
Online Optimization with Memory and Competitive Control

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Abstract

This paper presents competitive algorithms for a novel class of online optimization problems with memory. We consider a setting where the learner seeks to minimize the sum of a hitting cost and a switching cost that depends on the previous p decisions. This setting generalizes Smoothed Online Convex Optimization. The proposed approach, Optimistic Regularized Online Balanced Descent, achieves a constant, dimension-free competitive ratio. Further, we show a connection between online optimization with memory and online control with adversarial disturbances. This connection, in turn, leads to a new constant-competitive policy for a rich class of online control problems.

1 Introduction

This paper studies the problem of Online Convex Optimization (OCO) with *memory*, a variant of classical OCO [25] where an online learner iteratively picks an action y_t and then suffers a convex loss $g_t(y_{t-p}, \dots, y_t)$, depending on current and *previous* actions. Incorporating memory into OCO has seen increased attention recently, due to both its theoretical implications, such as to convex body chasing problems [11, 8, 37, 12], and its wide applicability to settings such as data centers [32], power systems [30, 9, 26], and electric vehicle charging [26, 17]. Of particular relevance to this paper is the considerable recent effort studying connections between OCO with memory with online control in dynamical systems, leading to online algorithms that enjoy sublinear static regret [4, 5], low dynamic regret [29, 31], constant competitive ratio [23], and the ability to boost weak controllers [3].

Prior work on OCO with memory is typically limited in one of two ways. First, algorithms with the strongest guarantees, a constant *competitive ratio*, are restricted to a special case known as Smoothed Online Convex Optimization (SOCO), or OCO with switching costs [16, 32, 24], which considers only one step of memory and assumes cost functions can be observed before actions are chosen. Second, algorithms proposed for the general case typically only enjoy sublinear *static regret* [6], which is a much weaker guarantee, because static regret compares to the offline optimal static solution while competitive ratio directly compares to the true offline optimal. It is known that algorithms that achieve sublinear static regret can be arbitrarily worse than the true offline optimal [22], and also may have unbounded competitive ratios [7]. The pursuit of general-purpose constant-competitive algorithms for OCO with memory remains open.

Our work is also motivated by establishing theoretical connections between online optimization and control. Recently a line of work has shown the applicability of tools from online optimization

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for control, albeit in limited settings [4, 5, 28, 23]. Deepening these connections can potentially be impactful since most prior work studies how to achieve sublinear regret compared to the best static linear controller [20, 5, 4, 19]. However, the best static linear controller is a weak benchmark compared to the true optimal controller [22], which may be neither linear nor static. To achieve stronger guarantees, one must seek to bound either the competitive ratio [23] or dynamic regret [29, 31], and connections to online optimization can provide such results. However, prior attempts either have significant caveats (e.g., bounds depend on the path length of the instance [29, 31]) or only apply to very restricted control systems (e.g., invertible control actuation matrices and perfect knowledge of disturbances [23]). As such, the potential to obtain constant-competitive policies for general control systems via online optimization remains unrealized.

Main contributions. We partially bridge the two gaps highlighted above. First, we propose a novel setting, OCO with *structured* memory, where the cost function depends on the previous p decisions and is not known precisely before determining the action. This setting generalizes SOCO to include more than one step of memory and to eliminate the assumption that the cost function must be perfectly known before choosing the action. Second, we propose a novel algorithm, Optimistic Regularized Online Balanced Descent, that has a constant and dimension-free competitive ratio for OCO with structured memory. This is the first algorithm with a constant competitive ratio for online optimization with memory longer than one step. Third, we provide a nontrivial reduction from a rich class of online control problems to OCO with structured memory and, via the reduction, show that a constant-competitive policy exists for this class of control problems. While not completely general, the class of problems is considerably more general than existing settings where competitive policies are known, e.g., the control matrix must be invertible and the disturbances are known in advance [23]. Finally, we use examples to (i) demonstrate the gap between the best offline linear policy and the true optimal offline policy can be arbitrarily large, and (ii) highlight that our algorithms can significantly outperform the best offline linear controller, which serves as the benchmark of no-regret policies.

2 Background and model

In this section, we formally present the problem setting in this paper. We first survey prior work on OCO with memory and then introduce our new model of OCO with structured memory. Throughout this paper, $M_{i:j}$ denotes either $\{M_i, M_{i+1}, \dots, M_j\}$ if $i \leq j$, or $\{M_i, M_{i-1}, \dots, M_j\}$ if $i > j$.

2.1 Online convex optimization with memory

Online convex optimization (OCO) with memory is a variation of classical OCO that was first introduced by Anava et al. [6]. In contrast to classical OCO, in OCO with memory, the loss function depends on previous actions in addition to the current action. At time step t , the online agent picks $y_t \in \mathcal{K} \subset \mathbb{R}^d$ and then a loss function $g_t : \mathcal{K}^{p+1} \rightarrow \mathbb{R}$ is revealed. The agent incurs a loss of $g_t(y_{t-p:t})$. Thus, p quantifies the length of the memory in the loss function. Within this general model of OCO with memory, Anava et al. [6] focus on developing policies with small *policy regret*, which is defined as:

$$\text{PolicyRegret} = \sum_{t=p}^T g_t(y_{t-p:t}) - \min_{y \in \mathcal{K}} \sum_{t=0}^T g_t(y, \dots, y).$$

The main result presents a memory-based online gradient descent algorithm that achieves $O(\sqrt{T})$ regret under some moderate assumptions on the diameter of \mathcal{K} and the gradient of the loss functions.

Online convex optimization with switching costs (SOCO). While the general form of OCO with memory was introduced only recently, specific forms of OCO problems involving memory have been studied for decades. Perhaps the most prominent example is OCO with switching costs, often termed Smoothed Online Convex Optimization (SOCO) [32, 14, 16, 23, 30, 24]. In SOCO, the loss function is separated into two pieces: (i) a *hitting cost* f_t , which depends on only the current action y_t , and a *switching cost* $c(y_t, y_{t-1})$, which penalizes big changes in the action between rounds. Often the hitting cost is assumed to be of the form $\|y_t - v_t\|$ for some (squared) norm, motivated by tracking some unknown trajectory v_t , and the switching cost c is a (squared) norm motivated by penalizing switching in proportion to the (squared) distance between the actions, e.g., a common choice $c(y_t, y_{t-1}) = \frac{1}{2} \|y_t - y_{t-1}\|_2^2$ [23, 30]. The goal of the online learner is to minimize its total cost over T rounds: $\text{cost}(\text{ALG}) = \sum_{t=1}^T f_t(y_t) + c(y_t, y_{t-1})$.

Under SOCO, results characterizing the policy regret are straightforward, and the goal is instead to obtain stronger results that characterize the *competitive ratio*. The competitive ratio is the worst-case ratio of total cost incurred by the online learner and the offline optimal. The cost of the offline optimal is defined as the minimal cost of an algorithm if it has full knowledge of the sequence $\{f_t\}$, i.e.: $\text{cost}(OPT) = \min_{y_1 \dots y_T} \sum_{t=1}^T f_t(y_t) + c(y_t, y_{t-1})$. Using this, the *competitive ratio* is defined as:

$$\text{CompetitiveRatio}(ALG) = \sup_{f_{1:T}} \frac{\text{cost}(ALG)}{\text{cost}(OPT)}.$$

Bounds for competitive ratio are stronger than for policy regret, since the dynamic offline optimal can change its decisions on different time steps [6].

In the context of SOCO, the first results bounding the competitive ratio focused on one-dimensional action sets [33, 10], but after a long series of papers there now exist algorithms that provide constant competitive ratios in high dimensional settings [16, 23, 24]. Among different choices of switching cost c , we are particularly interested in $c(y_t, y_{t-1}) = \frac{1}{2} \|y_t - y_{t-1}\|_2^2$ due to the connection to quadratic costs in control problems. The state-of-the-art algorithm for this switching cost is Regularized Online Balanced Descent (ROBD), introduced by Goel et al. [24], which achieves the lowest possible competitive ratio of any online algorithm. Other recent results study the case where $c(y_t, y_{t-1}) = \|y_t - y_{t-1}\|$ [11, 8, 37, 12]. Variations of the problem with predictions [14, 15, 30], non-convex cost functions [35], and constraints [34, 40] have been studied as well.

2.2 OCO with structured memory

Though competitive algorithms have been proposed for many SOCO instances, the SOCO setting has two limitations. First, the hitting cost f_t is revealed before making action y_t , i.e., SOCO requires one step exact prediction of f_t . Second, the switching cost in SOCO only depends on one previous action in the form $c(y_t, y_{t-1})$, so only one step of memory is considered. In this paper, our goal is to derive competitive algorithms (as exist for SOCO) in more general settings where more than one step of memory is considered. Working with the general model of OCO with memory is too ambitious for this goal. Instead, we introduce a model of OCO with *structured* memory that generalizes SOCO, and is motivated by a nontrivial connection with online control (as shown in Section 4.2).

Specifically, we consider a loss function g_t at time step t that can be decomposed as the sum of a hitting cost function $f_t : \mathbb{R}^d \rightarrow \mathbb{R}^+ \cup \{0\}$ and a switching cost function $c : \mathbb{R}^{d \times (p+1)} \rightarrow \mathbb{R}^+ \cup \{0\}$. Additionally, we assume that the switching cost has the form:

$$c(y_{t:t-p}) = \frac{1}{2} \left\| y_t - \sum_{i=1}^p C_i y_{t-i} \right\|_2^2,$$

with known $C_i \in \mathbb{R}^{d \times d}$, $i = 1, \dots, p$. Note that SOCO is a special case $p = 1$ and $C_1 = I$. As we show in Section 4.2, this form connects online optimization with online control. Intuitively, this connection results from the fact that the hitting cost penalizes the agent for deviating from an optimal point sequence, while the switching cost captures the cost of implementing a control action. Specifically, suppose y_t is a robot's position at t , and then the classical SOCO switching cost $\|y_t - y_{t-1}\|_2$ is approximately its velocity. Under our new switching cost, we can represent acceleration by $\|y_t - 2y_{t-1} + y_{t-2}\|_2$, and many other higher-order dynamics.

To summarize, we consider an online agent and an offline adversary interacting as follows in each time step t , and we assume y_i is already fixed for $i = -p, -(p-1), \dots, 0$.

1. The adversary reveals a function h_t and a convex *estimation set* $\Omega_t \subseteq \mathbb{R}^d$. We assume h_t is both m -strongly convex and l -strongly smooth, and that $\arg \min_y h_t(y) = \mathbf{0}$.
2. The agent picks $y_t \in \mathbb{R}^d$.
3. The adversary picks $v_t \in \Omega_t$.
4. The agent incurs *hitting cost* $f_t(y_t) = h_t(y_t - v_t)$ and *switching cost* $c(y_{t:t-p})$.

Notice that the hitting cost f_t is revealed to the online agent in two separate steps. The geometry of f_t (given by h_t whose minimizer is at $\mathbf{0}$) is revealed before the agent picks y_t . After y_t is picked, the minimizer v_t of f_t is revealed.

Unlike SOCO, due to the uncertainty about v_t , the agent cannot determine the exact value of the hitting cost it incurs at time step t when determining its action y_t . To keep the problem tractable, we

Algorithm 1: Regularized OBD (ROBD), Goel et al. [24]

Parameter: $\lambda_1 \geq 0, \lambda_2 \geq 0$

for $t = 1$ **to** T **do**

Input: Hitting cost function f_t , previous decision points y_{t-p}, \dots, y_{t-1}

$v_t \leftarrow \arg \min_y f_t(y)$

$y_t \leftarrow \arg \min_y f_t(y) + \lambda_1 c(y, y_{t-1:t-p}) + \frac{\lambda_2}{2} \|y - v_t\|_2^2$

Output: y_t

assume an estimation set Ω_t , which contains all possible v_t 's, is revealed to bound the uncertainty. The agent can leverage this information when picking y_t . SOCO is a special case where Ω_t contains only one point, i.e., $\Omega_t = \{v_t\}$, and then the agent has a precise estimate of the minimizer v_t when choosing its action [23, 24]. Like SOCO, the offline optimal cost in the structured memory model is defined as $\text{cost}(OPT) = \min_{y_1 \dots y_T} \sum_{t=1}^T f_t(y_t) + c(y_{t:t-p})$ given the full sequence $\{f_t\}_{t=1}^T$.

3 Algorithms for OCO with memory

In OCO with structured memory, there is a key differentiation depending on whether the agent has knowledge of the hitting cost function (both h_t and v_t) when choosing its action or not, i.e., whether the estimation set Ω_t is a single point, v_t , or not. We deal with each case in turn in the following.

3.1 Case 1: exact prediction of v_t ($\Omega_t = \{v_t\}$)

We first study the simplest case where $\Omega_t = \{v_t\}$. Recall that Ω_t is the convex set which contains all possible v_t and so, in this case, the agent has exact knowledge of the hitting cost when picking action. This assumption, while strict, is standard in the SOCO literature, e.g., [23, 24]. It is appropriate for situations where the cost function can be observed before choosing an action, e.g., [30, 26, 23].

Our main result in this setting is the following theorem, which shows that the ROBD algorithm (Algorithm 1), which is the state-of-the-art algorithm for SOCO, performs well in the more general case of structured memory. Note that, in this setting, the smoothness parameter l of hitting cost functions is not involved in the competitive ratio bound.

Theorem 1. *Suppose the hitting cost functions are m -strongly convex and the switching cost is given by $c(y_{t:t-p}) = \frac{1}{2} \|y_t - \sum_{i=1}^p C_i y_{t-i}\|_2^2$, where $C_i \in \mathbb{R}^{d \times d}$ and $\sum_{i=1}^p \|C_i\|_2 = \alpha$. The competitive ratio of ROBD with parameters λ_1 and λ_2 is upper bounded by:*

$$\max \left\{ \frac{m + \lambda_2}{m\lambda_1}, \frac{\lambda_1 + \lambda_2 + m}{(1 - \alpha^2)\lambda_1 + \lambda_2 + m} \right\},$$

if $\lambda_1 > 0$ and $(1 - \alpha^2)\lambda_1 + \lambda_2 + m > 0$. If λ_1 and λ_2 satisfy $m + \lambda_2 = \frac{m + \alpha^2 - 1 + \sqrt{(m + \alpha^2 - 1)^2 + 4m}}{2} \cdot \lambda_1$, then the competitive ratio is:

$$\frac{1}{2} \left(1 + \frac{\alpha^2 - 1}{m} + \sqrt{\left(1 + \frac{\alpha^2 - 1}{m} \right)^2 + \frac{4}{m}} \right).$$

The proof of Theorem 1 is given in Appendix C. To get insight into Theorem 1, first consider the case when α is a constant. In this case, the competitive ratio is of order $O(1/m)$, which highlights that the challenging setting is when m is small. It is easy to see that this upper bound is in fact tight. To see this, note that the case of SOCO with ℓ_2 squared switching cost considered in Goel and Wierman [23], Goel et al. [24] is a special case where $p = 1, C_1 = I, \alpha = 1$. Substituting these parameters into Theorem 1 gives exactly the same upper bound (including constants) as Goel et al. [24], which has been shown to match a lower bound on the achievable cost of any online algorithm, including constant factors. On the other hand, if we instead assume that m is a fixed positive constant. The competitive ratio can be expressed as $1 + O(\alpha^2)$. Therefore, the competitive ratio gets worse quickly as α increases. This is also the best possible scaling, achievable via any online algorithm, as we show in Appendix D.

Perhaps surprisingly, the memory length p does not appear in the competitive ratio bound, which contradicts the intuition that the online optimization problem should get harder as the memory length increases. However, it is worth noting that α becomes larger as p increases, so the memory length implicitly impacts the competitive ratio. For example, an interesting form of switching cost is

$$c(y_{t:t-p}) = \frac{1}{2} \left\| \sum_{i=0}^p (-1)^i \binom{p}{i} y_{t-i} \right\|_2^2,$$

which corresponds to the p^{th} derivative of y and generalizes SOCO ($p = 1$). In this case, we have $\alpha = 2^p - 1$. Hence α grows exponentially in p .

3.2 Case 2: inexact prediction of v_t ($v_t \in \Omega_t$)

For general Ω_t , ROBD is no longer enough. It needs to be adapted to handle the uncertainty that results from the estimation set Ω_t . Note that this uncertainty set is crucial for many applications, such as online control with adversarial disturbances.

To handle this additional complexity, we propose Optimistic ROBD (Algorithm 2). Optimistic ROBD is based on two key ideas. The first is to ensure that the algorithm tracks the sequence of actions it would have made if given observations of the true cost functions before choosing an action. To formalize this, we define the *accurate sequence* $\{\hat{y}_1, \dots, \hat{y}_T\}$ to be the choices of ROBD (Algorithm 1) with $\lambda_1 = \lambda$, $\lambda_2 = 0$ when each hitting cost f_t is revealed before picking \hat{y}_t . The goal of Optimistic ROBD (Algorithm 2) is to approximate the accurate sequence. In order to track the accurate sequence, the first step is to recover it up to time step $t - 1$ at time step t . To do this, after we observe the previous minimizer v_{t-1} , we can compute the accurate choice of ROBD as if both h_{t-1} and v_{t-1} are observed before picking y_{t-1} . Therefore, Algorithm 2 can compute the *accurate subsequence* $\{\hat{y}_1, \dots, \hat{y}_{t-1}\}$ at time step t . Picking y_t based on the accurate sequence $\{\hat{y}_1, \dots, \hat{y}_{t-1}\}$ instead of the noisy sequence $\{y_1, \dots, y_{t-1}\}$ ensures that the actions do not drift too far from the accurate sequence.

Algorithm 2: Optimistic ROBD

Parameter: $\lambda \geq 0$

for $t = 1$ **to** T **do**

Input: v_{t-1}, h_t, Ω_t

 Initialize a ROBD instance with $\lambda_1 = \lambda, \lambda_2 = 0$

 Recover $f_{t-1}(y) = h_{t-1}(y - v_{t-1})$

$\hat{y}_{t-1} \leftarrow \text{ROBD}(f_{t-1}, \hat{y}_{t-p-1:t-2})$

$\tilde{v}_t \leftarrow \arg \min_{v \in \Omega_t} \min_y h_t(y - v) + \lambda c(y, \hat{y}_{t-1:t-p})$

 Estimate $\tilde{f}_t(y) = h_t(y - \tilde{v}_t)$

$y_t \leftarrow \text{ROBD}(\tilde{f}_t, \hat{y}_{t-p:t-1})$

Output: y_t (the decision at time step t)

The second key idea is to be optimistic by assuming the adversary will give it $v \in \Omega_t$ that minimizes the cost it will experience. Specifically, before v_t is revealed, the algorithm assumes it is the point in Ω_t which minimizes the weighted sum $h_t(y - v) + \lambda c(y, \hat{y}_{t-1:t-p})$ if ROBD is implemented with parameter λ to pick y . This ensures that additional cost is never taken unnecessarily, which could be exploited by the adversary. Note that $\min_y h_t(y - v) + \lambda c(y)$ is strongly convex with respect to v (proof in Appendix E), so it is tractable even if Ω_t is unbounded.

Our main result in this paper (Theorem 2) bounds the competitive ratio of Optimistic ROBD.

Theorem 2 (Main result). *Suppose the hitting cost functions are both m -strongly convex and l -strongly smooth and the switching cost is given by $c(y_{t:t-p}) = \frac{1}{2} \|y_t - \sum_{i=1}^p C_i y_{t-i}\|_2^2$, where $C_i \in \mathbb{R}^{d \times d}$ and $\sum_{i=1}^p \|C_i\|_2 = \alpha$. For arbitrary $\eta > 0$, the cost of Optimistic ROBD with parameter $\lambda > 0$, is upper bounded by $K_1 \text{cost}(OPT) + K_2$, where:*

$$K_1 = (1 + \eta) \max \left\{ \frac{1}{\lambda}, \frac{\lambda + m}{(1 - \alpha^2)\lambda + m} \right\}, K_2 = \lambda \left(\frac{l}{1 + \eta - \lambda} + \frac{4\alpha^2}{\eta} - \frac{m}{\lambda + m} \right) \sum_{t=1}^T \frac{\|v_t - \tilde{v}_t\|_2^2}{2}.$$

The proof of Theorem 2 is given in Appendix E. This proof is nontrivial and relies on the two key ideas we mentioned before. Although Theorem 2 does not apply to the case $\lambda = 0$, we discuss it separately in Appendix F. Also, note that we can choose η to balance K_1 and K_2 and obtain a competitive ratio, in particular the smallest η such that:

$$\lambda \left(\frac{l}{1 + \eta - \lambda} + \frac{4\alpha^2}{\eta} - \frac{m}{\lambda + m} \right) \leq 0.$$

Therefore, we have $\eta = O(l + \alpha^2)$ and $K_2 \leq 0$. So the competitive ratio is upper bounded by:

$$O\left((l + \alpha^2) \max\left\{\frac{1}{\lambda}, \frac{\lambda + m}{(1 - \alpha^2)\lambda + m}\right\}\right).$$

However, the reason we present Theorem 2 in terms of K_1 and K_2 is that, when the diameter of Ω_t is small, we can pick a small η so that the ratio coefficient K_1 will be close to the competitive ratio of ROBD when v_t is known before picking y_t . This “beyond-the-worst-case” analysis is useful in many applications and we discuss it more in Section 4.3.

4 Application to competitive online control

Goel and Wierman [23] show a connection between SOCO and online control in the setting where disturbance is perfectly known at time step t and the control actuation matrix B is invertible, which leads to the only constant-competitive control policy as far as we know. Since the new proposed OCO with structured memory generalizes SOCO, one may expect its connects to more general dynamical systems. In this section, we present a nontrivial reduction from *Input-Disturbed Squared Regulators (IDSRs)* to OCO with structured memory, leading to the first constant-competitive policy in online control with adversarial disturbance.

4.1 Control setting

Input-disturbed systems. We focus on systems in controllable canonical form defined by:

$$x_{t+1} = Ax_t + B(u_t + w_t), \quad (1)$$

where $x_t \in \mathbb{R}^n$ is the state, $u_t \in \mathbb{R}^d$ is the control, and $w_t \in \mathbb{R}^d$ is a potentially adversarial disturbance to the system. We further assume that (A, B) is in controllable canonical form (see the right equation), where each $*$ represents a (possibly) non-zero entry, and the rows of B with 1 are the same rows of A with $*$ [36]. It is well-known that any controllable system can be linearly transformed to the canonical form. This system is more restrictive than the general form in linear systems. We call these *Input-Disturbed* systems, since the disturbance w_t is in the control input/action space. There are many corresponding real-world applications that are well-described by Input-Disturbed systems, e.g., external/disturbance force in robotics [38, 39, 18].

$$A = \begin{bmatrix} 0 & 1 & 0 & \dots & 0 \\ 0 & 0 & 1 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \dots & 1 \\ * & * & * & \dots & * \\ & & & & 0 & 1 & 0 & \dots & * \\ & & & & & 0 & 0 & 1 & 0 \\ & & & & & \vdots & \vdots & \vdots & \vdots \\ * & * & * & \dots & * & & & & 1 \\ & & & & & & & & \vdots \\ & & & & & & & & 0 & 1 & 0 & \dots & 0 \\ & & & & & & & & & 0 & 0 & 1 & \dots & 0 \\ & & & & & & & & & \vdots & \vdots & \vdots & \vdots & \vdots \\ & & & & & & & & & 0 & 0 & 0 & \dots & 1 \\ * & & & & & & & & & * & * & * & \dots & * \end{bmatrix}, \quad B = \begin{bmatrix} 0 & 0 & \dots & 1 \\ 0 & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \dots & 0 \\ 1 & 0 & \dots & 0 \\ 0 & 0 & \dots & 0 \\ 0 & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \dots & 0 \\ 0 & 1 & 0 & \dots \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \dots & 0 \\ 0 & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \dots & 1 \\ 0 & 0 & \dots & 1 \end{bmatrix}$$

Squared regulator costs. We consider the following cost model for the controller:

$$c_t(x_t, u_t) = \frac{q_t}{2} \|x_t\|_2^2 + \frac{1}{2} \|u_t\|_2^2, \quad (2)$$

where q_t is a positive scalar. The sequence $q_{0:T}$ is picked by the adversary and revealed online. The objective of the controller is to minimize the total control cost $\sum_{t=0}^T c_t(x_t, u_t)$. We call this cost model the *Squared Regulator* model, which is a restriction of the classical quadratic cost model. This class of costs is general enough to address a fundamental trade-off in optimal control: the trade-off between the state cost and the control effort [27].

Disturbances. In the online control literature, a variety of assumptions have been made about the noise w_t . In most works, the assumption is that the exact noise w_t is not known before u_t is taken. Many assume w_t is drawn from a certain known distribution, e.g., Agarwal et al. [5]. Others assume w_t is chosen adversarially subject to $\|w_t\|_2$ being upper bounded by a constant W , e.g., Agarwal et al. [4]. In a closely related paper, Goel and Wierman [23] connect SOCO with online control under the assumption that w_t can be observed before picking the control action u_t . In contrast, in this paper we assume that the exact w_t is not observable before the agent picks u_t . Instead, we assume a convex estimation set W_t (not necessarily bounded) that contains all possible w_t is revealed to the online agent to help the agent decide u_t . Our assumption is a generalization of Goel and Wierman [23], where W_t is a one-point set, and Agarwal et al. [4], where W_t is a ball of radius W centered at $\mathbf{0}$. Our setting can also naturally model time-Lipschitz noise, where w_t is chosen adversarially subject to $\|w_t - w_{t-1}\|_2 \leq \epsilon$, by picking W_t as a sphere of radius ϵ centered at w_{t-1} , which has many

real-applications such as smooth disturbances in robotics [38, 39]. Moreover, note that our setting is naturally adaptive because of the estimation set W_t (e.g., controller may choose more aggressive action if W_t is small), which is different from the classic \mathcal{H}_∞ control setting [41].

Competitive ratio. Our goal is to develop policies with constant (small) competitive ratios. This is a departure from the bulk of the literature [5, 4, 20, 19], which focuses on designing policies that have low regret compared to the optimal linear controller. We show the optimal linear controller can have cost arbitrarily larger than the offline optimal, via an analytic example (Appendix B). We again denote the offline optimal cost, with full knowledge of the sequence $w_{0:T}$, as $\text{cost}(OPT) = \min_{u_{0:T}} \sum_{t=0}^T c_t(x_t, u_t)$. For an online algorithm ALG , let $\text{cost}(ALG)$ be its cost on the same disturbance sequence $w_{0:T}$. The competitive ratio is then the worst-case ratio of $\text{cost}(ALG)$ and $\text{cost}(OPT)$ over any disturbance sequence, i.e. $\sup_{w_{0:T}} \text{cost}(ALG)/\text{cost}(OPT)$. We show in Section 4.2 an exact correspondence between this $\text{cost}(OPT)$ and the one defined in Section 2.2, so that the competitive ratio guarantees directly translate.

To the best of our knowledge, the only prior work that studies competitive algorithms for online control is Goel and Wierman [23], which considers a very restricted system with invertible B and known w_t at step t . A related line of online optimization research studies *dynamic regret*, or *competitive difference*, defined as the difference between online algorithm cost and the offline optimal [31, 29]. For example, Li et al. [31] bound the dynamic regret of online control with time-varying convex costs with no noise. However, results for the dynamic regret depend on the path-length or variation budget, not just system properties. Bounding the competitive ratio is typically more challenging.

4.2 A reduction to OCO with structured memory

We now present a reduction from *IDS*R, introduced in Section 4.1, to OCO with structured memory. This reduction allows us to inherit the competitive ratio bounds on Optimistic ROBD for this class of online control problems. Before presenting the reduction, we first introduce some important notations. The indices of non-zero rows in matrix B in (1) are denoted as $\{k_1, \dots, k_d\} := \mathcal{I}$. We define operator $\psi : \mathbb{R}^n \rightarrow \mathbb{R}^d$ as:

$$\psi(x) = \left(x^{(k_1)}, \dots, x^{(k_d)} \right)^\top,$$

which extracts the dimensions in \mathcal{I} . Moreover, let $p_i = k_i - k_{i-1}$ for $1 \leq i \leq n$, where $k_0 = 0$. The controllability index of the canonical-form (A, B) is defined as $p = \max\{p_1, \dots, p_d\}$. We assume that the initial state is zero, i.e., $x_0 = \mathbf{0}$. In the reduction,

we also need to use matrices $C_i \in \mathbb{R}^{d \times d}$, $i = 1, \dots, p$, which regroup the columns of $A(\mathcal{I}, :)$. We define C_i for $i = 1, \dots, p$ formally by constructing each of its columns. For $j = 1, \dots, d$, if $i \leq p_j$, the j th column of C_i is the $(k_j + 1 - i)$ th column of $A(\mathcal{I}, :)$; otherwise, the j th column of C_i is $\mathbf{0}$. Formally, for $i \in \{1, \dots, p\}$, $j \in \{1, \dots, d\}$, we have:

$$C_i(:, j) = \begin{cases} A(\mathcal{I}, k_j + 1 - i) & \text{if } i \leq p_j \\ \mathbf{0} & \text{otherwise.} \end{cases}$$

Based on coefficients $q_{0:T}$, we define:

$$q_{\min} = \min_{0 \leq t \leq T-1, 1 \leq i \leq d} \sum_{j=1}^{p_i} q_{t+j}, \quad q_{\max} = \max_{0 \leq t \leq T-1, 1 \leq i \leq d} \sum_{j=1}^{p_i} q_{t+j},$$

where we assume $q_t = 0$ for all $t > T$.

Theorem 3. Consider *IDS*R where the cost function and dynamics are specified by (2) and (1). We assume the coefficients $q_{t:t+p-1}$ are observable at step t . Any instance of *IDS*R in controllable canonical form can be reduced to an instance of OCO with structured memory by Algorithm 3.

Algorithm 3: Reduction to OCO with memory

Input: Transition matrix A and control matrix B

Solver: OCO with structured memory algorithm ALG

for $t = 0$ **to** $T - 1$ **do**

Observe: x_t, W_t , and $q_{t:t+p-1}$

if $t > 0$ **then**

$w_{t-1} \leftarrow \psi(x_t - Ax_{t-1} - Bu_{t-1})$

$\zeta_{t-1} \leftarrow w_{t-1} + \sum_{i=1}^p C_i \zeta_{t-1-i}$

$v_{t-1} \leftarrow -\zeta_{t-1}$

 Define $h_t(y) = \frac{1}{2} \sum_{i=1}^d \left(\sum_{j=1}^{p_i} q_{t+j} \right) \left(y^{(i)} \right)^2$

 Define $\Omega_t = \{-w - \sum_{i=1}^p C_i \zeta_{t-i} \mid w \in W_t\}$

 Feed v_{t-1}, h_t, Ω_t into ALG

 Obtain ALG's output y_t

$u_t \leftarrow y_t - \sum_{i=1}^p C_i y_{t-i}$

Output: u_t

Output: $u_T = 0$

A proof and an example of Theorem 3 are given in Appendix G. Notably, $\text{cost}(\text{OPT})$ and $\text{cost}(\text{ALG})$ remain unchanged in the reduction described by Algorithm 3. In fact, Algorithm 3, when instantiated with Optimistic ROBD, provides an efficient algorithm for online control. It only requires $O(p)$ memory to compute the recursive sequences. As stated in Algorithm 3 the recursive computation of y_t and ζ_t may have numerical issues. However this can be addressed in a straightforward manner when the algorithm is instantiated with Optimistic ROBD (see Appendix H).

4.3 Competitive policy

The reduction in Section 4.2 immediately translates the competitive ratio guarantees in Section 3 into competitive policies. As Theorem 2 suggests, we can tune η in Optimistic ROBD based on the quality of prediction. As a result, we present two forms of upper bounds for Algorithm 3 in Corollaries 1 and 2. Notably, Corollary 1 gives a tighter bound where good estimations are available, while Corollary 2 gives a bound that does not depend on the quality of the estimations.

In the first case, we assume that a good estimation of w_t is available before picking u_t . Specifically, we assume the diameter of set W_t is upper bounded by ϵ_t at time step t , where ϵ_t is a small positive constant. We derive Corollary 1 by setting $\eta = 1 + \lambda$ in Theorem 2.

Corollary 1. *In IDSR, assume that coefficients $q_{t:t+p-1}$ are observable at time step t . Let $\alpha = \sum_{i=1}^q \|C_i\|_2$, where $C_i, i = 1, \dots, p$ are defined as in Section 4.2. When the diameter of W_t is upper bounded by ϵ_t at time step t , the total cost incurred by Algorithm 3 (using Optimistic ROBD with parameter λ) in the online control problem is upper bounded by $K_1 \text{cost}(\text{OPT}) + K_2$, where:*

$$K_1 = (2 + \lambda) \cdot \max \left\{ \frac{1}{\lambda}, \frac{\lambda + q_{\min}}{(1 - \alpha^2)\lambda + q_{\min}} \right\}, K_2 = \lambda \left(\frac{q_{\max}}{2} + \frac{4\alpha^2}{1 + \lambda} - \frac{q_{\min}}{\lambda + q_{\min}} \right) \cdot \sum_{t=0}^{T-1} \frac{1}{2} \epsilon_t^2.$$

The residue term K_2 in Corollary 1 becomes negligible when the total estimation error $\sum_{t=0}^{T-1} \epsilon_t^2$ is small, leading to a pure competitive ratio guarantee. Further, if we ignore K_2 , the coefficient K_1 is only constant factor worse than the ratio we obtain when exact prediction of w_t is available.

However, the bound in Corollary 1 can be significantly worse than the case where exact prediction is available when the diameter of W_t is large or unbounded. Hence we introduce a second corollary that does not use any information about w_t when picking u_t . Specifically, we assume the diameter of set W_t cannot be bounded, so the upper bound given in Corollary 1 is meaningless. By picking the parameter η such that $\lambda \left(\frac{l}{1+\eta-\lambda} + \frac{4\alpha^2}{\eta} - \frac{m}{\lambda+m} \right) \leq 0$ in Theorem 2, we obtain the following result.

Corollary 2. *In IDSR, assume that coefficients $q_{t:t+p-1}$ are observable at time step t . Let $\alpha = \sum_{i=1}^q \|C_i\|_2$, where $C_i, i = 1, \dots, p$ are defined as in Section 4.2. The competitive ratio of Algorithm 3, using Optimistic ROBD with λ , is upper bounded by:*

$$O \left((q_{\max} + 4\alpha^2) \max \left\{ \frac{1}{\lambda}, \frac{\lambda + q_{\min}}{(1 - \alpha^2)\lambda + q_{\min}} \right\} \right).$$

Compared with Corollary 1, Corollary 2 gives an upper bound that is independent of the size of W_t . It is also a pure constant competitive ratio, without any additive term. However, the ratio is worse than the case where exact prediction of w_t is available, especially when q_{\max} or α is large.

Contrasting no-regret and constant-competitive guarantees. The predominant benchmark used in previous work on online control via learning is *static regret* relative to the best linear controller in hindsight, i.e., $u_t = -K^*x_t$ [19, 2, 4, 5, 20, 21, 1]. For example, Agarwal et al. [5] achieve logarithmic regret under stochastic noise and strongly convex loss, and Agarwal et al. [4] achieve $O(\sqrt{T})$ regret under adversarial noise and convex loss. However, the cost of the optimal linear controller may be far from the true offline optimal cost. Goel and Hassibi [22] recently show that there is a linear regret between the optimal offline linear policy and the true offline optimal policy in online LQR control. Thus, achieving small regret may still mean having a significantly larger cost than optimal. We illustrate this difference and our algorithm's performance by a 1-d analytic example (Appendix B), and also numerical experiments in higher dimensions (Section 4.4). In particular, we see that the optimal linear controller can be significantly more costly than the offline optimal controller and that Optimistic ROBD can significantly outperform the optimal linear controller.

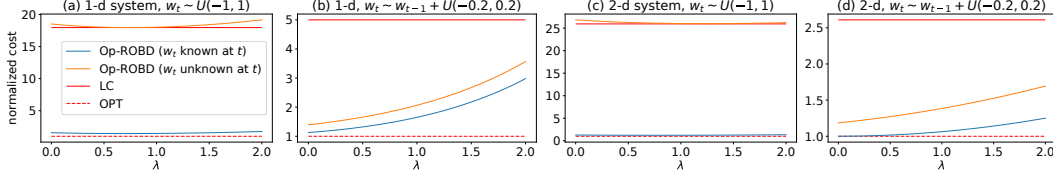


Figure 1: Numerical results of Optimistic ROBD in 1-d and 2-d systems, with different λ . LC means the best linear controller in hindsight and OPT means the global optimal controller in hindsight. LC is numerically searched in stable linear controller space. We consider two different types of w_t : w_t is i.i.d. random/random walk, and also two different settings: w_t is known/unknown at step t .

4.4 Numerical results

In this section we use simple numerical examples to illustrate the contrast between the best linear controller in hindsight and the optimal offline controller. We also test our algorithm, Optimistic ROBO, and then numerically illustrate that Optimistic ROBD can obtain near-optimal cost and outperform the offline optimal linear controller.

In the first example we consider a simple 1-d system, where the object function is $\sum_{t=0}^{200} 8|x_t|^2 + |u_t|^2$ and the dynamics is $x_{t+1} = 2x_t + u_t + w_t$. For the sequence $\{w_t\}_{t=0}^T$, we consider two cases, in the first case $\{w_t\}_{t=0}^T$ is generated by $w_t \sim \mathcal{U}(-1, 1)$ i.i.d., and in the second case the sequence is generated by $w_{t+1} = w_t + \psi_t$ where $\psi_t \sim \mathcal{U}(-0.2, 0.2)$ i.i.d.. The first case corresponds to unpredictable disturbances, where the estimation set $W_t = (-1, 1)$, and the second to smooth disturbances (i.e., a random walk), where $W_t = w_{t-1} + (-0.2, 0.2)$. For both types of $\{w_t\}_{t=0}^T$, we test Optimistic ROBD algorithms in two settings: w_t is known/unknown at step t . In the first setting, w_t is directly given to the algorithm, and in the latter setting, only W_t is given at time step t .

The results are shown in Figure 1 (a-b). We see that if w_t is known at step t , Optimistic ROBD is much better than the best linear controller in hindsight, and almost matches the true optimal when w_t is smooth. In fact, when w_t is smooth, Optimistic ROBD is much better than the best linear controller even if it does not know w_t at step t . Even in the case when $w_t \sim \mathcal{U}(-1, 1)$, and so is extremely unpredictable, Optimistic ROBD's performance still matches the best linear controller, which uses perfect hindsight.

Our second example considers a 2-d system with the following objective and dynamics:

$$\min_{u_t} \sum_{t=0}^{200} 8\|x_t\|_2^2 + \|u_t\|_2^2, \quad \text{s.t. } x_{t+1} = \begin{bmatrix} 0 & 1 \\ -1 & 2 \end{bmatrix} x_t + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u_t + \begin{bmatrix} 0 \\ 1 \end{bmatrix} w_t,$$

where (A, B) is the canonical form of double integrator dynamics. For this 2-d system, similarly, we test the performance of Optimistic ROBD with two types of w_t .

The results are shown in Figure 1 (c-d) and reinforce the same observations we observed in the 1-d system. In particular, we see that the optimal linear controller can be significantly more costly than the offline optimal controller and that Optimistic ROBD can outperform the optimal linear controller, sometimes by a significant margin.

5 Concluding remarks

We conclude with several open problems and potential future research directions. Our results show the existence of constant-competitive algorithms in a novel class of online optimization with memory, which generalizes SOCO. We also show the existence of constant-competitive control policies in *Input-Disturbed Squared Regulators (IDSRs)*, which is more general than prior work [23]. Following on our work, it will be interesting to understand the breadth of the class of online optimization problems that admit constant-competitive algorithms, and the breath of the class of online control problems where constant-competitive policies exist. Obtaining results (positive or negative) is an important and challenging future direction.

Broader Impact

Online convex optimization with switching cost (SOCO) has been widely used in commercial and industrial applications such as data centers, power systems, and vehicle charging. By proposing a generalization of SOCO together with new algorithms with competitive ratio guarantees in this setting, this paper opens a new set of applications for online optimization. Additionally, the results provide new fundamental insights about the connection between online optimization and control. However, like many other theoretical contributions, this paper’s results are limited to its assumptions, e.g., strongly convex cost functions.

We see no ethical concerns related to the results in this paper.

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