix}, \tag{4.16}$$

and $\mathcal{G}_1(\cdot)$, $\mathcal{G}_2(\cdot,\cdot)$, $\mathcal{G}_3(\cdot,\cdot,\cdot)$ are defined in (3.12). With the notations in (4.16), we consider the closed-loop strategy (3.15)–(3.19), where $K_1^{(1)}, K_1^{(2)}, K_3^{(2)}, K_4^{(1)}$ have the same forms as in (3.18), $v^{(1)},\ v^{(2)} = 0$, and

$$K_3^{(1)}(t) = 0,\quad K_2^{(1)}(t,s) = D_1(t)^\top \mathcal{G}_1(t) C_3(t) F(t,s),\quad K_2^{(2)}(t,\alpha,s) = (0, I)^\top F(\alpha, s),$$

$$K_4^{(2)}(t,\alpha,s) = \Big(\int_t^\alpha \tilde{F}(\theta',s)^\top B_3(\theta')^\top d\theta', \int_t^\alpha\int_t^\beta \tilde{F}(\theta',s)^\top B_3(\theta')^\top d\theta' F(\alpha,\beta)^\top d\beta\Big)^\top. \tag{4.17}$$

Then, as a result of Theorem 3.6, we derive the following result.

COROLLARY 4.7. *Let* (A1)–(A2) *hold and* $A_2, B_2, C_2, Q_2, R_2, b, \sigma = 0$. *Then, the closed-loop strategies* (3.15)–(3.16) *with* (4.17) *and the following process are optimal:*

$$u^*(t) = K_1^*(t)x^*(t) + \int_{t_0}^t K_2^*(t,s)x^*(s)ds + \int_{t_0}^t K_4^*(t,s)u^*(s)ds,\ t \in [t_0, T]. \tag{4.18}$$

Remark 4.8. LQ problems for deterministic integro-differential equations were treated in [30], see also [16, Subsection 5.5]. Both of them derived the Riccati systems and the closed-loop optimal controls in the spirit of (4.18). However, they need $A_1, B_3 \equiv 0$, $A_3 \equiv 1$, $F(\cdot,\cdot)$ is convolution form, $Q_3 \equiv 0$, Q_1, R_1 are time-invariant.

As to the case of stochastic integro-differential equations, let us point out the discussion in [16, Subsection 5.3] where the stochastic integro-differential equation is directly regarded as a special SVIE. However, there are no closed-loop controls in the spirit of (4.18) and the corresponding Riccati systems. To our best knowledge, the above Corollary 4.7 appears for the first time.

4.5. Case V: Stochastic control systems without delay.

In this subsection, we look at the SDEs case. On the one hand, given $P = (P^{(1)}, P^{(2)})$, (η, ζ) satisfying the Riccati system (3.11) and the backward SVIE (3.13), respectively, we define

$$\mathcal{P}(t) = (I,0,0)\Big(\int_t^T P^{(1)}(s)ds + \int_t^T\int_t^T P^{(2)}(s_1,s_2,t)ds_1ds_2\Big)(I,0,0)^\top,\ 0 < t < T,$$

$$\widetilde{\eta}(t) = \int_t^T (I,0,0)\eta(s,t)ds,\quad \tilde{\zeta}(t) = \int_t^T (I,0,0)\zeta(s,t)ds,\ 0 < t < T. \tag{4.19}$$

On the other hand, we consider

$$
\begin{cases}\dot{\mathcal{P}}(t)+\mathcal{P}(t)A_1(t)+A_1(t)^\top\mathcal{P}(t)+C_1(t)^\top\mathcal{P}(t)C_1(t)+Q_1(t)-(\mathcal{P}(t)B_1(t)\\ \quad +C_1(t)^\top\mathcal{P}(t)D_1(t))\mathcal{R}(t)^{-1}\big(B_1(t)^\top\mathcal{P}(t)+D_1(t)^\top\mathcal{P}(t)C_1(t)\big)=0,\ 0<t<T,\\ \mathcal{P}(T)=0,\end{cases} \tag{4.20}
$$

where $\mathcal{R}(\cdot)=R_1(\cdot)+D_1(\cdot)^\top\mathcal{P}(\cdot)D_1(\cdot)$. And consider the following backward stochastic differential equation:

$$
\begin{cases}d\widetilde{\eta}(t)=-\big\{\big[A_1^\top(t)-\big(\mathcal{P}(t)B_1(t)+C_1^\top(t)\mathcal{P}(t)D_1(t)\big)\mathcal{R}(t)^{-1}B_1^\top(t)\big]\widetilde{\eta}(t)\\ \quad+\big[C_1^\top(t)-\big(\mathcal{P}(t)B_1(t)+C_1^\top(t)\mathcal{P}(t)D_1(t)\big)\mathcal{R}(t)^{-1}D_1^\top(t)\big]\tilde{\zeta}(t)\\ \quad+\big[C_1^\top(t)-\big(\mathcal{P}(t)B_1(t)+C_1^\top(t)\mathcal{P}(t)D_1(t)\big)\mathcal{R}(t)^{-1}D_1^\top(t)\big]\mathcal{P}(t)\sigma(t)\\ \quad+\mathcal{P}(t)b(t)\big\}dt+\tilde{\zeta}(t)dW(t),\quad 0<t<T,\\ \widetilde{\eta}(T)=0.\end{cases} \tag{4.21}
$$

Then, we have the following result.

COROLLARY 4.9. *Let* (A1)-(A2) *hold such that* $A_2, A_3, B_2, B_3, C_2, C_3$, Q_2, Q_3, $R_2=0$. *Then,* $\mathcal{P}(\cdot)$ *and* $(\widetilde{\eta}(\cdot),\widetilde{\zeta}(\cdot))$, *defined by* (4.19), *are the unique solutions to* (4.20) *and* (4.21), *respectively. In addition, the five-tuple* $(K_1^*(\cdot),0,0,0,v^*(\cdot))$ *is the optimal closed-loop strategy of Problem* (P), *where*

$$
\begin{aligned}&K_1^*(t)=-\mathcal{R}(t)^{-1}\left(B_1(t)^\top\mathcal{P}(t)+D_1(t)^\top\mathcal{P}(t)C_1(t)\right),\ t\in[t_0,T],\\ &v^*(t)=-\mathcal{R}(t)^{-1}\Big(B_1^\top(t)\widetilde{\eta}(t)+D_1^\top(t)\tilde{\zeta}(t)+D_1^\top(t)\mathcal{P}(t)\sigma(t)\Big),\ t\in[t_0,T].\end{aligned}
$$

Remark 4.10. When delays appear in Problem (P), the optimal closed-loop strategy $(K_1^*(\cdot),v^*(\cdot))$, the equation (4.20) and the equation (4.21) reduce to that in [32].

5. Concluding remarks.

In this paper we study a general stochastic LQ optimal control problem, where the coefficients are time-varying, and both state delay and control delay can appear in the state equation and the cost functional. We put the original state process and its delay processes together for dimension expansion, and use the Volterra integral system without delay to describe the new process, then transform the original delayed problem into the control problem without delay. Based on the equivalent problem, we propose the closed-loop solvability of the delayed problem, and assure it by the solvability of the Riccati system and the extended backward SVIEs. Furthermore, we derive the optimal closed-loop outcome control and obtain the solvability of the associated Riccati system. Finally, we study several stochastic systems and find that our results are consistent with those in the existing literature.

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Appendix.

The proof of Proposition 2.2:

Proof. Without loss of generality, assume that $T = t_0 + n\delta$ with an integer n. Let $\mathbf{X}(\cdot)\equiv(x(\cdot)^\top, z(\cdot)^\top, u(\cdot)^\top)^\top$. From the first equation in the closed-loop system (2.2), we obtain the integral form for $x(\cdot)$. Similar to the processing of (3.6), we derive the expression for $z(\cdot)$. Therefore,

$$\mathbf{X}(t) = \boldsymbol{\varphi}(t) + \int_{t_0}^t \mathbf{A}(t,s)\mathbf{X}(s)ds + \int_{t_0}^t \mathbf{C}(t,s)\mathbf{X}(s)dW(s), \quad t \in (t_0, t_0+\delta), \tag{A.1}$$

where

$$\mathbf{A}(t,s)\equiv\begin{bmatrix} A_1(s) & A_3(s) & \mathbf{A}_{13}(t,s) \\ \mathcal{E}(t,s)A_1(s) & \mathcal{E}(t,s)A_3(s) & \mathbf{A}_{23}(t,s) \\ K_1(t)A_1(s)+K_2(t,s) & K_1(t)A_3(s) & \mathbf{A}_{33}(t,s)\end{bmatrix},$$

$$\mathcal{E}(t,s)\equiv\int_s^t F(t,r)dr\mathbf{1}_{(s,T)}(t),\ \ \mathbf{A}_{13}(t,s)\equiv B_1(s)+B_2(s+\delta)\mathbf{1}_{[t_0,t-\delta)}(s)+\int_s^t B_3(r)\tilde{F}(r,s)dr,$$

$$\mathbf{A}_{23}(t,s)\equiv\int_s^t F(t,r)(B_1(s)+B_2(s+\delta)\mathbf{1}_{[0,r-\delta)}(s)+\int_s^r B_3(\theta)\tilde{F}(\theta,s)d\theta)dr,$$

$$\mathbf{A}_{33}(t,s)\equiv K_1(t)(B_1(s)+B_2(s+\delta)\mathbf{1}_{[t_0,t-\delta)}(s)+\int_s^t B_3(r)\tilde{F}(r,s)dr)+K_4(t,s),$$

$$\mathbf{C}(t,s)\equiv\begin{bmatrix} C_1(s) & C_3(s) & D_1(s) \\ \mathcal{E}(t,s)C_1(s) & \mathcal{E}(t,s)C_3(s) & \mathcal{E}(t,s)D_1(s) \\ K_1(t)C_1(s) & K_1(t)C_3(s) & K_1(t)D_1(s)\end{bmatrix},$$

and

$$\boldsymbol{\varphi}(t)\equiv\begin{bmatrix} \xi(0)+\int_{t_0}^t\big(A_2(s)\xi(s-\delta-t_0)+B_2(s)\varsigma(s-\delta-t_0)+b(s)\big)ds \\ \quad +\int_{t_0}^t\big(C_2(s)\xi(s-t_0-\delta)+\sigma(s)\big)dW(s) \\ \int_{t_0}^t F(t,s)\Big(\xi(0)+\int_{t_0}^s B_2(r)\varsigma(r-\delta-t_0)dr\Big)ds \\ +\int_{t_0}^t\mathcal{E}(t,s)(A_2(s)\xi(s-\delta-t_0)+b(s))ds+\int_{t_0}^t\mathcal{E}(t,s)(C_2(s)\xi(s-\delta-t_0)+\sigma(s))dW(s) \\ K_1(t)\xi(0)+K_1(t)\int_{t_0}^t\big(A_2(s)\xi(s-\delta-t_0)+B_2(s)\varsigma(s-\delta-t_0)+b(s)\big)ds \\ +K_1(t)\int_{t_0}^t\big(C_2(s)\xi(s-t_0-\delta)+\sigma(s)\big)dW(s)+K_3(t)\xi(t-\delta-t_0)+v(t)\end{bmatrix}.$$

Notice that $K_1(\cdot)\in L^2(t_0,T;\mathbb{R}^{m\times n})$ and $\sigma(\cdot)\in L^2_{\mathbb{F}}(0,T;\mathbb{R}^n)$. Then, we obtain

$$\mathbb{E}\int_{t_0}^T|K_1(t)\int_{t_0}^t\sigma(s)dW(s)|^2dt \leqslant \int_{t_0}^T|K_1(t)|^2dt\mathbb{E}\int_{t_0}^T|\sigma(s)|^2ds<\infty.$$

In addition, by (A1), the Holder inequality and $(K_1(\cdot),K_2(\cdot,\cdot),K_3(\cdot),K_4(\cdot,\cdot),v(\cdot))\in\mathbb{L}$, we obtain $\boldsymbol{\varphi}(\cdot)\in L^2_{\mathbb{F}}(t_0,T;\mathbb{R}^{2n+m})$, $\mathbf{A}(\cdot,\cdot)\in L^2(\Delta_2(t_0,T);\mathbb{R}^{(2n+m)\times(2n+m)})$, $\mathbf{C}(\cdot,\cdot)$ $\in\mathscr{L}^2(\triangle_2(t_0,T);\mathbb{R}^{(2n+m)\times(2n+m)})$. Thus, by the solvability of SVIEs (or Proposition

2.2 in the Arxiv version of this paper [28]), (A.1) admits a unique solution $\mathbf{X}(\cdot) \in L^2_{\mathbb{F}}(t_0, t_0+\delta; \mathbb{R}^{2n+m})$, which implies that $x(\cdot) \in L^2_{\mathbb{F}}(t_0, t_0+\delta; \mathbb{R}^n)$ and $u(\cdot) \in L^2_{\mathbb{F}}(t_0, t_0+\delta; \mathbb{R}^m)$. Furthermore, by the definition of the solution of the first equation in (2.2), $x(\cdot) \in L^2_{\mathbb{F}}(\Omega; C([t_0, t_0+\delta]; \mathbb{R}^n))$, which implies the existence of the solution to (2.2). As for the uniqueness, since (A.1) and (2.2) are equivalent, it can be obtained from the uniqueness of the solution to (A.1). Hence, the closed-loop system (2.2) admits a unique solution on $[t_0, t_0+\delta]$. Then, the same steps are repeated on $[t_0+\delta, t_0+2\delta]$, $[t_0+2\delta, t_0+3\delta]$ and so on. The terminal time T is finite. Thus, (2.2) admits a unique solution on $[t_0, T]$. Regarding the estimate (2.3), the detailed proof process is provided in the Arxiv version. ∎

The proof of Proposition 3.1:

Proof. To show the equivalence, it is sufficient to prove that under (A1), the $X(\cdot)$ defined in (3.7) is the unique solution of SVIE (3.8). In terms of Proposition 2.1 and the solvability of SVIEs (or Proposition 2.2 in the Arxiv version of this paper [28]), we only need to prove the following results:

$$A(\cdot,\cdot)\in L^2(\Delta_2(0,T);\mathbb{R}^{(3n)\times(3n)}), B(\cdot,\cdot)\in L^2(\Delta_2(0,T);\mathbb{R}^{(3n)\times m}), R(\cdot)\in L^\infty(0,T;\mathbb{S}^m),$$
$$C(\cdot,\cdot) \in \mathscr{L}^2(\triangle_2(0,T);\mathbb{R}^{(3n)\times(3n)}),\ D(\cdot,\cdot) \in \mathscr{L}^2(\triangle_2(0,T);\mathbb{R}^{(3n)\times m}),$$
$$Q(\cdot)\in L^\infty(0,T;\mathbb{S}^{3n}), \tilde b(\cdot,\cdot)\in L^{2,1}_{\mathbb{F}}(\triangle_2(0,T);\mathbb{R}^{3n}), \tilde\sigma(\cdot,\cdot)\in L^2_{\mathbb{F}}(\triangle_2(0,T);\mathbb{R}^{3n}).$$

Notice that

$$\int_0^T\int_0^t |\mathcal{E}(t,s)A_1(s)|^2 ds dt \leqslant \int_0^T |A_1(s)|^2 ds \int_0^T \Big(\int_0^t |F(t,r)|dr\Big)^2 dt.$$

Then, by $A_1(\cdot)\in L^2(0,T;\mathbb{R}^{n\times n})$ and $F(\cdot,\cdot)\in L^\infty(\Delta_2(0,T);\mathbb{R}^{n\times n})$, we have $\mathcal{E}(\cdot,\cdot)A_1(\cdot) \in L^2(\Delta_2(0,T);\mathbb{R}^{n\times n})$. In terms of Assumption (A1), $A(\cdot,\cdot)\in L^2(\Delta_2(0,T);\mathbb{R}^{(3n)\times(3n)})$. Using the Holder inequality and Assumption (A1), we can prove the integrability of $B(\cdot,\cdot)$, $C(\cdot,\cdot)$, $D(\cdot,\cdot)$, $Q(\cdot)$, $R(\cdot)$, $\tilde b(\cdot,\cdot)$ and $\tilde\sigma(\cdot,\cdot)$, thus the proof is completed. ∎

The proof of Theorem 3.3:

Proof. Inspired by [17], let us introduce the following Riccati system:

$$\text{(A.2)}\quad \begin{cases} P^{(1)}(t) = Q(t)+(C^\top\ltimes P\rtimes C)(t)-(C^\top\ltimes P\rtimes D)(t)\\ \qquad\times(R(t)+(D^\top\ltimes P\rtimes D)(t))^{-1}(D^\top\ltimes P\rtimes C)(t),\ 0<t<T,\\ P^{(2)}(s,t,t) = P^{(2)}(t,s,t)^\top = (P\rtimes A)(s,t)\\ \qquad-(P\rtimes B)(s,t)(R(t)+(D^\top\ltimes P\rtimes D)(t))^{-1}(D^\top\ltimes P\rtimes C)(t),\ 0<t<s<T,\\ \dot P^{(2)}(s_1,s_2,t) = (P\rtimes B)(s_1,t)(R(t)+(D^\top\ltimes P\rtimes D)(t))^{-1}\\ \qquad\times(B^\top\ltimes P)(s_2,t),\quad 0<t<(s_1\wedge s_2)<T, \end{cases}$$

where for each $M_1 : \triangle_2(0,T)\to\mathbb{R}^{d_1\times(3n)}$, $M_2 : \triangle_2(0,T)\to\mathbb{R}^{(3n)\times d_2}$ with any positive integers d_1, d_2,

$$\text{(A.3)}\quad \begin{aligned} &(M_1\ltimes P)(s,t) \equiv M_1(s,t)P^{(1)}(s) + \int_t^T M_1(r,t)P^{(2)}(r,s,t)\mathrm{d}r,\ 0<t<s<T,\\ &(P\rtimes M_2)(s,t) \equiv P^{(1)}(s)M_2(s,t) + \int_t^T P^{(2)}(s,r,t)M_2(r,t)\mathrm{d}r,\ 0<t<s<T,\\ &(M_1\ltimes P\rtimes M_2)(t) \equiv \int_t^T M_1(s_1,t)\Big[P^{(1)}(s_1)M_2(s_1,t)+\int_t^T P^{(2)}(s_1,s_2,t)M_2(s_2,t)\,ds_2\Big]ds_1. \end{aligned}$$

By Corollary 6.7 in [17], the equation (A.2) admits a unique solution $(P^{(1)}, P^{(2)}) \in \Pi(0,T)$ such that $R+(D^\top\ltimes P\rtimes D) > \beta I$ for some constant $\beta > 0$. Next we will equivalently transform (A.2) into (3.11). To this end, we first show that

$$\text{(A.4)}\quad (C^\top\ltimes P\rtimes C)(t) = (C_1(t),C_2(t),C_3(t))^\top\mathcal{G}_1(t)(C_1(t),C_2(t),C_3(t)),$$
$$\text{(A.5)}\quad (C^\top\ltimes P\rtimes D)(t) = (C_1(t),C_2(t),C_3(t))^\top\mathcal{G}_1(t)D_1(t),$$

$$(A.6)\quad (D^\top\ltimes P\rtimes D)(t)=D_1(t)^\top\mathcal{G}_1(t)D_1(t),\ \ (D^\top\ltimes P\rtimes C)(t)=D_1(t)^\top\mathcal{G}_1(t)(C_1(t),C_2(t),C_3(t)).$$

Notice that

$$C(s,t)=\Upsilon(s,t)(C_1(t),C_2(t),C_3(t)),$$

$$(C^\top\ltimes P\rtimes C)(t)=\int_t^T C(s,t)^\top P^{(1)}(s)C(s,t)ds+\int_t^T\int_t^T C(s_1,t)^\top P^{(2)}(s_1,s_2,t)C(s_2,t)ds_1ds_2.$$

Then, (A.4) holds. Similarly, by $D(s,t)=\Upsilon(s,t)D_1(t)$, we obtain (A.5)–(A.6). Next we treat the terms $(P\rtimes A)$ and $(P\rtimes B)$. From $A(s,t)=\Upsilon(s,t)(A_1(t),A_2(t),A_3(t))$,

$$(P\rtimes A)(s,t)=\Big[P^{(1)}(s)\Upsilon(s,t)+\int_t^T P^{(2)}(s,r,t)\Upsilon(r,t)dr\Big](A_1(t),A_2(t),A_3(t)).$$

On the other hand, we observe that

$$B(t,s)=\int_s^t\Pi(t,s,\theta)(B_1(s)^\top,B_2(s+\delta)^\top,(B_3(\theta)\tilde F(\theta,s))^\top)^\top d\theta.$$

Then, we deduce

$$\begin{aligned}(P\rtimes B)(s,t)&=\int_t^s P^{(1)}(s)\Pi(s,t,\theta)(B_1(t)^\top,B_2(t+\delta)^\top,(B_3(\theta)\tilde F(\theta,t))^\top)^\top d\theta\\ &\quad+\int_t^T\int_t^r P^{(2)}(s,r,t)\Pi(r,t,\theta)(B_1(t)^\top,B_2(t+\delta)^\top,(B_3(\theta)\tilde F(\theta,t))^\top)^\top d\theta dr.\end{aligned}\tag{A.7}$$

Hence, after some direct calculations, together with (A.4)–(A.7), we see that (A.2) can be written as (3.11), which completes the proof of Theorem 3.3. ∎

The proof of Theorem 3.4:

Proof. Introduce the following Type-II extended backward SVIE:

$$\begin{cases}d\eta(t,s)=-\Big\{(P\rtimes\tilde b)(t,s)+\Gamma^*(t,s)^\top(D^\top\ltimes P\rtimes\tilde\sigma)(s)+\Gamma^*(t,s)^\top\int_s^T\big[B(r,s)^\top\\ \qquad\times\eta(r,s)+D(r,s)^\top\zeta(r,s)\big]dr\Big\}ds+\zeta(t,s)dW(s),\ 0<s<t<T,\\ \eta(t,t)=(C^\top\ltimes P\rtimes\tilde\sigma)(t)+\Xi^*(t)^\top(D^\top\ltimes P\rtimes\tilde\sigma)(t)+\int_t^T(A(r,t)+B(r,t)\\ \qquad\times\Xi^*(t))^\top\eta(r,t)dr+\int_t^T(C(r,t)+D(r,t)\Xi^*(t))^\top\zeta(r,t)dr,\ 0<t<T,\end{cases}\tag{A.8}$$

where

$$\Xi^*(t)\equiv-(R(t)+(D^\top\ltimes P\rtimes D)(t))^{-1}(D^\top\ltimes P\rtimes C)(t),\ 0<t<T,$$

$$\Gamma^*(s,t)\equiv-(R(t)+(D^\top\ltimes P\rtimes D)(t))^{-1}(B^\top\ltimes P)(s,t),\ 0<t<s<T.$$

Under Assumptions (A1)–(A2), it follows from Theorem 3.2 in [17] that Equation (A.8) admits a unique solution $(\eta,\zeta)\in L^2_{\mathbb{F},c}(\triangle_2(0,T);\mathbb{R}^{3n})\times L^2_{\mathbb{F}}(\triangle_2(0,T);\mathbb{R}^{3n})$. After a careful observation, we have that

$$\begin{aligned}&(P\rtimes\tilde b)(t,s)=\Big[P^{(1)}(t)\Upsilon(t,s)+\int_s^T P^{(2)}(t,r,s)\Upsilon(r,s)dr\Big]b(s),\\ &(C^\top\ltimes P\rtimes\tilde\sigma)(t)=(C_1(t),C_2(t),C_3(t))^\top\mathcal{G}_1(t)\sigma(t),\\ &(D^\top\ltimes P\rtimes\tilde\sigma)(s)=D_1(s)^\top\mathcal{G}_1(s)\sigma(s),\quad C(t,s)=\Upsilon(t,s)(C_1(s),C_2(s),C_3(s)),\\ &D(t,s)=\Upsilon(t,s)D_1(s),\ B(t,s)=\int_s^t\Pi(t,s,\theta)(B_1(s)^\top,B_2(s+\delta)^\top,(B_3(\theta)\tilde F(\theta,s))^\top)^\top d\theta.\end{aligned}$$

Then, we see that (A.8) can be rewritten as (3.13), which completes the proof. ∎

Before proving Theorem 3.6, according to [17], we need some auxiliary results about the new control problem with the state equation (3.8) and the cost (3.9).

To begin with, for any given $t_0 \in [0,T)$, we consider the following system:

$$
\text{(A.9)}\quad \begin{cases} X^{t_0,\xi,\varsigma}(t) = \varphi(t) + \int_{t_0}^{t} \big[A(t,s)X^{t_0,\xi,\varsigma}(s) + B(t,s)u^{t_0,\xi,\varsigma}(s) + \tilde{b}(t,s)\big]ds \\ \quad + \int_{t_0}^{t} \big[C(t,s)X^{t_0,\xi,\varsigma}(s) + D(t,s)u^{t_0,\xi,\varsigma}(s) + \tilde{\sigma}(t,s)\big]dW(s),\ t_0<t<T, \\ \Theta^{t_0,\xi,\varsigma}(s,t) = \varphi(s) + \int_{t_0}^{t} \big[A(s,r)X^{t_0,\xi,\varsigma}(r) + B(s,r)u^{t_0,\xi,\varsigma}(r) + \tilde{b}(s,r)\big]dr \\ \quad + \int_{t_0}^{t} \big[C(s,r)X^{t_0,\xi,\varsigma}(r) + D(s,r)u^{t_0,\xi,\varsigma}(r) + \tilde{\sigma}(s,r)\big]dW(r),\ t_0<t<s<T, \\ u^{t_0,\xi,\varsigma}(t) = \Xi(t)X^{t_0,\xi,\varsigma}(t) + \int_t^T \Gamma(s,t)\Theta^{t_0,\xi,\varsigma}(s,t)\mathrm{d}s + \omega(t),\ t_0<t<T. \end{cases}
$$

In terms of [17], we call any triplet $(\Xi,\Gamma,\omega) \in \mathcal{S}(t_0,T) \equiv L^\infty(t_0,T;\ \mathbb{R}^{m\times n}) \times L^2\left(\triangle_2(t_0,T);\mathbb{R}^{m\times n}\right) \times L^2_{\mathbb{F}}(t_0,T;\mathbb{R}^m)$ the *causal feedback strategy*. For any $(\Xi,\Gamma,\omega) \in \mathcal{S}(t_0,T)$, $\xi \in C([-\delta,0];\mathbb{R}^n)$ and $\varsigma \in L^2(-\delta,0;\mathbb{R}^m)$, let the triplet $(X^{t_0,\xi,\varsigma}, \Theta^{t_0,\xi,\varsigma}, u^{t_0,\xi,\varsigma})$ be the solution to the system (A.9) and write $u^{t_0,\xi,\varsigma} = (\Xi,\Gamma,w)\,[t_0,\xi,\varsigma]$. A causal feedback strategy $(\Xi^*,\Gamma^*,\omega^*) \in \mathcal{S}(t_0,T)$ is called a *causal feedback optimal strategy* of the new control problem if

$$
J\big(t_0,\xi,\varsigma;(\Xi^*,\Gamma^*,\omega^*)\,[t_0,\xi,\varsigma]\,\big) \leqslant J\big(t_0,\xi,\varsigma;u\big),
$$

for any $(\xi,\varsigma) \in C([-\delta,0];\mathbb{R}^n) \times L^2(-\delta,0;\mathbb{R}^m)$ and any $u(\cdot) \in L^2_{\mathbb{F}}(t_0,T;\mathbb{R}^m)$.

The following result gives the closed-loop solvability for the new control problem, and its proof can be referred to in the Arxiv version of this paper [28].

Lemma A.1. *Let Assumptions* (A1)–(A2) *hold. Then, for any given* $t_0 \in [0,T)$, *the causal feedback optimal strategy* $(\Xi^*,\Gamma^*,\omega^*)$ *of the new control problem on* $[t_0,T]$ *with* (3.8) *and* (3.9), *is given by* (3.14) *and for* $t_0 < t < T$,

$$
\omega^*(t) = -\mathcal{R}(t)^{-1}\Big(D_1(t)^\top \mathcal{G}_1(t)\sigma(t) + \int_t^T \Big[\int_t^s \mathcal{B}(\theta,t)^\top \Pi(s,t,\theta)^\top \eta(s,t)d\theta
$$

$$
\text{(A.10)}\qquad + D_1(t)^\top \Upsilon(s,t)^\top \zeta(s,t)\Big]ds\Big),
$$

where $\Pi(\cdot,\cdot,\cdot), \Upsilon(\cdot,\cdot), \mathcal{R}(\cdot), \mathcal{G}_1(\cdot)$ *and* $\mathcal{G}_3(\cdot,\cdot,\cdot)$ *are defined by* (3.10), (3.12), *respectively.*

The proof of Theorem 3.6:

Proof. The following is a brief proof. For more details, please refer to the Arxiv version of this paper [28]. The idea of the following arguments is to explicitly construct the desired five-tuple closed-loop strategy by the causal feedback strategy $(\Xi^*,\Gamma^*,\omega^*)$ in Lemma A.1. To this end, we divide the proof into 3 steps.

Step 1: Given $\Xi^*(\cdot), \Gamma^*(\cdot,\cdot)$ in (3.14), for later convenience we decompose them as $\Xi^*(t) = \big[\Xi_1^*(t), \Xi_2^*(t), \Xi_3^*(t)\big], \Gamma^*(s,t) = \big[\Gamma_1^*(s,t), \Gamma_2^*(s,t), \Gamma_3^*(s,t)\big]$. In this step, we prove that the following process is an optimal closed-loop outcome control of Problem (P):

$$
u^*(t) = K_1^*(t)x^*(t) + \int_{t_0}^t K_2^*(t,s)x^*(s)ds + K_3^*(t)x^*(t-\delta)
$$

$$
\text{(A.11)}\qquad + \int_{t_0}^t K_4^*(t,s)u^*(s)ds + v^*(t),\ t_0<t<T,
$$

where

$$
\text{(A.12)}\quad K_1^*(t) = \Xi_1^*(t) + \int_t^T \Big[\Gamma_1^*(s,t) + \Gamma_2^*(s,t)\mathbf{1}_{\left([t+\delta]\wedge T,\infty\right)}(s) + \int_t^s \Gamma_3^*(s,t)F(s,\theta)d\theta\Big]ds,
$$

$$
\text{(A.13)}\quad K_2^*(t,s) = \Xi_3^*(t)F(t,s) + \Gamma_2^*(s+\delta,t)\mathbf{1}_{[t-\delta,T-\delta]}(s) + \int_t^T \Gamma_3^*(\theta,t)F(\theta,s)d\theta,
$$

$$
\text{(A.14)}\quad K_3^*(t) = \Xi_2^*(t),
$$

$$K_4^*(t,s)=\int_{s+\delta}^T\Big[\Gamma_1^*(r,t)+\Gamma_2^*(r,t)\mathbf{1}_{(s+2\delta,\infty)}(r)\mathbf{1}_{[0,T-\delta)}(t)+\int_{s+\delta}^r\Gamma_3^*(r,t)F(r,\theta)d\theta\Big]dr$$
$$\times B_2(s+\delta)\mathbf{1}_{[t-\delta,T-\delta]}(s)+\int_{s}^T\int_{\theta'}^T\Big(\Gamma_1^*(r,t)+\Gamma_2^*(r,t)\mathbf{1}_{[t_0,T-\delta)}(\theta')$$
$$\times\mathbf{1}_{[t_0,T-\delta)}(t)\mathbf{1}_{(\theta'+\delta,\infty)}(r)+\int_{\theta'}^r\Gamma_3^*(r,t)F(r,\theta)d\theta\Big)B_3(\theta')\tilde F(\theta',s)drd\theta', \tag{A.15}$$

$$v^*(t)=\omega^*(t)+\int_t^{T\wedge(t_0+\delta)}\Gamma_2^*(s,t)\xi(s-t_0-\delta)ds+\int_{t-\delta}^{t_0}\Big[\int_{s+\delta}^T\big[\Gamma_1^*(r,t)+\Gamma_2^*(r,t)$$
$$\times\mathbf{1}_{(s+2\delta,\infty)}(r)\mathbf{1}_{[0,T-\delta)}(t)+\int_{s+\delta}^r\Gamma_3^*(r,t)F(r,\theta)d\theta\big]drB_2(s+\delta)\Big]\varsigma(s-t_0)ds\mathbf{1}_{[t_0,t_0+\delta]}(t), \tag{A.16}$$

and $\omega^*(\cdot)$ is defined by (A.10).
By Proposition 3.1, given $(\Xi^*,\Gamma^*,\omega^*)$ in Lemma A.1, the optimal control of Problem (P) is given by

$$u^*(t)=\Xi^*(t)X^*(t)+\int_t^T\Gamma^*(s,t)\Theta^*(s,t)ds+\omega^*(t),\ \ t_0<t<T, \tag{A.17}$$

where $X^*(\cdot)\equiv\big[x^*(\cdot)^\top,y^*(\cdot)^\top,z^*(\cdot)^\top\big]^\top$, and

$$\Theta^*(s,t)=\varphi(s)+\int_{t_0}^t\big[A(s,r)X^*(r)+B(s,r)u^*(r)+\tilde b(s,r)\big]dr$$
$$+\int_{t_0}^t\big[C(s,r)X^*(r)+D(s,r)u^*(r)+\tilde\sigma(s,r)\big]dW(r),\quad t_0<t<s<T.$$

Our next idea is to rewrite (A.17) into (A.11). For later convenience, let $\Theta^*(\cdot,\cdot)=\big[\Theta_1^*(\cdot,\cdot)^\top,\Theta_2^*(\cdot,\cdot)^\top,\Theta_3^*(\cdot,\cdot)^\top\big]^\top$. It then yields

$$u^*(t)=\Xi_1^*(t)x^*(t)+\Xi_2^*(t)x^*(t-\delta)+\Xi_3^*(t)\int_{t_0}^tF(t,s)x^*(s)ds$$
$$+\int_t^T\Big[\Gamma_1^*(s,t)\Theta_1^*(s,t)+\Gamma_2^*(s,t)\Theta_2^*(s,t)+\Gamma_3^*(s,t)\Theta_3^*(s,t)\Big]ds+w^*(t). \tag{A.18}$$

As to Θ_1^*, Θ_2^*, Θ_3^*, by the Fubini theorem, we obtain

$$\Theta_1^*(s,t)=x^*(t)+\int_t^{s\wedge(t+\delta)}B_2(r)u^*(r-\delta)dr+\int_t^sB_3(r)\int_{t_0}^t\tilde F(r,\theta)u^*(\theta)d\theta dr, \tag{A.19}$$

$$\Theta_2^*(s,t)=\xi(s-\delta-t_0)\mathbf{1}_{[t_0,t_0+\delta]}(s)+\mathbf{1}_{(\delta+t_0,\infty)}(s)\Big\{x^*(t\wedge(s-\delta))$$
$$+\int_{t\wedge(s-\delta)}^{(t+\delta)\wedge(s-\delta)}B_2(r)u^*(r-\delta)dr+\int_{t\wedge(s-\delta)}^{s-\delta}B_3(r)\int_{t_0}^t\tilde F(r,\theta)u^*(\theta)d\theta dr\Big\}, \tag{A.20}$$

and

$$\Theta_3^*(s,t)=\int_{t_0}^s\Big[F(s,r)x^*(t\wedge r)+\int_{t\wedge r}^{(t+\delta)\wedge r}B_2(\theta)u^*(\theta-\delta)d\theta+\int_{t_0}^{t\wedge r}\int_{t\wedge r}^rB_3(\theta)\tilde F(\theta,\theta')u^*(\theta')d\theta d\theta'\Big]dr.$$

Substitute the above estimate and (A.19)–(A.20) into (A.18), and apply the Fubini theorem to each of the resulting terms. Then, the optimal closed-loop outcome control (A.17) of Problem (P) becomes (A.11), and $K_1^*(\cdot),K_2^*(\cdot,\cdot),K_3^*(\cdot)$, $K_4^*(\cdot,\cdot),v^*(\cdot)$ are given by (A.12)–(A.16).

Step 2: In this step, we give furthermore explicit representations of K_1^*,K_2^*,K_3^*, K_4^* and v^* by means of $(P^{(1)},P^{(2)})$ and other given coefficients of the optimal control problem. Let $P=(P^{(1)},P^{(2)})$ be the solution to the Riccati–Volterra equation (3.11), and decompose them as $P^{(1)}(\cdot)=\big(P_{ij}^{(1)}(\cdot)\big)_{1\leqslant i,j\leqslant 3}$ and $P^{(2)}(\cdot,\cdot,\cdot)=\big(P_{ij}^{(2)}(\cdot,\cdot,\cdot)\big)_{1\leqslant i,j\leqslant 3}$. Then, by (3.10) and (3.14), for $i=1,2,3$, we have

$$\Xi_i^*(t)=-\mathcal{R}(t)^{-1}D_1(t)^\top\mathcal{G}_1(t)C_i(t),\quad t_0<t<T,$$

$$\Gamma_i^*(s,t) = -\mathcal{R}(t)^{-1}\int_t^T \mathcal{B}(\theta,t)^\top \Big(\Pi(s,t,\theta)^\top \mathbf{1}_{(t_0,s)}(\theta)\big[P_{1i}^{(1)}(s)^\top, P_{2i}^{(1)}(s)^\top, P_{3i}^{(1)}(s)^\top\big]^\top$$
$$+\int_\theta^T \Pi(r,t,\theta)^\top\big[P_{1i}^{(2)}(r,s,t)^\top, P_{2i}^{(2)}(r,s,t)^\top, P_{3i}^{(2)}(r,s,t)^\top\big]^\top dr\Big)d\theta,\ t_0<t<s<T. \tag{A.21}$$

From (A.15), we have

$$K_4^*(t,s)=\Big\{\int_{s+\delta}^T\Big[\Gamma_1^*(r,t)+\Gamma_2^*(r,t)\mathbf{1}_{(s+2\delta,\infty)}(r)\mathbf{1}_{[t_0,T-\delta)}(t)+\int_{s+\delta}^r\Gamma_3^*(r,t)F(r,\theta)d\theta\Big]dr$$
$$\times B_2(s+\delta)\Big\}\mathbf{1}_{[t-\delta,T-\delta]}(s)+\int_t^T\int_{\theta'}^T\Big(\Gamma_1^*(r,t)+\Gamma_2^*(r,t)\mathbf{1}_{[t_0,r-\delta)}(\theta')\mathbf{1}_{[t_0,T-\delta)}(t)$$
$$+\int_{\theta'}^r \Gamma_3^*(r,t)F(r,\theta)d\theta\Big)B_3(\theta')\tilde F(\theta',s)drd\theta' \equiv I_1(t,s+\delta)\mathbf{1}_{[t-\delta,T-\delta]}(s)+I_2(t,s),$$

which implies that

$$I_1(t,s)=\int_s^T\Big[\Gamma_1^*(r,t)+\Gamma_2^*(r,t)\mathbf{1}_{(s+\delta,\infty)}(r)\mathbf{1}_{[t_0,T-\delta)}(t)+\int_s^r\Gamma_3^*(r,t)F(r,\theta)d\theta\Big]drB_2(s).$$

By (A.21) and some calculations, we derive

$$I_1(t,s)=-\mathcal{R}(t)^{-1}\Big\{\int_t^T\mathcal{B}(\theta,t)^\top\Big[\int_{s\vee\theta}^T\Pi(r,t,\theta)^\top P^{(1)}(r)^\top\Big(I,\mathbf{1}_{(s+\delta,\infty)}(r)\mathbf{1}_{[0,T-\delta]}(t)I,$$
$$\int_s^r F(r,\theta')^\top d\theta'\Big)^\top dr+\int_s^T\int_\theta^T\Pi(\alpha,t,\theta)^\top P^{(2)}(r,\alpha,t)^\top\Big(I,\mathbf{1}_{(s+\delta,\infty)}(r)\mathbf{1}_{[0,T-\delta]}(t)I,$$
$$\int_s^r F(r,\theta')^\top d\theta'\Big)^\top d\alpha dr\Big]d\theta\Big\}B_2(s).$$

Similarly, by (A.21), we can treat I_2 and then deduce $K_4^*(\cdot,\cdot)$ in (3.16).

Similar to the above steps, by (A.12) and (A.21), we get $K_1^*(\cdot)$ in (3.15). From (A.13) and (A.21), we obtain $K_2^*(\cdot,\cdot)$ in (3.16). By (3.12) and (A.14), we derive $K_3^*(\cdot)$ in (3.15). In addition, combining (A.10), (A.16), (A.21) and applying the Fubini theorem, we deduce $v^*(\cdot)$ in (3.17).

Step 3: In this step, we show that $(K_1^*(\cdot),K_2^*(\cdot,\cdot),K_3^*(\cdot),\ K_4^*(\cdot,\cdot),v^*(\cdot))$ is the optimal closed-loop strategy of Problem (P) on $[t_0,T]$ in terms of Definition 2.3.

In fact, by the optimality in Step 1, it is sufficient to prove that $(K_1^*(\cdot),K_2^*(\cdot,\cdot),$ $K_3^*(\cdot),K_4^*(\cdot,\cdot),v^*(\cdot))\in\mathbb{L}$. Next we prove that $K_1(\cdot)\in L^2(t_0,T;\mathbb{R}^{n\times m})$. Since $(P^{(1)},P^{(2)})\in\Pi(0,T)$, we have

$$\operatorname*{ess\,sup}_{t\in(0,T)}|P^{(1)}(t)|+\Big(\int_0^T\int_0^T\sup_{t\in[0,s_1\wedge s_2]}|P^{(2)}(s_1,s_2,t)|^2ds_1ds_2\Big)^{\frac12}<\infty.$$

By the boundedness of $F(\cdot,\cdot)$, we obtain

$$\sup_{t\in(0,T)}\int_t^T|\Upsilon(s,t)^\top P^{(1)}(s)\Upsilon(s,t)|ds\leqslant M\operatorname*{ess\,sup}_{t\in(0,T)}|P^{(1)}(t)|\int_0^T\Big|1+\int_0^s|F(s,r)|dr\Big|^2ds<\infty.$$

Here and hereafter M is a generic constant. Similarly one can treat the case of $P^{(2)}$. Thus the above two estimations imply the boundedness of $\mathcal{G}_1(\cdot)$. Recall Theorem 3.3, $\mathcal{R}(\cdot)\geqslant\beta I$ for some constant $\beta>0$. Then, the boundedness of $R_1(\cdot),R_2(\cdot),D_1(\cdot)$ imply that $\mathcal{R}(\cdot)^{-1}$ is bounded. Notice that

$$\int_{t_0}^T\Big|\int_t^T\int_t^T\mathcal{B}(\theta,t)^\top\int_\theta^T\Big(P^{(2)}(\alpha,r,t)\Pi(r,t,\theta)\Big)^\top dr\Upsilon(\alpha,t)d\alpha d\theta\Big|^2dt$$
$$\leqslant\int_{t_0}^T\Big|\int_t^T|\mathcal{B}(\theta,t)|\int_\theta^T\int_t^T\Big(\frac{1}{r-t}+1+\frac{1}{r-t}|\mathcal{E}(r,t)|+\frac{1}{r-t}|\mathcal{E}(r,t+\delta)|+|\mathcal{E}(r,\theta)|\Big)$$
$$\times|P^{(2)}(\alpha,r,t)|\big(1+|\mathcal{E}(\alpha,t)|\big)d\alpha drd\theta\Big|^2dt. \tag{A.22}$$

By the boundedness of $F(\cdot,\cdot)$, $B_1(\cdot)$, $B_2(\cdot)$ and $B_3(\cdot)$, we deduce

$$\int_{t_0}^{T}\Big|\int_{t}^{T}|\mathcal{B}(\theta,t)|\int_{\theta}^{T}\int_{t}^{T}\frac{1}{r-t}|P^{(2)}(\alpha,r,t)||\mathcal{E}(\alpha,t)|d\alpha dr d\theta\Big|^2 dt$$

$$\text{(A.23)} \leqslant M\int_{0}^{T}\int_{0}^{T}\sup_{t\in[0,\alpha\wedge r]}|P^{(2)}(\alpha,r,t)|^2 d\alpha dr < \infty.$$

Similar to (A.23), we can deal with other terms in (A.22) and prove that $K_1(\cdot)\in L^2(t_0, T;\mathbb{R}^{n\times m})$. Furthermore, we can verify that $(K_1^*(\cdot), K_2^*(\cdot,\cdot), K_3^*(\cdot), K_4^*(\cdot,\cdot), v^*(\cdot)) \in \mathbb{L}$. $\square$