

Convex Synthesis of First-Order Methods for Time-Varying Smooth Strongly Convex Optimization

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Abstract—Time-varying optimization is fundamental to decision-making in dynamic environments, where objectives evolve over time due to exogenous signals or data streams. However, algorithms designed for static problems yield suboptimal decisions in dynamic scenarios, even asymptotically. In this paper, we develop a robust control synthesis framework to systematically design first-order methods for smooth strongly convex problems that vary in time. Our approach leverages both convex robust control synthesis in the static setting and the internal model principle by directly embedding a model of the underlying variability into the designed algorithm.

I. INTRODUCTION

Optimization algorithms play a central role in modern control, machine learning, and networked systems, underpinning decision-making processes in applications ranging from large-scale data analytics to cyber-physical and energy systems. Recent advances have established a systems-and-control perspective for algorithm analysis and design, whereby iterative optimization methods are modeled as dynamical systems in feedback with nonlinear gradient oracles, enabling their analysis and design via tools from dissipativity theory, passivity, and robust control [1]–[4]. Building on this viewpoint, convex synthesis approaches [5] have emerged as a principled framework for the automated design of algorithms, casting algorithm construction as a robust control synthesis problem, enabling the systematic exploration of algorithmic structures beyond classical hand-crafted schemes and leading to provably optimal methods [6].

Despite these advances, existing synthesis approaches address *static* optimization problems, while many applications of interest involve *time-varying* objectives driven by exogenous signals, evolving environments, or streaming data. In such settings, standard first-order methods exhibit nonzero steady-state error [7], as they lack mechanisms to compensate for persistent temporal variations. From a control-theoretic perspective, this limitation stems from the absence of appropriate internal models [8], [9].

According to the internal model principle of time-varying optimization [8], [9], perfect tracking and disturbance rejection require embedding a model of the exogenous signals within the optimization dynamics. Yet, this principle has not been systematically integrated in convex synthesis [5].

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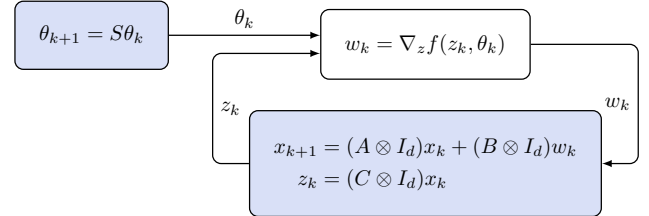


Fig. 1. Block diagram of a first-order method for time-varying optimization. The exosystem generates the time-varying parameter θ_k , which affects the gradient of the objective. The method is a dynamical system with state x_k that generates a sequence of points z_k at which to evaluate the gradient based on measurements w_k of the time-varying gradient.

Contributions: Our main contribution is to demonstrate how the convex synthesis procedure from [6] can be adapted to incorporate an internal model of the temporal variability of the problem, thereby extending the approach to time-varying optimization. Our design is based on the internal model principle of time-varying optimization [8], [9], and its effectiveness is illustrated through numerical simulations.

Related works: The systems-and-control perspective of optimization has motivated algorithm synthesis methods that go beyond classical hand-crafted designs, including direct synthesis with worst-case convergence guarantees [10], IQC-based structure-exploiting design [11], linear matrix inequality (LMI)-based synthesis for optimization and saddle-point problems [12], and convex synthesis frameworks for accelerated algorithms and extremum control [5], [13]. In parallel, time-varying optimization has been studied from both online and control-theoretic perspectives. When no explicit model of temporal variability is available, one typically obtains dynamic-regret or input-to-state-stability type guarantees [14]–[16]. When the temporal variability can be modeled or estimated, prediction-correction and related model-based schemes can achieve substantially improved tracking performance [17]–[21]. More recently, these directions have started to intersect with robust control tools for time-varying optimization [9], [19]. Fundamentally, the internal-model viewpoint connects exact asymptotic tracking in time-varying optimization to output regulation theory, showing that exact tracking requires embedding a suitable model of the temporal variability in the algorithm [9], [20]. Particularly relevant are [22], [23], where output regulation of nonlinear models is achieved by linear controllers that incorporate more dynamics than those generated by the exosystem. These developments motivate our work: we integrate internal model-based designs with robust control synthesis to form a unified framework to design optimization algorithms tailored to structured time-varying problems.

II. PROBLEM SETUP

Consider an unconstrained optimization problem in which the objective function depends on a time-varying parameter:

$$\text{minimize } f(z, \theta_k), \quad (1)$$

where $f : \mathbb{R}^d \times \mathbb{R}^p \rightarrow \mathbb{R}$ is the objective function, $z \in \mathbb{R}^d$ the decision variable, and $\theta : \mathbb{N} \rightarrow \mathbb{R}^p$ a time-varying parameter. We make the following assumption on the objective function.

Assumption 1 (Objective): For any fixed parameter $\theta_o \in \mathbb{R}^p$, the function $z \mapsto f(z, \theta_o)$ is L -smooth and μ -strongly convex with known parameters $0 < \mu < L$. $\square$

The objective being L -smooth means that the gradient $\nabla_z f$ is Lipschitz continuous with parameter L , and the objective being μ -strongly convex means that $z \mapsto f(z, \theta_o) - \frac{\mu}{2}\|z\|^2$ is convex. With this assumption, the optimization problem has a unique optimal trajectory $z^* : \mathbb{N} \rightarrow \mathbb{R}^d$. We use $\mathcal{F}_{\mu, L}$ to denote the set of all functions that satisfy Assumption 1.

The optimization problem varies in time due to the parameter θ_k , which we assume is generated by a (known) LTI system.

Assumption 2 (Exosystem): The parameter signal $\theta : \mathbb{N} \rightarrow \mathbb{R}^p$ is generated by an autonomous LTI system satisfying

$$\theta_{k+1} = S\theta_k \quad \text{for all } k \in \mathbb{N} \quad (2)$$

and some initial condition $\theta_0 \in \mathbb{R}^p$. Moreover, all the eigenvalues of S have unit modulus, all exosystem trajectories are bounded, and the model S is known (with θ_0 unknown). $\square$

The requirement that (2) is known is motivated by [8], [9], which show that knowledge of the exosystem is necessary to compute an exact optimizer of (1).

We consider designing first-order optimization methods that query the gradient of the objective at each iteration. The method selects a point z_k at which to query the gradient, and then receives the corresponding value of the gradient

$$w_k = \nabla_z f(z_k, \theta_k), \quad (3)$$

with $\nabla_z f$ the gradient of f with respect to its first argument. To exclude exosystem modes that do not influence the gradient (and are therefore irrelevant), we assume the following.

Assumption 3 (Absence of zero dynamics): The objective f and exosystem trajectory θ are such that $\nabla_z f(z, \theta_k) = 0$ for all $k \in \mathbb{N}$ and some $z \in \mathbb{R}^d$ implies $\theta_k = 0$ for all $k \in \mathbb{N}$. $\square$

An optimization algorithm is a mapping from w to z . We assume the algorithm is causal, linear, time-invariant, strictly proper, and acts homogeneously across each dimension of $\mathbb{R}^d$. Formally, we consider methods of the form

$$x_{k+1} = (A \otimes I_d)x_k + (B \otimes I_d)w_k, \quad (4a)$$

$$z_k = (C \otimes I_d)x_k, \quad (4b)$$

for some $A \in \mathbb{R}^{n \times n}$, $B \in \mathbb{R}^{n \times 1}$, and $C \in \mathbb{R}^{1 \times n}$. We assume (A, C) is detectable without loss of generality [5, §2.2]. The algorithm is illustrated in Figure 1.

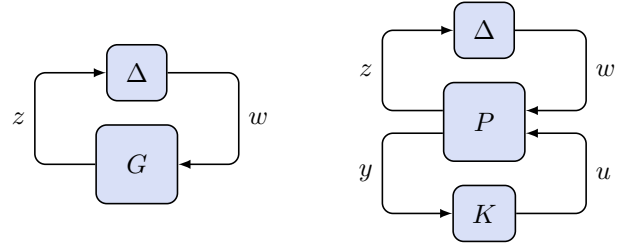


Fig. 2. Block diagrams of system interconnections. (Left) The algorithm transfer function $G(z)$ in feedback with an uncertainty Δ as in Thm. 1. (Right) Plant P in feedback with controller K and uncertainty Δ as in (8).

For the algorithm (4) to solve time-varying optimization problems, it must in particular be capable of solving time-invariant problems (e.g., when the objective does not depend on θ_k). A necessary condition for this is that the pair (A, C) has an observable eigenvalue at one [6, §II.C]. This, in turn, implies the existence of a fixed point.

Assumption 4 (Fixed point): There exists $x_* \in \mathbb{R}^{nd}$ such that

$$x_* = (A \otimes I_d)x_* \quad \text{and} \quad (C \otimes I_d)x_* \neq 0. \quad \square$$

Definition 1: We say that algorithm (4) (locally) asymptotically tracks the optimizer of (1) with rate $\rho \in (0, 1)$ if there exist constants $c > 0$ and $\delta > 0$ such that, for any initial condition x_0 with $\|x_0 - x_*\| < \delta$,

$$\|z_k - z_k^*\| \leq c \rho^k \|x_0 - x_0^*\| \quad \text{for all } k \in \mathbb{N}, \quad (5)$$

where $z_k^* \in \mathbb{R}^d$ is the unique optimizer at each k and x_k^* is the corresponding fixed point of (4). Moreover, the tracking is robust with respect to a set of objective functions and exosystem trajectories if the bound holds for all such instances.

With this setup, we can now state our main goal.

Problem 1: Design an efficient procedure that, given the objective function parameters μ and L and the temporal variability model S , automatically selects the state-space matrices (A, B, C) in (4) such that the resulting method robustly asymptotically tracks the optimizer of (1) with optimal (i.e., minimal) rate ρ . Optimality is with respect to all admissible choices of state-space matrices (A, B, C) , and robustness is with respect to all objective functions f and exosystem trajectories θ that satisfy Assumptions 1 to 3. $\square$

III. INTERNAL MODEL EMBEDDING

In this section, we derive a structure for (4) to ensure that the algorithm achieves asymptotic tracking. This will then enable us to reformulate Problem 1 as a robust control problem.

Asymptotic tracking of the optimizer imposes specific structural requirements on the method. In the time-invariant case (in which $S = I$ so that θ_k is constant), it is well-known that (4) must have the form of an LTI system in series with an integrator [5, §2.2]. When the objective varies in time, by the internal model principle of time-varying optimization [8], [9], this generalizes to the requirement that the method must embed knowledge of the exosystem in its dynamics.

Building on this, we now present the main result of this work. To that end, let Δ denote the set of static maps Δ such that $w = \Delta(z)$ if and only if $w_k = \nabla f(z_k)$ for some $f \in \mathcal{F}_{\mu,L}$ with $\nabla f(0) = 0$. Given multi-index $\alpha \in \mathbb{N}^p$ and eigenvalues $\lambda = (\lambda_1, \dots, \lambda_p)$ of S , we define $\lambda^\alpha := \lambda_1^{\alpha_1} \lambda_2^{\alpha_2} \dots \lambda_p^{\alpha_p}$. The set of *harmonics* associated with λ is then

$$\Omega_\lambda := \{\lambda^\alpha \mid \alpha \in \mathbb{N}^p\}. \quad (6)$$

That is, Ω_λ contains all possible products of the eigenvalues of S , including repeated products, and characterizes all modes that can arise from their combinations.

Example 1: If the exosystem contains a single frequency $\phi = \pi/3$, then S has eigenvalues $\lambda = (e^{j\pi/3}, e^{-j\pi/3})$, in which case the set of harmonics is $\Omega_\lambda = \{0, \pm \frac{\pi}{3}, \pm \frac{2\pi}{3}, \pi\}$.

Theorem 1 (Internal model-based optimization design): Let $0 < \mu < L$ and $\rho \in (0, 1)$. Let (A, B, C) be the state-space matrices of an algorithm (4). Then, the following statements are equivalent:

- (i) Algorithm (4) locally asymptotically tracks the optimizer of (1) with rate ρ for all functions f and exosystem trajectories θ that satisfy Assumptions 1 to 3.
- (ii) There exists a proper rational transfer function $K(z)$ such that $G(z) = C(zI - A)^{-1}B$ factors as

$$G(z) = K(z)H(z) \text{ where } H(z) := \frac{z^{|\Omega_\lambda|-1}}{\prod_{\omega \in \Omega_\lambda} (z - \omega)}, \quad (7)$$

and the feedback interconnection of algorithm (4) with uncertainty Δ (see Figure 2) is robustly exponentially stable¹ with rate ρ for all $\Delta \in \Delta$. $\square$

By Theorem 1 designing an algorithm (4) that tracks the optimizer of (1) is equivalent to solving a robust control problem with plant P and uncertainty set Δ . From a control-theoretic viewpoint, the structural condition (7) admits the following interpretation: the transfer function $H(z)$ captures the required internal model through its pole structure and is thus regarded as the *plant*. In turn, $K(z)$ shapes the behavior of $H(z)$ and is therefore interpreted as the *controller*.

Let (A_p, B_p, C_p) state-space realization of the transfer function $H(z)$. By Theorem 1, the algorithm must then have the form shown in Figure 2 (right) with plant

$$\begin{bmatrix} z \\ y \end{bmatrix} = P \begin{bmatrix} w \\ u \end{bmatrix} \quad \text{where} \quad P = \left[\begin{array}{c|cc} A_p & B_p & 0 \\ \hline 0 & 0 & 1 \\ C_p & 0 & 0 \end{array} \right], \quad (8)$$

where P denotes the system operator of the plant. We let $n_p := |\Omega_\lambda|$ denote the plant dimension, which coincides with the number of exosystem harmonics.

The remainder of this section is devoted to proving Theorem 1. The proof relies on two lemmas.

¹Robust exponential stability with rate $\rho \in (0, 1)$ amounts to ensuring that there exists $c > 0$ such that, for all $\Delta \in \Delta$ and all x_0 , the closed-loop state x_k satisfies $\|x_k\| \leq c\rho^k \|x_0\|$ for all $k \geq 0$.

Lemma 1 (Internal model principle): Fix the objective parameters μ and L , exosystem model S , algorithm matrices (A, B, C) , and rate $\rho \in (0, 1)$. Suppose the feedback interconnection of algorithm (4) with uncertainty Δ (see Figure 2 (left)) is robustly locally exponentially stable with rate ρ for all $\Delta \in \Delta$. Then, item (i) in Theorem 1 is equivalent to:

- (iii) There exists an analytic mapping $\sigma : \mathbb{R}^p \rightarrow \mathbb{R}^n$ satisfying the internal model kinematic and output equations:

$$\sigma(S\theta) = A\sigma(\theta) \quad \text{and} \quad \nabla_z f(C\sigma(\theta), \theta) = 0.$$

Proof. The result follows from [8, Theorem 2]. $\blacksquare$

We now explore some consequences of condition (iii). Since σ is real analytic, it admits a (locally convergent) multivariate power series expansion of the form

$$\sigma(\theta) = \sum_{\alpha \in \mathbb{N}^p} c_\alpha \theta^\alpha, \quad \theta^\alpha := \theta_1^{\alpha_1} \dots \theta_p^{\alpha_p}, \quad (9)$$

where the coefficients $c_\alpha \in \mathbb{R}^n$ are uniquely determined. The monomials $\{\theta^\alpha\}_{\alpha \in \mathbb{N}^p}$ form a linearly independent basis for analytic functions, so this representation is unique.

If S is diagonalizable with eigenvalues $\lambda = (\lambda_1, \dots, \lambda_p)$, then in diagonalized coordinates one has $(S\theta)^\alpha = \lambda^\alpha \theta^\alpha$, where $\lambda^\alpha := \lambda_1^{\alpha_1} \dots \lambda_p^{\alpha_p}$. Substituting the expansion into the kinematic relation $\sigma(S\theta) = A\sigma(\theta)$ yields

$$\sum_{\alpha \in \mathbb{N}^p} \lambda^\alpha c_\alpha \theta^\alpha = \sum_{\alpha \in \mathbb{N}^p} A c_\alpha \theta^\alpha.$$

By linear independence of the monomials, the coefficients of each θ^α must match, which gives $(A - \lambda^\alpha I)c_\alpha = 0$ for all $\alpha \in \mathbb{N}^p$. In addition, by the implicit function theorem, there exists an optimizer $z_*(\theta)$ such that $\nabla_z f(z_*(\theta), \theta) \equiv 0$. Since the optimizer is unique, the output condition requires

$$C \sum_{\alpha} c_\alpha y^\alpha = C \tilde{\sigma}(y) = z_*(y) = \sum_{\alpha} d_\alpha y^\alpha,$$

where $d_\alpha \in \mathbb{R}$ are the coefficients in the series expansion of $z_*(y)$. Again matching coefficients gives $C c_\alpha = d_\alpha$. To summarize, a mapping σ with series expansion (9) satisfies the internal model conditions if and only if $(A - \lambda^\alpha I)c_\alpha = 0$ and $C c_\alpha = d_\alpha$ for each multi-index $\alpha \in \mathbb{N}^p$. This insight leads to the following result on the algorithm structure.

Lemma 2 (Algorithm structure): Fix parameters μ and L , exosystem S , and algorithm matrices (A, B, C) . Suppose S is diagonalizable with eigenvalues $\lambda = (\lambda_1, \dots, \lambda_p) \in \mathbb{C}^p$. Then, item (iii) in Lemma 1 is equivalent to the following:

- (iv) For each harmonic $\omega \in \Omega_\lambda$, A has an eigenvalue at ω and the following non-resonance condition holds:

$$\begin{bmatrix} A - \omega I & B \\ C & 0 \end{bmatrix} \text{ full rank.} \quad \square$$

Proof. (iv) $\Rightarrow$ (iii). From (iv), there exists an eigenvector $v_\alpha \in \mathbb{C}^n$ of A with eigenvalue $\lambda^\alpha \in \mathbb{C}$ for each $\alpha \in \mathbb{N}^p$. Moreover, non-resonance implies that $\begin{bmatrix} A - \lambda^\alpha I & B \\ C & 0 \end{bmatrix} \begin{bmatrix} v_\alpha \\ 0 \end{bmatrix}$ is nonzero, so $C v_\alpha \neq 0$. From our previous discussion, the

mapping σ of the form (9) with $c_\alpha = d_\alpha(Cv_\alpha)^{-1}v_\alpha$ satisfies the internal model conditions, so (iii) holds.

(iii) $\Rightarrow$ (iv). Consider the series expansion of σ in (9). Suppose that, for some α , the optimizer contains mode y^α , meaning that $d_\alpha \neq 0$. The conditions on c_α imply that it is an eigenvector of A with eigenvalue $\omega = \lambda^\alpha$. Suppose the non-resonance condition fails with this α . Then there exists a nonzero pair (p, q) such that $\omega p^\top = p^\top A + q^\top C$ and $0 = p^\top B$. Multiplying the kinematic internal model condition on the left by $p^\top$ and using this first equation yields $p^\top \sigma(S\theta) = \omega p^\top \sigma(\theta) - q^\top z^*(\theta)$, where $z^*(\theta) = C\sigma(\theta)$ is the optimizer. Now consider a trajectory θ_k of the exosystem and define $y_k := p^\top \sigma(\theta_k)$. This signal evolves according to the linear difference equation $y_{k+1} - \omega y_k = -q^\top z^*(\theta_k)$, which has natural frequency ω . We can choose f such that its optimal trajectory is such that the forcing term $-q^\top z^*(\theta_k)$ is nonzero at this frequency, which then resonates with the system to grow unbounded. But σ is continuous from (iii) and the exosystem trajectory is bounded from Assumption 2, so y_k must be bounded — a contradiction. Therefore, the non-resonance condition is satisfied, so (iv) holds. ■

We now have the tools required to prove Theorem 1.

Proof of Theorem 1. Item (iv) of Lemma 2 forces the algorithm transfer function $G(z)$ to have a pole at each harmonic $\omega \in \Omega_\lambda$. Therefore, $G(z)$ must factor as (7) for some proper rational transfer function $K(z)$. With this structure, Problem 1 becomes that of designing $K(z)$ such that (4) is robustly exponentially stable for all time-invariant objective functions that satisfy Assumption 1, from which the claim in Theorem 1 follows. ■

IV. ROBUST CONTROL-BASED DESIGN OF METHODS FOR TIME-VARYING OPTIMIZATION

With Problem 1 reformulated as a robust control problem, we now use the convex synthesis methodology from [6], [24] to design the controller $K(z)$. Once obtained, the algorithm transfer function is in (7), the matrices (A, B, C) are any realization of this transfer function, and the algorithm is (4).

A. Transformations

Following this strategy, we first apply a chain of transformations to put the system into standard form [6]. We first exponentially weight the signals so that stability of the transformed system is equivalent to exponential stability of the original system. To that end, define the exponential signal weighting map $T_\rho(z_0, z_1, z_2, \dots) = (z_0, \rho z_1, \rho^2 z_2, \dots)$ with parameter $\rho > 0$. The map T_ρ is linear and invertible with inverse $T_{\rho^{-1}}$. The transformed system is shown in Figure 3. The transformed system is Lyapunov stable² if and only if the original system is exponentially stable with rate ρ [6].

We next filter the input and output of the (transformed) uncertainty through a static filter to produce the signals

²Exponential stability means there exists $c > 0$ such that, for every $\bar{x}_0$, $\|\bar{x}_k\| \leq c \rho^k \|\bar{x}_0\|$ for all k . Lyapunov stability is the same with $\rho = 1$.

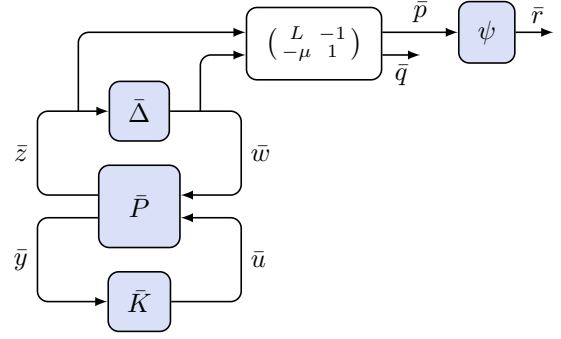


Fig. 3. Equivalent robust control setup after exponential scaling and filtering. Signals are scaled by $T_{\rho^{-1}}$, e.g., $\bar{u} = T_{\rho^{-1}}u$, and the plant is transformed as $\bar{P} = T_{\rho^{-1}} \circ P \circ T_\rho$, and similarly for the uncertainty and controller. The input $\bar{z}$ and output $\bar{w}$ of the transformed uncertainty $\bar{\Delta}$ are then passed through a static map, with the first output $\bar{p}$ then passed through a dynamic filter ψ resulting in $\bar{r}$.

$\bar{p}$ and $\bar{q}$. All admissible trajectories of the transformed system satisfy the passivity property $0 \leq \sum_{k=0}^T \bar{q}_k^\top \bar{p}_k$ for all $T \in \mathbb{N}$ [6]. In fact, we can generate a parameterized set of constraints by filtering $\bar{p}$ through the following system, known as a Zames–Falb multiplier [25],

$$\psi = \left[\begin{array}{c|c} A_f & B_f \\ \hline C_f & D_f \end{array} \right] = \left[\begin{array}{cccc|c} 0 & 1 & \dots & 0 & 0 \\ 0 & 0 & \ddots & \vdots & \vdots \\ \vdots & \vdots & \ddots & 1 & 0 \\ 0 & 0 & \dots & 0 & 1 \\ \hline \lambda_\ell & \lambda_{\ell-1} & \dots & \lambda_1 & \lambda_0 \end{array} \right].$$

The output $\bar{r}$ of this filter also satisfies the passivity property $0 \leq \sum_{k=0}^T \bar{q}_k^\top \bar{r}_k$ for all $T \in \mathbb{N}$ if the filter parameters $\lambda_0, \dots, \lambda_\ell \in \mathbb{R}$ belong to the set

$$\Lambda_\ell^\rho = \left\{ (\lambda_0, \dots, \lambda_\ell) \mid \lambda_1, \dots, \lambda_\ell \leq 0, \sum_{j=0}^{\ell} \rho^{-j} \lambda_j \geq 0 \right\}.$$

The transformed plant combined with the filter yield

$$\left[\begin{array}{c} \bar{r} \\ \bar{y} \end{array} \right] = \left[\begin{array}{cc|cc} A_f & 0 & -B_f & (L - \mu)B_f \\ 0 & \rho^{-1}A_p & \rho^{-1}B_p & \rho^{-1}\mu B_p \\ \hline C_f & 0 & -D_f & (L - \mu)D_f \\ 0 & C_p & 0 & 0 \end{array} \right] \left[\begin{array}{c} \bar{q} \\ \bar{u} \end{array} \right].$$

For notational convenience, we denote this system by

$$\hat{P} = \left[\begin{array}{c|cc} \hat{A} & \hat{B}_w & \hat{B} \\ \hline \hat{C}_z & \hat{D}_{zw} & \hat{D}_z \\ \hline \hat{C} & 0 & 0 \end{array} \right].$$

To summarize, for any transformed uncertainty $\bar{\Delta}$ with $\Delta \in \mathbf{\Delta}$, all trajectories of the transformed system in Figure 3 satisfy the passivity property $0 \leq \sum_{k=0}^T \bar{q}_k^\top \bar{r}_k$ for all $T \in \mathbb{N}$ whenever the filter parameters satisfy $\lambda \in \Lambda_\ell^\rho$.

B. Analysis

Before designing controllers, we begin with the simpler problem of analyzing the convergence rate of a fixed controller. Let K be a controller of dimension n_c , and let $(\mathcal{A}, \mathcal{B}, \mathcal{C}, \mathcal{D})$

denote a state-space realization of the corresponding system from $\bar{q}$ to $\bar{r}$ in Figure 3. To simplify the notation, we define:

$$\mathcal{L}(X, A, B, C, D) = (\cdot)^\top \begin{pmatrix} X & 0 & 0 & 0 \\ 0 & -X & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} A & B \\ I & 0 \\ C & D \\ 0 & 1 \end{pmatrix},$$

$$\mathcal{M}(Y, A, B, C, D) = (\cdot)^\top \begin{pmatrix} Y & 0 & 0 & 0 \\ 0 & -Y & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} -I & 0 \\ A^\top & C^\top \\ 0 & -1 \\ B^\top & D^\top \end{pmatrix},$$

where $(\cdot)$ denotes the corresponding symmetric part of the matrix. We then have the following result.

Proposition 1 (Analysis): If there exists a symmetric matrix $\mathcal{X} \in \mathbb{S}^{n_p + \ell + n_c}$ and filter parameters $\lambda \in \Lambda_\ell^\rho$ such that

$$\mathcal{X} \succ 0 \quad \text{and} \quad \mathcal{L}(\mathcal{X}, A, B, C, D) \prec 0, \quad (10)$$

then the interconnection in Figure 2 (right) is robustly exponentially stable with rate ρ for all uncertainties $\Delta \in \Delta$. $\square$

C. Convex synthesis with fixed multiplier

The analysis condition is not simultaneously convex in $\mathcal{X}$, λ , and K . When λ is fixed, however, the controller synthesis follows from seminal $\mathcal{H}_\infty$ synthesis [26]. To that end, let

$$\hat{U} = \text{diag}(I_\ell, C_{p\perp}, 1), \quad \hat{V}^\top = \begin{bmatrix} B_f^\top & \frac{\mu}{\rho(L-\mu)} B_p^\top & D_f^\top \end{bmatrix}_\perp$$

where $M_\perp$ denotes a matrix whose columns are a basis for the kernel of M . Then, there exists a controller K and matrix $\mathcal{X} \succ 0$ such that the analysis LMI (10) is feasible if and only if there exist symmetric matrices $\hat{X}, \hat{Y} \in \mathbb{S}^{n_p + \ell}$ such that

$$\hat{U}^\top \mathcal{L}(\hat{X}, \hat{A}, \hat{B}_w, \hat{C}_z, \hat{D}_{zw}) \hat{U} \prec 0, \quad (11a)$$

$$\hat{V} \mathcal{M}(\hat{Y}, \hat{A}, \hat{B}_w, \hat{C}_z, \hat{D}_{zw}) \hat{V}^\top \succ 0, \quad (11b)$$

$$\begin{pmatrix} \hat{Y} & I \\ I & \hat{X} \end{pmatrix} \succ 0. \quad (11c)$$

D. Convex synthesis over causal Zames–Falb multipliers

The matrix inequalities in (11) are not linear in λ . For the case of causal Zames–Falb multipliers, however, a clever convexification was discovered in [6]. This convex synthesis approach adapted to our particular setting is as follows.

Define the state transformation matrix

$$T = \begin{bmatrix} (L - \mu)^{-1} I_\ell & 0 \\ (L - \mu)^{-1} N & \sum_{j=0}^{\ell} \lambda_j \rho^j A_p^{-j} \end{bmatrix} = \begin{bmatrix} T_f \\ \tilde{T} \end{bmatrix},$$

where $N \in \mathbb{R}^{n_p \times \ell}$ is the solution to the Sylvester equation

$$A_p N - \rho N A_f + \mu B_p C_f = 0. \quad (12)$$

With the annihilator matrix $V^\top = [\rho^{-1} \mu B_p^\top \quad L - \mu]_\perp$, consider the following matrix inequalities:

$$\hat{U}^\top \mathcal{L}(\hat{X}, \hat{A}, \hat{B}_w, \hat{C}_z, \hat{D}_{zw}) \hat{U} \prec 0, \quad (13a)$$

$$V \mathcal{M}(\tilde{Y}, \rho^{-1} A_p, \tilde{T} \hat{B}_w, 0, \hat{D}_{zw}) V^\top \succ 0, \quad (13b)$$

$$\begin{pmatrix} \tilde{Y} & \tilde{T} \\ \tilde{T}^\top & \hat{X} \end{pmatrix} \succ 0. \quad (13c)$$

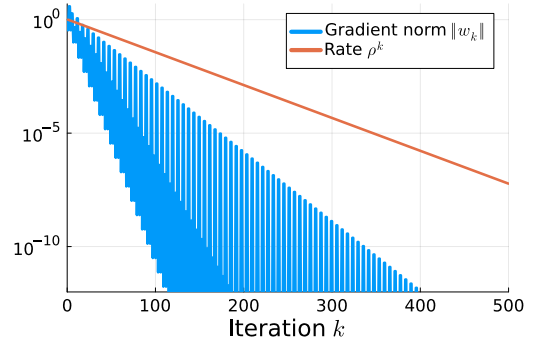


Fig. 4. Simulation of the synthesized controller on a time-varying regularized logistic regression problem; see Section V-A.

We can now state the main convex synthesis result from [6].

Theorem 2: Fix the rate $\rho \in (0, 1)$, number of multipliers $\ell \in \mathbb{N}$, and model $S \in \mathbb{R}^{p \times p}$. The following are equivalent.

- 1) There exists an algorithm (4) such that the analysis LMI (10) is feasible for some $\mathcal{X}$ and $\lambda \in \Lambda_\ell^\rho$.
- 2) There exist matrices $N \in \mathbb{R}^{n_p \times \ell}$, $\hat{X} \in \mathbb{S}^{n_p + \ell}$, and $\tilde{Y} \in \mathbb{S}^{n_p}$ as well as parameters $\lambda \in \Lambda_\ell^\rho$ that satisfy the Sylvester equation (12) and LMIs (13). $\square$

The statements in Theorem 2 imply the existence of a controller for which the algorithm (7) exponentially tracks the optimizer of (1) for all functions f and trajectories θ that satisfy Assumptions 1 to 3. Moreover, these are *convex* constraints and hence provide an efficient procedure to verify the existence of an algorithm that exponentially tracks the optimizer with a given rate; the minimal rate can then be found by bisection over ρ . The controller can then be reconstructed using (10), thereby solving Problem 1.

V. NUMERICAL INVESTIGATION OF THE METHODOLOGY

A. Simulation

Consider the instance of (1) with objective

$$f(z, \theta_k) = \frac{1}{2} (z - e_1^\top \theta_k)^2 + a \log(1 + e^{bz}), \quad (14)$$

where $f : \mathbb{R} \times \mathbb{R}^p \rightarrow \mathbb{R}$ and $e_1 = (1, 0, \dots, 0) \in \mathbb{R}^p$. This models a logistic regression problem with time-varying regularization, which satisfies Assumption 1 with parameters $\mu = 1$ and $L = 1 + \frac{ab^2}{4}$. We used $a = 1$ and $b = 6$, and we generated θ_k with frequencies $\phi = 0$ and $\phi = \pi/3$. The harmonics are those in Example 1, and the transfer function in (7) is $H(z) = z^5/(z^6 - 1)$. The synthesized controller has (approximate) transfer function $K(z) = -0.18/z^5$ with rate $\rho = 0.9672$. In Figure 4, we plot the gradient norm $\|w_k\|$ of the trajectory along with the theoretical rate ρ^k , illustrating that the algorithm achieves exponential tracking.

B. Convergence rates

The convergence rate depends on the objective parameters μ and L , the exosystem S , and the length ℓ of the multiplier used to characterize the gradient. To better understand how the rate varies with these parameters, we plot ρ as a function

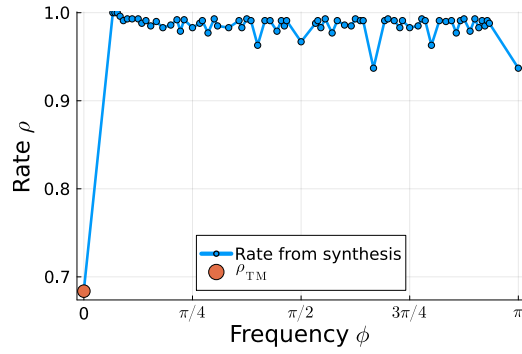


Fig. 5. Rate ρ of the synthesized algorithm as a function of exosystem frequency ϕ with $\mu = 1$, $L = 10$, and $\ell = 1$.

of the exosystem frequency ϕ in Figure 5 with $\mu = 1$, $L = 10$, and $\ell = 1$. The controller is then synthesized using the harmonics Ω_λ , where $\lambda = (e^{j\phi}, e^{-j\phi})$ if $0 < \phi < \pi$, $\lambda = 1$ if $\phi = 0$, and $\lambda = -1$ if $\phi = \pi$. Also shown is the rate of the triple momentum method [27], which achieves the optimal rate $\rho_{\text{TM}} = 1 - \sqrt{\mu/L}$ in the time-invariant case when $\phi = 0$.

We now draw several observations from Figure 5:

- In the low-frequency range of ϕ , the rate appears to decrease with ϕ , indicating that, in some cases, there exists an algorithm that converges at a better rate for faster-varying problems than for slowly varying ones³.
- The rate is significantly slower than the time-invariant counterpart (where $\rho = \rho_{\text{TM}} \approx 0.6838$), even for slow time variations (small $\phi > 0$).

VI. CONCLUSIONS

We showed how to systematically embed internal models into the convex synthesis framework from robust control to design first-order optimization methods for smooth, strongly convex objectives that vary in time. The methodology is constructive and directly implementable whenever a model of the temporal variability is available, thereby enabling principled algorithm design with guaranteed tracking and robustness properties. Extensions include nonlinear exosystem models and adaptive algorithms that estimate the model online.

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³This departs from [28], where, for quadratic objectives, the lower bounds on the convergence rate do *not* depend on the frequency of the temporal variation, but only on the order of the exosystem model. This discrepancy may stem from a limitation of the synthesis, which employs Zames–Falb multipliers with $\ell = 1$, or it may reflect a gap between the theoretical lower bounds and the attainable rates.

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